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An Object-Oriented
Computer Aided Design Program
for
Traditional Control Systems Analysis

THESIS

Wayne E. Bell, 1LT, USAF

AFIT/GE/ENG/92D-03

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THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Electrical Engineering

Wayne E. Bell, B.S.
1LT, USAF

December 1992

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Preface

When I began doing homework in the controls sequence here at AFIT, it quickly became obvious that all work had to be done on a computer. The complexity of the available software became obvious just as quickly. MatLab, $Matrix_X$, and Mathmatica were all available, but only on the Sun workstations at school, and they weren't very user friendly. ICECAP-PC quickly became the program of choice because of its user friendly interface and its availability on home computers. However, ICECAP-PC's shine began to tarnish as the coursework became more advanced and ICECAP-PC proved to be highly unreliable and underpowered.

Being a programmer from way back, I took it upon myself to be the champion of the Class of '92 and began debugging ICECAP-PC. What began as an interest became an obsession and grew into the scope of an entire thesis. ICECAP-PC was really the perfect thesis topic for me. My primary sequence is Digital Engineering and my secondary sequence is Digital Controls. The algorithms, literature reviews, example problems, etc. associated with working on ICECAP-PC provided a remarkable education in both Digital Engineering and Controls. And extending ICECAP-PC into the QFT toolboxes provided an opportunity to learn some things beyond just traditional control algorithms.

ICECAP-PC version 10 represents the extent of the work I and Fred Trevino have been able to achieve in bringing ICECAP-PC into the 21st Century. I only hope that thesis workers will follow us sooner than we followed our predecessors. The longer the code is left without thesis students, the harder it is for the new students to bring it back up to speed with current technology. However, we have provided ICECAP-PC thesis students with an object-oriented, algorithmically sound foundation for at least five years of adding new toolboxes. This means that follow-on students can add toolboxes for LQG, Kalman filtering, Butterworth filter templates, Lag-Lead controller design, discrete QFT, nonlinear QFT, etc. before any of them have to worry about porting to the latest language. My guess is that the next port will be to

a Microsoft Windows environment that is hosted within a 64-bit operating system (no 640K barrier due to DOS). This is fully possible using the new Borland PASCAL 7.0. Whatever ICECAP-PC's future code development holds, I firmly believe students are better off using ICECAP-PC than they are using the commercial packages. ICECAP-PC teaches the process more than just spitting out a computer generated answer.

I would like to thank Dr Horowitz for his many pearls of wisdom on both life and QFT. It is indeed an honor to have such an esteemed man of history as part of my thesis committee. I also thank Dr Houpis for being another controls powerhouse on my committee. I especially want to mention his work in putting together the QFT Symposium. That symposium and the Proceedings had to be the single largest contributor to my education in QFT. And to meet the people whose names were on all the papers and texts I have read was truly significant.

And now for a man who deserves his own paragraph on this page of personal salutes: Dr Lamont. Never again should such a respectable professor have to persevere such an obnoxious thesis student as I. As much as Fred is every professors wet dream, I am the nightmare that wakens them at night in a cold sweat. Thank you, Dr Lamont, for being a helluva guy to hang around at OktoberFests and for being just as helluvan educator. P.S. If you ***ever*** add any FORTRAN code to our beautiful PASCAL, I'll come back for a PhD!

On a personal level, I thank my wife Donna for living through all the nights the tippy-tapping on the keyboard kept her awake till dawn. And I thank her for all those *other* nights she was awake till dawn. I also thank my venerable thesis buddy, Fred-dude. Bravo for his understanding of object-oriented code, matrix algorithms, and loud-mouthed lieutenants ("kids"). Don't you all just love old guys?

Wayne E. Bell

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Abstract

This thesis is a continuation of the ICECAP-PC research project conducted under Prof. Gary B. Lamont at the Air Force Institute of Technology. It is an ongoing development of a public domain Computer Aided Design package for Control Engineering and Digital Signal Processing students, faculty and practitioners with a special emphasis on education.

This investigation begins with the software maintenance task of restructuring, debugging, and testing the functional version of ICECAP-PC 9.0. This is done for both transfer function and matrix portions of the package as well as continuous and discrete portions. The continuous, traditional portions are then ported to a new object-oriented program structure which is the primary focus of this effort. New interactive graphics capabilities are then added as well as new procedures for the time and frequency response plots. All basic math algorithms are rewritten to be more accurate within a contemporary personal computer environment. All algorithms are optimized for speed, performance, and memory requirements on personal computers. A new user-programmable macro file capability is then designed and implemented to assist in the black box testing of the new code. Finally, using a program extension concept called a toolbox, a Multiple-Input-Single-Output (MISO) Quantitative Feedback Theory (QFT) toolbox is created. This toolbox allows manual, interactive, and automatic QFT design for continuous, linear, time invariant MISO control system problems.

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1 Introduction

Computer Aided Control System Design (CACSD) software development is an inherently complex process because of (1) the multitude of mathematical operations and capabilities required, and (2) the variety of requirements posed by the end users. Most programs today are modular in structure and tasks are compartmentalized into functional procedures (subroutines). User commands given are processed through a hierarchical tree of procedures until the commanded function is fully executed. Relatively new, and growing rapidly, is the use of object-oriented programming (OOP) techniques. While the software engineering community embraces this technique with open arms, other engineering disciplines, control systems engineering included, have been slow to adopt this technology. This is unfortunate since object-orientation provides an ideal structure for CACSD program design, because structural complexities are elegantly resolved. This thesis will break new ground in applying OOP to CACSD software.

This chapter will introduce this topic by presenting a history of CACSD development, then a history of ICECAP-PC development, and finally the goals of this thesis effort.

1.1 History of CACSD [Kheir, 1988]

The evolution of CACSD directly follows the evolution of control system theory itself. The defense industry has been the major driving force in the development of automatic control

systems since World War II as increasingly sophisticated weapon systems have been needed. In the period between 1930 to 1950, the largest category of problems was the SISO (Single-Input Single-Output) systems, and design was predominantly performed in the frequency domain. Prominent figures were W. R. Evans and H. Nyquist. Early control system problems were solved without the aid of computers, and only simple cases (by today's standards) could be considered.

As systems became more complex and MIMO (Multiple-Input Multiple-Output) problems were presented, the frequency domain graphical techniques of the earlier decades failed to produce solutions. Among others, R. Kalman led engineers into the time domain where systems were represented in state space by a set of first-order differential equations in place of nth-order ordinary differential equations. Concurrent with these developments was the advent of the computer age. Engineers began producing code to solve very specific problems. However, there was no single collection of routines unified under a single package until the late seventies. [Dongarra, 1979; O'Brian, 1977; Smith, 1976] In the early days of computing, the largest obstacle was the lack of interactive systems. Programs were placed on punch cards and run in batch mode--a process that was extremely time consuming.

In the early seventies, researchers began to again look at the frequency domain for control systems solutions, and diversification of theory began to rapidly take place. Different approaches were presented for different classes of problems. Concurrent with these developments, was the development of collections of routines, each being developed for a specific purpose. In 1977, Fredrick L. O'Brian in his masters thesis at the Air Force Institute of Technology developed the *Consolidated Computer Program for Control System Design* which was a collection of these routines. [O'Brian, 1977] In 1978, follow on work at AFIT produced TOTAL, recognized as the first interactive CACSD program. In 1979, another such product, INTOPS was produced. In the fall of 1989, K. J. Åström and G. Golub held the first

Conference On Numerical Techniques in Control. At this conference, Cleve Moler, demonstrated the newly released MATLAB software package which has since become the most widely used program for control systems design.

MATLAB was not designed for CACSD use at all and had many shortcomings. [Kheir, 1988:644] Several other software programs have since come to the surface to address these shortcomings including Matrix_X by Integrated Systems and Control-C from Systems Control. Many of these programs, now much more mature, offer considerable power but come at considerable price. There still exists a need for a quality public domain CACSD program directed at the educational community. ICECAP-PC fulfills this requirement.

1.2 History of ICECAP-PC

Since 1977, graduate students at the Air Force Institute of Technology (AFIT), under the direction of Prof. Gary B. Lamont, have contributed to the Interactive Control Engineering Computer Analysis Package (ICECAP-PC) program. ICECAP-PC traces its origin to a masters thesis entitled *Consolidated Computer Program for Control System Design* by Fredrick L. O'Brian. [O'Brian, 1977] As a follow on effort, Stanley Larimer, in his thesis effort entitled *An Interactive Computer-Aided Design Program for Discrete and Continuous Control System Analysis and Synthesis* created the program known as TOTAL. [Larimer, 1978] TOTAL incorporated the ability to analyze systems in both the discrete and the continuous time domains and was developed in FORTRAN for the CDC Cyber. In 1981, Glen Logan rehosted TOTAL for the DEC VAX-11/780 and renamed the program ICECAP-PC. In 1982, Charles Gembarowski researched human factors engineering concepts and added the menu driven interface implemented in Pascal. Work continued on the VAX version of ICECAP-PC through many thesis cycles and in 1985, Susan Mashiko and Gary Tarczynski developed the program for the personal computer, renaming it ICECAP-PC. This version of ICECAP-PC went through

nine design revisions, the last being 9.0. The current task and subject of this thesis development is the rehosting of ICECAP-PC into an object-oriented (OO) format and the expansion of its capabilities through add-on modules called *toolboxes*.

Object-orientation provides an advanced logic and implementation structure, and effectively addresses the software engineering issues of extendibility, maintainability, reusability, etc. Additionally, the addition of toolboxes provides extended capabilities to ICECAP-PC by implementing new control system theories without modification of the core ICECAP-PC code. In this latest edition of ICECAP-PC, both MISO and MIMO QFT toolboxes are included.

ICECAP-PC is a public domain CACSD tool targeted for educational use. Every effort is made to ensure that ICECAP-PC Release 10 is mathematically correct, rich in capability, and both easy and quick to use. The purpose is simply to challenge the state-of-the-art in CACSD software design. Thus, the new ICECAP-PC is easier to use, more accurate, faster, leaner, more capable, and more robust than any prior version.

1.3 General Objectives

This project encompassed three basic objectives: The development of an object-oriented, user friendly CACSD environment, the refinement of numerical methods used by ICECAP-PC in the solution of modern and classical control problems, and the development and inclusion of MISO and MIMO QFT toolboxes. For a discussion of the modern controls and MIMO QFT toolbox, reference [Trevino, 1992].

The long-standing guiding goal for ICECAP-PC design has always been to emphasize an educational interface and data presentation, while at the same time emphasizing algorithm design and computational power. Because of this, most ICECAP-PC functions have at least two options for the user: interactive design for the new student and automatic mode for the

advanced user. The interactive screens hold the student's hand and walk him through the design process teaching him the techniques the computer uses to generate its results. In automatic mode, ICECAP-PC executes its algorithms with no interaction with the student and quickly produces its results.

1.3.1 The Object-Oriented CACSD Environment. The first general objective is to provide a CACSD environment to perform basic control system analysis functions. These functions include polynomial and matrix manipulations and time and frequency domain analysis. The environment must also include a user-friendly interface including graphical presentations, help, and macro facilities. While these exist already in the current functional version of ICECAP-PC, they are not provided with the sophistication available with modern software design techniques. In the case of ICECAP-PC, both structural and interface sophistication are lacking. Very few engineering programs are written with human factors concepts included in the design process. A good interface is not merely a luxury but frees the engineer to concentrate on the problem at hand not having to struggle with the computer itself.

1.3.2 The Refinement Of Numerical Methods. The second objective, the refinement of numerical methods used in ICECAP-PC is important for two reasons. First, mathematical procedures of previous ICECAP-PC versions are dated, having been developed in the late seventies and early eighties. Much progress has been made since then, and even the standard usage of Linpack [Dongarra, 1979] and Eispack [Smith, 1976] routines no longer provides optimal speed and accuracy. Second, the mathematical engine of previous ICECAP-PC versions was developed by a series of control systems engineering students with little focus on computer engineering and numerical methodology. The current thesis work is being

accomplished by students with primary experience in digital and software engineering and secondary experience in control engineering. As a result, the algorithms in the previous ICECAP-PC mirrored solution techniques taught in standard math courses taken by engineering students. Some of these methods can be unstable or inaccurate when coded into a computer program. A very good example of this is the quadratic equation. Coding the quadratic equation directly can yield very large roundoff error in the vicinity of $b^2 \approx 4ac$, because the subtraction of small similar numbers on a computer leads to a loss of significant digits. However, a more computer-optimized numerical solution of the quadratic equation is easily obtained from a number of numerical methods texts and is now included in ICECAP-PC.

This investigation specifically revises the algorithms used for polynomial and transfer function manipulation, including basic math operations as well as response type algorithms. This effort also provides a new mathematical engine, including transcendental functions, basic math, and numerical conditioning. Much additional work in this area is reported in [Trevino, 1992].

1.3.3 Toolboxes. In order to project ICECAP-PC into the future, it is necessary to provide extendibility of the basic ICECAP-PC program. While the basic ICECAP-PC provides many useful functions, it does not include many of the more powerful and recent control theories such as H_∞, LQG and QFT. An early design decision [Trevino, 1992] was to provide hooks for their future implementation using a toolbox concept. In this new concept, future control engineering students can add to ICECAP-PC by devising a toolbox to implement a specific theory. In fact, the final design goal is the development of QFT toolboxes for the solution of MISO and MIMO control systems problems. This is of special interest to the Air Force and to flight control problems because of its ability to incorporate plant variation. While

much work has been done in the area of MISO QFT program design [Yaniv, 1992; Sating, 1992; Bailey, 1992], this research seeks a program specifically tailored to educational purposes. The referenced CAD packages are all used in educational environments; however, each is designed to be more functional than tutorial. For example, their help systems provide information on how to use the programs, but no tutorial insight into the underlying equations and assumptions or engineering insight into the design process. Also each package uses advanced computer algorithm techniques to enhance the QFT design process (e.g. Sating's use of M_L contour tangency to templates instead of the traditional UHFB). While it is desirable to eventually include as many of these advanced techniques as possible in ICECAP-PC, it is the primary goal of ICECAP-PC to provide the traditional techniques the student must learn in order to solve QFT design problems by hand. Therefore, the use of the UHFB and the inclusion of interactive boundary specification and interactive loop shaping methodology is appropriate. With these tools, a student can manually generate bounds on a graphics terminal as well as modify the L_o curve. After learning the theory behind these techniques, the student can do subsequent designs in the automatic generation mode or using some advanced computer techniques.

1.4 Report Organization

This report presents the results of this design effort by developing three subject areas (object-oriented design, user-interface and Quantitative Feedback Theory) from general concept to specific implementation. **Chapter 2** presents the research conducted. It does so in a general manner exploring numerous alternatives and discussing basic concepts. **Chapter 3** gives a set of specific requirements for ICECAP-PC based on the research presented in **Chapter 2**. **Chapters 4 and 5** discuss the actual design and implementation of ICECAP-PC. The discussion of **Chapter 4** presents the development of the ICECAP-PC 9.0A code from the

version 9.0 code, the porting of the ICECAP-PC 9.0A into the new object-oriented version 10, and the design of the new user interface. **Chapter 5** presents both an in-depth look at the toolbox concept and specifically at the MISO QFT toolbox. **Chapter 6** provides a discussion on the testing methodology used in the development of the ICECAP-PC code in general and of the numerical methods developed. **Chapter 7** contains the concluding remarks and recommendations for future ICECAP-PC development.

1.5 Summary

In summary, this investigation covers three major engineering disciplines. First, OO software engineering--the ability to design, write, and validate OO computer programs--is central to this effort. Second, the coding of advanced control system algorithms and the application of problem solving techniques are equally important. Third, mathematical rigor is fundamental to any CACSD program and much attention is paid to this discipline in this investigation.

2 Technical Review

This chapter presents the research conducted in preparation for the project design. A literature review and investigation are accomplished in three subject areas: (1) OO modeling and design, (2) user interfaces, and (3) quantitative feedback theory. Thus it forms a general basis of knowledge upon which program specifications are constructed and a final design implemented. A literature review of OO modeling and design was considered necessary to provide the techniques necessary to redesign ICECAP-PC into an OO environment. A literature review of user-interfaces was accomplished in order to piggy-back on the extensive work already accomplished in the field of human factors engineering by government researchers and software publishing companies. A literature review of QFT was necessary to provide a full understanding of the assumptions and theory underlying a computer-based implementation of QFT design. The only other area in which a literature review was deemed necessary to this thesis development is in the area of numerical analysis. This review topic is addressed in [Trevino, 1992].

Section 2.1, *Object-Oriented Design Discussion and Terminology,* gives a general discussion on the emerging and still somewhat nebulous field of OO analysis (OOA), modeling, and design (OOD). Object-orientation is not a mere program structure, but a unique logic methodology that views a problem space in a different context than any classical problem solving approach. An OO structure models the real world, which is a collection of things or objects, more closely than a functionally decomposed design. As mentioned above, it is still a developing field, and there are as many modeling systems as there are authors; all of which differ in syntax but agree in basic logical decomposition. This project adheres to the modeling system presented by Rumbaugh as well as borrowing some ideas from Pressman. [Rumbaugh, 1991; Pressman, 1987]

Section 2.2, *Literature Review of Human Interface Design,* examines user interfaces of existing computer software packages as well as Human Factors Engineering (HFE: the science which studies human interaction with machines) guidance on the topic. A full understanding of HFE was crucial to the successful completion of this project, and much work was accomplished to insure that the ICECAP-PC user interface was efficient for the advanced user while at the same time tutorial for the beginning student.

Section 2.3, *Literature Review of the Quantitative Feedback Theory*, covers the mathematical and theoretical foundations of the Quantitative Feedback Theory developed by Dr Isaac Horowitz. This section is included herein because it forms the general basis of knowledge for the development of the MISO QFT and MIMO QFT toolboxes.

Another research topic of special interest to this project is the design of numerical algorithms. This research is presented by another student who was also involved in the ICECAP-PC project [Trevino, 1992]. The reader is referred to this study for the general conceptual development of the numerical engine within ICECAP-PC.

2.1 Object-Oriented Design Discussion and Terminology

In the software design process, the objective is to develop a high-level design and then to decompose this design into lower level modules until reaching the primitive level (implementation/coding). Two software design approaches to decomposition are functional and object-oriented design (OOD).

Most packages today are written using functional programming techniques. Tasks are modularized into functional procedures (subroutines). Commands given by the user are processed through a hierarchical tree of procedures until the commanded function is fully carried out. Thus a functional program is a collection of sequential statements which the

program sequentially executes, operating on its information in the way each program line instructs.

An OO program is also modular except the modules are objects. Objects are executable records that contain both data and procedures (methods) that operate on that data. Further, OO programs are not sequential in nature but are event-driven. An event is, for example, the user selecting a command from a menu object. The menu object contains an event-handler that sends appropriate messages to the other objects in the program telling each of them what object function the user has asked to be performed. Each object can operate on its data in order to achieve that function. Thus the big difference between OO programs and functional programs can be viewed as nouns doing verbs (objects responding to messages) instead of verbs acting on nouns (sequential statements doing something to stored data). This section explains what is involved in using OOD, and what advantages and disadvantages OOD has over functional design.

2.1.1 Terminology. In order to understand OOD, the reader needs a comprehensive understanding of the terms used in the OO field. The following section is an exhaustive dictionary of the terms used in this section.

Abstract Data Types: Examples of data types can include integers, characters, and boolean variables. However, the state of the data can be viewed after associated operations. A more formal method of defining these data types is the concept of abstract data types (ADT). By formal definition, an ADT is a three-tuple, (D, F, A), where D represents the domains of the data type, F the functions, methods, or operations on the data type, and A is a set of axioms (first-order predicate calculus) that encode the desired semantics of the operations. Generally, an ADT is an encapsulated data structure and associated operations without an explicit enumeration of the axioms in order to provide ease of development. The

invisibility of an ADT's state and the separation of its interface component from its implementation are the distinguishing features which separate an ADT from a simple data type such as an integer.

Object: In order to understand the concept of an object, several preliminary concepts dealing with computers and computer programs must be understood. All computer programs operate on structured data sets. Typical data structures are stacks, queues, arrays and records. A reasonably new and important data structure is that of an object. An object is an instance of an *object class ADT* and contains both data and methods (executable procedures) that operate on that data. Thus an object is unlike other typical computer data structures because it can modify its information and can send instructions to other objects to change their information. An object is implemented in a computer program by three main parts: its *data*, an *event handler*, and *methods*. Two of these are, in fact, the (D, F) of the ADT data type mentioned previously. The domain *data* is the useful information the object maintains and is stored in the computer's memory under the object's name. The *event handler* is a listing of messages to which the object can respond and the functional *methods* the object should enact if the corresponding message is received. The *methods* are the typical computer program instructions which operate on the object's information and which send messages to other objects.

Methods: As was mentioned previously in the definition of Object, methods (also called operations or functions) are executable procedures that operate on the object's data. Their counterpart in functional programming would be subroutines. The set of object methods can be further classified by their functional type. Although these terms are useful for understanding, most applications do not classify specific object operational types.

Constructors: These methods generate or construct memory locations for an object's instantiated (see below) variables.

Destructors: These methods remove an instantiated object from the computer's memory and release that memory for later use.

Selectors: These methods perform a selection of the current state generally to output some data or make a decision as to the next process (a series of tasks or methods).

Iterators: These operations perform an iteration over the object data structure.

Exceptions: These methods, after determining that an error has occurred, perform a desired set of tasks.

Class: A class is a higher level of abstraction than an object, that is, a set of objects can share a common structure and common behavior. A class is defined as a collection of operations (methods) and the data types the methods operate on. When the data and methods can be accessed by other objects, they are visible by definition. If they can not be accessed by another object, then the data and methods are defined as invisible; i.e., information hiding. The class interface consists of public (visible) elements, private (not visible) elements, and protected (visible only to subclasses) elements. In selecting a class, the criteria includes reusability, complexity, and applicability. This definition represents a general ADT concept as previously presented.

Instantiation: An object is by definition an instantiation or instance of a class. An instance can be thought of as the variable name where the class is the type the variable name is defined as being. So while a class defines the methods to operate on data and describes the data types to describe the data structure, classes do not contain any real data until they are instantiated into existence as an object. Objects of the same class, therefore, share the same methods but not the same instantiated variables! Two objects of the same class may each own a variable named DATA_ITEM, but if Object1 changes its instance of the variable, the DATA_ITEM in Object2 is unchanged. However, the method they each run to modify that DATA_ITEM is indeed the same method inherited from their common parent class.

Inheritance: An important property of an object is *inheritance*. Class inheritance is a relationship among classes whereby one class shares the structure and behavior defined in one or more other classes. An object by definition inherits the methods and data types of its associated class when it is instantiated. Thus, under instantiation, unique data variables are created for the object, but the class methods are used for the object methods. In addition the instantiated object can have new code defining its own unique methods. This is called *polymorphism* and is discussed later. An inheritance hierarchy of objects is a tree structure that permits any object in the tree to inherit and operate using any method or data type in an object class higher in the tree. Thus the object has inherited the methods and data structures higher in the tree. The utility of this inheritance is that once an object type has been fully written and tested, the programmer never needs to modify it again. These same tested capabilities can be used by future objects by simply declaring them to be children of the first object's class. This vastly simplifies the process of software development and maintenance providing far better reusability than simple functional software design.

Inheritance and instantiation differ in the way they are implemented in different programming languages. Object classes in Turbo Pascal V 6.0 are defined with the **type** statement and brought into existence upon being instantiated in the **var** section of the program. For example, an object called NewPoly, an instantiation of class PolyObjectType which is a child of the parent class DataIOType, could be declared with the statements in **Listing 1**.

In this example, a parent object class called DataIOType is defined to have three polynomials (two operands and a result) and basic file I/O procedures to retrieve and store the polynomials to file. The object class PolyObjectType is declared as a child of DataIOType. Thus, it *inherits* all three polynomials and the two I/O procedures (methods) from DataIOType. They are present in PolyObjectType just as though they had been explicitly declared. Note

```
PROGRAM SomeProgram;
TYPE

Polynomial = Array[1..Max_Coefficients] of real;

{Parent Object Class Declaration}
DataIOType = object
     {Data Structures}
     Poly1      : Polynomial;
     Poly2      : Polynomial;
     Poly3      : Polynomial;
     {Methods}
     PROCEDURE : RetrievePoly(PolyName: String; var OutPoly: Polynomial);
     PROCEDURE : StorePoly(PolyName: String; var OutPoly: Polynomial);
end;

{Child Object Class Declaration}
PolyObjectType = object(DataIOType)
     {No new data structures}
     {Some new methods}
     CONSTRUCTOR: Init;
     PROCEDURE  : HandleEvent(EventType); {EventType is a reserved word}
     PROCEDURE  : AddPoly(InPoly1,InPoly2: Polynomial: var OutPoly: Polynomial);
     PROCEDURE  : MultPoly(InPoly1,InPoly2: Polynomial: var OutPoly: Polynomial);
     DESTRUCTOR : Done;
end;

VAR
       NewPoly  : PolyObjectType;

BEGIN
       NewPoly.Init;
       ...
       ...
       NewPoly.Done;
END.
```

Listing 1 Basic Inheritance

further that PolyObjectType has an event handler, a constructor and a destructor. The HandleEvent method is necessary for external communication (message reception) with other objects. The constructor initializes a specific instance of the PolyObjectType class when a variable of the type PolyObjectType is instantiated. In this case, NewPoly becomes a specific instantiation of the class PolyObjectType. Each such variable declaration constitutes an instantiation of PolyObjectType and this can be accomplished as many times as the programmer desires.

The above example clearly demonstrates the principles of inheritance and instantiation. Inheritance defines the structure and capabilities of an object class while

instantiation defines lines of ownership and control of actual data. The two concepts are quite different and understanding this difference is key to understanding OOP.

Polymorphism: If a child class redefines a method of its parent class, it is said to be *polymorphing* that method. For example, if the previous example class PolyObjectType defined a method called RetrievePoly just like in its parent, and then changed the program statements RetreivePoly executes, then one would say PolyObjectType polymorphed the method RetreivePoly. [Borland, undated:95]

Object-Oriented Analysis (OOA): OOA is an approach to problem definition and partitioning. OOA initially generates the high level design of objects from which OOD is then initiated. OOA attempts to identify the classes and objects that model the application context. Domain analysis attempts to identify the classes, objects, operations and relationships that are common to all applications within a specified domain. Classification of classes in this process can be quite difficult in general. Approaches to classification include categorization, clustering and prototyping. Categorization groups entities together based upon properties or characteristics that form a predefined category. Clustering refers to grouping entities according to some high level description such as name. Prototyping refers to the predefining of a prototypical type for a class of objects and other objects are members of that class if they resemble this type. [Pressman, 1987:146-148]

Object-Oriented Design (OOD): OOD is a design methodology using OO decomposition with appropriate icons for 2D presentation. The OOD process consists of identifying the classes and objects at some level of abstraction, identifying the data and operations of each class and object, identifying the relationships between classes and objects, and implementing classes and objects into modules. [Pressman, 1987:334]

Object-Oriented Programming (OOP): OOP is a programming technique in which the data structures are represented as cooperating collections of objects, each object being an

instance of a class within a hierarchy of classes that permit inheritance. OOD and OOP evaluation of objects (or classes) can be done using standard programming discipline metrics such as object coupling, cohesion, sufficiency, completeness and primitiveness. Coupling refers to the relationship between objects, cohesion refers to the relationship between internal object constructs, sufficiency and completeness refer to the object having enough of all possible behaviors so as to be useful, and primitiveness is when a desired program behavior can only be implemented by accessing invisible structures of an object. [Pressman, 1987:230-232]

OOD Notation: Notation of OOD can be expressed in a set of hierarchical graphs: class diagrams, object diagrams, module diagrams, process diagrams, state transition diagrams and timing diagrams. Although not elucidated here, specific icons are associated with the characteristics of each diagram. A class diagram presents each class and its relationship with other classes. The dynamic behavior of the class is represented by a state transition diagram which portrays the transition from state to state as caused by an event as well as the actions resulting from a state change. The object diagram presents each object and its relationship to others. Since objects are created and destroyed during program execution, the object diagram represents the dynamics of the object. Object diagrams are prototypical classifications, so it follows that class and object diagram development documents the logical design of the system. Module diagrams present the encapsulation of classes and objects. All the diagrams should be evaluated in terms of the formerly mentioned programming metrics. Furthermore, message synchronization between objects should be defined on these diagrams. Message synchronization types include simple, synchronous, balking, timeout, and asynchronous.

2.1.2 The OOD Process. The OOD process consists of identifying the classes and objects at some level of abstraction, identifying the data and operations of each class and

object, identifying the relationships between classes and objects, and implementing the classes and objects into modules. OOD allows the programmer to take advantage of three important software design concepts: abstraction, information hiding, and modularity. The process of OOD begins with OOA. Pressman offers an easily understood approach for OOA which is summarized in the following. [Pressman, 1987:334-346]

First, a paragraph is written in plain English language that describes the function to be performed by the computer program. Objects are extracted from the paragraph by underlining the nouns in the sentences. Attributes of objects are extracted by underlining the adjectives of the sentence and grouping them with their associated objects (nouns they modify). Methods are identified by underlining all the verbs, verb phrases, and predicates in the sentences. Attributes of the methods are found by underlining all the adverbs and grouping them with their associated methods (verbs they modify). Now each grouping of objects and methods is identified as either part of the solution or part of the problem. Now the programmer is ready to enter the object-oriented design (OOD) phase.

Again a paraphrased and modified methodology for OOD from the work of Pressman is borrowed. The steps are:

1. Define the problem to be solved.
2. Decompose the problem into objects.
3. Determine each object's required data.
4. Determine each object's required methods.
5. Determine interfaces between objects and methods.
6. Determine a parent-child hierarchy related to the data and methods.
7. Determine inheritance/polymorphism relationships related to the data and methods.
8. Create a user-interface object.

9 Create each object.

The first four steps are already arrived at in the OOA phase of the design. Obviously, there exist many techniques for iteratively applying these four steps further down levels of abstraction until finally arriving at the primitive level. At this lowest level the objects required to solve the problem are obvious, as are the methods they need to perform, and the data they need to own.

Determining interfaces between objects and methods is done by determining how each object depends on the others. From this it can be determined what messages each object needs to send to the other objects and when. Thus event-handling routines are designed for each object, so they can perform the desired methods when the message is received.

The next two steps are very much related and display one of the advantages of OOP at the implementation level. The objects that have methods and data types in common are grouped into classes. These classes can be completely separate from one another, or they may have common data items or common methods. Whenever possible, blocks of code should not be repeated, so the common data and methods are grouped into a class of their own and other classes are made children of that new class. This class may not make sense as an object in itself and there may never be an object who is a direct instantiation of it, but its children have tighter code since they have this *library* of ready-made methods to use.

Now the step of creating an object who serves as the menuing system and output screen interface between the human user and the internal objects is added. This object contains the overall event-handling method as well as most of the file I/O and screen I/O.

The final step is to pick a particular language and implement the design in code. The next section describes just such a language.

2.1.3 Borland Turbo Vision. Borland$_{TM}$ provides an excellent pre-defined object library in its Turbo Vision package available with Turbo Pascal and Turbo C++. The Turbo Vision object library provides a predefined framework to develop OO windowing applications including:

1. Multiple, resizeable, overlapping windows (view the same function on multiple planes such as s, z and w)
2. Mouse support
3. Drop-down menus and dialogue boxes for user input
4. Buttons, scroll bars, check boxes and radio buttons
5. Standardized event handling for keyboard and mouse events
6. Context sensitive help windows

Experience with Turbo Vision has shown that while it presents an extremely steep learning curve, time spent learning it is worthwhile. One word of caution: if the decision is made to build an application with Turbo Vision, the entire project should be built using Turbo Vision objects and standards. Attempting to mix standard functional code with Turbo Vision objects only creates memory and display conflicts. Another point to note is that Turbo Vision programs are not portable between platforms; they are limited to MS-DOS computers.

Turbo Vision consists of a family tree of predefined object types that provide a basic user interface. This tree is shown in **Listing 2**. The term *family tree* is used to indicate the inheritance lines of each object. This is a different concept than a simple hierarchical tree. From **Listing 2**, it is seen that the root object is TObject. TObject has no ancestors and is extremely limited in function. It has a constructor (Constructor INIT), a destructor (Destructor DONE), and a method (Procedure FREE) that disposes of the object and frees its memory. TObject has six children, among whom are TView, TCollection, TStream, and TResourceFile. TView is of primary importance because its children provide the user interface.

```
TObject──┬─TView──┬─TGroup──────┬─TProgram──────────TApplication
         │        │             ├─TDesktop
         │        │             └─TWindow──────────┬─TDialog
         │        │                                └─THistory
         │        ├─TScroller──────TTextDevice──────TTerminal
         │        ├─TScrollBar
         │        ├─TCluster──────┬─TCheckBoxes
         │        │               └─TRadioButtons
         │        ├─TInputLine
         │        ├─THistory
         │        ├─TListViewer───┬─TListBox
         │        │               └─ThistoryViewer
         │        └─TMenuView─────┬─TMenuBar
         │                        └─TMenuBox
         ├─TCollection
         ├─TStream
         └─TResourceFile
```

Listing 2 Abbreviated Turbo Vision Family Tree

TView is the parent to all objects that can write to the screen. The converse is also true; all objects that can write to the screen are children of TView. The Turbo Vision standard is that all screen writes be accomplished via the TView.Draw method. While it is possible to use the standard Pascal **write** and **writeln** statements, it violates the Turbo Vision standard and their use is strongly discouraged. The **writeln** and **read** statements employed for user input are replaced by dialogue boxes which are descendants of TView. TView has another important property worth noting: it is the lowest object on the tree that is capable of message transmission and reception. Thus, any object that needs to communicate with other objects should be a descendant of TView whether or not it displays to the screen. All the workhorse type objects in Turbo Vision are made descendants of TView. For example, a matrix object, a polynomial object, or a transfer function object should all be descendants of TView. TView has several descendants, among whom are TApplication, TDesktop, TMenuBar, TWindow, TDialog, and TScroller. The following discussion is limited to these objects since they are of primary importance. For further information, the Borland Turbo Vision Guide that is packaged with Turbo Pascal is highly recommended. [Borland, 1991]

Also from **Listing 2** it is seen that TApplication is a child of TProgram which is a child of TGroup which is a child of TView. Thus TApplication is a descendant, several generations removed, of TView. *The focal point of any Turbo Vision program is always a child of TApplication which the programmer must define.* This object owns all other objects through instantiation, owns the screen desktop, handles all message dispatching, communicates directly with the main menu, manages idle times, and processes computer errors. Furthermore, there should only be one TApplication object for any given program, because there can only be one desktop area for input and output to occur. Thus, to write a DSP program, for example, the main program would be a child of TApplication. It would be declared in Turbo Vision as shown in **Listing 3**.

```
PDSP = ^TDSP
TDSP = Object(TApplication){Note TDSP is a child of TApplication}
      CONSTRUCTOR: Init;
      PROCEDURE  : HandleEvent(var Event: TEvent); virtual;
      PROCEDURE  : Idle; virtual;
      PROCEDURE  : InitMenuBar; virtual;
      PROCEDURE  : InitStatusLine; virtual;
      PROCEDURE  : OutOfMemory; virtual;
      DESTRUCTOR : Done; virtual;
end;
```

Listing 3 Hypothetical DSP Object Class

From **Listing 3** it is seen that TDSP is a child of TApplication. PDSP is a pointer type to the TDSP type. Turbo Vision makes heavy use of dynamically allocated variables and uses pointers abundantly. Each virtual method listed above is a polymorphed version of identically named methods in ancestor objects. In other words, it is the programmers responsibility to overwrite the ancestor methods in order to fully define the desired interface and program operation--any inherited method not redefined uses its parent's method as is. The InitMenuBar and InitStatusLine methods instantiate the menu bar and status line objects that define the user interface and menu structure. The HandleEvent method processes all events (menu events, mouse events, keyboard events, message broadcast events, etc.) and

sends messages to the proper objects in response to these events. The OutOfMemory method guards against memory overflow errors and the Idle method does background maintenance during idle periods when the user has not requested any commands.

TDialog is a child of TWindow which is a child of TGroup which is a child of TView. Descendants of TDialog provide pop-up dialogue boxes for user input. Dialogue boxes contain radio buttons, check boxes, list boxes, and input lines. Radio buttons are input devices that allows the user to choose only one item among a list of options. Check boxes are input devices that allow the user to choose any combination of items among a list of options. List boxes provide a list of items to choose from such as files on disk or directories. Input lines provide text entry of string variables. Each of these (radio buttons, check boxes, list boxes and input lines) are themselves object descendants of TView. Specifically TRadioButtons is the radio button object, TCheckBoxes is the check box object, TListBox is the list box object and TInputLine is the input line object. Each are polymorphed and instantiated into a descendant of a TDialog object by the programmer. Examples are abundant in the Turbo Vision Guide. [Borland, 1991]

Other objects worth brief mention are TDesktop, TMenuBar, TStatusLine, and TWindow. TDesktop is a child of TGroup which is a child of TView. It is simply the background view upon which all other visible views appear. TMenuBar is the menu bar object that displays and controls drop down menus. TStatusLine provides a bottom frame to display and control shortcut keystrokes and other useful information such as remaining heap size. TWindow is merely a frame that borders views with a frame.

Event Handling is always a big design concern in OOP. In Turbo Vision, all event handling is processed via a TEvent type record. TEvent is a record that identifies the type of event that has occurred and the specific command that has been requested. All events are not commands; however, all commands are events. For example, the movement of a mouse pointer

is not a command, but it is an event. All Turbo Vision objects have event handlers to process TEvent records; however, the polymorphed descendant of TApplication is the focal point for all event handling. Assume the basic event handler in **Listing 4** is defined for the TDSP descendant of TApplication described in **Listing 3**.

```
PROCEDURE TDSP.HandleEvent(var Event: TEvent);
{Note the Event variable is a record of TEvent type}

procedure DosShell;
begin
   ...
end;

begin
   TApplication.HandleEvent(Event);
   if Event.What = evKeyDown then begin
        {Desktop Hotkeys}
        'A', 'a': About;
        'C', 'c': Calculator;
        'X', 'x': DosShell;
   end;

   if Event.What = evCommand then begin
      case event.command of
         cmTFCopy    : Message(TransFunction, evBroadcast, brTFCopy   , nil);
         cmTFDefine  : Message(TransFunction, evBroadcast, brTFDefine , nil);
         cmTFDisplay : Message(TransFunction, evBroadcast, brTFDisplay, nil);
     end;
   end;
end;
```

Listing 4 Event Handler For Hypothetical DSP Object

This example shows the basic operation of a hypothetical TDSP event handler. Note that the first action taken is a call to the parent's event handler (TApplication.HandleEvent). This is to process non-command events such as mouse movement and cursor key presses. Turbo Vision does a nice job of handling these maintenance events and relieves the software engineer from a great burden! If the Event.What field is equal to the predefined integer constant named evKeyDown and the key pressed is an **a**, **c**, or **x**, the appropriate subroutines are called. For proper OOP, these subroutines should be local to the TDSP.HandleEvent method. If the Event.What field is equal to one of the predefined integer constants named cmTFCopy, cmTFDefine, or cmTFDisplay, TDSP.HandleEvent sends a message to an object instantiated as TransFunction. Note that (1) the message is directed to a specific instantiated

object and that (2) message transmission is a predefined function of Turbo Vision. Thus the software engineer is again relieved of a great burden! The message is transmitted as an event of evBroadCast type and sends the command brTF... which is a predefined integer constant (the software engineer must predefine these constants in a global unit). The TransFunction object must then contain its own event handler to receive this message and process it accordingly.

As demonstrated in the previous paragraph, Turbo Vision provides several tools to relieve the software engineer of many mundane chores of interface design while allowing all the benefits of programming in a standard high-level language. Execution speed, numerical precision, and mathematical algorithms are all designed with far greater control and efficiency in a fourth generation language (4GL) than could ever be attained by commercial control system packages designed with their own language interpreters. Once the initial steep obstacle of learning OOP and the Turbo Vision 4GL are mastered, building applications becomes a quick and rewarding task.

2.1.4 Advantages of OOP Over Functional Programming. The following opinions were formed from specific experiences in modifying and debugging the functional version of ICECAP-PC and then translating it into OO code. While the experiences discussed here are from a specific package, they can certainly--based on current literature of similar design projects--be generalized.

A typical danger spot in functional programming is opening a data file in one section of the code and then closing the file in some later section of code. The danger is in forgetting to close the file or in bypassing the close command with an unexpected conditional branching statement. In OOP, a database-type object is used that is the only object in the program that can get and save data from a particular file. Therefore, for each data file only one **open**

command and one **close** command are used for the entire program. This abstracts the file I/O function so that the programmer need only call the database object to read or write to the file without worrying about opening or closing the file. The drawback to this approach is speed. If each read from a data file must open and close the file, reading in an entire frequency response listing will take considerable time. Furthermore, it is easier to store some data files as sequential files, not as random access files which the data base object approach requires. Thus, in some situations the data base concept has been abandoned for the traditional approach; however, strict adherence to a single **open** and **close** command per file is still vehemently enforced.

Another drawback in functional programming is the clutter that arises from the user interface code. Again OOP uses an object to abstract this task from the programmer. The user interface object abstracts the programmer from having to worry about any user I/O while writing the mathematical code, etc. One object deals with user requests and translates them into event messages to be sent to the *workhorse* objects. Likewise, the same object returns the workhorse answers to the user in some appropriate screen format.

The same nature of abstraction in OOP allows the software engineer to abstract a problem to a higher level for debugging or original design. For example, if the programmer is developing code in the math object and needs to tell the user interface object to print an answer to screen, he does not need to know how the user interface object does it, he just sends the user interface object a message telling it what information to print, and the user interface object can take care of it. From the software engineer's point of view during debugging or design, he can design at the highest level of abstraction listing the upper level tasks that need to be done to solve the problem and assume that some object can do each task. Then the programmer moves down one level of abstraction and takes each task and breaks it down into sub-tasks assuming some object (or method) can do each sub-task. This is done down to the

primitive/coding level. Debugging is broken down the same way. The programmer looks at the input and output of the highest level object. If it is wrong, he looks at the input and output of each of the objects in the next level down. He then only has to break down the object that has incorrect output. Because each object is self-contained, it makes maintenance very easy.

After the main objects in the program have been fully defined in terms of what data they need and what methods they need, inheritance is used to decrease the size of the code. Parent objects are defined for all the main categories of workhorse objects. The parent objects contain all the methods that the workhorse objects hold in common. This means that each of the workhorse objects can be smaller because they can globally access the methods they inherit from their parent. The parent contains methods to decipher user textual input, ones to work with data files, and other general purpose type methods.

OOP disciplines produce more reliable code due to modular debugging and using existing objects that have been debugged through years of use. In the case of ICECAP-PC, the benefits of two worlds have been inherited . At the lowest level, the program has its I/O based on a commercially produced and tested package (Turbo Vision). At mid-level, the object methods are based on the basic control system algorithms from ICECAP-PC (developed over several thesis projects and used by a large student body for many years). After the OO program had been tested at all levels of abstraction and it was apparent that each object performed its functions properly and that all the objects communicated among themselves properly, new objects could be added to the existing reliable code with a high degree of confidence in the reliability of the CACSD package as a whole.

The same OOP disciplines produce more maintainable code due to the self-sufficiency of objects. Proper OOP techniques avoid the use of global variables and low functional independence which often plagues functional program modules. If each object is compiled

separately and it responds with expected output responses to test inputs, then it does not display the undesirable dependence qualities of low cohesion or coupling with some other object. This research finds that following proper OOP disciplines results in highly cohesive code, because each object is functionally bound to operate on its data alone. Of course, while objects higher on the parent-child tree own more data, they still perform only one higher level function: it receives messages to change its data in some way, and it can do it. Then that higher level object is made up of smaller objects who are each functionally bound to operate on their more specific piece of data. This recurses down through the object tree until the primitive level is reached. At this lowest level, very cohesive methods (subroutines) are written. In the same way, following proper OOP disciplines results in low coupling between objects, because each object is again functionally bound to operate on its data alone.

2.1.5 Disadvantages of OOP Over Functional Programming. Only two disadvantages with using OOP have been experienced, neither of which are directly related to OOP itself. The first can be attributed to learning a new programming language and learning a new way of thinking about algorithms to solve problems. The second can be attributed to the decision to operate within an MS-DOS environment.

Any time a new programming syntax must be adopted, there is a learning curve that must be overcome. With OOP this is doubly true, because not only must the syntax of Turbo Vision, or some other OO language package, be learned, but the software engineer must also change their logical concept of problem solution. Humans typically think in functional (data flow) terms. For example, if a person wants to sign their name on a piece of paper, the algorithm they might imagine to solve this problem might be:

(a) I hc'd inkpen.

(b) I lay paper flat on table.

(c) I move inkpen to trace out my name.

The person who thinks in terms of objects might imagine this algorithm:

MAN: Name, sign yourself.

NAME: Paper, display me.

PAPER: Hand, lay me flat on the table.

INKPEN: Hand, use me to trace out the NAME pattern on the PAPEP.

In this example, consider the HAND as being the primitive level or the coding level of the methods. Humans tend to think more in terms of the first example scenario; therefore, the transition into OOP is not as intuitively easy as using functional programming techniques.

Any time code is developed within the MS-DOS environment, limitations are placed on how much memory room is available for use by the program. A stack cannot be larger than 64K, variable declarations cannot be larger than 64K, and the compiled program and heap space (dynamic variable space) cannot exceed 640K. The 640K barrier can be overcome in Turbo Pascal by breaking the compiled code into overlay units, but even then each overlay unit cannot be larger than 64K and must be able to be compiled to some extent separately from the other units. These memory restrictions place some limit on how closely a programmer can follow the generally accepted rules of OOP.

2.1.6 Summary of OOD and OOP. Object-oriented design and programming have grown to a standard practice because of benefits over functional design and programming. Such advantages include the reuse of existing software components, more maintainable systems, reduction of developmental risk, and use of OOP language constructs. Disadvantages include the higher cost of development and possible performance degradation

due to message passing, the multi-layer abstraction, hierarchy of classes, and associated memory and execution overhead.

The OO approach generally results in smaller systems because of reusable subsystems and thus are more amenable, providing a economic framework for evolution. The original ICECAP-PC was developed using the functional design approach as were its predecessors. The new OO version of ICECAP-PC provides for better maintenance and user interface.

2.2 Literature Review of Human Interface Design

The quality of a computer package's user-interface is important to the user as well as to the software developer, because if the user does not like to use the software, it may become what the industry calls *shelfware* and never be used. It is a common trap for a software developer to take the attitude that his software is so powerful that the customer would be crazy to not want to use it. But while professional salesmen can make any good package look amazingly powerful during the in-store demonstration, it is the great package that can be brought back to the office and allow the practicing engineers to make it look amazingly powerful. The difference between these good and great packages is the user-interface. Desiring ICECAP-PC to be a great CACSD package, the goal of this thesis effort is to design a user-interface which engineers feel comfortable using.

AFIT thesis students have been developing ICECAP-PC since 1984, and it has gained a large user base that spans the US. It is a living package in that user response forms are constantly received and used to improve the software. The user response forms typically cover three main topics: can a new capability be added to ICECAP-PC, can an existing capability be corrected, and can an interface function be corrected/modified. A vast majority of the response forms and complaints from local users deal with the last topic: user-interface. Many students have at times become frustrated with the ICECAP-PC interface as they spend

valuable homework time traversing the hierarchical menu structure trying to get the package to produce the desired results. Even though advanced users can type in complete strings of commands at one time, access to the underlying commands are still not very easily accessed. This is why it is important for AFIT thesis work to focus on improving the ICECAP-PC user-interface. Furthermore, providing AFIT students and government engineers with a ***free*** CACSD package fills a potentially expensive need for the US Government. Software licenses for commercial packages with no more capability than ICECAP-PC can cost $1000 per user. Thus, ICECAP-PC fills a viable need by remaining a state-of-the-art CACSD package. With new object-oriented technology and advanced menuing techniques along with HFE principles, ICECAP-PC can once again challenge the state-of-the-art in user-interfaces.

The first part of this section describes the current ICECAP-PC user-interface. The second part describes the technical implications of HFE rules to user-interface design. The third part describes the user-interfaces of current commercial packages. The combination of the information described in these sections then produces new design criteria for the improved ICECAP-PC user-interface.

2.2.1 ICECAP-PC 9.0. ICECAP-PC 9.0 has a user-interface that was cutting-edge for its time (mid-80s), but the new graphical user-interfaces of today's commercial software have significantly increased the expectations of today's computer user. The user-interface for ICECAP-PC 9.0 requires typing in command words, offers no mouse-activated menus, offers no *hot keys* (press one function key or CONTROL/ALT key sequence to represent a long command string), offers very rudimentary semi-context-sensitive on-line help, and offers no interactive graphics displays for plots and graphs.

When the user runs ICECAP-PC, they are presented with a listing of the highest level command words--one of which is HELP. HELP can be requested for basic system use or for

specific commands [Moore, 1984:Ch III, 24]. Typing in the word HELP gives pseudo context sensitive help information. At the highest menu level, help can be requested for the overall system instead of a menu item. Help is not available at the dialogue screen levels.

The command listing is in the form of four columns sorted alphabetically across the screen and displayed above a command prompt. The menu command words for different menu levels are grouped sometimes functionally and sometimes logically (Display, Define, Transform but then DSP, QFT). The user types in one of the command words (abbreviations are allowed) at the prompt and is then either presented with a lower level listing of command words or a question-and-answer dialogue screen in which to enter ranges and other parameters required to properly display the requested information. An example of a lower level menu might be if the user types in the command DEFINE at the highest menu level, the next menu level might list MATRIX, POLYNOMIAL, or TRANSFER FUNCTION in order to specify what is to be DEFINED. These lower level menus extend four levels deep at the lowest level, before dialogue screens are finally reached. Two levels deep is the average. Advanced users can avoid reading all the menu listings by typing in a whole sequence of command words at once. For example, if an expert user desired a root locus plot, they could type DISPLAY LOCUS TF2 AUTOMATIC, instead of typing each command separately and waiting for a new menu listing before typing in the next command word. [Moore, 1984:Ch III, 13]

After the user has specified the information they desire to see by entering up to four levels of command words, they then must answer question dialogue screens up to four screens deep. Dialogue screens request the user's desired axis ranges, data format, plot titles, forcing functions, etc. Once the graph or listing is displayed on screen, the user has no way to interact with it. They cannot change the scale or change some model parameter to see how it affects the graph. Their only recourse is to press the ENTER key and be sent all the way

back to the highest menu again where they type in the same command words and reanswer the dialogue screens.

Another symptom of an aging user interface is the uninformative error messages ICECAP 9.0 generates for the user. If the user types in a number wrong-- if they accidentally enter a letter--or if they enter an unrecognized command, the program responds with the message "input not a number" or "invalid command," and returns the user to the blank prompt to reenter the text. It gets worse when an error in the program causes the whole system to crash, because then all the user is given is a cryptic Turbo Pascal error number and the hexadecimal memory location where it occurred, and the program exits unceremoniously to the DOS prompt. All the user can do then is restart the program and begin again.

A third shortcoming of the interface system is that some program commands assume other commands have been previously performed. For example, for no apparent reason to the new user, ICECAP-PC does not display a requested graph. No error message is given; just the wrong graph or an empty graph is displayed. The more experienced user has learned that sometimes hidden sequences of commands must be entered before certain operations perform as desired. To display a root locus of OLTF, it is assumed that OLTF has already been defined. Transforming from the S to the Z domain assumes that the sampling period has already been set under the MODIFY command. Even worse, MultiPlots assume you have already saved the data files using the UPDATE command. To display a *graph* of a frequency response assumes you have already displayed a *listing* of the frequency response. This type of pseudo-error grows more common as the user enters the more advanced toolboxes within ICECAP-PC, like the digital signal processing or the root locus sections.

There are some further annoyances with the graphic routines within ICECAP-PC. First, the dialogue screens for graphics have only a few options per screen so the user is brought through several screens before they see any graphs. Second, the many dialogue

screens do not offer default values for their data fields, and the data must be entered every time because the fields have no memory of what they were the last time. Third, when a frequency response listing for a certain range of frequencies is generated, the graph can be displayed for different ranges of frequencies, but the data file is not regenerated. This means that while the limits of the graph has changed, the resolution of the data has not changed. And the final annoyance is that all graphics displays are non-interactive. Even to just change the range of frequencies displayed on the graph, the user must exit from the graph all the way back to the very top menu and reenter every command and every dialogue screen to redisplay the graph with new limits. And if they want that better resolution, they must first go through all the commands to regenerate the listing of the response data.

In summary, ICECAP-PC offers the functions required to do CACSD, but it lacks the polish today's user expects from a software package. However, while the user must type in command words through several layers of menus to finally get to the data display, at least all their options are always displayed for them at every prompt. So while it is cumbersome to use, users do eventually figure out how to get the results they desire.

2.2.2 Human Factors Engineering. It has not been until the last few years that HFE has become an essential part of software design. It has not been that software designers consider HFE unimportant, they just could not accommodate the added overhead HFE techniques required. The limitations of computer resources in processing power, graphics resolution, and memory size limited software designers to worrying only about accomplishing tasks; limited resources were available for worrying about how a task was accomplished. But in the last five years, personal computers have exploded the amount of resources available to software designers. The Intel 486 processor and Super VGA graphics and four-megabyte memory chips allow plenty of resources to not only accomplish a task but also offer enough

power to handle the overhead of an elaborate graphical user-interface system. So now that the computer industry can accommodate the demands of the HFE community, HFE specialists have a voice in the design of new software systems. The following paragraphs discuss some of these current voices.

2.2.2.1 *Ravn.* Ole Ravn made an insightful summarization of the HFE shortcomings of most CACSD package user-interfaces. He said that most CACSD packages today "do not support the user in the iteration process of solving a design problem." He explains that these packages are just a collection of toolboxes into which the user can put an input and get some output, but that "the combination of these tools are [sic] up to the user. . . . It is up to the user to evaluate the results and decide what to do next." He also explains that most packages do not offer user interaction with the displayed data allowing the user to change some parameter and see how it affects the displayed graph (or whatever). He closes by pointing to the inability of most packages to allow the user to interact in one domain (frequency, time, etc.) and watch the effects on a display in another domain. His work in designing user-interfaces shows the best method is to allow the user to communicate their desired command by selecting labeled buttons on graphics screens using a mouse. The resulting information display remains on the same screen as the command buttons allowing it to be iteratively changed by adjusting model parameters, etc. The user is able to modify what command buttons appear on the screen and even to modify what they do when selected. Multiple views of the same information can be put on the screen at the same time thereby allowing changes made in one domain to be displayed in other domains or graph types. Each view is updated once the user changes the parameters in any of the other views. Context sensitive help is available on any object or command on the screen just by pointing to it with the mouse and pressing a mouse button. [Ravn, 1989: 35-38]

2.2.2.2 *Barker.* H. A. Barker and several other British engineers from the University College of Swansea also grilled the state-of-the-art command line driven CACSD packages and called for mouse-driven, interactive graphical user-interfaces. These authors also describe mouse-selectable labeled buttons and warn against hierarchical menus which can have many levels of depth and slow down the user. These authors also point out five important advantages of graphical user-interfaces to the engineering user. First, novice users find graphical interfaces easier to learn and more like the way they might solve the problem with pencil and paper. Second, the graphical interface may allow new design techniques by grouping large amounts of input information into a single icon or by displaying information in ways never before practical. Third, multiple windows allow the engineer to see how data changed in the design window directly affects the data presented in the simulation window. Or perhaps the engineer might display three different simulation windows to see how his changes affect different experiments. Fourth, pictures of everyday items can make the data presentation seem more intuitive to the user and remove a layer of haze from the design process. Finally, if all CACSD packages use a standard graphical representation of data, new packages or new additions to packages will be easier to learn. [Barker, 1989:88]

2.2.2.3 *Smith.* Sidney L. Smith has been publishing guidance on applying HFE to software for over 30 years. His document to be summarized herein contains over 944 HFE guidelines for designing software user-interfaces, and is probably the most complete and practical work in the field. The guidelines cover the areas of data entry, data display, data transmission, data protection, sequence control, and user guidance. While 122 of his guidelines directly apply to the new ICECAP-PC user-interface, listing and discussing each of them is beyond the scope of this paper. However, some of his more general statements are listed here. It is also important to note that the two areas of data transmission

and data protection are not discussed at all, because they are not needed for the ICECAP-PC user-interface.

First, Smith presents the general objectives of good data entry design. "The general objectives of designing data entry functions are to establish consistency of data entry transactions, minimize input actions and memory load on the user, ensure compatibility of data entry with data display, and provide flexibility of user control of data entry." He goes on to give hundreds of specific rules for keystrokes, text editing, forms and tables, plots and drawings, and default values. [Smith, 1986:11]

Second, Smith presents the general concepts for data display. He says context, consistency, and flexibility are the most important concepts. "Somehow a means must be found to provide and maintain context in data displays so that the user can find needed information. . . . Design guidelines must emphasize the value of displaying no more data than the user needs, and the importance of maintaining consistent display formats so that the user always knows where to look for different kinds of information, on any one display and from one display to another." He again goes on to give hundreds of specific rules for text and graphic displays, forms and tables, data ordering and spacing, colors, and windowing techniques. [Smith, 1986:93]

Third, Smith presents the general guidelines for sequence control. He explains that while both consistency of control actions and minimal control actions required of the user are both important, consistency must always win in a trade-off. This is because while the designer might think he is helping the user by reducing required keystrokes by designing some clever key sequence, the user will probably end up resenting the additional learning and confusion. The clever key sequences can be included for expert users, but should be invisible to the novice who wants to see every action executed the same way. This novice-expert flexibility should be present throughout the user-interface. It guarantees a minimal memory load on the user.

He goes on to say that an alternative to special *hot keys* (this term refers to any keyboard key combinations that are pressed simultaneously) would be to have command icons displayed on the screen and allow their activation by a pointing device. He warns against long, multileveled menus activated by a mouse. The last general guideline for sequence control is to make the most frequently accomplished tasks the easiest to transact. [Smith, 1986:213-215]

The final topic Smith presents concerns user guidance. "The fundamental objectives of user guidance are to promote efficient system use (i.e., quick and accurate use of full capabilities), with minimal memory load on the user and hence minimal time required to learn system use, and with flexibility for supporting users of different skill levels." Smith presents scores of rules dealing with error messages, alarms, prompts, labels, and documentation. He proclaims the need for context sensitive help down to the command or error message level. He also says that the help system should allow general browsing through its contents allowing the user to read all available help on every topic. [Smith, 1986:291, 330-331]

2.2.3 Commercial Packages. This section analyzes each commercial package against three criteria. First, the menuing system must be efficient and intuitive. It must be flexible enough to teach and guide the novice without hindering the expert from quickly accessing the power of the underlying routines. It must not add considerable time overhead which significantly increases the time required to solve the problem at hand. Second, the on-line help must provide guidance at appropriate levels. Third, the presentation of information on the computer screen must enhance the utility of the system. For example, the color or the way information is displayed must not be distracting or awkward to the engineer. And if the displayed information does not look the same as it would if the engineer were working the problem on paper, the differences must add some new insight into the data and not just be arbitrarily chosen to be different. Also, the user should be able to interact with the

graphics display in order to modify parameters and watch the effects these changes have on the graphics display. These systems are not being ranked or graded, rather, their best aspects are mimicked and their worst aspects are avoided.

2.2.3.1 MicroSoft Windows

2.2.3.1.1 Menuing System [Microsoft, 1990:25]. In the last year, Microsoft Windows 3.0 has quickly become the standard menuing system for both business and entertainment software. While this is probably due more to Microsoft's dominance of the software industry than to their application of HFE to Windows' graphical user-interface, any user-interface designer should weigh the advantages of emulating the Windows menuing system. New users of their system would learn the interface quickly since it looks and feels like their other Windows software. Microsoft has certainly invested immense assets into HFE studies on how to design a good user-interface, so by emulating their results, the new design would probably inherit the benefits of their research. And finally, there are many software development tools available on the market to provide this Windows emulation.

The Windows menuing system is a list of commands displayed across the top line of the screen. Two specific commands always found are **FILE** (used for disk access) and **HELP** (used for guidance). The novice user selects the desired command by pointing at the desired command word with the mouse pointer and pressing the mouse button. This produces a *pop-down* menu that extends a new list of command words below the command just selected. The user then selects a command word from that list using the mouse. This command either produces the desired output or displays a dialogue box prompting for further details before producing the desired output. The slightly more advanced user can trace through the menu system without using the mouse by holding down the ALT key and typing the activation letter

(activation letters are the underlined letter in a command word display) of the command they desire. The expert user can also just type a hot key combination corresponding to the command they desire. A hot key combination can be any combination of the ALT, SHIFT, CONTROL, alphanumerics, or function keys.

Windows also offers a menuing system enhancement which Microsoft calls a *toolbar*. This toolbar is a few rows of icons on the lines right below the menu line. These toolbars are user-definable to represent any command found in the menuing system. Thus, they offer a type of mouse-sensitive hot keys. Some of these icons have pop-down menus built into them that are activated when the icon is selected. These pop-down menus do not contain command words, instead they contain the options available for whatever the icon represents. For example, if the icon were the FONT icon and it were selected, its menu would display all the available fonts for the text, and when the user then selected one, it would become the current font.

2.2.3.1.2 On-Line Help [Microsoft, 1990:70]. Microsoft has developed a very elaborate help system for Windows. Help is available either by selecting the help command word from the main menu or by pressing the first function key (F1). If the user selects the menu command word, a pop-down menu is presented offering the opportunity to browse all on-line help topics. If the user presses F1, context-sensitive help is provided for whatever command they were currently executing. The help appears in a separate window with its own menu line and toolbar. The user can open help volumes for any installed Windows applications, they can search for the occurrence of a specific word or topic in the current help volume, and they can do other functions related to reading the help files.

2.2.3.2 Directory Commander (dCOM)

2.2.3.2.1 Menuing System [DAC, undated:25-30]. The

dCOM program is a DOS shell. A DOS shell is simply a user-interface for DOS--DOS, by the way, stands for Disk Operating System and is simply the command structure that controls the lowest level computer functions, like looking at the contents of disks and copying disk files. dCOM is a perfect example of a program whose menu system allows access to any command by a single hot key combination. When the user presses a hot key, the command is executed and the results are immediately displayed on the screen. For example, if the screen contains a listing of all the files on a disk, and the user presses the hot key ALT-T (hold the ALT key down and press T at the same time), a *tag marker* appears next to every filename. Then if the user presses the hot key D, all the *tagged* files are Deleted. While there are thousands of DOS shell programs on the market, none are more efficient in their menuing system as dCOM. dCOM is more efficient than Windows because every possible command has its own hot key, whereas in Windows less than a quarter of the commands have been assigned hot keys.

2.2.3.2.2 On-Line Help [DAC, undated:44]. While the dCOM menuing system is extremely powerful for the experienced user, it has a very high learning curve for the new user. There are no command prompts or menu lists asking the user what to do next, and the on-line help is neither context-sensitive nor very extensive. Pressing H brings up the only available help. This help is basically just a listing of all the hot keys and the DOS commands to which they correspond.

2.2.3.3 Turbo Vision

2.2.3.3.1 Menuing System [Borland,1990:7-22]. Turbo Vision is a command library for the programming language Turbo Pascal. Applications written in Turbo Pascal can use the user-interface support offered by the Turbo Vision package. Turbo Vision offers the best features of dCOM and Windows as discussed above. It allows either the mouse or the keyboard to drive the hierarchical menu system and dialogue boxes of Windows.

It allows the bypassing of the menu levels by use of a *toolbar* or hot keys. And it allows, at the expense of programmer effort, each command to be assigned a hot key as with the dCOM interface.

2.2.3.3.2 On-Line Help [Borland, 1990:130]. Turbo Vision allows help messages to be context sensitive down to the current view, where a view is the current command in a menu listing or the current dialogue box or the current display window. So the user can use the mouse to select an object they want help on and press the help hot key, or they can select the help command word from the menu and browse through the help files. As with Windows, all help appears in a separate window. Commands offered in the help window include commands to display a table of contents of all help topics and an alphabetical index of words in the help file. All the functions offered by the Microsoft Windows help system are available with Turbo Vision, but the displays look different (presumably to avoid a lawsuit).

2.2.4 CACSD Packages. This study evaluated numerous commercial CACSD packages. Their menuing systems and help systems were all simple variants of those already described and are not discussed here. However, these packages offer new information in determining design rules for the data display portion of a CACSD package user-interface. The analysis of these packages investigates how they use the display of information to give engineers new insights into the problems they are trying to solve, and also how they provide the user with some way to interact with the graphics display in order to see directly the effects of changing parameters on the graphics display. The packages evaluated are Program CC, Mathcad for Windows, MatrixX, and Matlab.

2.2.4.1 Program CC [Thompson, 1985:Ch 2, 21-26]. Program CC is perhaps the commercial CACSD package most similar to ICECAP-PC. It offers comparable functions and menuing system and on-line help; however, its data display is slightly superior in the way it allows user interaction. After a graph is drawn, a menu of display format commands is also presented. With this menu, the user can change limits of axes, move a cursor that reports useful screen location data, change foreground and background options, print the screen, add labels, thicken lines, center the plot, zoom in and out, change the state output being displayed, add more points in a given range, and compute some figure of merit values. While allowing the user to interact with the format of the data display is an improvement over the norm, it still does not allow the user to change the model parameters and see how this affects the graph. However, Program CC does demonstrate all the necessary ingredients needed for user-interactive graphics design.

2.2.4.2 Mathcad for Windows [MathSoft, 1991: 13-38]. While Mathcad for Windows is not a CACSD package, it is a complex-math package; therefore, its data display characteristics are fully transferable to a CACSD package user-interface. The feature that makes Mathcad unique among all the other packages analyzed is that its input and output format looks exactly as it would if the user wrote it on paper (in terms of symbol placement, not in terms of freehand drawing). Answers and graphs are presented just as they would look on paper drawn manually. Output graphs are generated in resizable regions right on the same screen as the equations that generated them. And if the user changes any of the equations affecting the graph (by clicking on them with the mouse and retyping some of the parameters) the graph is instantly updated. Mathcad is certainly a good demonstration of the technology desperately needed in today's CACSD packages.

2.2.4.3 Matrix$_X$ and System_Build. Matrix$_X$ is available for personal computers (PCs) as well as for Sun workstations. The PC version offers no new information to this investigation, but the Sun version presents a third method for allowing the user to interact with the graphics display. The basic user-interface is a command line where the user types in long, complicated command sentences. When the user types in the command to generate a graph, a graphics window appears at the top right corner of the screen and the plot is generated. The user can continue typing commands at the command line screen and add plots to the graph, change the format of the graph, etc. However, the user still cannot change model parameters and see the changes reflected in the graph. They can change the model parameters and then request a new graph of these changes to be drawn on the same graph as the old plot. This is very close to the desired, but still is not very easy to use. [Integrated Systems, 1986a]

System_Build is an add-on package to Matrix$_X$, specifically it is an "interactive, menu-driven graphical environment for building, modifying, and editing computer simulation models." Matrix$_X$'s System_Build package is the best system building interface in the industry. The user connects icons with input/output lines and defines the icons to represent formulas and functions. While System_Build is clearly part of the data input system, it is mentioned here in the discussion of data output because if System_Build could be paired with the interactive graphics displays of MatrixX, i.e., if the changes the user made to the graphical representation of the system model--System_Build--could be automatically represented in the graphics display, a superior user-interface would be the result. This interface would offer the desired interactive ability and still be very easy to use. [Integrated Systems, 1986b]

2.2.4.4 Matlab [Moler, 1987]. While Matlab is by far the industry standard for CACSD packages in terms of performance, it is one of the worst for

user-interfaces. Its command structure offers direct access to the underlying math routines and provides a widely used macro language, yet it is so difficult to learn and so slow to use that it hardly offers any guidelines for user-interface design rules. Its data display system offers the same level of disappointment. The graphs are rudimentary and offer nothing to user interaction. It has only been mentioned in this paper because any respectable paper on CACSD should reference Matlab.

2.2.5 Summary of User Interfaces. After researching the user-interface design principles of HFE, and after evaluating the state-of-the-art in current commercial user-interface packages and CACSD packages, some optimal combination of the features found in this research can form design rules for the new ICECAP-PC user-interface. Design rules are thus stated in **Section 3.4** for the menuing system, the on-line help, and the data display.

2.3 Literature Review of the Quantitative Feedback Theory

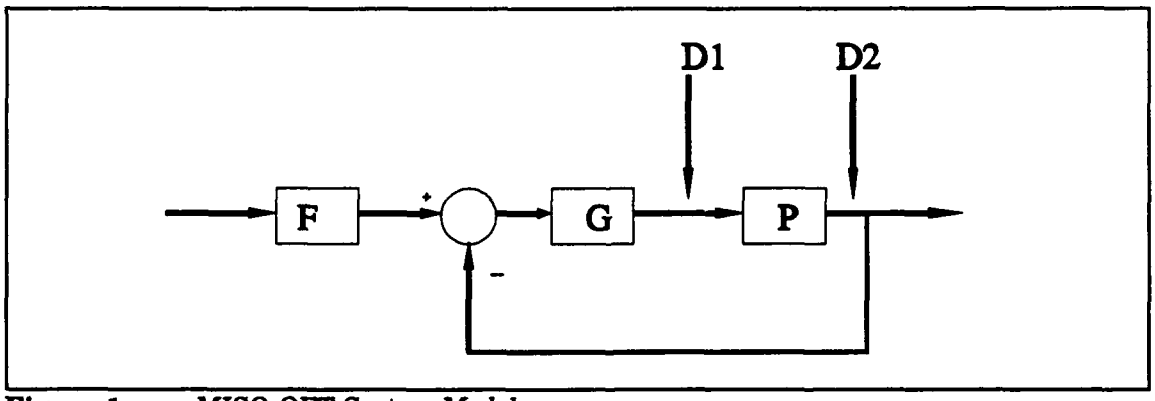

Figure 1 MISO QFT System Model

2.3.1 The Design Problem. Consider designing a practical, linear, time-invariant feedback controller for a plant model with uncertainty in parameter and disturbance. Due to plant uncertainty, there is a set {P} of plants. The set {P} of plants consists of all possible combinations of plant variations which could be a very large number of specific plants.

The QFT method, developed by Dr Isaac Horowitz, quantitatively defines the problem in the form of (1) sets $\{T_R\}$ of acceptable command or tracking input/output relations and (2) sets $\{T_D\}$ of acceptable disturbance input/output relations and (3) a set {P} of possible plants. The design objective is to guarantee that the control ratio, $\mathbf{T_R = Y/R}$, is a member of $\{T_R\}$ for all P in {P}.

2.3.2 The Design Approach. The QFT design (QFD) approach is a frequency domain technique that provides robust performance despite plant uncertainties and disturbances. The general model has three inputs: a tracking input **R**, a plant input disturbance $\mathbf{D_1}$ and a disturbance $\mathbf{D_2}$ (this can be sensor noise, wind gusts, etc) as shown in **Figure 1**. P is the symbol for the plant, G is the compensator to be designed and F is a pre-filter that also requires design. L = GP is defined as the loop transmission (open-loop transfer function). If only G is available as a design parameter, the system is referred to as a single degree of freedom control loop. If F is added, two degrees of freedom are available. Thus, the QFT method is a two degree of freedom design. This approach has sufficient generality for modelling a variety of systems.

2.3.3 The Design Procedure. The ICECAP-PC QFT package closely follows the design procedure specified by Dr Horowitz and Dr Houpis [D'Azzo, 1988:728). This procedure is summarized as follows:

1. Synthesize upper and lower tracking response transfer functions T_{RU} and T_{RL} to meet minimum and maximum specifications.
2. Synthesize T_D, the upper disturbance response transfer function.

3. Define a set of plants $\{P_j\}$ from all possible $\{P\}$ such that the frequency response of the set $\{P_j\}$ defines the perimeter of all possible frequency responses of $\{P\}$.

4. Select a representative nominal plant P_o from the set $\{P_j\}$. Normally, the best selection is the lower-left plant as seen on a Nichols chart template.

5. Determine the disturbance bounds $\mathbf{B}_D$ on the loop transmission L_0.

6. Determine the tracking bound $\mathbf{B}_R$.

7. Define the composite bounds as the most restrictive combination of the bounds determined in steps 6 and 7.

8 Design the loop transmission L_0 for the nominal plant P_0 to meet, as closely as possible, the composite bounds determined in step 7.

9. Synthesize the prefilter **F**.

10. Simulate system behavior to verify correct design.

2.3.4 Summary of QFT. A detailed discussion of the MISO QFT method and literature search can be found in the *QFT Toolbox User's Manual* in **Appendix E** and is not repeated here for the sake of brevity.

2.4 Summary

In this chapter, we developed a general basis of knowledge in three critical areas. First, we discussed the general concepts of object-oriented programming including the analysis, design, and implementation of OO program structures. We discussed OO terminology, talked about Borland's Turbo Vision OO fourth generation language, and discussed the advantages and disadvantages of object-orientation. We found that from the standpoint of software

engineering goals, reusability, extendibility, etc, object-orientation is far superior to any other known construct. However, it does present a steep learning curve as it requires both a different logic structure and a different implementation structure, presenting the new programmer with unknowns in both the problem space and the implementation space of a computer program.

The second general area of discussion was user interfaces. We discovered that there are many design decisions to be made with the user interface due to the many different ways of presenting information to the user. We examined the HFE guidelines developed from scientific research as well as the field-tested interfaces of popular commercial software packages.

Finally, we developed the general mathematical background for the Quantitative Feedback Theory. This development provides a roadmap for future implementation of QFT toolboxes (a complete discussion on the toolbox concept is given in **Chapter 4**).

The general knowledge attained from the research outlined in this chapter forms the basis for the specifications given in **Chapter 3** and for the actual implementation of ICECAP-PC as given in **Chapters 4** and **5**. The next task is to develop the specifications for ICECAP-PC.

3 Requirements and Specifications

This chapter defines the specific requirements of the ICECAP-PC program. First, we consider general traits such as accessibility, portability, etc. While many of these traits seem obvious, they do bear on the final platform selection and program structure. Second, we describe the desired human interface. Third, we develop a list of desired mathematical capabilities that define the basic math engine of ICECAP-PC.

We do not develop an OOA model as described in **Chapter 2**. While a complete OOA model would certainly be expected in large government software contracts, experience dictates that future ICECAP-PC programmers are unlikely to use it. Little use was found for previous functional models; therefore, they are deemed an unnecessary expenditure of valuable development time for this thesis effort. Furthermore, most of the work in developing a highly complex object structure was accomplished by Borland in developing the Turbo Vision 4GL which ICECAP-PC inherited in its entirety. The only additional work done in the ICECAP-PC object structure was to extend the structure with the new ICECAP-PC objects. Therefore, only a basic object model of ICECAP-PC is given within [Trevino, 1992], and specific object descriptions are expanded in **Chapter 4** as needed to aid in the discussion of the actual ICECAP-PC structure. By being able to avoid a full OOA of ICECAP-PC and apply a more prototypical approach to the code design, we are able to produce the broad capabilities of a CACSD package in the short period of time of a thesis effort. Programmers who desire to work with the ICECAP-PC code will gain all the insight required by reading this thesis and [Trevino, 1992]. **Appendix D**, *ICECAP-PC Programmer's Manual*, provides all the specifics required to make calls to the ICECAP-PC object methods, while the OO PASCAL code itself provides self-documentation.

3.1 General Traits

3.1.1 Accuracy. As discussed in **Section 1.3.2**, numerical accuracy is fundamental in any CACSD program. We want to provide the best possible numerical support for control engineering calculations. This has several implications. First, we must insure that we are using state-of-the-art numerical techniques. To insure this, every major algorithm must undergo thorough review with outdated procedures being rewritten. Second, because ICECAP-PC specifically addresses control systems engineering, we can make certain assumptions. For instance, we can assume that a realizable transfer function has real coefficients in both numerator and denominator. This directly bears on our root finder as we can implement a faster and more accurate algorithm by assuming exact conjugates for complex pairs. Also, we can assume a set range of expected values. Very few control systems--and certainly no educational control systems--have transfer functions with coefficients less than 1×10^{-6} or greater than 1×10^{8}. Thus, the range of numbers where we desire the greatest accuracy is quite achievable and reasonably defined. Third, the accuracy requirement encourages the use of the highest precision floating point number supported by standard software, the IEEE Std 754 80-bit extended real number, for all calculations as discussed in [Trevino, 1992; IEEE, 1985].

3.1.2 Speed. We desire ICECAP-PC to be very fast in interface and calculation. First, we seek a nimble, responsive interface that provides rapid command access and execution. This requires (1) concise interface code, (2) the intelligent use of memory (a scarce resource in MS-DOS), and (3) an interface based on the fewest possible keystrokes for command execution. Command line interfaces provide rapid access to commands and direct control over command options but may be frustrating to an expert control engineer who is not completely familiar with the package. Menu based interfaces are often sluggish and present

too much overhead. We need to combine the best of both worlds providing rapid menus and single line data (matrix, polynomial, transfer function) definitions. Second we seek rapid numerical solution wherever possible without risking accuracy.

3.1.3 Reusability. ICECAP-PC is a two-way educational program. First it provides educational support for the control systems student--the user. Second, it provides an educational experience for contributing authors who over the years have developed the program. ICECAP-PC code should be structured in such a way as to provide support to other engineering students in programming projects. For instance, the mathematical engine should be easily ported to other programs in other disciplines. This is a matter of code design and placement.

3.1.4 Portability. ICECAP-PC need not be portable across different platforms because of the prevailing accessibility of MS-DOS machines on which ICECAP-PC was meant to run. However, ICECAP-PC should run independently and not require the purchase of additional software or hardware other than a 80286 or better personal computer. Because of the numerical sophistication required by ICECAP-PC algorithms, we decided not to support micro-processors lower than the 80286.

MS-DOS compatible computers come in a variety of configurations, and where possible we should support advanced features such as expanded memory, math co-processors, high resolution graphics, etc. Many high level languages specifically address these features as compiler options and our choice of platform includes these considerations. Indeed, personal computers based on the 80386 and 80486 family of processors offer considerable improvements in performance in math operations as well as memory availability.

3.1.5 Accessibility. ICECAP-PC should be readily available to the widest audience possible. Ideally, ICECAP-PC should be available to every controls engineering student across the country. The best way of achieving this is to write the program for the MS-DOS compatible platforms as this is by far the most popular computer platform available. Additionally, the ICECAP-PC program must be an .EXE file, rather than a macro of some other mathematical program. This keeps a potential user from needing to purchase an expensive commercial package to host the macro files. In order to make the program accessible, we also need to provide it at a minimal expense. As ICECAP-PC is a public domain program, we provide it free of charge to any interested party.

3.1.6 Graphics Presentation. Graphical representation of system responses is basic to the study of control systems. ICECAP-PC has always provided a rich set of graphical tools that are easy to use and understand. However, we desire to improve the graphics engine by (1) providing direct plots of graphic screens to printers, (2) providing interactive graphics for educational purposes, and (3) providing multiple graphics windows. Interactive graphics allow the user to modify a transfer function and watch the effect on a frequency or time response. Thus the user can see directly the effect of added poles and zeros on a transfer function. This is especially important for the QFT problem. Multiple graphics windows would allow the display of several graphs at once. For instance, the user should be able to view both a time and frequency domain plot of a transfer function simultaneously. Each of these would greatly improve ICECAP-PC. However, we must emphasize that this is a relatively low priority in this project being superseded by the structural redesign of the program itself.

3.1.7 Intuitive Interface. In **Section 1.3.1**, we stated that a major design goal was the development of a truly intuitive user interface. Now, based on the research done in **Section 2.2**, we list the general characteristics of this interface.

1. The interface should be based on a pull-down menu structure accessible via keyboard or mouse for ease of use.
2. Keyboard commands should be executed with minimal keystrokes. The ideal number of keystrokes for a given command execution is 1.
3. The interface should be event-driven. An event driven interface is one that provides the user maximum control rather than constraining user actions through a hierarchical menu structure.
4. The interface should be very fast and responsive. Command access speed should be limited only by the user.
5. The interface should display efficient use of memory and leave as much as possible for data manipulation. This is of primary importance in a PC environment with limited memory.
6. Data entry for matrices, polynomials and transfer functions should be in a format common to several commercial engineering programs such as MatLab and Matrix_x thus providing a smooth learning curve for new users. Direct entry of complex numbers should be allowed.
7. The interface should provide a log file capability so that work performed is saved to a formatted ASCII file that can be turned in as homework or examined by a practicing engineer.
8. Mathematical structures should appear in commonly accepted forms. Matrices should look like matrices, polynomials should look like polynomials, etc.

9. Both scientific notation and fixed decimal numerical display should be available to the user.

10. A pop-up context sensitive help facility should be provided and easily accessible.

11. All graphics data should be written to an ASCII text file so that it can be imported to other programs.

12. A user programmable macro language should be provided.

3.2 Programming Standards

Programming standards are extremely important in any project involving different working groups separated by long periods of time. However, no previous thesis developed a complete set of guidelines for program structure. We now present the following set of basic rules to follow in the development of ICECAP-PC. These rules are arbitrary and stated for the sake of continuity.

Program Code

- Indents are to be made with three spaces. No tab characters are allowed in the source code.
- All main procedures are to be visible in the interface section of their prospective units and listed in alphabetical order. There are to be no hidden procedures.
- All units are to be listed in the *uses* clause of the main program file whether or not the main program file calls the unit directly. Experience shows that some compilers (Borland Turbo Pascal) cause intermittent mathematical errors in units not listed in the uses clause.

- Compilation is to take place with full boolean evaluation turned off. There is code in the root finder that will not work under full boolean evaluation.
- Internal procedures (procedures of procedures) are to be denoted as in **Listing 5**. Note that the main procedure has **PROCEDURE** in caps while the internal procedure has **procedure** in small letters.

```
PROCEDURE ImAMainRoutine

procedure ImAnInternalRoutine
var
   variables: variable
begin
   Internal Routine Code
end;

begin
   Main Routine Code
end;
```

Listing 5 Internal Procedure Format

```
        Program Code Here

{Algorithm Test Code}
{->
        Debugging Code Here;
<-}

        Program Code Here;
```

Listing 6 Embedded Debugging Code

```
{
   This is garbage code
}
```

Listing 7 Temporarily Commenting Out Code

Comments

- Comments are to be denoted with { and } to facilitate proper software maintenance.
- Code that is temporarily commented out is to have brackets placed on the left hand margin. For example, **Listing 6** shows the proper way to temporarily comment out unneeded code.
- Embedded debugging code that is left in place is to be commented out as shown in **Listing 7**. From this listing, note that the debugging code is commented out with {-> and <-} placed at the left hand margin. Also note that the debugging code is indented properly with the normal program code. Finally, the debugging code is noted with a {Algorithm Test Code} header placed on the left hand margin. The advantage to using this system is that debugging code is readily activated by completing the {->} and {<-} symbols.

3.3 Mathematical Specification

The mathematical engine of ICECAP-PC is based on complex arithmetic. This infers two things. First, this means that the entire data structure of the previous versions of ICECAP-PC must be redefined as they are based on real numbers rather than complex numbers. Second, this means that we must allow for the direct entry of complex numbers for polynomial and transfer function factors (but not their coefficients) and for matrices.

The first requirement to be determined was that of how many significant digits must internal numbers represent. Specifically, how accurate must numbers be to do discrete 3x3 MIMO QFT for 10 plants when each plant is 10th order with no common terms. How many significant digits per root or coefficient? Using engineering judgement (Dr Lamont's experience) and the fact that this is only an educational package, the number of significant digits for roots and coefficients was specified to be twelve and the maximum order was

specified to be twelve also. The problem is that the IEEE extended number data structure can only provide 19-20 significant digits per number stored. Given twelve 12-significant-digit roots, thirteen 144-significant-digit coefficients would be needed for exact reconstruction when moving between root and polynomial form. A simple example helps to explain why this is so. Assume a polynomial has two roots, -1.12 and -2.43, which are stored in a number format that maintains three significant digits. The coefficient form of this polynomial would then be found by multiplying (1.00s + 1.12)(1.00s + 2.43). The resulting coefficients would be 1.00, 3.5500, and 2.7216. Now assume we want to return to the root form at a later time and we know one root is -1.12. We know the last coefficient is the product of the two roots, so we simply divide 2.7216 by -1.12 to find the value of the second root, -2.43. Or at least this is how we would have done it by hand. Remember now that the numbers could only be stored for three significant digits. Suddenly the three coefficient values become 1.00, 3.55, and 2.72. At first, this does not seem significant, we only lost 0.0016 off the last coefficient. However, repeat the dividing of the last coefficient by the known root to find the remaining root and you get 2.72 / -1.12 = 2.42! The actual answer would have been 2.42857... and you would have expected the computer to round up to 2.43 before storing the answer; however, this would only be true if your computer was designed to do so, and it probably is not. Thus, approximately half the significant digits are lost for each multiplication/division pair. Thus, for the above stated requirements of twelve 12-significant-digit roots, thirteen 144-significant-digit coefficients would be required. This requirement is not directly obtainable using the IEEE extended number format and the standard mathematical routines provided by PASCAL. One solution would be to mimic the solution used in Mathmatica and provide higher significant digit representation by rewriting all math functions and using a new number format. In effect, to get one number to represent 144 significant digits, you would use 8 numbers each represent 19 to 20 significant digits. Another solution is to utilize iterative methods when moving

between root and polynomial form, using error bounds to gain the required number of significant digits in reconstruction and to design math algorithms specifically to avoid loss of significant digits. The latter solution was chosen and implemented.

The other mathematical specification after accuracy is that of scope. The required scope of ICECAP-PC's mathematical operations is presented in **Listing 8**. This compendium

Matrix Operations
- Addition
- Adjoint
- Controllability Matrix
- Determinant
- Eigenvalues
- Eigenvectors (Modal Matrix)
- Hermite Normal Form
- Inverse
- Linear Quadratic Regulator
- Multiplication
- Observability Matrix
- Rank
- Resolvent Matrix
- Scaler Multiplication
- State Space to Transfer Function
- Subtraction
- Transpose

Polynomial Operations
- Addition
- Polynomial Curve Fitting
- Multiplication
- Subtraction

Transfer Function Operations
- Addition
- Domain Conversion (s,z,w')
- L^Hospitals Rule
- Multiplication
- Partial Fraction Expansion
- Subtraction
- Time Domain Response
- Time Domain Equation
- Transfer Function to State Space

Time Domain Analysis
- Figures of Merit
- Responses to Inputs

Frequency Domain Analysis
- Bode Plots, Interactive
- Margins (gain and phase)
- Nichols Charts, Interactive
- Polar Plots
- Root Locus, Interactive

Listing 8 Desired Mathematical Capabilities for ICECAP-PC

of capabilities is for the most part simply an inheritance from the previous versions of ICECAP-PC. Additions have been made to the matrix functions to accommodate the new MIMO QFT toolbox (which also accounts for the new L^Hospitals Rule within the transfer function capabilities). This scope of function covers a majority of the CACSD capabilities listed in exhaustive form in [Kheir, 1988].

3.4 Human Interface Specification

Section 3.1 lists a set of general goals for an intuitive interface. A set of specific specifications based on the research reported in **Section 2.2** are now given to meet these goals. They are defined as follows:

3.4.1 Menuing System. The menuing system must allow access to any command by three ways: (1) a hierarchical menu activated by a mouse or by keyboard, (2) a toolbar icon activated by a mouse, or (3) by pressing a hot key on the keyboard. The menuing system must maintain the look and feel of Microsoft Windows 3.1. The menu must be a list of command words displayed across the top line of the screen. The user selects the desired command by pointing at the desired command word with the mouse pointer and pressing the mouse button. This produces a *pop-down* menu that extends a new list of command words below the command just selected. If selected, these commands must either produce the desired output or display a dialogue box prompting for further details before producing the desired output. If a menu command produces a dialogue box and not immediate output, then the command word will be followed by an ellipsis (...) to so indicate to the user. Under no circumstances may the menu levels exceed below the *pop-down* menus.

Commands that require a certain sequence in activation are made unavailable until the user completes the prior commands. This must be conveyed to the user by displaying unavailable commands in a different color in the menu listings and by making them insensitive to activation. Also these commands must appear in their chronological order in the menu listing to assist the user in remembering the sequence of design steps.

The input of large collections of data must be represented in pictorial form whenever possible. One example of this is a system build function where the user connects icons with input/output lines and then defines what functions the icons represents. This system build

function must be able to drive graphic displays allowing the user easy interaction with the iterative design process.

3.4.2 On-Line Help. Context sensitive help must be available down to the command and error message level. The help content should provide instructions for program use, but should also provide engineering insight into the design process. The system must allow activation of the help window either by a hot key or icon activation or by menu selection. Help must appear in a separate window and always allow access to a list of keywords and topics. By selecting from these lists, the user must be able to read all available help on every topic.

3.4.3 Data Display. The package must display information in a form which gives the user insight into the problem being solved. Listed information must be orderly and legible and able to be displayed in graphical form. Graphics should provide full color and high resolution to not impair the users understanding of the graph.

Because ICECAP-PC is an educational tool, all information must be able to be presented in a report format suitable for handing in with homework. Session activity should be separate from large data listings and graphical plots to provide the processor a clearer understanding of what the student *did* as opposed to what the student *got*.

Multiple graphics windows must be allowed to be viewed and updated simultaneously. All command executions must update all active windows and create new windows if appropriate. Menus and icons must be accessible during graphics displays allowing the user to modify model parameters in one window and watch the effects on a display in another window. Different windows must allow their data to be displayed in different domains (time, frequency, etc.).

3.5 Summary

This chapter lays the foundation for the implementation of ICECAP-PC by giving a set of specifications for the program. The specifications were first given in general form in **Section 3.1**. Here we saw a set of desired characteristics for the ICECAP-PC program. All of these characteristics will be satisfied in an OO format. **Section 3.2** gives a set of guidelines for the structure of the code. **Section 3.3** lists a set of mathematical capabilities that must be included in ICECAP-PC. **Section 3.4** specified the desired human interface. The interface itself was not specified because it is dependant on the choice of platform given in **Section 4.1**. However, the look, feel and behavior of the interface is clearly specified. These specifications now form the basis for the development of the program itself.

4 Design and Implementation - ICECAP-PC

This chapter describes the design, structure and implementation specifics of ICECAP-PC Version 10. Discussion covers improving ICECAP-PC 9.0, porting ICECAP-PC 9.0A, implementing the new user interface, updating mathematical algorithms, and creating a new macro language. As in any programming project, several design iterations occurred, some minor and some extensive, such as the change from simple objects to object families and actors. As the effort progressed, the concept evolved from a very simple model to a more complex modular model that was required to meet the speed and memory limitations of a personal computer.

4.1 PASCAL

In way of introduction to this section on design decisions, we start by answering the overall question of why we chose to use PASCAL. While Ada and C++ were considered viable options, the decision was made to design ICECAP-PC 10 using PASCAL. [see **Section 2.1.3** in this thesis and Trevino, 1992] This decision was made because Turbo PASCAL 6.0 with Turbo Vision provides a CASE environment as described by Chikofsky. [Chikofsky, undated] As such it provides all the software development tools to accomplish the specifications given in **Chapter 3**.

A full blown CASE environment, as currently available, is not easy enough to use to provide the limited time scale of a master's thesis with enough advantages to warrant such a large expenditure of cash. Furthermore, Lempp and Lauber highlight a specific weakness in current CASE tools is their inability to provide a graphical representation of program data flow, function flow, and control flow--the largest problem associated with rewriting ICECAP-PC 9A. [Lempp, undated:105] However, the underlying goals of a CASE environment are still

desirable: to force disciplined techniques in software development, to increase productivity, and to decrease maintenance required later as the program is modified. [Lempp, undated:105]

The Integrated Development Environment (IDE) within Turbo PASCAL coupled with the OO language of Turbo Vision satisfies most of the goals of a CASE environment. [Chikofsky, undated; Borland, undated; Borland, 1991] The IDE provides a productive environment in which to write code. The integrated debugger allows the programmer to single step through the code and watch variable states change while at the same time watching the program output. The program profiler allows the programmer to optimize completed code for speed and efficiency by analyzing procedure call frequency, overlay file access frequency, and disk access frequency, along with other useful datums. The integrated editor provides a full function word processor to allow quick code writing with minimal overhead. And at any time during the code writing, the programmer can use the integrated compiler to find errors in the new code. All of these integrated tools when combined together into one environment provide the software development tools typically provided by a CASE environment. However, it is the Turbo Vision package which forces a structured approach on the code development and provides easy follow-on maintenance and expandability/portability due to its OO structure. These are also important aspects of a CASE environment.

Borland Turbo C++ For Windows with Object Vision would have provided the same IDE and object-orientation. It was initially believed that C++ would make an easier port later to XWindows on the SUN workstations. However, after analyzing the SUN work station technical capabilities, it was discovered that XWindows is not at all compatible with Microsoft Windows. The main problem is with the graphics routines. DOS graphics is done using .BGI screen driver files and the GRAPH.TPU command unit, but these do not work on a UNIX workstation which uses ANSII exclusively. Also, the existing ICECAP-PC code was already in Turbo PASCAL. Thus porting ICECAP-PC 9A into C++ and then later into UNIX would

be two very difficult ports, where porting from ICECAP-PC 9A into PASCAL Turbo Vision and later into UNIX would only be one difficult port. Because time for porting the code had to be balanced with time required to write the new QFT functions, the decision was made to keep ICECAP-PC in PASCAL and not convert to C++. Ada was not chosen because there is no available CASE environment for Ada.

4.2 Object-Orientation

Another introductory design decision was made to implement the new ICECAP-PC using OO technology. [refer back to **Section 2.1** for details on OOP]

After thoroughly understanding the functional version of ICECAP-PC, it became clear that a new approach to developing large, complex CAD packages was required. This new approach would have to ensure that the new code provided modularity to assist follow-on students in working with the code. It would have to provide independence of the modules so that different students could develop different modules at different times. It would have to provide testability of the modules so that each could be independently validated. And the new approach would have to ensure reliability of the CAD package as a whole, because a tool that is not reliable cannot be used by an engineer even for educational purposes. This new approach was found to be OO technology.

4.2.1 Modularity. OO discipline forces modularity on the design through logical decomposition of the problem into smaller and smaller elements. It brings the modular programming of PASCAL to its ultimate conclusion. [Pressman, 1987:336]

4.2.2 Independence. With strict modularity, comes the reward of self-contained modules with a single input and output. Objects force independence through

keeping their procedures and data hidden from other objects; no object can directly access the methods of another object. This is referred to also as encapsulation. [Pressman, 1987:340]

4.2.3 Testability. With a well-defined input/output pair, testability is gained. It becomes a simple task to apply a test set of inputs and validate proper output responses.

4.2.4 Reliability. After thorough testing, reliability of the module can be concluded. If all the modules are reliable, the whole program is reliable. Furthermore, with object inheritance, a piece of code can be reused repeatedly once it has been proven reliable only once.

These concepts are nothing new to good modular programming in PASCAL; however, the degree of the discipline is forcibly higher in OOP. OOP also offers a new way of looking at problem solutions and a new way of grouping up subroutines into tight little bundles called objects. So along with the traditional values, some new advantages are gained as well.

4.3 ICECAP-PC 9.0 to ICECAP-PC 9.0A

This investigation begins with the software maintenance task of debugging and testing the functional version of ICECAP-PC 9.0 and restructuring it into a more modular form in ICECAP-PC 9.0A. This is done for both transfer function (traditional) and matrix (modern) portions of the package as well as continuous and discrete portions. This new version of ICECAP-PC was produced in order to provide a bug-free, algorithmically reliable version of the functional ICECAP-PC. With this version, the OO ICECAP-PC could be developed by just cutting and pasting in the basic subroutines from 9.0A.

4.3.1 Fast Prototyping. Fast prototyping was used both in the past and current development of the ICECAP-PC code. This is appropriate. Studies have shown that for "educational" programs, fast prototyping is more suitable than specifying. [Curtis, undated:298] Specifically, it was found that prototyping yielded smaller programs which were lower in functionality and robustness, but easier to use and learn. Also fast prototyping yielded designs which were harder to integrate with other parts of the software package. The largest benefit of fast prototyping for thesis students is the absence of the planning and documentation overhead associated with specifying. However, fast prototyping should not become an excuse for lazy coding. True use of fast prototyping would be to throw together code that proves something can be done, and then throwing it all away and design the code from scratch using the specification method. The method of fast prototyping used in developing ICECAP-PC is slightly different. The prototype is put together with more care and attention to detail--less "fast". When the concept is proven to work, the prototype code is polished into the final product using the IDE.

4.3.2 Unit Decomposition. One problem with the old code was that the version of Turbo PASCAL which was current when the unit decomposition was accomplished (version 3.0) only supported units with a maximum compiled size of 64K. The design decision was made back then to decompose the ICECAP-PC program according to functional classification--a typical decision made in functional programming. This resulted in a large number of small units which each contained a large number of routines whose only relationship grouping them together was a similarity in their function. Thus, all the basic math routines were grouped in a unit, all the display routines were together, all the frequency response routines were together, all the time response routines were together, etc. When the units grew to be larger than 64K, it would be divided into two units, then three, etc. The units

grew quickly as the package's power increased. For example, where there was first only an s-domain frequency response procedure with all its supporting routines in a unit, there later grew a z-domain routine and then a w-domain routine. As the package grew over the years, the functional connection between the routines in a unit became more abstract and tenuous, and thus as a later programmer tried to trace through a high level routine, they found themselves searching through many units trying to find the location of the procedure called in the high level routine they were modifying.

4.3.3 Validating the Code. The original plan was to validate the algorithms in the functional version of the code, so they could be brought directly into the new OO version of the code without revision. This goal was unachievable due to an inability to compile the code within the Integrated Development Environment (IDE) of Turbo PASCAL. The IDE is the CASE environment we were to use to debug and trace through the algorithms. Memory limitations and the size of the functional version units would not allow a successful compilation within the IDE. Therefore, the decision was made to move ahead to the OO version of the code which, due to the nature of OO code, would allow use of the IDE.

4.4 ICECAP-PC 9.0A to ICECAP-PC 10

As stated in **Section 4.2**, ICECAP-PC was to be ported to an OO structure. Thus, ICECAP 9.0 was debugged and made more modular to prepare for the port to an OO structure. This intermediate version was named ICECAP 9.0A. After 9.0A was completed, the new OO framework was developed for ICECAP-PC 10.0. Complete details of the initial design of the OO program structure can be found in a companion thesis. [Trevino, 1992] The original intent was to completely validate the algorithms within 9.0A and to bring these algorithms directly into an OO menuing system and help environment. There were two main reasons this

idea was abandoned. First, as stated above, the algorithms within 9.0A were unable to be validated due to the inability to use the IDE. Second, mixing the two technologies did not provide a very effective way to marry the two output techniques. The functional output technique writes directly to the computer screen, erasing anything that gets in the way. The OO output technique passes information to be displayed to a desktop object which maintains a windowed environment and writes information to the windows. This same type of incompatibility prevented any usable way to abort out of a functional algorithm and return to the OO menuing system. This hybrid system was tested on users at the 1992 QFT Symposium at Wright-Patterson AFB, OH but was not well received due to these inadequacies. Therefore, the decision was made to not only bring the algorithms into the new OO menuing environment, but also to recode the algorithms as objects. However, rewriting code takes considerably more time than validating code when the code was written using the fast prototyping technique. And it was the extreme *prototypical* state of the functional ICECAP-PC code that preempted work in the **z**- and **w'**-domains--time was only available to rewrite and validate the S-domain code.

Because the goal of this thesis effort was to follow all the rules of proper software engineering, all prototypical code had to be discarded as only "proof of concept" examples, and the routines completely recoded and validated on a broad range of problem exemplars. This was achieved for all the S-domain routines in the basic ICECAP-PC package. It was achieved to a large degree on the MISO toolbox code, and completely on the MIMO toolbox code. It was also done for the new macro toolbox. In fact, the MIMO and macro toolboxes are the first toolboxes developed completely during this thesis period, all other modules inherited to some degree code from the functional version of ICECAP-PC.

We tried to implement the concepts in the paper "In Search of Elegance". [Fisher, 1992:37-46] *Elegance* maintains that while there are several ways to solve problems, the

better way is that way which has tighter code, less confusion, and the more clever solution. The old ICECAP-PC worked, but it was not elegant. The new OO version of the code is much more elegant. The paper also points out that object-orientation in itself does not guarantee elegance. The author encourages the programmer to not be afraid to throw out objects and replace them with objects that make more sense, even if it seems like the time designing the first object is wasted. The time is not wasted, the design just progressed to a higher level with the first object being an initial design step. We designed many objects which were eventually *eleganced* right out of the program. Several math algorithms were coded in several different ways, with only the most elegant solution remaining in the final code. The root finding algorithm is probably the largest example of this [reference **Section 4.4.6.1** as well as Trevino, 1992].

Our method of *elegant fast prototyping* was not very successful in designing ICECAP-PC 9A since the IDE was unavailable to us, but it has proven extremely successful with ICECAP-PC 10. The difference is the use of our CASE environment (the IDE and Turbo Vision is discussed in **Section 4.1**). ICECAP-PC 9.0A would not compile within the IDE due to memory limitations. These limitations disappeared with the use of OOP; therefore, the decision was made to not waste valuable design time trying to validate the algorithms without the use of the IDE tools and to move forward to ICECAP-PC 10. Thus, most of the algorithm analysis and validation was done, not in ICECAP-PC 9.0A as originally planned, but in ICECAP-PC 10.0 using our IDE CASE environment. The CASE environment allows construction of better initial code, and much better polishing techniques for the final code. With ICECAP-PC 9A the only insight the programmer had into how the code was working was to put in some WRITELN statements here and there that would dump the internal variable states from time to time. With ICECAP-PC 10's development inside the CASE environment, the programmer can see the program output in one window, the variables and their values in

another window, and the code statements being executed in a third window. It becomes very easy to fully understand what the code is doing in such an environment.

One by one the functions were brought into ICECAP-PC 10.0 from 9.0A. This process involved

(1) globally changing variable names to match the more English-language-oriented names of 10.0,

(2) creating the data structures for the routine,

(3) creating the object support (broadcast message designators, menubar commands, etc) for the routine,

(4) providing error handling support for the routine (abort codes and their associated text messages),

(5) exploring newer algorithms more appropriate for computer environments,

(6) accomplishing white box testing on the algorithm during runtime using the Turbo Pascal Integrated Development Environment,

(7) accomplishing black box testing on the routine using a page or two of test cases,

(8) writing macro files to represent the black box examples for ease of use, and

(9) optimizing the compilation of the code for memory and speed.

4.4.1 Variable Names. Extensive translation from nondescriptive variable names to very long and descriptive variable names was accomplished. For example, the variable **idis_angle** has now been translated to **MISOData^.ObservePhase**. This variable holds the integer value of the phase angle the user wishes to observe during MISO boundary calculations. The use of very descriptive variable names and procedure names provides almost

self-documenting code, thus removing much of the need for a data dictionary and a programmer's manual.

4.4.2 Data Structures. The concept of data structures is very important to the success of a complex CAD package. With proper data structure design, the integrity of the data being manipulated inside the CAD package can be more reliably maintained. The goal of the data structure design is to provide global access to the main data items while at the same time keeping a fence around the data collection so that pieces of it are not changed by accident. For example, if the data item of concern is a transfer function, it would have associated with it a domain (s, z, or w') in which its information was defined. If there were a second piece of data which was another transfer function whose domain was different than the first, then there would have to be some way of telling which transfer function was defined for which domain. Now, if **domain** were a global variable designed to be used for all transfer functions, it would have to be assigned one domain while the first transfer function were being manipulated and a different value while the second transfer function were being manipulated. Obviously, unnecessary conflict has created an unreliable operating environment. However, with proper data structure design of the transfer function data item, a more reliable environment can be created. Thus the following sections describe the polynomial and transfer function data structures required for traditional control algorithms [For discussion of the Matrix data structure, the reader is referred to Trevino, 1992 which deals with modern control algorithms].

4.4.2 The Polynomial Data Structure. **Listing 9** shows the structure of a basic complex number as represented in ICECAP-PC. Each complex number has a real part and an imaginary part defined by **realpart** and **imagpart**. While it could be

```
Extended_complex  = record
  realpart : extended;
  imagpart : extended;
end;
```

Listing 9 The Extended Complex Data Structure

argued that there should also be a polar form of each complex numbered stored as perhaps **magnitude** and **angle**, this would double the memory requirements for all number storage. The cost in memory is not considered worth the limited utility offered by the second form of the number. There are some rather large arrays of complex numbers stored in memory at times so the cost in doubling it would be large. There are, however, few times in the code when the polar form of numbers are required. Furthermore, if both forms of complex numbers were stored, then every time one of the forms elements were changed, the other form would have to be calculated. This type of CPU overhead could be a considerable slow down to program execution. Thus, the design decision was made to not store the polar form of complex numbers directly, but to offer magnitude and angle functions to give the polar form with simple function calls whenever needed.

The choice of using a record data type was also an important one. It would be a viable solution to define two variables for every complex number, e.g., **ValueRealpart** and **ValueImagpart**. While this solution could be made to work through strict adherence to variable naming, it tends to be prone to sloppy programming practice. A programmer in a hurry eventually starts shortening the names to things like **Xr** and **Xi** and then later they get used for *real* and *integer* instead of *real* and *imaginary* in some procedure somewhere accessing them globally for purposes they were not intended for. When **Value** is declared to be a variable of record type, these sloppy programming practices are avoided. The variable is used by calling it **Value.realpart** and **Value.imagpart**, which is less likely to be confused

later and used globally for a purpose for which it was not intended. The advantage of using record types becomes more pronounced as we get into the polynomial and transfer function data structures where instead of only having two fields, there are many.

Listing 10 shows the final form of the polynomial data structure. Through extensive

```
Root_Poly_Type  = array[1..Max_Degree] of extended_complex;

Coeff_Poly_Type = array[ 1..Max_Degree1] of extended;

Polynomial = record
  name     : string;        {Holds Poly Name}
  gain     : extended;
  degree   : integer;
  Factored : Root_Poly_Type;
  PolyForm : Coeff_Poly_Type;
end;

PolyPtr    = ^Polynomial;
```

Listing 10 The Polynomial Data Structures

experience with the old ICECAP-PC code, it was determined that the pieces of data needed to fully define a polynomial were as listed. The **name** field holds a string that uniquely describes each polynomial. The names used in ICECAP-PC are Polynomial A, Polynomial B, etc. The **gain** field holds the value of the gain coefficient for the polynomial. The **degree** field holds the order of the polynomial. The **Factored** field is an array that holds Max_Degree complex numbers representing the roots of the polynomial. Max_Degree is currently set to 20. The **PolyForm** field is an array that holds Max_Degree1 numbers representing the coefficients of the polynomial. Max_Degree1 is always one more than Max_Degree. The Root_Poly_Type and Coeff_Poly_Type are defined separately because they are often needed for temporary variable types inside routines. The PolyPtr is a pointer variable to a polynomial type and is also defined separately for use in typing local variables and procedure parameters.

4.4.2.2 The Transfer Function Data Structure. **Listing 11** shows the final form of the transfer function data structure. Also through extensive experience

```
TransFunc = record
  name     : string;        {Holds TF Name}
  domain   : char;          {Used for domain s, w, or z that values were entered as}
  samp_per : extended;      {Used for discrete sampling period}
  num      : Polynomial;
  den      : Polynomial;
end;
TFPtr      = ^TransFunc;
```

Listing 11 The Transfer Function Record

with the old ICECAP-PC code, it was determined that the pieces of data needed to fully define a polynomial were as listed. The **name** field holds a string that uniquely describes each transfer function. The names used in ICECAP-PC are OLTF, CLTF, FTF, GTF, etc. The **domain** field holds a single character which describes what frequency domain its information is defined for. If the domain field is one of the discrete domains, then the **samp_per** field holds the sampling period for which the information is defined. The **num** and **den** fields hold the numerator and denominator polynomials of the transfer function.

4.4.3 Global Records. There are many ways to handle information passing among routines: pass parameters in procedure calls, use global variables, share data files, etc. Each of these has shortcomings. In the functional version of ICECAP-PC, the first two approaches were used. Experience with the problems associated with the functional version of ICECAP-PC led us to using the shared data files for the OO version of the code. Passing large sets of parameters in procedure calls was found to overflow the stack segment which is limited to a maximum size of 64K in Turbo PASCAL. Using global variables tended to produce logical errors in the code when variables originally intended to be used for one purpose

were surreptitiously used for another. Also, since objects cannot explicitly pass parameters when they call one another, the shared data files seemed to be the obvious choice. This choice was soon found to be a poor one. Data files slowed down program execution considerably and required considerable overhead code. Because parameter passing is an inappropriate for OO code, the decision was made to return to the use of global variables. However, in order to avoid the possible errors associated with using global variables, an elegant application of data structures was used. The global variables would be stored in records. There is one record for each logical grouping of variables. An example of this would be the graphics routine's global record. Consider the frequency response procedure calling the graphics display procedure. Much data must be passed between the two for proper operation. The old approach would have been for the frequency response procedure to pass its variable names to the graphics display procedure's equivalents. With our new approach, the frequency response procedure has a global record called FreqData, and the graphics display procedure has a global record called PlotData. There also exists a third procedure called Freq2PlotRecord which translates the FreqData variables into the PlotData equivalents. Thus, instead of passing a large number of parameters, the controlling routine simply makes three procedure calls: the call to the frequency response, a call to Freq2PlotRecord, and the call to the graphics display. This method offers several practical advantages beyond the solution of the possible induced logic errors. It keeps fewer routines in memory at one time, it allows for more complex algorithms or manipulations to be performed on the data between the frequency response and the plot routine than a simple parameter passing, and it provides memory savings by moving the variables from local storage to global pointer variable records. Furthermore, when you read the code, each variable becomes very obvious who has authority over its contents since its owners name is part of its name, i.e., **FreqDat^.MinFreqValue**. This will provide the safeguard against the possible logical errors induced by misusing global variables--while a

programmer might use a global variable named **min** for just about anything, a global variable named **FreqDat^.MinFreqValue** has only one obvious use.

```
Time_Data_Type = Record
    TF,
    FFTF           : TransFunc;
    ForceFuncType  : Integer;
    DataFileName   : String;
    DataFile       : File of Extended;
    First,
    Final,
    Delta          : extended;
 end;
```

Listing 12 The Time Response data structure

4.4.3.1 The Time Response Data Structure. **Listing 12** shows the data structure used to support the time response functions. The fields in the record represent every piece of global data that need to be external to the time response object so that calling routines can initialize the values before sending a message to the time response object to manipulate the data. The **TF** field holds the transfer function which is to have its time response calculated. The **FFTF** field holds the forcing function which drives the response. The **ForceFuncType** integer is used to make some calculation decisions easier to code; it is easier to use a CASE statement based on an integer than it is to analyze a transfer function to determine if it is a ramp or impulse. The **DataFileName** and **DataFile** fields describe the desired file to be used for storage of the time response results. **First, Final,** and **Delta** fully describe the range of time for the response.

4.4.3.2 The Frequency Response Data Structure. **Listing 13** shows the data structure used to support the frequency response functions. The fields in the record represent every piece of global data that need to be external to the frequency response object so that calling routines can initialize the values before sending a message to the

```
FreqRangeType = (LOW, MED, HIGH, USER);

Freq_Data_Type = Record
   TF                      : TransFunc;
   DataFileName            : String;
   DataFile                : File of Extended;
   FreqArray               : Array[1..MaxPlotGlb] of extended;
   FreqArrayString         : Array[1..MaxPlotGlb] of string[13];
   FreqRange               : FreqRangeType;
   First,
   Final,
   Delta                   : extended;
   HzOrRad,
   LogOrLinear,
   MagOrPhase,
   NormOrDec,
   NumDecade,
   NumPoint,
   PowerOfTen,
   RadOrDeg                : Integer
end;
```

Listing 13 The Frequency Response data structure

frequency response object to manipulate the data. The **TF** field holds the transfer function which is to have its frequency response calculated. The **DataFileName** and **DataFile** fields describe the desired file to be used for storage of the frequency response results. The specification of the range of frequencies for which to take the response is not nearly as straight forward as the time response is. First of all, **FreqArray** and **FreqArrayString** are required to hold each value of frequency for which a response point is to be calculated--the array of numbers is for manipulation, the array of strings is for use in dialog boxes where the user types them in directly. This preassignment of values is required to provide enough flexibility for the routines to be used for toolboxes like QFT which only take frequency responses at discrete frequency points and not over ranges of frequencies. Forcing all toolboxes to assign a discrete list of frequencies for the response, loses nothing since computer frequency response algorithms calculate discrete points anyway. What is gained is the generality that a toolbox which requests a *continuous* response can fill the discrete array of frequencies using its first, last, and delta, while with the same routine, a toolbox which requests a response at only specific frequencies can fill the array with those specific frequencies. The **FreqRange** field

is currently only being used by the MISO QFT toolbox, and allows the user to fill the FreqArray fields with some default sets of frequencies, if desired. **First**, **Final**, and **Delta** while no longer used in response calculations are still used in requesting the user's desires and in parts of the plot routine. **HzOrRad** if assigned a value of zero signals the user desires frequencies listed in Hertz. A value of one signals radians/second to be used. This clever combination of variable name and logical use (Hz or Rad, 0 or 1) is maintained throughout the ICECAP-PC code, replacing the more common use of boolean flags. This convention makes the use of global variables more intuitive to the programmer who needs to make calls to the procedures they are used for. If a boolean was used, the programmer would always be asking himself whether false meant Hertz or radians/sec. **LogOrLinear** when assigned a value of zero signals the user desires any plot to be shown with a logarithmic frequency axis. A value of one signals a linear axis. If a logarithmic response is requested, then the **NumDecade** field holds the number of decades the user desires to have calculated and the **PowerOfTen** field holds the power of ten at which the user desires to begin the calculation, e.g., 10^{-1}, 10^{2}, etc. If a linear response is requested, then the **NumPoint** field holds the number of frequencies to be calculated. This value is, of course, calculated automatically from First, Last, and Delta and is only stored for ease of coding counter loops within the response procedures. The **MagOrPhase** flag is used in the plot routines. ICECAP-PC displays frequency plots as two separate plots--one for magnitude and one for phase; however, mechanically there is nothing different between them. The old ICECAP-PC code had separate routines to print magnitude and phase plots, but using the MagOrPhase flag allows the new ICECAP-PC code to use the same routine for both. Basically, the frequency response is stored in a 3 position array: the first position holds the frequency, the second holds the magnitude, and the third holds the phase. All the flag does is increments the position which is read from the array for the value axis of the plot. The **NormOrDec** field communicates the user's desire for normal or decibel

magnitude values. Finally, the **RadOrDeg** field specifies whether to represents phases in radians or degrees.

```
 VectorArray        = array[ 1..MaxPlotGlbl ] of extended; {7k}
Plot_Data_Type      = Record
     DataFileName   : String;
     DataFile       : File of Extended;
     HorzValue,
     VertValue      : VectorArray;
     Grid,
     LastPlot,
     NicColorFlag   : Boolean;
     MaxHorzAxis,
     MaxVertAxis,
     MinHorzAxis,
     MinVertAxis    : Extended;
     Color,
     DisplayCount,
     LogOrLinear,
     MagAngBoth,
     Nichols,
     NormOrDec,
     NumDecade,
     NumPlot,
     NumPoint,
     PowerOfTen     : Integer;
     Palette        : PaletteType;
     GenTitle,
     HorzTitle,
     Title,
     VertTitle,
     Mm,
     Wm             : String;
end;
```

Listing 14 The Graphics data structure

4.4.3.3 The Graphics Data Structure. **Listing 14** displays the graphics data structure. It is one of the largest data structures in ICECAP-PC taking up about 20K of heap space. While most of the fields listed are self explanatory, the first four deserve mention. The **DataFile** fields hold the name of the file to be plotted. The HorzValue and VertValue arrays hold the screen scaled values of the data to be plotted.

4.4.4 Object Support. While there are numerous objects defined throughout the ICECAP-PC code, only the ones which represent significant design decisions are discussed

herein. For a complete discussion of the design of the ICECAP-PC objects reference Trevino, 1992. The following sections describe the transfer function, time response, frequency response, graphics, root locus, menu control, and file viewing objects.

4.4.4.1 *The TFUNC Object Structure.* The TFUNC object structure is a family of actor objects which handle all polynomial and transfer function operations. This object is fully addressed in Trevino, 1992.

4.4.4.2 *The TIME Object Structure.* This object provides all support for time responses, time equations, figures of merit, and partial fraction expansions. Methods can be accessed with user interface dialog boxes or directly like procedure calls.

4.4.4.3 *The FREQ Object Structure.* This object provides all support for frequency responses. Methods can be accessed with user interface dialog boxes or directly like procedure calls.

4.4.4.4 *The GRAPHICS Object Structure.* This object handles graphics in a vastly more efficient manner than the old ICECAP-PC code. In the first place, the old ICECAP-PC had extremely large data structures supporting its graphics routines, while this routines only takes about 20K of data. Further, the methods are modularized so that the same routines can be called in different sequences in order to produce a plot of a single function, or a plot of multiple functions. In the old ICECAP-PC, this required completely separate routines. Finally, all graphics (except the root locus) is done using this single object and its data structure. This relieves the problem with the old code where each routine that needed to do graphics had large local variables to hold the data.

4.4.4.5 The Root Locus Object Structure. The root locus algorithms within ICECAP-PC are still based on the Newton-Raphson technique as described in [Ash, 1968:576-582] and are among the best on the market. What is new about the root locus routines in ICECAP-PC is that they are now interactive. The user can move a cursor using the arrow keys. As the cursor traces along the root locus, it displays the gain and root position.

4.4.4.6 The Control Object Structure. The Control object provides a means of memory management. When an object is instantiated, it takes up large pieces of heap memory. All the Control object does is serve as a central reception point for messages being passed between objects. When Control receives a message, it instantiates the receiving object and sends it the message. When the object has accomplished what the message asked, Control uninstantiates it from memory. The Control object concept coupled with use of overlay files is as effective at reducing memory requirements as the actor concept. However, on '286 computers and some slow '386 computers, speed is degraded appreciably using the Control object. Using both actors and control objects has proven to be the best solution. The control objects provide the centralized message interface and memory management, while the small size of the actor objects ensure that speed is maintained.

The Control object also provides a layer of abstraction for toolbox programmers. All functions in ICECAP-PC are called by sending a message simply to the Desktop. Since the Control object is instantiated into the Desktop, it receives the message and handles it. What this means to the programmer is that all they need to know is a listing of messages; they do not need to know which object handles a message, that is decided within the Control object. Furthermore, any number of control objects can be instantiated into the Desktop at the same

time, so all a toolbox programmer must do to make his object methods accessible to the rest of ICECAP-PC is provide a control object which handles his message events.

4.4.4.7 The FileView Object Structure. The FileView object is a full screen editor provided as a part of the Turbo Vision package. It provides a prebuilt capability for ICECAP-PC to display frequency response listings and other long listings of data which would otherwise clutter the main viewer window on the ICECAP-PC desktop. It allows the listings to be saved as any filename the user or program specifies. It also provides editing, scrolling, and searching of the text. It will even allow opening several files at once. The limitation is that each file opened be smaller than 64K and that there be at least 100K of heap space available when the editor is first called.

4.4.4.8 Other Objects. There are several other objects defined for the traditional control portion of ICECAP-PC. There is a Digital Signal Processing object and others in differing levels of development. These are not considered important parts of this thesis effort and are left for detailed coverage within the Programmer's Manual in **Appendix D**.

4.4.5 Error Handling Routines. Error handling routines are extremely important to a user friendly package. It is imperative that the program never crash to DOS without telling the user why. The ultimate error handling routine would detect the error, trap the error, try to solve the error itself and continue with the program, or at least send a message to the user describing what happened and then return to some stable state and continue with the program. Turbo PASCAL provides the tools necessary to accomplish this;

however, the time required to write the routines to handle all the functions in ICECAP-PC would be impractical for thesis students.

The current solution is to use a global **AbortCode** variable which is tested after each function call for an error condition. Each object in ICECAP-PC has a **HandleAbort** method which displays an error message box to the user and exits the current procedure. The limitation of this solution is that it only works for errors that can be detected before the runtime module aborts to DOS.

4.4.6 Algorithm Improvement. All the basic algorithms which provide the kernel of math support for ICECAP-PC are rewritten to be more accurate within a digital computer environment. The algorithms are also optimized for speed and memory requirements on personal computers. The details of this discussion are provided in a companion thesis [Trevino, 1992] and are not discussed here. However, there are four topics which are general enough to be addressed here under this heading: the root finder algorithms, the logarithm plot algorithms, zero testing, and conditioning numbers.

4.4.6.1 The Root Finder. For a complete discussion of the root finder upgrade, reference [Trevino, 1992]. The root finder is the centerpiece of any CACSD package. It is important to be able to move between polynomial form and factored form of a polynomial. There are errors in the accuracy of a given set of roots as well as a reconstruction inaccuracy in terms of how well those roots can regenerate the original polynomial coefficients. We have tried to provide some insight to the student as to how accurate the roots currently being displayed for a polynomial really are. The only way to know the accuracy of the individual root values is to know what the actual roots are supposed to be. Thus, in real time operation, the only test for root accuracy is their accuracy in reconstructing the original

polynomial coefficients. There are several quick and easy tests that can be used to determine the coefficient reconstruction accuracy. The two easiest, and the two chosen for implementation within ICECAP-PC are that (1) the sum of all roots should equal the second polynomial coefficient and (2) the product of all roots should equal the last coefficient. The largest of these two errors is then taken as the root accuracy. This raw number can be printed for the user, or it can be divided by the value of the smallest coefficient and multiplied by 100 to give a percentage error term. ICECAP-PC currently displays the latter.

In order to improve the root finder, first a baseline set of test exemplars was collected. We used the old code to generate a page of boundary test cases; one example for every order polynomial, twice, triple, quad, and hept repeated real and complex roots, six to ten repeated real roots, and all purely imaginary roots. Second, the error bound routine was added to the old code. Then the error bounds for each of the test cases were generated. Third, the new root finding algorithms were added to the code and the test cases were rerun to generate new error terms. The best algorithms could then be chosen based on the error bound results.

The results of the upgrade were mixed. While the old code produced more accurate roots in examples with several repeated roots, the new code produced extremely better roots in polynomials with no repeated roots. Further it was found that in the old code while the roots were not nearly as close to the actual root values as those the new code found, the reconstruction error terms generated by the code were **smaller** for the less accurate roots of the old code. For example, the new algorithm finds roots correctly to 19-20 significant digits, but the old algorithm only finds them to 8-12 significant digits. However, the reconstruction errors for the old code were being reported at values suggesting 30-50 significant digits, while the new code's errors suggested roots with only 10-15 significant digits. The reason for this disparity phenomenon is that the root errors in the old code were always symmetrical about the actual root values. If one root is a little less than its actual value, the next root will be

a little more than its actual value. Because of these mixed results, both the old and new root finder algorithms are maintained in the code, and an optimizing algorithm calls both routines and compares their resulting error terms to determine which roots to accept. This is only a temporary solution. The more accurate roots of the new algorithm is more desirable for most modern control techniques using matrices or when doing repeated transfer function multiplications, while the more accurate factored to polynomial form transition capability is more desirable for doing most traditional controls algorithms or when doing repeated transfer function additions.

4.4.6.2 Logarithm Plots. New algorithms for displaying logarithm plots had to be generated due to the new plot routines. The old routines always produced the maximum possible number of discrete points along the horizontal axis using spline techniques. This meant that each point was evenly spaced along the axis, thus the logarithmic nature of the plot was produced in the routines which generated the values of the points along that horizontal axis, i.e., it would generate fewer points in the lower part of a decade and more points in the upper part of a decade so that when it plots, the points are evenly spaced on the screen. This approach required much overhead in preprocessing data before plotting and would not allow plotting of discrete values along the horizontal axis--there always had to be exactly the maximum number of points. The new ICECAP-PC is more elegant in its approach. Any number of points with any spacing between them can be sent directly to the response routines and then to the plotting routines with no preprocessing. The plotting routines calculate the required location of the data point along the horizontal axis at plot time based on a simple logarithmic formula. An added advantage of this new approach to plotting graphics is that the graph produced is a true representation of the points calculated in the response routines. In the old ICECAP-PC, the spline routines would produce a smooth

curve that might mislead the user by producing peak frequencies or rise times that were simply not true. The results were a function of the number of points generated and the value of the delta time or frequency used. Future versions of ICECAP-PC will add the spline smoothing algorithm as a user option.

4.4.6.3 *Zero Testing.* There were extensive problems in the algorithms in the old code not testing for zero and causing runtime errors when divide by zeros occurred. There were further problems with the PASCAL language itself generating floating point errors when operations were done on zero or near-zero values. This has been taken care of in the new code by being very careful to do frequent zero testing of variables, and by a bug-fix/code patch from Borland for our PASCAL compiler. This is discussed in further detail in **Section 6.3**.

4.4.6.4 *Conditioning Numbers.* It was found that a large number of the runtime errors caused in the old code were due to operations being performed on variables which had not been initialized to a zero value. While some compilers handle this task automatically, Turbo PASCAL does not. Therefore, routines were written to initialize matrices, polynomials, and transfer functions to zero values.

Another aspect of conditioning numbers is that of truncation. Even though extended number types within PASCAL can represent numbers as small as 3.4E-4932, the algorithms and mathematical functions cannot practically operate at these accuracies since they can only maintain 19-20 significant digits. What this means is that there can be significant quantization error introduced into mathematical results. We found that setting the arbitrary floor on numerical representation at 1E-100 tended to produce more precise answers. Basically, the way this floor is used is to condition operands before an operation and the

results afterwards. To condition a number, you simply set it equal to 0.0 if it is less than 1E-100. In the root finder, we even go so far as to truncate all fractional parts of numbers below 1E-100. This tends to keep the root finder more stable. An interesting note is that the old ICECAP-PC truncated fractional parts of roots below 1E-6, even for discrete domains. The problem with setting these arbitrarily assumed floors is that someone's entire design might exist at values of very small magnitude poles--especially in a discrete design. The simple solution is to keep the user informed through help screens about any assumptions like these which are made. All they would have to do is simply scale all their design values by a few orders of magnitude to bring it back up to a level which is practical on a computer. Obviously, 1E-100 is not a pragmatically provable optimum number, and future thesis work should include some analysis of performance improvements by tweaking this global number.

4.4.7 Unit Decomposition. With the newer version of Turbo PASCAL allowing units larger than 64K and with the use of OOP, the newer version of ICECAP-PC offers a decomposition that is easier to use and maintain. In the first object decomposition of ICECAP-PC, there were basically three objects: Matrix, TransFunc, and Graphics [for a complete object decomposition reference Trevino, 1992, but for this discussion it is accurate enough to only refer to the three main objects]. Each object was defined by two units. One unit held the object definition along with all the user interface overhead, and one unit held the basic math routines associated with the object. This dual unit concept provided a single unit to contain the OO support for the menu system, and a single unit to be used by new toolboxes for lower level math support. For example, the code inside the main ICECAP-PC program to handle menubar requests for a frequency response would generate a message to the TransFunc object inside the TransFunc unit. The TransFunc object would then produce a dialog box to allow the user to select which transfer function to display a response for and how to display

the results. However, the code inside the MISO QFT toolbox to handle menubar requests for template generation would generate a message to whatever object handles template generation and would display a dialog box appropriate to that function. But when that object began to calculate the templates and needed to generate frequency responses for them, it would directly call the frequency response procedure inside the PolyTFMath unit. The TransFunc object would thus be avoided so that no dialog boxes concerning frequency responses are generated.

This dual unit decomposition was later decomposed further into *actors*. [Trevino, 1992] The actors are just a further object decomposition of the three major ICECAP-PC objects into three object families. For example, instead of having the Matrix object contain methods for MatrixAdd and MatrixMultiply, the methods were made objects themselves. Thus the basic Matrix object is called MatrixBasic, and the MatrixAdd method was made a child object of MatrixBasic and is called MatrixAdd. Each of these new actor objects are stored in their own units. Thus MatrixBasic is stored in unit MatBasic (the name was shortened to be a valid 8-character DOS file name), and MatrixAdd is stored in unit MatAdd. The advantage of these single-method objects and single-object units is speed. The small units make the time required to swap the units in and out of the overlay file very short. And while the number of unit files on disk is very large, the naming convention being very similar to the actual method name avoids the old confusion of wondering what unit a certain method is stored in.

4.4.8 Compiler/Memory Issues. The basic ICECAP-PC CAD package represents 1155 compiled lines of code and almost 500K of executable code. If one includes all the toolboxes, the package has over 1 Meg of executable code and almost 1.5 Meg of PASCAL programs. It is obvious that some type of magic must be worked to get a 1 Meg program to execute in the 640K that a PC offers any program. This magic is worked by the PASCAL compiler. Through a combination of overlays, actors, control objects, pointer

variables, and expanded memory, an ICECAP-PC CAD environment is created that can offer the user a library of toolboxes that are unlimited by size or number. The following paragraphs discuss this compiler magic.

There is considerable trade off in the compilation structure of ICECAP-PC. The slowest XT can run ICECAP-PC, but we can lessen the amount of overlays and compile without 286 instructions to improve reliability and speed on the underpowered XT processor. A 486 on the other hand can take full advantage of expanded memory overlays and special compiler instructions to maximize available heap to solve larger problems.

The more we overlay during compilation time, the more heap space that is available for larger order transfer functions, etc. The display buffer size, maximum number of response values, maximum screen resolution, maximum order or transfer functions and matrices, etc. are all chosen arbitrarily at compile time. This allows ICECAP-PC to be tailored for individual use. In fact, through the control objects, one could delete every other function of ICECAP-PC and its toolboxes quickly and easily to allow only one type of problem to be solved. This would free up enough heap space to maybe double or triple the maximum order of the problem to be allowed.

Many lessons were learned about which parts of ICECAP-PC could be put into overlays to free up heap space. It was found through the use of the Turbo Profiler that overlaying the basic Turbo Vision units such as App, Memory, Objects, Dialogs, Menus, and Views would give 50K of additional heap space, but only at the sacrifice of severe overlay access--thus slow response--on 286 machines. Also overlaying any unit whose .TPU file compiled to more than 64K also severely slows down the system. Also any unit accessed in the ICECAP-PC.IDLE routine should not be overlaid or a constant disk read results from swapping in and out that unit. Furthermore, sending broadcasts simply to the Desktop requires every single unit to be read in from the overlay one at a time to see how it responds to the broadcast. For this

reason, it is best to specify one unit in all broadcast commands. Finally, storing the overlay file in expanded memory or on a RAM disk vastly improve performance.

In addition to the use of overlays, is the use of actors and control objects discussed previously. By applying all the *tricks* we have learned, it is possible to run ICECAP-PC in as little as 100K of RAM. This is quite an achievement for a package of such power, and makes ICECAP-PC very portable over personal computer platforms--XTs, laptops, etc. However, the best performance is produced by running ICECAP-PC in 640K of RAM with a few hundred kilobytes of expanded memory available for the overlay files. With the new Borland PASCAL 7.0 discussed in **Chapter 7,** it becomes possible to avoid the 640K RAM barrier and run ICECAP-PC in up to 16 Meg of RAM. This is due to Borland PASCAL's new ability to exploit the protected mode of the new '386 and '486 CPUs.

4.5 User Interface Development

4.5.1 The Menuing System. **Figure 2** shows the friendly user interface Turbo Vision has enabled ICECAP-PC to provide. Every command within ICECAP-PC can be accessed through a single-level pull-down menu system. The matrix pull down menu is shown as an example in **Figure 3**. The internal mechanics of the menus are very simple to implement for the programmer. For every key word shown on the menus, there is a corresponding hot key specified (F1, Alt-X, etc), a help context topic (hcFrequencyResponse, hcFileOpen, etc), and a command word to generate (cmFrequencyResponse, cmfileOpen, etc). When the user clicks the right mouse button on a menu item, the help context topic is sent to the help object which then displays the relevant help dialog boxes for that menu item. If the left mouse button is clicked on the menu item, its command word is sent to the ICECAP-PC HandleEvent method. The HandleEvent method then searches a large CASE statement to find what action should be taken to respond to the user's selection of the menu item. Typically this

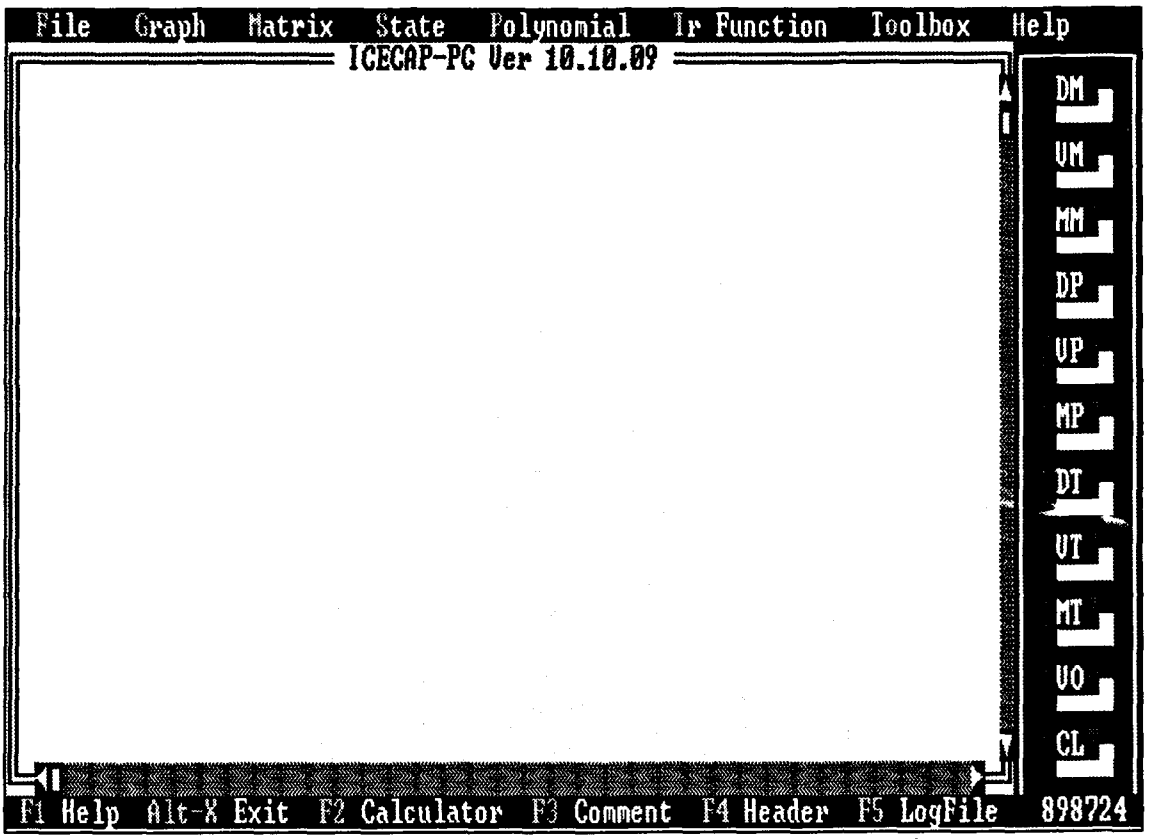

Figure 2 The ICECAP-PC menuing system, button bar, and status bar.

response is to broadcast a command word to the main Control object which instantiates the required object to carry out the user request. For example, the user selects Frequency Response from the menu. The MenuBar object then generates the cmFrequencyResponse command word. The HandleEvent method detects this and broadcasts the brFrequencyResponse broadcast command to the Control object. The Control object then instantiates the Freq object and executes the FrequencyResponse method.

While the mechanics of the menuing system are very simple, the logical construction of the menu system is not. Regardless of how effective the underlying algorithms are inside the CAD package, if the user does not find the interface efficient, they will not use the CAD

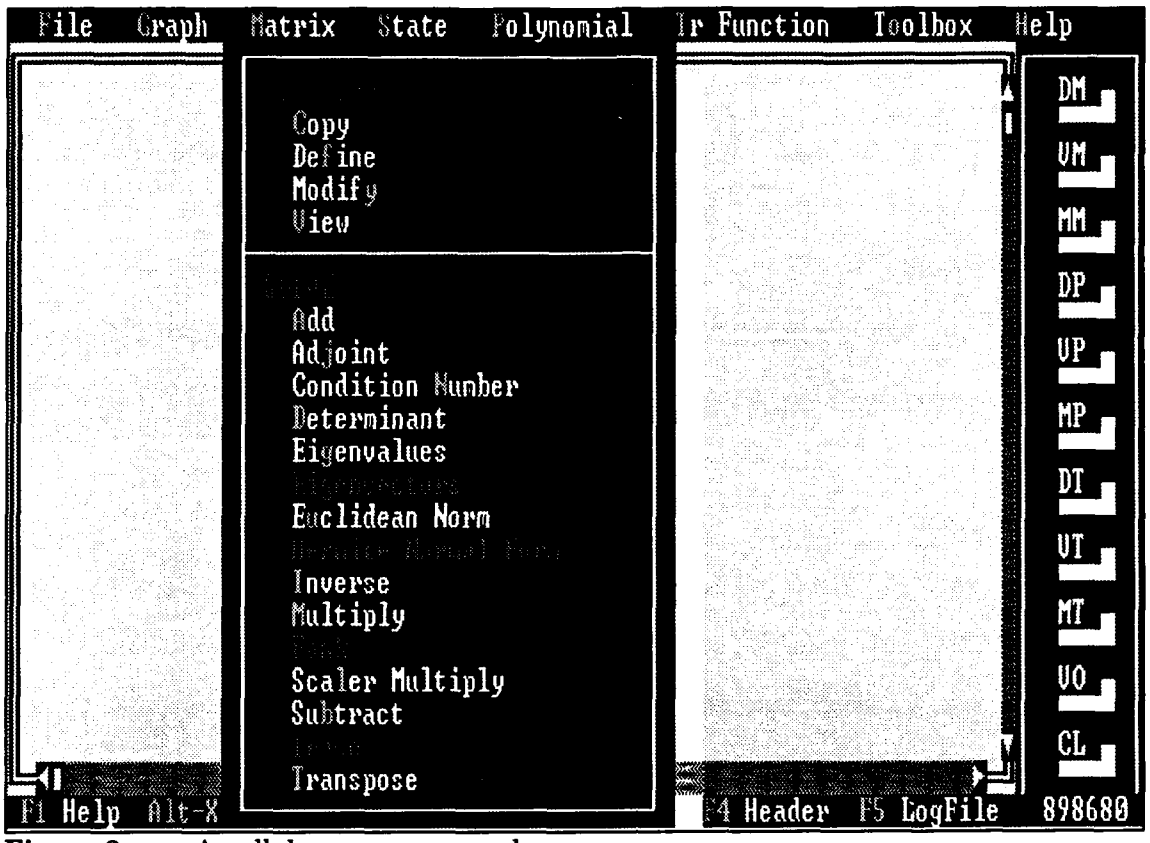

Figure 3 A pull down menu example

package. This is why the ICECAP-PC menuing system avails so many options for user access to the ICECAP-PC commands. The mouse accesses a command through at most one menu level. Single letter keystrokes make the menus pull down just like the mouse, and another single letter keystroke selects the pulled down menu's items, thus avoiding but simulating the use of the mouse. Single *hot key* commands select the menu commands directly. Hot keys are CTRL or ALT keystroke combinations. The mouse also selects from a column of buttons on the right side of the display to access popular commands directly just like hot keys.

Even when users have selected desired commands and have entered the dialogue boxes which allow them to specify the requested action to the program, every effort has been made to minimize the required user interaction. **Figure 4** shows an example of this. Instead of

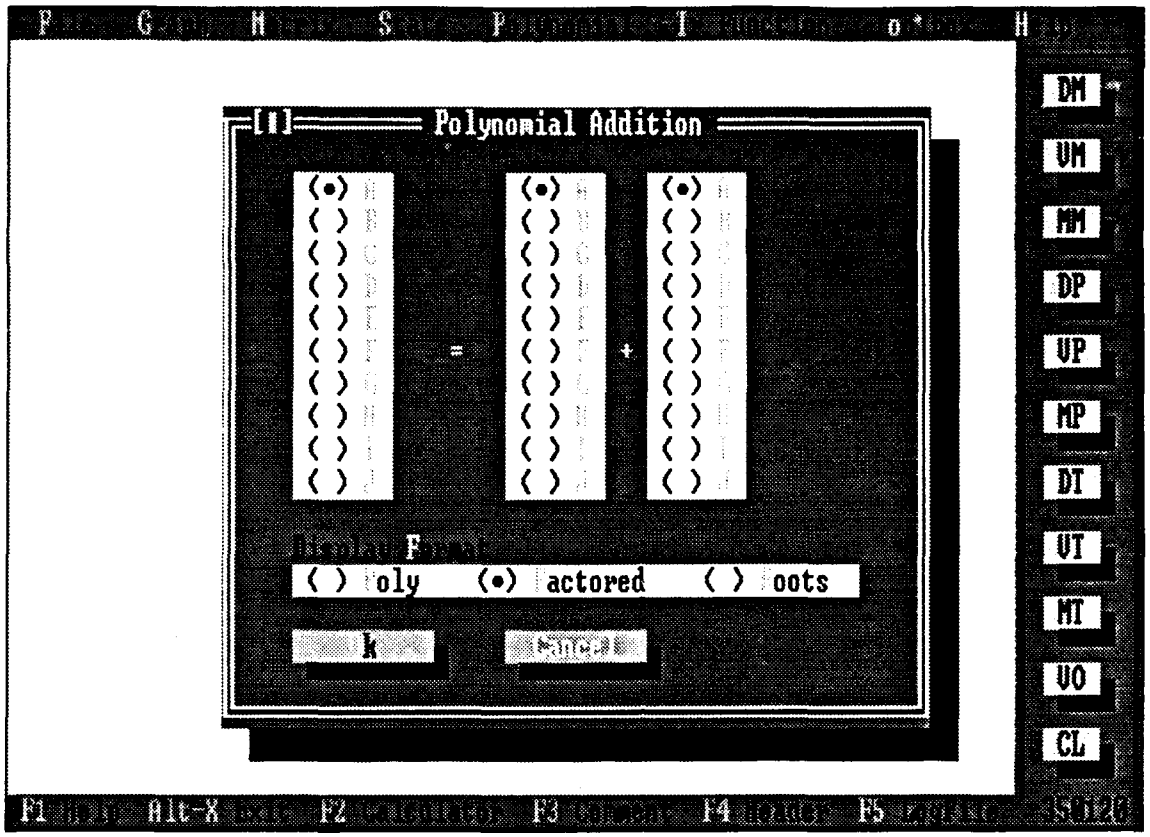

Figure 4 A dialog box example

making the user type in the name of the two polynomials they want to add and type in the name of the polynomial to store the result in, the interface provides a listing of all the possible polynomials. The user then just clicks on the desired polynomial name with the mouse or presses the letter highlighted in the desired polynomial name, or uses the arrow keys to crawl the cursor to the desired polynomial and presses the ENTER key. At most the user must go through two dialogue boxes before they get the desired output, and typically only one dialogue box is required.

One of the difficulties of the menuing system is the limited supply of alphabet letters. Ideally you would like the first letter of every command word to be its hot key and the key to press if you are not using the mouse. However, you inevitably have several commands in the

same menu that start with the same letter. The solution is to either think of other command words that mean the same thing and start with unique letters or use the second, third, or last letter to specify that command word. Another difficulty was found with the *hot keys*. Turbo Vision only supports recognition of the ALT key. The plan originally was to have each main pull down menu to have its own key designation. For example, every command in the Matrix menu could be accessed by pressing the Alt key and the letter of the matrix command word desired, whereas every command in the Transfer Function menu could be accessed by using the CTRL key. However, with eight main pull down menus, the supply of unique hot keys was soon used up. With some research, it was found that the Left Shift, Right Shift, ALT, and CTRL keys as well as any combination of the four could be detected in Turbo Vision with some fancy coding in the Get Event. This was not given a high priority, and is thus left for future development.

Even the appearance of the menuing system was studied and made as aesthetically pleasing as possible. The colors were selected based on proven HFE knowledge on the impact of colors on the human mind. [Smith, 1986:180-186] The main menu commands were all selected to be nouns with all the pull down menu commands being verbs. This has been found to be the most understandable interface for humans. [Smith, 1986:231-247] In the ICECAP-PC package the menu commands were ordered alphabetically since the order is not as important as speed of finding the desired command. But in the current QFT toolboxes, which are more tutorial in nature, it was important for the user to have the commands in the chronological order in which the QFT design method demands them to be executed. The menu was also placed on the top of the screen instead of to the side. A status bar is always kept visible at the bottom of the screen. A toolbar is always kept visible to the right of the screen.

Further, the attempt was made to make the menuing system as intelligent as possible. In the old ICECAP-PC, if the user requested a graph of a frequency response that had not yet

been calculated, a graph appeared of whatever was calculated last, i.e., if the user requested a graph of a frequency response of OLTF and the last frequency response to be calculated was of CLTF, the graph would be of CLTF. With the new OO ICECAP-PC menuing system, this does not happen. If the user requests a graph of the OLTF frequency response without first requesting a listing of the frequency response, the frequency response object first generates the required response data before plotting it. This same technology should be carried out in later work with ICECAP-PC. When the user is looking at a plot on the screen and they desire to change the range of frequencies for the plot, the graphics object should receive that input from the user. It should then not simply reprint the same data showing only the requested range spread out more on the screen, but it should completely recalculate the response data using the maximum available screen resolution (640x480 right now). This is a common flaw in every CACSD package on the market today. What first year controls student has not gone through nine iterations of frequency responses trying to zero in on the peak overshoot of a transfer function? The *wall* that kept this thesis effort from accomplishing this very simple coding task was the lack of an interactive graphics capability. There is no way of allowing the student to click on the horizontal axis and produce a dialogue box where they can reenter the horizontal range.

4.5.2 Number Format. Internal representation is all integers or longints and extendeds. The output can be formatted by the user to the number of decimal places displayed from 0 to 14, scientific or decimal form. The complex letter can be i or j. In the future an ability should be added to allow the user to click on any number and see it displayed with every single stored digit.

4.5.3 User Configuration Files. From experience with previous versions of ICECAP-PC, we knew there to be a need for the user to be able to set global environment parameters and save them off in a startup file. However, an even better capability of Turbo Vision was discovered; the entire state of the desktop display and variable values can be saved off to a configuration file and later be recalled.

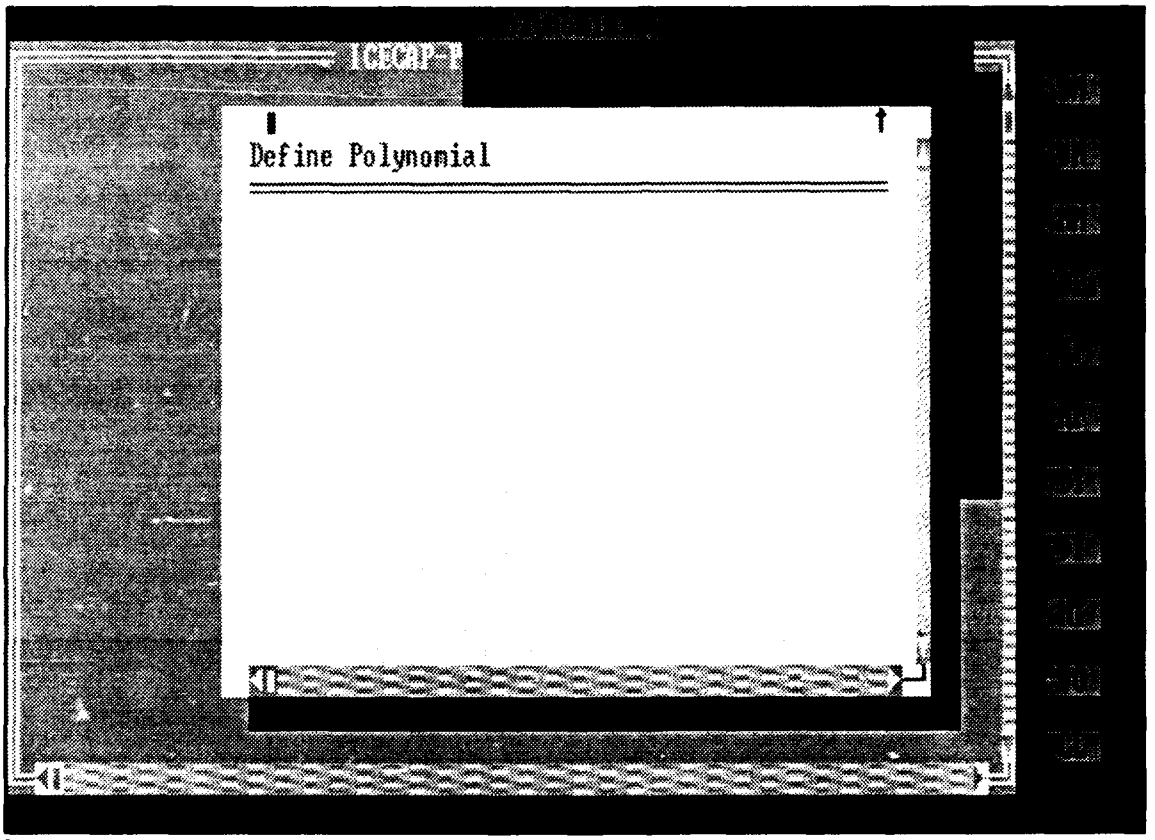

Figure 5 An example help window

4.5.4 On-Line Help System. **Figure 5** shows an example help window called up by clicking the right mouse button on the Define Polynomial menu command. The help files are very easy to create. Using a text editor, you type in the help text. Each group of text

on a certain topic is started with a keyword which ties it to a menu command or dialog box. Then a separate help compiler is run on the help file to produce a runtime help system file.

It is important that these help files not only contain information on how to use the program and the allowed format of entries, but also information to educate the user. This type of information includes engineering rules of thumb for design, the formulae used by the code for the chosen algorithm, assumptions made in the chosen algorithm, as well as the AFIT professor engineering experience and insight into the design process. With this type of on-line help, ICECAP-PC would be more valuable than any commercial package for its help system alone regardless of how well it cranked out answers to problems.

4.5.5 Data Presentation. Several breakthroughs were made in the area of designing ICECAP-PC's routines for data presentation. These include session logging, data listings, and interactive graphics.

As discussed in **Section 3.4.3**, it is important that output reports produced by an educational package be different than those produced by commercial packages. The professor must be able to easily separate session log files from long data listings and graphics plots. By keeping these separate, he can determine what the student *did* to produce the incorrect answers in the listings and plots. ICECAP-PC has been designed to provide that separation [Trevino, 1992]. The session logging function within ICECAP-PC, shown in **Figure 7**, first allows the student to put a header at the beginning of the session file which displays his name and the class and session information. The logging function then pipes all data displayed in the main display window to an ASCII file whose format is exactly as it appears on the computer screen. During this log, the student can enter directly any comments he might want to make about what is on the screen. When a long listing, such as a frequency response, is produced by ICECAP-PC, the output is not listed in the main window but in a full screen

```
File   Graph   Matrix   State   Polynomial   Tr Function   Toolbox   Help
                    ICECAP-PC Ver 10.10.09

Wayne Bell
Student
Problem #5.3 EENG 660

: The transfer function for problem 5.3 is given below

OLTF

 3.5000 (s + 1.0000)(s + 2.0000)
 ---------------------------------
(s + 2.0000 ± j2.0000)(s + 4.0000)

: All this is being logged to a text file!

: The text file looks just like the screen.

DM
UM
MM
DP
UP
MP
DT
UT
MT
UO
CL

F1 Help  Alt-X Exit  F2 Calculator  F3 Comment  F4 Header  F5 LogFile   351216
```

Figure 6 A log file example

editor window, as shown in **Figure 7**. After the student has added any comments or formatting he desires, he can save the file to any filename he chooses. The full screen editor provides many useful options such as scrolling and searching. For a full discussion of the editor function see **Section 4.4.4.7**. When a graphics screen is produced, the student can send it to a printer using external capture packages available with ICECAP-PC but not part of ICECAP-PC.

Several interactive graphics screens are also available within ICECAP-PC. Several students voiced an affection for the MATLAB and ProgramCC root locus function which shows the position of the poles and zeros as you change the gain value. This new interactive graphics capability has been added to the ICECAP-PC root locus routines. Also new procedures for

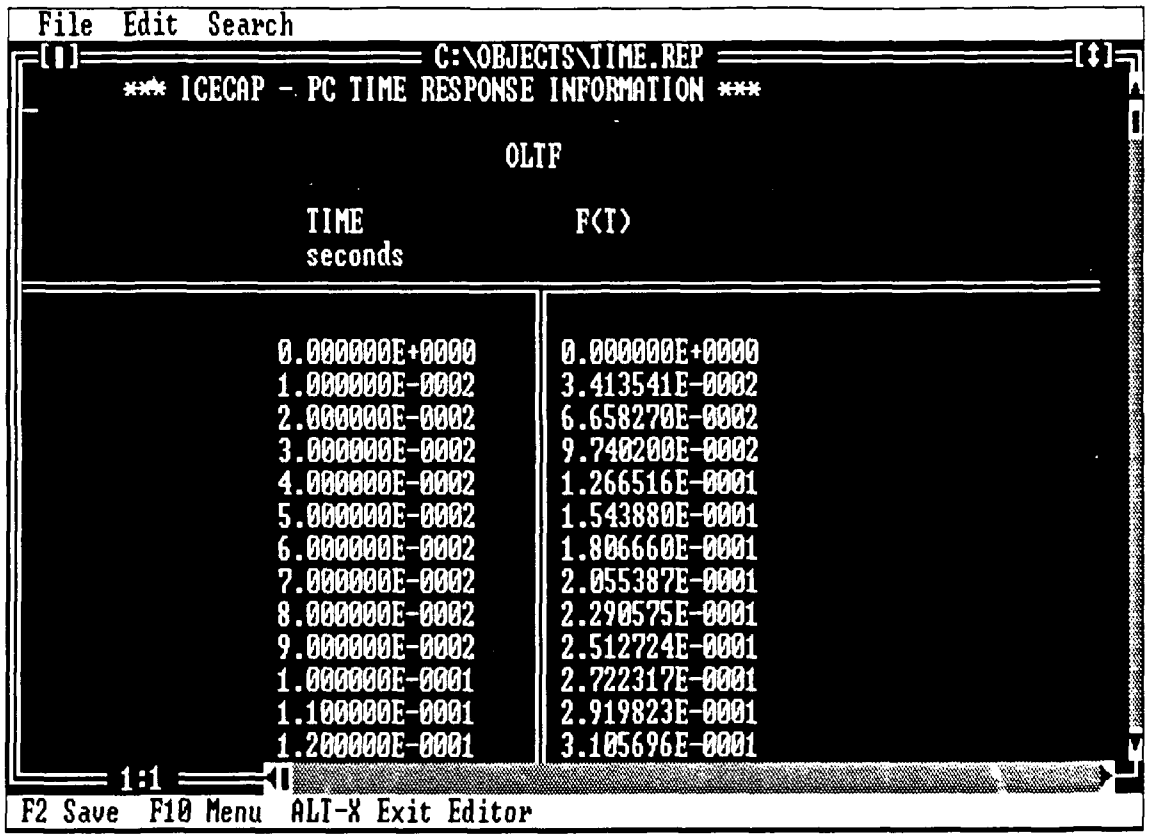

Figure 7 The full screen editor

interactive bound generation and loop shaping have been added in the MISO QFT toolbox. However, the level of graphical interaction does not meet all the requirements presented in **Section 3.4.3**. The Turbo Vision package ICECAP-PC is implemented in does not provide any predesigned facilities for interacting with graphics screens. Thus, time was not available to generate code for these functions directly. Pseudo-interaction was provided using existing procedures by putting the user in a loop between textually entering data and graphically displaying the results. Public domain routines for trapping the location of the mouse cursor on a graphics screen have been located, so the capability to interact with graphics screens does exist. It simply requires buttons to be drawn in specified regions on the display, and sensing

when that region is activated by the mouse. Then all that is left is writing procedures to produce the function associated with each button on the screen.

4.6 Summary

This section has discussed the design, alternatives, and implementation of the ICECAP-PC program. **Section 4.1** discussed the decision to used Borland Turbo PASCAL with Turbo Vision as the language to implement the design in. **Section 4.2** reiterated the importance of object-orientation to the code design. The code development from ICECAP-PC 9.0 to ICECAP-PC 9.0A was presented in **Section 4.3**. **Section 4.4** contains the bulk of the text of this section. It describes the design decisions made in porting ICECAP-PC 9.0A into the OO version 10. The user interface implementation is deliberated in **Section 4.5**.

5 Toolbox Design and Implementation - MISO QFT

This chapter describes the design, structure and implementation specifics of the MISO QFT Toolbox. First the toolbox concept is discussed in terms of why it was chosen, then the MISO QFT toolbox design is discussed.

5.1 The Toolbox Concept

The toolbox idea is meant to make ICECAP-PC infinitely expandable. Reference **Section 1.3.3** for a detailed discussion of the utility of the toolbox concept. For the design of toolboxes, there are two possible approaches: (1) make each toolbox a separate **.EXE** file, or (2) make each toolbox a separate object.

If option 1 is used, the toolbox program is run using the EXEC command inside the ICECAP-PC HandleEvent when the toolbox is chosen from the ICECAP-PC menubar. The .EXE file creates its own desktop and menubar and global variables; in fact, the main ICECAP-PC program is not even executing. One advantage of this option is it provides the highest level of independent compiling between ICECAP-PC and its toolboxes. Indeed, there are no references at all within ICECAP-PC to anything regarding the toolbox. Another advantage is that if the toolbox is unavailable, a dummy .EXE file can easily be substituted and print some type of nonavailability message. The primary disadvantage is that data is shared only through data files saved to disk. The other disadvantage is that this option uses much more memory than option 2 because there is twice the heap overhead in memory at one time since both programs are held in memory at once.

If option 2 is used, the toolbox object is called like any other object, except it replaces the menubar and button bar with its own. Its disadvantage is that this swapping must be done inside the ICECAP-PC code, so independent compiling is not possible. An advantage to this option is that data is shared through common global variables as well as data files.

Another advantage is that memory use is very efficient because the toolbox object requires very little overhead memory, and its unit can be put in ICECAP-PC's overlay file.

The decision was made to use both options in order to gain the advantages of both. During code development, the toolboxes are developed as separate .EXE files. This provides more memory space for the IDE tools to operate, as well as keeps the developing code completely separate from the finished ICECAP-PC product. Once the toolbox has been completely written and tested, the toolbox object definition can be made a part of ICECAP-PC. This is a simple transition, so there is little overhead time involved by using both options. The PASCAL file is changed from a PROGRAM file to a UNIT file with the change of a single file header word and the addition of an INTERFACE and IMPLEMENTATION section. The toolbox object is then changed from being a child of TApplication to being a child of TView. With a slight modification to the INIT method, the new toolbox object is part of the ICECAP-PC object family.

5.2 The MISO QFT Toolbox

As the focus of this thesis effort, a Multiple-Input-Single-Output (MISO) Quantitative Feedback Theory (QFT) toolbox was created. This toolbox allows manual, interactive, and automatic QFT design for continuous, linear, time-invariant MISO control systems problems. The implementation of this toolbox is discussed in the following sections.

In way of introduction, I will first offer some motivation as to why we needed to create yet another MISO QFT package since several very fine packages already exist. [Bailey, 1992; Sating, 1992; Yanev, 1992] First, it was desired to have a package which kept its menuing system, help text, and output true to the standard terminology offered by [Houpis, 1992c]. Second, it was desired to have a package which offered the user several different design approaches instead of just being a demonstration of the author's newly discovered

methodology. Also these different design approaches should include options to enter the design data directly, allow interactive design, or produce a fully automatic design. Third, it was desired to have a package which remained true to Dr Horowitz's original concepts and the methods one would need to solve the problem by hand--the basis for ICECAP-PC is not to solve a problem, but to teach the user how to solve a problem. An example of this would be the way several packages abandon the concept of the UHFB for the more advanced method of calculating tangencies between the desired M_L contour and each template. While this is a good technique for computer packages to offer, and ICECAP-PC will offer it as an option, the student must be shown how the UHFB works. Fourth, no other MISO QFT CAD package is based on OO technology, and we desired to see if object-orientation offered any new insights into the design algorithms or data displays. Finally, it is the goal of AFIT to spread the use of the QFT method as wide as possible. Because ICECAP-PC already has a very large international user base, it was desirable to offer a public domain QFT extension to ICECAP-PC.

5.3 The MISO Process

A complete explanation of the QFT MISO design process (of which this is a summary) can be found in the QFT Toolbox User's Manual in **Appendix E** of this thesis. For brevity's sake and to avoid useless repetition, only the philosophy behind the process is discussed here in the thesis body.

Above all other goals the author holds for the QFT MISO Toolbox is that it teaches the user how to do basic QFT design by hand. The danger in automating a design process to the level of leaving out the human entirely is the same danger in giving a loaded shotgun to an infant who does not understand what it is for or how to use it safely. It is only fruitful for a computer program to handle the mundane detailed calculations of a long design process, if the

human could have done them by hand if they had the time. If the user could not do it by hand, then they do not have the insight into the assumptions and tradeoffs made by the computer to ensure the final design is adequate. It is this belief that has driven the design of the MISO QFT toolbox. Whenever possible (time permitting) three approaches to each design step have been included: (1) the user accomplishes the design by hand and enters the results directly, (2) the user interactively accomplishes the design with the computer package, and (3) the computer package accomplishes the design with no user involvement. Furthermore, the help screens for each step include insightful information into the formulas and algorithms used, assumptions made, tradeoffs made, etc.

Another design goal was to keep the design process true to Dr Horowitz's methods. [Horowitz, 1981] An example of this would be the way the package handles the use of the Ultra High Frequency Bound (UHFB) and the choice of the nominal plant. [Ballance, 1992:74] The purpose of the UHFB is to guarantee stability of the design at high frequencies, and the choice of the nominal is to give a point to design for to insure that none of the template intersects the specified M_L contour. With the computational power available to today's computers, it would have been possible to eliminate the need for the traditional UHFB by simply using the exact M_L contour specified and doing many more computations than possible by hand in ensuring that no plants intersect the M_L contour. However, the goal is to teach students to understand the concepts, not to find the least conservative design, so the UHFB is left in the design process. Further, it is commonly not mentioned in text books [see [D'Azzo, 1988:704] and their reference to [Horowitz, 1981] for example, also [D'Azzo, 1988:728]] that the choice of the nominal plant is not random. The later Houpis & Lamont text makes the point that the nominal plant must be the plant from the given set of plant variations with the smallest magnitude and most negative phase. [Houpis 1992, 541] However, no explanation is given that this choice is so the UHFB can be used as the actual stability bound. [Ballance,

1992:76] If any other nominal plant were chosen, the UHFB would have to be calculated very differently. [Houpis, 1992:532] The template would have to be moved all around the specified M_L contour and the points of tangency would be the top of the ashcan. The vertical portion of the ashcan would be the old UHFB plus the distance from the correct nominal point to the selected nominal point. **Figure 8** illustrates this. If the nominal plant is chosen to be the most negative phase and lowest magnitude point on the template (lower lefthand corner) then the M_L contour becomes the top of the stability bound since the nominal point moves tangently right along it. And if the templates become a simple straight line of height V at very high frequencies, then the bottom of the stability bound would be the bottom of the M_L contour lowered by V distance, thus forming an ashcan shape. While ICECAP-PC does not allow the student to choose any point as the nominal other than the one just discussed, part of the toolbox design process presents this issue to the student.

The ashcan form of the stability bounds used in ICECAP-PC is not always valid. One example is if a MIMO design uses different phase margins for each row of the plant matrix, then the templates at very high frequencies do not tend to a vertical line. They have widths which are a multiple of 90 degrees. [D'Azzo, 1988:706]

The toolbox is rather unique in the variety of ways the plant variations can be generated. The student can enter the plant transfer functions directly, specify coefficient variations, or specify pole/zero variations, or specify the latter two combined with convex hulls as discussed in the following paragraph. Each of the functions are pretty obvious how they would be implemented, however, it is perhaps not so obvious if these variations actually generate a valid set of plants. Given a transfer function $1 / (s^2 + as + b)$, and the specification that 'a' and 'b' vary between 1 and 5, how can one prove that selecting a set of 25 plants (one for (a,b) = (1,1), (1,2) ... (1,5) ... (5,5)) provides a valid controller designed to satisfy those 25 plants. Perhaps the 26th plant would have been invalid for the designed controller. Perhaps

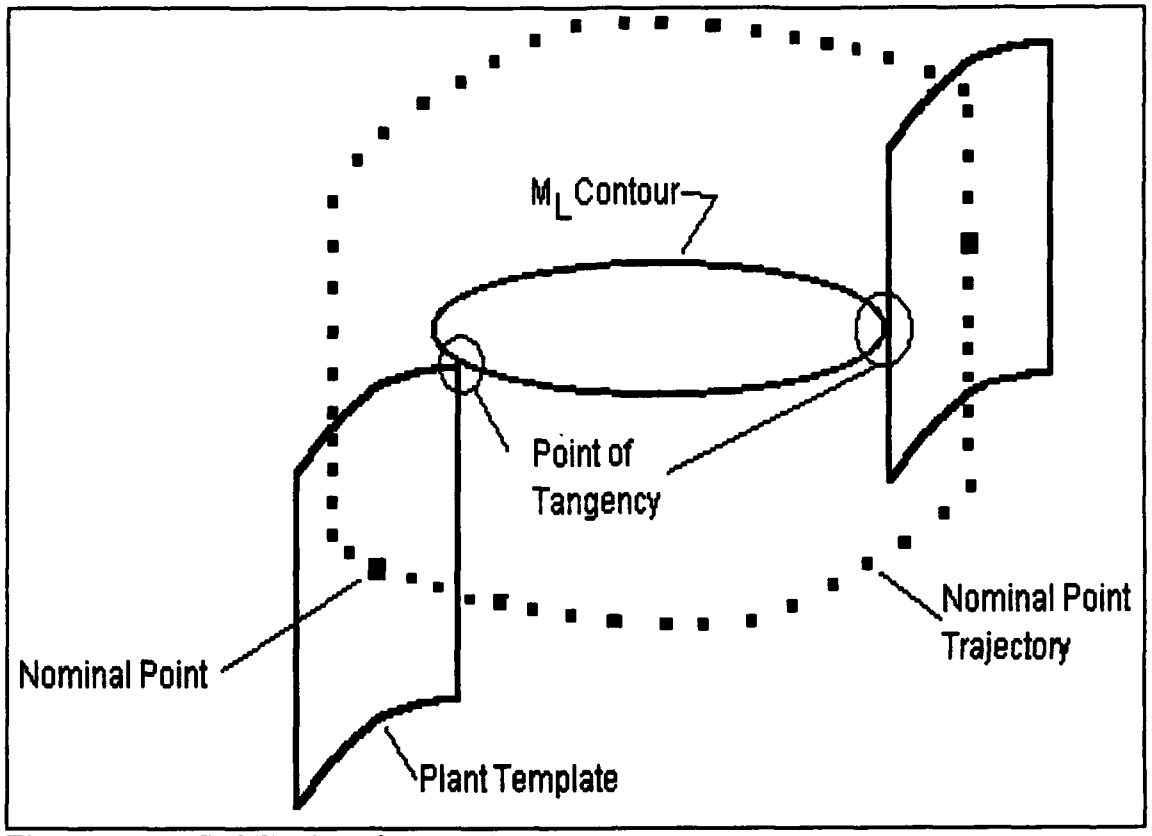

Figure 8 Stability bound generation

100 plants would have been a better choice. **Figure 9** shows the resulting roots from varying the 'a' and 'b' coefficients. How can it be said that a plant case within this region but not chosen as part of the plant set would not generate a frequency response that would invalidate the controller design? The algorithm used in the MISO toolbox simply divides any coefficient variation into 5 linear points and makes every possible combination of every coefficient. So if an example has five coefficients (fourth order) and one coefficient is chosen to vary, ICECAP-PC generates five plant cases. If two coefficients are selected to vary, 25 plants are generated; three coefficients, 125 plants, etc.

The same type of uncertainty exists for the variation of poles and zeros. Further uncertainty is introduced when complex roots are varied. If $-A \pm jB$ allows A and B each to

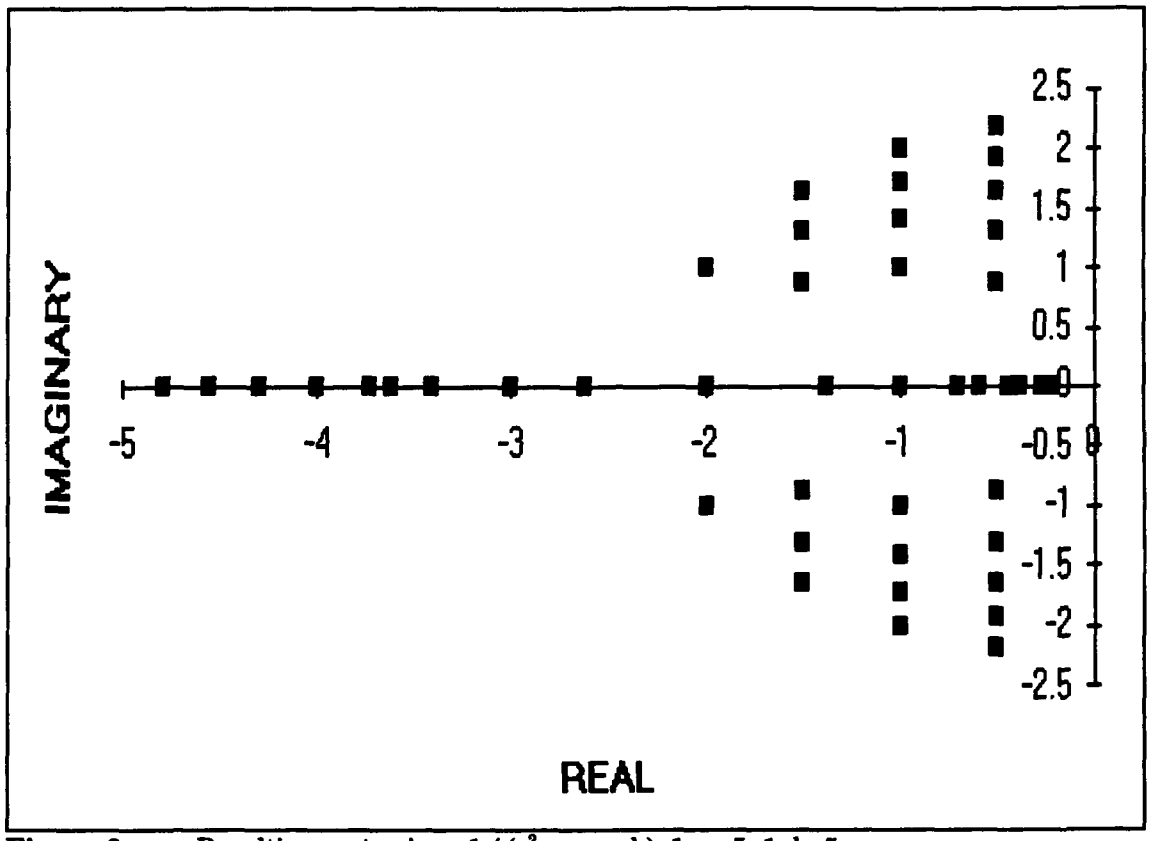

Figure 9 Resulting roots given $1 / (s^2 + as + b)$, $1<a<5$, $1<b<5$

vary from 1 to 5, a square region is obviously formed, but what should be the pattern of the selected plant cases? Should only the roots formed along the exterior of the square region be selected, or should some of the internal roots be selected also. The algorithm used in the MISO toolbox creates a box with an X in the middle resulting in a total of 21 plant cases per complex root (thus 42 actual plant cases since they come in complex pairs).

A further design goal was to apply new techniques to the QFT design process whenever possible. One new technique is the use of convex hulls to provide a more reliable design of the controller. The design can be said to be more reliable because the design of the controller is only valid for every plant in the set of plant variations, and if the number of plants in the set is increased, the resulting controller is valid for more plant cases. The problem is in trying

to choose a representative set of plants where an infinite number of plant variations are possible. At a given frequency, the various plants generate different magnitudes and phases; however, only a finite set of the plants generate magnitude-phase pairs that are on the border of the region enclosed by all the plant response pairs. The convex hull routine, in essence, wraps a string around the region of plant responses for a given frequency and picks the plant cases that are on the border of the region. [Nievergelt, 1993:307-313] This provides a region defined by a minimal number of plant cases (thus easing computation overhead during design) which covers a much larger number of plant variations. These convex hulls always cover a region of plant variation larger or equal to the actual with less or equal number of plant cases in the set. Thus the convex hull set of plants gives a more conservative answer with less computation than the case of using all the plants. On the other hand, the resulting controller is indeed more conservative in that valid operating regions have been covered up by the convex hull borders. These is a problem, however, with digital representation of a convex region. Our current implementation is to only represent the region by the points found by the algorithm to reside at the borders of the region. This becomes a problem when boundary curves are not smooth, but have some high frequency type characteristics. It then becomes possible for the boundary curve to violate the template region without the algorithm noticing it. This is displayed in **Figure 10**. Thus it is important that the convex hull option be used for an initial design to make the processing time shorter, but then if the design proves invalid in the simulation, it will have to be redone without convex hulls.

Another unique feature of the toolbox is how the user can define the stability specification. The toolbox allows the definition in one of three different ways: M_L-contour, phase margin (γ), or peak overshoot (M_P). When any one of these three are specified, the toolbox calculates the other two as well as calculating the corresponding gain margin. Gain margin is not allowed as the specification entry, because it is unreliable. A slight change in

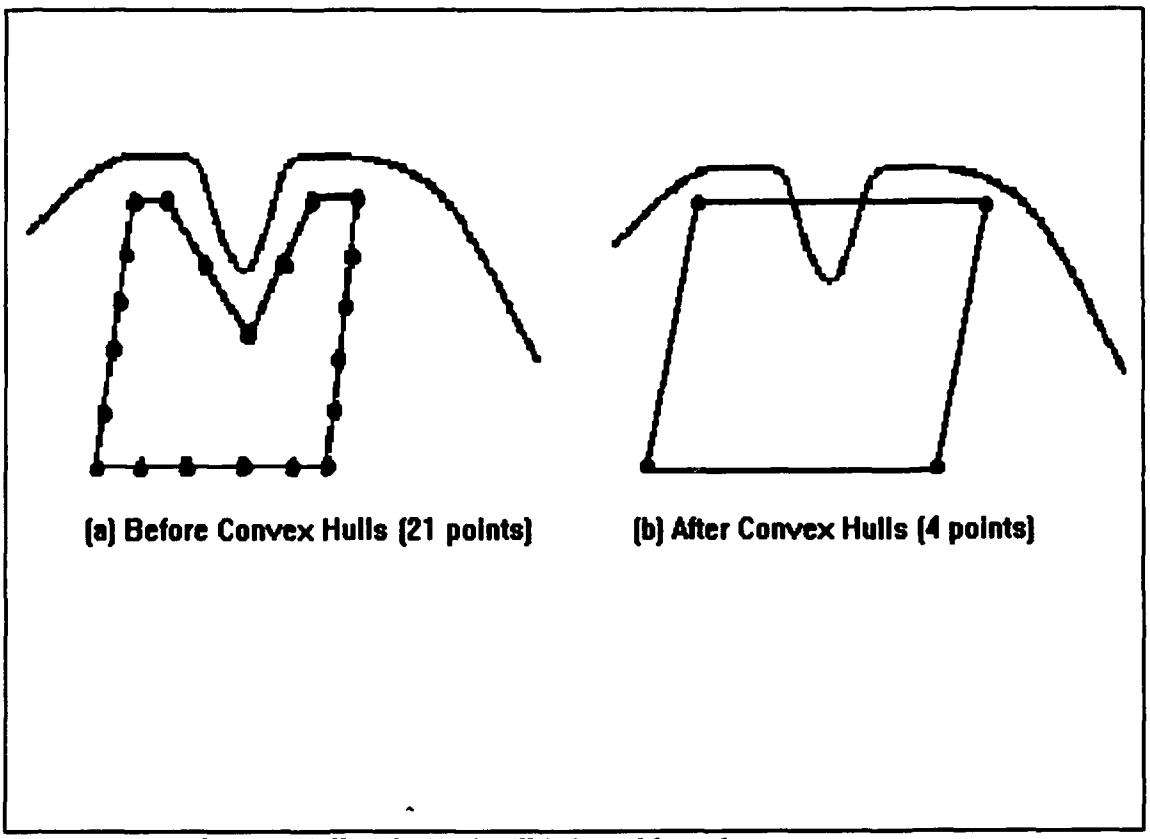

Figure 10 Convex Hull violation by ill-behaved bound

gain margin results in a drastic change in phase margin, thus making it extremely susceptible to error in a computer environment. M_P is also peculiar since it is a time domain specification while the others are all frequency domain specifications. While the user is allowed to specify M_P, the code assumes this value to be equivalent to M_M (the corresponding frequency domain specification). [D'Azzo, 1988:705] This feature is provided because design problems are more often specified in terms of M_P than M_M.

5.4 Code Development

5.4.1 The MISO Data Structure. **Listing 15** shows the data structures supporting the MISO QFT Toolbox. The **NumPlant** field stores the number of plant variation

```
TPFileType = File of Extended;
MISODataType = Record
        NumPlant                : Integer;
        UseConvexHulls          : Boolean;
        TPFile                  : Array[1..16] of TPFileType;
        Observe                 : Boolean;
        ObservePhase            : Integer;
        ObserveTPNumber         : Integer;
        LoopShaping             : Boolean;
        ManualTrBound           : Boolean;
        Image                   : Pointer;
        ImageSize               : word;
        MoveTPNumber            : Integer;
end;

StabilityBoundsType = Record
        GainMargin : extended;
        PhaseMargin: extended;
        MLContour  : extended;
        Mp         : extended;
end;
```

Listing 15 MISO data structures

cases are being designed for. **UseConvexHulls** is a flag designating whether or not the user has opted to use convex hulls to decrease the required number of design plant cases. **TPFile** is a unique data field. During the calculation of the plant frequency responses, all the template files are kept open simultaneously (which required a file buffer extending unit obtained from Borland). As each response point is calculated, it is stored directly to the template file along with the plant identifier which generated it. This really increases the speed of this portion of the code, because a lot of sorting and copying is avoided. And next to the overall simulation, the template generation process is the longest w.r.t. time, so this algorithm optimization was a welcomed improvement. The three **Observe** fields keep track of whether the user requested to watch the computer solve for a particular tracking bound point. **LoopShaping** and **ManualTrBound** are flags used to determine if the user is in the interactive algorithms. This is required since some of the routines must respond differently during interactive periods. **Image**, **ImageSize**, and **MoveTPNumber** are also used in the interactive graphics routines. They hold the information about the template which the user has selected for interactive bound generation.

The **StabilityBoundsType** record is used to hold the stability specifications. It is self explanatory from its field names.

5.4.2 The MISO Object. The MISO Object itself really consists of little more than the support for the menubar. Its only job is to act as the go-between for the user and its constituent objects. There are six of these constituent objects within MISO: QBounds, QSpecPla, QDistTem, QFilter, QLoopSha, and QSimulat. Essentially, there is one object per main menu noun. Each object contains the methods to handle each of the verbs in their respective pull down menu. These objects have not been decomposed into actors; however, MISO does use the Control object concept as discussed in **Section 4.4.4.6**.

5.5 User Interface Development

5.5.1 The MISO Menu Structure. **Figure 11** shows the desktop for the MISO QFT toolbox. The menu command words are all nouns and are listed in chronological design order. Beyond that, the menuing system design is identical to that of the main ICECAP-PC package.

5.5.2 Interactive Graphics.

5.5.2.1 Loop shaping. There are three overall approaches to loop shaping within a CAD package: (1) manual, (2) interactive, and (3) automatic. Manual loop shaping has been implemented. Manual loop shaping requires the student to leave the MISO toolbox, and use ICECAP-PC to build an L_o that meets the tracking and boundary restraints. When the L_o transfer function has been found, the student returns to the MISO toolbox and enters that L_o directly. Interactive loop shaping provides the student with an iterative loop of entering poles and zeros and seeing the resulting graph with the tracking and

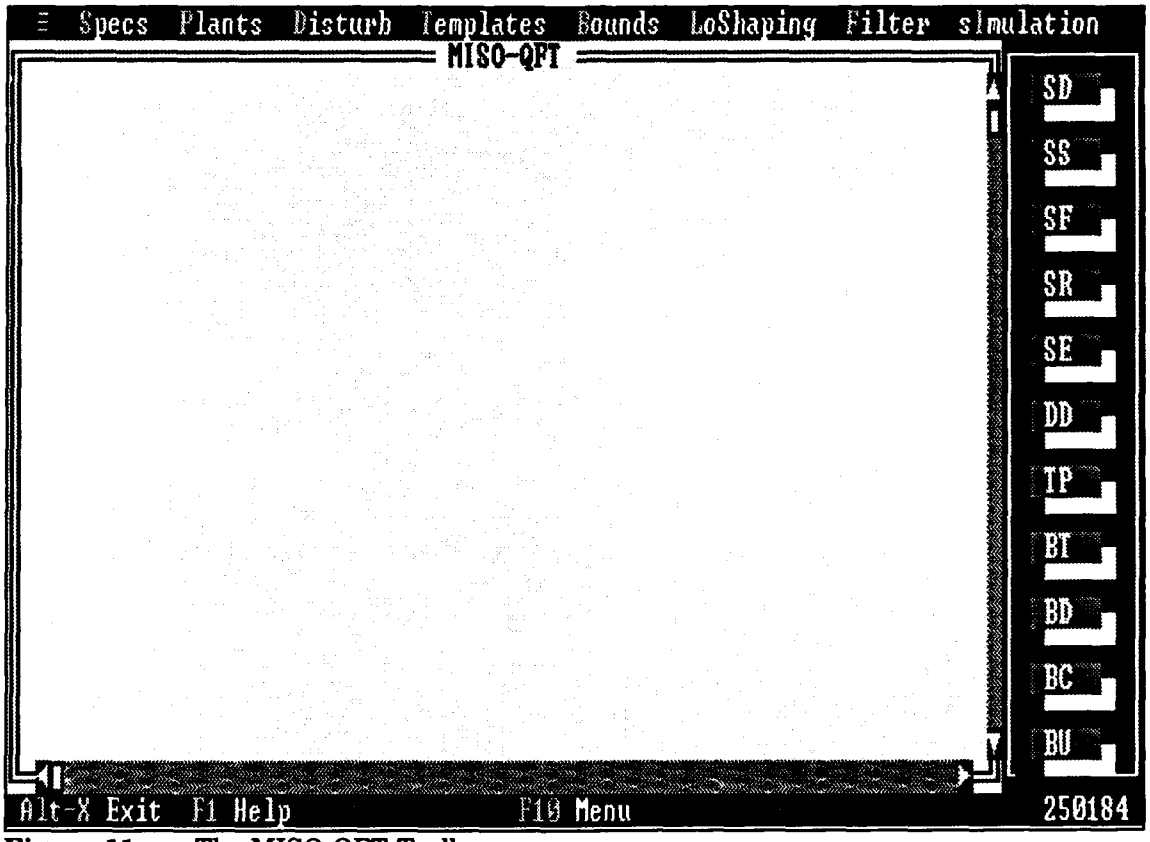

Figure 11 The MISO QFT Toolbox menu

bounds plots superimposed. This has also been implemented in a crude sort of way.

It was initially desired to have a graphics plot of the L_o with all the bounds displayed in one window while the Lo transfer function was being displayed in a second window. This mixture of text and graphics windows was found to not be possible with Turbo Vision. The next option was to display buttons in a region within the graphics region next to the plot. These buttons, when clicked on with the mouse, would activate a second region in the graphics window where poles and zeros could be added to the L_o transfer function. While public domain code to support this process was located, the time required to implement such interactive graphics screens was not available. Thus we were forced to go with the simple implementation of a design loop which iterates between the L_o modification and the graphics display.

The fully automated construction of an L_o was also not implemented due to the same time constraints. The implementation, however, would be a straight forward port of Dr Thompson's linear programming code. [Thompson, 1990]

5.5.2.2 Bound Generation. The same issues associated with interactive graphics screens for the loop shaping routines apply to bound generation. However, more progress has been made with the bound generation interaction than with the loop shaping due to the simplicity of the bound generation task. The user can choose to interact with the tracking bound generation routines in two ways. First, they can watch the computer display textual listings of the calculations it is making for a particular template for a particular bound point. Or secondly, they can choose to move a plant template around on the L_o graphics screen using the cursor keys. The screen displays several pertinent position values as the template moves around. When the user finds a position of the template that matches the δ_R value for that template at that phase, they press the INSERT key to mark a point on the screen representing a point on the tracking bound. When they finish marking a collection of points, they are saved to the same file which the computer would have generated automatically if automatic generation had been selected.

5.6 Summary

This chapter appears short compared to the previous chapter while the work done was the bulk of the thesis effort. This is misleading. In order to make this thesis body less cluttered and more modular--much like the code--the bulk of this chapter is really contained within **Appendix E**.

Section 5.1 presented the options available in implementing the toolbox concept. **Section 5.2** introduced the MISO QFT Toolbox design. **Section 5.3** highlighted some of the

more pertinent design decisions made during the MISO process implementation. **Section 5.4.1** discussed the design of the MISO data structure. **Section 5.4.2** presented the MISO object design. **Section 5.5.1** detailed the design of the MISO user interface. Finally, **Section 5.5.2** presented the implementation of interactive graphics routines within the bound generation and loop shaping functions.

6 Testing and Validation

This chapter covers the testing and validation of numerical algorithms used in ICECAP-PC as well as the correct operation of the user interface. It does not contain code certification tests because the Turbo-Pascal integrated environment contains several excellent debugging tools including the ability to allocate and de-allocate break points on the fly, the ability to monitor and change variable values during program execution, and a *watch window* where the software engineer can watch a complete range of variables while single stepping through the code. Virtually all code used in this project was validated using this environment and very little was left in the way of script files, text reports, etc.

We did perform extensive testing on algorithms to ensure the best possible numerical accuracy. It was impossible to include all these tests; therefore, this chapter contains a representative sample.

6.1 Black Box Testing

Black box testing treats a program as a black box that accepts an input, operates on it, and generates an output. Using a large test set of previously solved exemplars, a program can be validated to work over a large range of problems. Text books proved to be a source for examples, but not the best source for examples. Text books tend to have problems worked on dated software packages that may not have the numerical precision of ICECAP-PC. A better source tends to be MATRIXx and MATLAB. The best source, of course, are problems worked by hand.

An important group of black box problems is to use zero transfer functions or zero matrices, etc. These examples often uncover divide by zero errors and floating point overflows.

Another important group of exemplars were those for the transfer function, polynomial, or matrix definition lines. Different users input the item definition in different ways. Spaces

are put in different places, commas are used instead of spaces, complex conjugate pairs may both be entered or not, the complex letter could be put either before or after the sign of the complex value (i.e., 2 -j2 or 2 j-2), etc. The effort was made to keep as few rules as possible placed on the user. To do this, there was required a large number of exemplars to try to cover every foreseeable type of user input.

6.2 Macro File Object

The purpose of the macro files is to store all of the black box example pages for easy rerun after any significant change to the ICECAP-PC package. The same examples can be used for tutorial purposes by new users to watch the ICECAP-PC commands in execution. The macro file object operates on a simple principle: it replicates the keystrokes the user would use. The macro files consist of a single keystroke per line. The macro object simply reads the line and enters the keystroke directly into ICECAP-PC's GetEvent method simulating the human keyboard input. There are also special commands for inserting comments and pauses and end of file.

Later work could easily add a macro recording function to allow users to record keystroke sequences into a macro file for later rerun. This would be easy to implement by just reversing the code in the macro object.

The difficulty of creating the macro object was in determining what event codes were generated when the user pressed a key. The Event.What field is equal to evKeyDown. The Event.KeyCode field is equal to a HEX value unique for each character. The Event.CharCode is equal to the ASCII character for the key. The Event.ScanCode is equal to a HEX value unique for each key. ALT and CTRL key combinations follow the same rules. Some special keys like the ENTER or ALT key combinations also have unique settings for the Event.Buttons field and the Event.Command field.

If not for the IDE, it would have been impractical to trap these events during runtime and examine their content. A single keystroke can generate several separate events (updating screen colors, updating what is displayed, internal flags, etc), so several conditions must be checked on the trap you set. However, once every possible keystroke was trapped and the event record examined, it was easy to recreate the keystroke from within a macro file.

6.3 White Box Testing

White box testing is like black box testing, but it does not ignore the internal code implementation of the algorithm. To do white box testing, an example must be constructed to test every decision point in the code. If it were not for the IDE, this task would have been insurmountable to test a package as large as ICECAP-PC. However, with the IDE each routine could be single stepped through while watching a window showing all the variables. This is the single greatest contributor to the reliability of the new ICECAP-PC code. "Playing computer" by watching the state transitions of the data allowed us to not only completely debug our code but also to create better algorithms more suitable to a computer implementation. By watching all the variables, you become aware of which very large numbers are being added to very small ones, which variables are being divided by variables very close to zero, etc.

The highest contributor to the unreliability of the old ICECAP-PC code was that it used too much memory to run within the IDE. Its only white box testing was accomplished using print statements inside the code to dump variable values now and then. The IDE is infinitely more powerful than this antiquated method of white box testing.

Another error in the old ICECAP-PC not found in the new ICECAP-PC due to advanced white box testing is the opening of files which are never closed. In the new ICECAP-PC, only two object methods open, access, and close any file. One method writes to the file and

one method reads from the file. An example is that GetTF and StoreTF are the only two places in ICECAP-PC where the transfer function data file is ever accessed.

Another error discovered in the old ICECAP-PC by white box testing not to be found in the new ICECAP-PC is passing parameters to procedures in the wrong order. First, the object-oriented nature of the new code made procedures more single-input, single-output in nature so much of this problem was relieved. But for the procedures that still required large amounts of data transfer, global records were used, as discussed in Section . An example of this would be the frequency response procedure calling the graphics display procedure. Much data must be passed between the two for proper operation. The old approach would have been for the frequency response procedure to pass its variable names to the graphics display procedure's equivalents. With our new approach, the frequency response procedure has a global record called FreqData, and the graphics display procedure has a global record called PlotData. There also exists a third procedure called Freq2PlotRecord which translates the FreqData variables into the PlotData equivalents. Thus, instead of passing a large number of parameters, the controlling routine simply makes three procedure calls: the call to the frequency response, a call to Freq2PlotRecord, and the call to the graphics display. This method offers several practical advantages beyond the solution of the white box testing errors. It keeps fewer routines in memory at one time, it allows for more complex algorithms or manipulations to be performed on the data between the frequency response and the plot routine than a simple parameter passing, and it provides memory savings by moving the variables from local storage to global pointer variable records. Furthermore, when you read the code, each variable becomes very obvious who has authority over its contents since its owners name is part of its name, i.e., FreqDat^.MinFreqValue.

The third major white box testing error uncovered in the old code was testing on a real type variable against exact zero, i.e., **if x = 0.0 then do** something. It is obvious to

experienced programmers that this might make sense to an algorithm to be done by hand, but not to an algorithm implemented on a computer. Round off error and representation errors (quantization) in floating point numbers in a computer can cause zero values to not exactly be 0.0. Thus testing for exact 0.0 is not practical in a computer algorithm and must be replaced with testing for logical zero. The old zero tests have been replaced by the global function IsZero. So now the same line of code would look like **if IsZero(x) then do** something. However, even testing for a logical zero can still be a problem on a computer. The IsZero function has continued to be a plague that cannot be cured. The following brief history of the function helps to explain why this is true.

The original IsZero function looked like **Listing 16**. ZeroVal is a global constant currently set to 1E-100 which has been found to be a good global zero test value. While the choice of 1E-100 is purely arbitrary, and some analysis could be done to optimize this number, good results have been achieved using it. The explanation for why this ZeroVal must be used can be found in **Section 86**. This version of the IsZero function continually cause runtime errors whenever A was a number very close to zero (1E-4930 or so). The reason for this is somewhere in the Turbo PASCAL language itself. It was first believed that it had something to do with the fact that although extended type numbers have a representation range from

```
FUNCTION IsZero(A : extended) : boolean;
begin
        If (abs(A) < ZeroVal) then
                    IsZero := true
                else
                    IsZero := false;
end;
```

Listing 16 Original IsZero function

3.4E-4932 to 1.1E4932, they can only represent about 19 to 20 significant digits. Thus, the comparison between 1E-4930 (A) and 1E-100 (ZeroVal) caused an error somewhere internally when PASCAL tried to subtract the two numbers from each other and test the sign of the result to solve the inequality.

```
FUNCTION IsZero(A : extended) : boolean;
var
   T : extended;

begin
        IsZero := True;
        If (abs(A) <> 0.0) then begin
                T := trunc(log10_ext(abs(A)));
                If T < trunc(log10_ext(ZeroVal)) then
                     IsZero := true
                else
                     IsZero := false;
        end;
end;
```

Listing 17 Second IsZero function

Thus, the second generation IsZero function addressed this problem with the code in **Listing 17**. It was believed that the log function would remove the comparison of relatively large numbers to near-zero numbers by only looking at their powers. Also the compiler would translate the **<> 0.0** line into a simple BZero call and not have to do any comparisons. As clever as this was, the routine still crashed on near-zero numbers. Using the IDE facilities it was found that the problem had not been with the comparisons at all, it was the ABS function built into PASCAL that was causing the error. As the code was examined, it was noticed that the ABS function no longer served any purpose, so it was removed. The third generation IsZero function is given in **Listing 18**.

The function now worked until it reached the ABS(A) hidden in the third line of code. Because the absolute value function is such an easy one to implement, a local ABSOL function was added, as shown in **Listing 19**. This function is in the current code, and has thus far

```
FUNCTION IsZero(A : extended) : boolean;
var
   T : extended;

begin
        IsZero := True;
        If (A <> 0.0) then begin
                T := trunc(log10_ext(abs(A)));
                If T < trunc(log10_ext(ZeroVal)) then
                     IsZero := true
                else
                     IsZero := false;
        end;
end;
```

Listing 18 Third IsZero function

```
FUNCTION IsZero(A : extended) : boolean;
var
   T : extended;

function absol(var a : extended) : extended;
begin
        If a < 0.0 then
                a := -1.0 * a;
        absol := a;
end;

begin
        IsZero := True;
        If (A <> 0.0) then begin
                T := trunc(log10_ext(absol(A)));
                If T < trunc(log10_ext(ZeroVal)) then
                     IsZero := true
                else
                     IsZero := false;
        end;
end;
```

Listing 19 IsZero function with local ABSOL function

proven stable. Turbo PASCAL just does not behave well when using extended type numbers and testing near zero values. There have many such examples of bizarre errors associated with extended type variables. These errors have led us to believe later thesis effort could be devoted to porting ICECAP-PC to a C++ language not produced by Borland International. There are two reasons for this: (1) PASCAL languages in general do not support math functions as well as C++ and are less predictable when running the code on different machine platforms, and (2) Borland's Turbo C++ uses the same core math assembler code and has the

same extended type numerical problems due to the interface between the programming language and the 80x86 CPU architecture [Borland, 1992a; Borland, 1992b]. If true, this would mean Borland's Turbo C++ would have the same zero problems. It is suggested that zero testing be done with C++ before any port effort is expended needlessly. The new Borland PASCAL 7.0 discussed in Chapter 7 may also offer an option. Experimentation is required to determine if the new compiler offers any improvements in its handling of extended real numbers, or if porting to the Microsoft Windows version of the compiler makes any difference in its numerical engine.

Another source of white box testing errors in the old code was to use a GetMem to assign a block of memory to some type of pointer variable and never call FreeMem to release it. After the program ran for a while and called so many of these, it would simply overflow the heap and crash to DOS.

There is a danger in truncating an extended number to store it into a longint. If the extended number is larger than **maxlongint**, a runtime error is generated. You must also test for 0.0 before calling any log10 function.

6.4 User Requests

Feedback from a large student user group has provided continued insight into how to improve the user interface and required functions. The complaints and frustrations along with the compliments have been used to adjust and improve the user interface and scope of functions. The student group includes all the controls students who use ICECAP-PC to do their homework.

6.5 MIMO QFT and LQR/LQG Example

A full MIMO 3x3 S-domain (PCT) problem was worked from beginning to end by hand and by using ICECAP-PC 10.0 to validate its results and to gain insight in both its user interface and missing capabilities. The example chosen was taken from a 1989 AFIT thesis by Capt David Bossert. [Bossert, 1989] The same problem was also solved using LQR/LQG by hand and by using $MATRIX_x$ to try to gain insight on the advantages or disadvantages of other modern control techniques versus QFT as well as commercial CACSD packages versus ICECAP-PC. Of course, working a MIMO problem not only validates the MIMO toolbox, but the MISO toolbox as well, along with the core ICECAP package, since each of these pieces are needed to solve a MIMO problem.

Capt Bossert used ICECAP to design the system and validated his solutions using Macsyma to simulate the controlled system. The differences between his results and ours can be explained by his use of pole cancellation assumptions. He was using an older version of ICECAP which only supported transfer functions of order 10 or less. Therefore, to keep his intermediates from growing too large during the matrix inversions, he had to manually cancel some pole-zero pairs that would not otherwise have been cancelled.

6.6 The Root Finder

Appendix B shows listings of our tests comparing ICECAP-PC's root finder with that of PC-Matlab. In all cases we exceed the accuracy attained in Matlab, often by several decimal places. However, in the process we noticed something that forced us to modify our algorithm. The ICECAP-PC root finder first calls the Laguerre method [Vetterling, 1985] to make the initial cut at the roots. The Laguerre method returns a set of values whose error with the actual roots is symmetrical with the actual roots in the case of root multiplicity. Hence coefficient reconstruction is extremely accurate after root finding with the Laguerre algorithm. The second step used by the ICECAP-PC root finder is the polishing of the rough roots with

either the Bairstow method [Vetterling, 1985] in the case of real pairs or with Brents method [Vetterling, 1985] in the case of single real roots or high root multiplicity. We were able to achieve extremely accurate roots with these two polishing methods. Improvements of 4-5 decimal places over Laguerre's method was common. However this added accuracy came at a loss of error symmetry about the actual values. *Polynomial coefficient reconstruction is often degraded with the better roots found by the polishing methods!* We finally modified our algorithm as follows.

We modified the root finder to take the first cut using Laguerre, store the Laguerre roots, take the second cut using Bairstow and Brent, and store the polished roots, reconstruct the polynomial coefficients with the Laguerre roots and find a reconstruction error, reconstruct the polynomial coefficients with the polished roots and find the polished reconstruction error, and compare the two errors taking the root set yielding the least reconstruction error. Very often ICECAP-PC settles on the less accurate set of roots because the coefficient reconstruction error is minimized.

6.7 Summary

While much work has been done to validate the ICECAP-PC 10 code, much work remains. Code validation is a process which never ends for the life of the program. Each time the code is examined and each time a new problem example is solved using the package, improvements and enhancements are made. No computer program is ever fully verified. No matter how many thesis students offer their experience to the evolution of ICECAP-PC, there will always be Achilles' heels in the algorithms--one more example that the algorithms cannot solve or one more error that has been overlooked. However, if constant application of the validation tools discussed in this chapter is maintained, ICECAP-PC will remain a stable platform in which to design control systems.

In **Section 6.1** the black box testing validation tool was discussed. In **Section 6.2** we described how the macro file object is used to support black box testing. In **Section 6.3** we explained the use of the IDE for white box testing and how this testing turned up problems with the older version of ICECAP-PC. In **Section 6.4** the feedback received from the local AFIT controls student users group was discussed. **Section 6.5** discussed the large design problem used to validate both QFT toolboxes as well as the core ICECAP-PC package and how these results were compared to the results obtained from using LQR/LQG on Matrix_X. Finally, validation of the root finder was discussed in **Section 6.6** and compared to results obtained from PC-MATLAB.

7 Conclusions and Recommendations

7.1 Conclusions

The purpose of this research project was the development of a CACSD program to meet the needs of an ever more sophisticated educational system. In a day when computer analysis and simulation pl ys an increasingly important role, control systems engineers need a solid grasp of the computer sciences. This project exercises the disciplines required by today's control systems engineer: mathematical rigor, numerical analysis proficiency, advanced OOP skills, human interface engineering, and control systems engineering. The end product is a fast, efficient and accurate program with inherent expansion capability.

Fundamental control systems engineering is, of course, the heart of the ICECAP-PC program. While engineers of other disciplines will undoubtedly find utility in the basic ICECAP-PC program, they are in fact directed at the control systems engineer. Both classical and modern control capabilities are provided in the basic ICECAP-PC program. Furthermore, the Quantitative Feedback Theory is implemented in both its MISO and MIMO forms. The addition of interactive bounds generation and interactive L_0 development provides an ideal educational platform for QFT.

Because the object library from Borland Turbo Vision was available for use, productivity in this thesis effort was much higher than would be typically expected in software development. The functional version of ICECAP-PC always suffered in the contemporary human factors engineering area because only so much time could be devoted to menuing systems, output screen formatting, and context sensitive help screens. Using the professionally packaged object library of Turbo Vision, the we were able to focus almost completely on mathematical algorithms and let the commercial package take care of user I/O. Because of this, the authors have been able to work on expanding ICECAP-PC's CACSD toolboxes beyond that which could otherwise have been accomplished. Furthermore, future

thesis students will be able to go even farther since the overhead of porting the ICECAP-PC subroutines into an OO environment has already been accomplished.

7.1.1 General Objectives. The general objectives of this research effort are presented in **Section 1.3** as the development of an OO CACSD environment, the refinement of numerical methods, and the development of a MISO QFT toolbox. Each objective was achieved. The implementation of the OO environment is discussed in **Chapter 4**. Numerical analysis, an art often overlooked by engineers, was fundamental to the success of this project. Virtually every numerical algorithm in ICECAP-PC underwent some form of modification. Much of this is discussed in **Section 4.4**. Finally, the implementation of the MISO QFT toolbox is presented in **Chapter 5**.

The specific design requirements and specifications for this research effort are presented in **Chapter 3**. Each of these specifications were met and are discussed in the following.

7.1.2 General Traits. The general traits presented in **Section 3.1** were largely accomplished through the use of OO technology. OO development and programming, which involves not only a new code structure but an entirely new logic and modeling process, is the software development basis of the future. OO decomposition provides software reusability, extendibility, and maintenance in a way functional decomposition never could. This is why virtually all new commercial operating system development is taking place using object-orientation. The engineering disciplines are late comers to object-orientation and none of the commercial CACSD packages are built on this paradigm as of yet. In this regard, ICECAP-PC is now a pioneer in the area of placing a CACSD package in an OO format. Certainly, this should draw much attention from outside institutions.

7.1.3 Programming Standards. The programming standards discussed in Section 3.2 were all accomplished. The resulting code is very easy to read and follow, and we consider it self-documenting.

7.1.4 Mathematical Specifications. The mathematical specifications presented in **Section 3.3** were achieved and discussed throughout **Section 4.4** as well as all of **Chapter 6**. There is considerable improvement in the numerical accuracy, reliability, and scope of function of ICECAP-PC 10 vs. ICECAP-PC 9.0. Accuracy and reliability have been improved by improving and validating the mathematical algorithms within ICECAP-PC as well as making every internal number representation an extended real type--some algorithms within 9.0 were still using normal real types. An important example of this is the root finder. For nonrepeated roots, the new algorithms can find the roots to the accuracy of machine representation (19-20 significant digits) as opposed to 9.0's ability to find the roots to 8-12 significant digits. The scope of ICECAP-PC's matrix math functions have been greatly enhanced in order to provide modern technique support for the MIMO toolbox.

7.1.5 Human Interface Specifications. Finally, the user interface requirements given in **Section 3.4** were achieved and discussed in **Section 4.5**. The menuing system allows effective access to the ICECAP-PC commands for both the novice and experienced user. The on-line help is so advanced, it may one day become more valuable than ICECAP-PC's problem solving functions. The desired data display capabilities of ICECAP-PC were achieved (except the ability to display multiple graphics windows), but this area needs further research and development.

The user interface of ICECAP-PC 10 is state-of-the-art and far surpasses that of all previous ICECAP-PC versions as well as surpassing the interfaces in most commercial

CACSD packages. The on-line help facility available within ICECAP-PC is also vastly improved and as convenient and effective as any available in other CACSD packages. The ability to just click the right mouse button on anything help is desired on is very effective. The data presentation part of ICECAP-PC's user interface is currently only average, but with further development of the interactive graphics routines, they could be superior to any CACSD package currently available.

At this point, we must emphasize that excellence in all of the above disciplines mean nothing if the human interface is ignored. In todays business climate, intuitiveness is key rather than superfluous to software design. An intuitive program is quickly learned saving expensive engineering time for the actual design process. The adage that "the utility of a program is inversely proportional to its interface" is absolute nonsense. There are many excellent OO interface development tools that remove much of the burden of interface development such as mouse support, drop down menus, etc. ICECAP-PC uses one such tool, the Borland Turbo Vision language extension.

The result of exercising the above disciplines is a CACSD program that challenges the state-of-the-art in CACSD program design in form, in use, and in utility. There is still much work to be done. However, we laid complete, cohesive foundation paving the way for future development of ICECAP-PC and broke new ground in applying object-orientation to CACSD packages.

7.2 Recommendations

ICECAP-PC would be considered in the software industry to be a medium sized software development project. To a single thesis student, this translates into an insurmountable task. It was never expected that all our goals for ICECAP-PC would be

achieved in an 18-month thesis period. The following paragraphs outline the most important remaining goals.

7.2.1 Error Handling Routine. There is a need for an object which can trap all system error interrupts before the program crashes to DOS. The routine could then print a message to the user describing what has happened, clear all the system flags, and return to execution.

7.2.2 Database Object. The original data file storage/retrieval system was at first a single file. Single file in the beginning, but then broke into TFs, POLYs, MATRIX.

There is an extensive need for future thesis effort to address the construction of a database object. This new object would serve at least two purposes: (1) consolidate all the data files into one, and (2) serve as a data dictionary for the code development. The same database object could maintain the two separate databases.

Having a database object that can keep track of the various sets of data has become more important as the MIMO QFT toolbox has matured. There is both overhead in the code and user interface for keeping the MISO equivalent session files straight as well as disk clutter overhead for all the MIMO datafiles. There are also some tricky techniques in the code to take care of the different transfer function names and filenames between the basic ICECAP-PC and the MISO QFT toolbox. A global TransFuncFileName variable is used to make the GetTF and StoreTF, etc procedures global. And a special type of header variable had to be made global for all the transfer function dialogue boxes to work in both QFT and normal ICECAP-PC. A database object could be used as an overseeing monitor to keep these types of differences straight. It would also make the code more purely OO by representing this

database function as an object structure instead of the spread out pieces of functional code we have patched the problem with.

The importance of a database object is also seen in our lack of a data dictionary for our code. While a data dictionary is viewed as a traditional part of a large CAD package such as ICECAP-PC, it was not given a large priority in this thesis effort. We believe we have replaced the need for a data dictionary by using global records instead of separate global variables. For example, all the global variables needed to allow any toolbox to use the graphics object are maintained in the PlotData record. This has some profound advantages over the old technique of putting all global variables in the global file called ICEDEL.PAS.

First, there is no confusion on what variables must be set before a graphics call; set each of the variables in the record that pertain to the call about to be made.

Second, the despicable practice of using a global variable for one purpose in one section of code and then using it for another in a different set of code is eliminated; who would even think of using PlotData.HorzGraphSize as a counter variable in a frequency response procedure.

Third, the PlotData record can be made into a pointer variable so that no matter how large the arrays become inside the record, they are always stored in heap space (640K) instead of the data segment (64K); this has a profound impact on making the size and number of toolboxes available to ICECAP-PC virtually unlimited.

Fourth, while the global variables needed for the graphics object, for example, could be made part of the interface section of the graphics object itself--and perhaps this is the most purely OO approach--this is not a practical solution. This would mean that for the frequency response object to send its response data to the graphics object for plotting, the frequency object would have to instantiate the graphics object inside itself. It is obvious that the levels of this object instantiation could become very memory expensive very quickly. By using the

global records, only one object must be maintained in memory at any one time along with one pointer for every object's global data record. Thus, the frequency response object builds its data variables and then assigns them appropriately into the graphics object's data record. Then the frequency response object is removed from memory since its job is complete, and the graphics object is instantiated and signaled to operate its plot method on its global data record.

Finally, if the database object is ever created, the record structure will make the implementation of the database object almost invisible to the current code.

7.2.3 The Root Finder. The current root finder, crucial to MIMO QFT, reaches performs at the level of the floating point resolution of the machine. This isn't good enough. ICECAP-PC should guarantee root finding to 20 significant decimal digits. In order to do this, calculations must be performed with far greater resolution, say 100-200 decimal digits. None of the IEEE 754 floating point number definitions provide for this. Therefore, the root finder must declare its own data structure and operate this way. Defining a new data structure for a number entails defining all the base mathematical routines such as addition, subtraction, etc. Several options are available and should be studies. Consider the following definitions

In the first example, a number is defined as a record of two extended numbers. Operations on this type would be very fast, but may lack in other areas. The second example defines a number as two very large integer arrays and the third defines a number as two string variables. Each of these definitions could yield advantages and disadvantages and should be studied for possible use in the root finder.

7.2.4 Multiple Windows. Future thesis work should build multi-windowed displays which allow the student to view several different types of plots at one time for the

```
Number = Record
   Integerpart: extended;
   Decimalpart: extended;
end;

Number = Record
   IntegerPart: Array[1..1000] of integer;
   DecimalPart: Array[1..200] of integer;
end;

Number = Record
   UpperIntegerPart: String;
   LowerIntegerPart: String;
   DecimalPart:      String;
end;
```

Listing 20 Possible Numerical Definitions

same transfer function, or to view several domains at one time for the same plot. Current barriers to this are that we do not know how to do multiple graphics windows and that having multiple objects instantiated at once would require more than the available heap space.

7.2.5 Interactive Graphics. The multiple graphics windows work came to a halt when it was found that Turbo Vision could not support graphics in anything but full screen operation. Interacting with the graphics screens --i.e., changing the transfer function and having the graphics plot update immediately--is still possible using on-screen buttons and the mouse, but only after extensive time investment. The L_0 shaping interactive routines are a first attempt at this, but far from what they could be after follow-on thesis work.

Picture the computer screen divided into four active windows. In the lower left corner is the window where the poles and zeros of an L_0 transfer function are entered. Above that is a window containing the resulting Nichols chart of this L_0. The two windows on the right side contain the bode plot magnitude and phase of the L_0. This four-windowed screen would almost seem like a multi-tasking environment within our OO environment. Each window would be represented by an object, and whenever the user interacts with one window by

creating an event, each object would receive the event message. Each object would react to the events. If the user selects the lower left window area and modifies a pole or zero, that windows event would react by redrawing the transfer function. The other three objects would also react by redrawing the graphs in their windows for the new transfer function.

7.2.6 Interactive Tracking Specification Generation. Currently the QFT Toolbox requires T_{RU} and T_{RL} to be designed off-line by the user and entered manually. The design of these specification transfer functions is crucial to a successful QFT design, and an educational package like ICECAP-PC should include a tutorial type environment to assist the user in constructing these transfer functions. Valuable insights into their construction could be offered through the help facilities during their design. One example of the kind of help that should be made available is a simultaneous display of δ_R, so the user can readily see if the current T_{RU} and T_{RL} transfer functions provide a δ_R which is monotonically increasing for all frequencies. Another example would be some text screens of the engineering wisdom of the AFIT staff. For example, a recent situation arose where the figure of merit specifications on T_{RU} and T_{RL} were such that an all-real-pole transfer function would not work. [Houpis, 1992b] A complex pair of poles was added near a real pole to provide a response which had a quicker rise time, but no overshoot. This type of engineering insight would be an invaluable addition to every help screen for every function within ICECAP-PC. Indeed, if ICECAP-PC's help facilities became a depository for engineering experience and rules of thumb, the value of the help screens would quickly surpass the value of the package for educational purposes.

7.2.7 Augmented Model Bound Generation. As discussed in the QFT Users Manual, it is important that T_{RU} and T_{RL} be designed so that δ_R is monotonically increasing for all frequencies. It is suggested that at the highest frequency of performance concern, a zero

be added to T_{RU} and a pole be added to T_{RL} to avoid problems at high frequencies. Later work on ICECAP-PC should add an AUGMENT MODEL command which does this for the user who may not have known to do it in the initial design of T_{RU} and T_{RL}.

The MISO QFT toolbox needs to allow the user to adjust the Bl and Bu tracking responses to account for disturbance from cross terms in a MIMO design. [Sating, 1992] The new code would simply need to allow the user to modify the listing of values for δ_R to make them more strict--smaller. The tracking bounds would then be generated using the new values of δ_R.

Another technique for augmenting the model was discovered during a telephone conversation with Capt David Bossert [Bossert, 1992]. He is currently researching a way to implement an upper bound on the magnitude of L_o at each design frequency to account for device saturation. He cites examples in his work where the large error gains associated with QFT design saturate actuators in systems for which he designs QFT controllers. These bounds would be used as upper bounds on the traditional composite bounds. ICECAP-PC should add a capability in the composite bound generation and in the loop shaping algorithms to account for this.

7.2.8 Interface to Commercial Packages. Because commercial packages offer such a wide variety of specific techniques, ICECAP-PC will never be able to offer all of them. Perhaps the largest lacking function is an ability to do state-time simulations. Because all of these functions cannot be offered directly, an ability to generate information in ICECAP-PC and then port this information to the other packages is desirable. Porting information in the reverse direction is also important. One might want to construct a very large system using $Matrix_X$'s System Build facilities and then input this information into ICECAP-PC in the form of matrices or transfer functions. ASCII formatted data files appear to be the standard media

of choice for most popular commercial CACSD packages. The problem is not in generating a properly formatted file in ICECAP-PC or reading a file into ICECAP-PC, the problem is in obtaining the file format for each commercial package. ICECAP-PC has the required functionality, what is now required is development time to build the required file formats.

7.2.9 System Build Toolbox. We believe a crude but effective system build type function could be easily constructed using the type of dialog box built for the FORM CLTF option. Many possible systems can be built from the one dialogue box. Several different basic types of dialogue boxes could be made available for hundreds of possible systems. The possibilities could grow exponentially if some of the dialogue boxes included other dialogue boxes as one of their element choices.

7.2.10 Discrete Toolboxes. Considerably more time was required in porting ICECAP-PC 9.0 to the OO ICECAP-PC 10 than was originally expected. This resulted in an incomplete incorporation of the discrete domain capabilities. Some of the work has been done, and more will be completed during the weeks after this thesis period ends, but work will remain for following thesis students.

7.2.11 Nonlinear Toolbox. A nonlinear toolbox is a larger task than most of the others listed here. The basic idea is to provide the user with an interactive environment in which to model nonlinearities as linear functions. The user then compares the time and frequency response characteristics of the model to those of nonlinear system and iterates the model design until the datums match within specifications.

7.2.12 Time Delay Toolbox. In order to solve the large class of problems which contain time delay elements, a time delay toolbox will need to be added to ICECAP-PC. This toolbox must handle time delays in both the time and frequency domains, both discrete and continuous. The transfer function routines must be augmented to allow the entry of a time delay symbol during transfer function definition.

7.2.13 Transcendental Functions Toolbox. There is a need for a screen to provide transfer function approximations to transcendental functions. For example, if a student has a transfer function with e^{as} which cannot be entered directly into the transfer function definition, he could enter the approximation screen and generate a pole-zero combination to approximate that function over some range. Possible functions would be the exponential, sine, and cosine.

7.2.14 Borland PASCAL 7.0. In the final weeks of this thesis period, Borland shipped the upgrade to Turbo PASCAL 6.0 as well as a new Turbo Vision. This new version provides some startling breakthroughs. The 640K memory barrier for personal computers is eliminated with a new DOS Protected Mode Interface (DPMI) driver which has been released to public access. This results in increased speed for ICECAP-PC since the use of overlay files are no longer needed. It also results in higher order problems and higher resolution listings and plots. The new Integrated Development Environment (IDE) further expands its CASE-like features. Also new compilers and dialog box builders allow ICECAP-PC to be easily ported to the Microsoft Windows environment, if desired. Finally, if the user has a '386 or '486 machine, the new compiler allows mathematical enhancement instructions which can increase math performance up to five times. The disadvantage of the new PASCAL is that it no longer supports XT machines, at least a '286 processor is required.

7.3 Summary

In summary of both **Chapter 7** and the research paper as a whole, the author must emphasize his enthusiasm for what has been achieved with ICECAP-PC 10. AFIT has had a long and proud tradition of producing state-of-the-art CACSD packages for the public domain. TOTAL was the first at AFIT and the first in the world. ICECAP-PC 10 is also a first in the world: the first OO CACSD package for the public domain. Its OO user interface has no equal both for beginning users who need extra help and for the advanced users who want direct access to the functions they need. The full screen editor and the log file options ICECAP-PC now provides allow the student to produce extremely readable output reports to hand in with their homework. The elegance of the OO code and the extensive white and black box testing accomplished provide protection against both runtime errors and unreliable answers. By far, ICECAP-PC 10 is the best choice for students and professors alike in their choice for CACSD software to use for class and thesis work.

Appendices

Appendix A Bibliography

Appendix A: Bibliography

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Extensive information can be found on some older aspects of ICECAP-PC in the references, including old version data dictionaries and programming manuals. Copies of these documents can be obtained from Defense Technology Information Center (DTIC) using the indicated AD number. The appropriate address for the above documents is:

Defense Logistic Agency
Defense Technology Information Center (DTIC)
Cameron Station
Alexandria, VA 22304-6145

Appendix B Testing and Validation

Appendix B: Testing and Validation

This appendix contains several test results for numerical algorithms used in ICECAP-PC. This is a representative sample and not a complete list simply because there are far too many tests to include with any meaning.

1. Matrix Condition Number Test (pg B-4)

This test of the matrix condition number algorithm first finds the condition number of a given matrix per eq 2-2. It then finds the inverse of the matrix and determines the difference between the actual roundoff error and the projected roundoff error (eq 2-3). We found that for matrix inversion, the actual roundoff error sometimes exceeded the projected error. However, for other operations (not shown) the projected roundoff error gave a good maximum error estimate. We performed this test because at one point in the project we considered using the error anticipated by eq 2-2 to round off the resultant matrix elements. It remains an open option, but one we did not implement.

2. QR Shift Algorithm Test (pg B-5)

Our development of the QR Shift algorithm is based on the code given in Numerical Recipes for Pascal (Press, 1988). This source implements the QR Shift for the general real valued matrix that may contain complex eigenvalues in conjugate pairs. It recommends a three part sequence of balancing, upper Hessenberg conversion, and QR Shift (Sec II). However Numerical Recipes says nothing about a general complex valued matrix that may have single complex eigenvalues. No other reference that handled this case either. We instead build a test bench in Matlab to perform the QR Shift. The effort was a near failure until our discovery that after the QR Shift algorithm, complex eigenvalues can be hidden as eigenvalues of a 2x2 block along the main diagonal! With this discovery, we were able to modify the code from Numerical Recipes to handle the general complex valued matrix. This algorithm now appears in ICECAP-PC replacing that of previous versions that used roots of the characteristic equation. The listing for test 2 yielded this discovery!

3. QR Shift Code Modification Test (pg B-9)

Section 4.3 shows the testing performed on the final version of the ICECAP-PC QR Shift algorithm. It is included as an example of setting test points inside a numerical method to watch variables under iterations.

4. QR Shift Final Verification for multiple eigenvalues (pg B-29)

Section 4.4 shows some final validation tests for the QR Shift algorithm as implemented in ICECAP to determine behavior in the presence in multiple real eigenvalues. We found that in the presence of multiple real eigenvalues, the error associated with the calculated eigenvalues was symmetric about the actual eigenvalues. Therefore, we gave careful consideration to using the eigenvalue algorithm to perform root finding for polynomials via the fabrication of Jordan-Canonical matrices. However, as Jordan-Canonical matrices are notoriously ill-conditioned and imbalanced, this process would yield considerable error for high order polynomials. Therefore, standard root finding techniques are used for polynomials in ICECAP-PC.

5. LU Decomposition (pg B-30)

Section B-5 shows the final stage of testing for the LU Decomposition algorithm used for the general complex matrix. The purpose of this test was simply to take several

matrices, decompose them into their upper and lower triangular components and then multiply these two components to see what error resulted. We did this for several matrices. This section shows a real matrix, a poorly condition Hilbert matrix and a general complex matrix.

6. Inversion of Plant Matrix (pg B-32)

This section shows the tests performed on the LU Decomposition algorithm for matrices of transfer function as implemented in the MIMO QFT toolbox. During the process of testing this code, we worked out a 3x3 matrix inversion by hand and compared it step by step with the computer answers. In all cases of discrepancy, the computer was right and I was wrong! The reader interested in LU Decomposition as a solution to the inverse of plant matrix P should consider working out such an example by hand. It then becomes quite interesting to watch root cancellation take place on a element by element basis.

7. The Root Finder (pg B-37)

Section B-7 shows our tests comparing our root finder with that of PC-Matlab. In all cases we exceed the accuracy attained in Matlab, often by several decimal places. However, in the process we noticed something that forced us to modify our algorithm. The ICECAP-PC root finder first calls the Laguerre method to make the initial cut at the roots. The Laguerre method returns a set of values whose error with the actual roots is symmetrical with the actual roots in the case of root multiplicity. Hence coefficient reconstruction is extremely accurate after root finding with the Laguerre algorithm. The second step used by the ICECAP root finder is the polishing of the rough roots with either the Bairstow method in the case of real pairs or with Brents method in the case of single real roots or high root multiplicity. We were able to achieve extremely accurate roots with these two polishing methods. Improvements of 4-5 decimal places over Laguerre's method was common. However this added accuracy came at a loss of error symmetry about the actual values. *Polynomial coefficient reconstruction is often degraded with the better roots found by the polishing methods!* We finally modified our algorithm as follows.

8. Root Finder Coefficient Reconstruction Error Test (pg B-40)

After encountering the above mentioned problem we modified the root finder to take the first cut using Laguerre, store the Laguerre roots, take the second cut using Bairstow and Brent, and store the polished roots, reconstruct the polynomial coefficients with the Laguerre roots and find a reconstruction error, reconstruct the polynomial coefficients with the polished roots and find the polished reconstruction error, and compare the two errors taking the root set yielding the least reconstruction error. Very often ICECAP settles on the less accurate set of roots because the coefficient reconstruction error is minimized.

Matrix Condition Number Test

Fred L. Trevino, 1st Lt
EENG 799
Instructor: Prof Lamont

Comment:
The following matrix is a Hilbert (badly conditioned matrix) for n = 3

Matrix A

```
 1.0000  0.5000  0.3333
 0.5000  0.3333  0.2500
 0.3333  0.2500  0.2000
```

Matrix B = The Inverse Matrix Of Matrix A

Matrix B

```
  9.0000  -36.0000   30.0000
-36.0000  192.0000 -180.0000
 30.0000 -180.0000  180.0000
```

Matrix B

```
    9.000000000000000020    -36.000000000000000100     30.000000000000000100
  -36.000000000000000100    192.000000000000001000   -180.000000000000001000
   30.000000000000000100   -180.000000000000001000    180.000000000000001000
```

Comment:
Note that error has crept into the 17th bit position as predicted by Chapra

Comment:
Condition numbers can therefore be used to truncate error at known low bits

Comment:

The second test uses *LU* Decomposition to test the inverse of the 3x3 Hilbert Matrix

Matrix A

```
 1.00000000000000  0.50000000000000  0.33333333333333
 0.50000000000000  0.33333333333333  0.25000000000000
 0.33333333333333  0.25000000000000  0.20000000000000
```

Matrix B = The Inverse Matrix Of Matrix A

Matrix B

```
   8.999999999999999970   -35.999999999999999900    29.999999999999999900
 -35.999999999999999900   191.999999999999999000  -179.999999999999999000
  29.999999999999999900  -179.999999999999999000   179.999999999999999000
```

Comment:
it is only acurate to 15 significant bits

Matrix B

```
  9.00000000000000  -36.00000000000000   30.00000000000000
-36.00000000000000  192.00000000000000 -180.00000000000000
 30.00000000000000 -180.00000000000000  180.00000000000000
```

Comment:
Here we see that the calculation of the inverse is only accurate to 15 significant bits reguardless of which method we use for a 3x3 matrix. Freds eq predicts rouding error to the 19-3=16th bit. The fifteenth bit must be used for rounding, therefore rounding to 14 sig digits will produce the exact correct answer.

Eigenvalues using QR Shift

```
Fred L. Trevino
25 June 92
This is a test of Dr Jones QR Shift Algorithm for a general complex matrix
with single eigenvalues.  This will validate the formation of the Householder
matrix by the method taught by Dr Jones.
==========================================================================

» a

a =

   1.0000 + 1.0000i   4.0000 - 2.0000i   3.0000 - 1.0000i
   4.0000 + 2.0000i   4.0000             6.0000 + 8.0000i
        0 + 1.0000i   3.0000             1.0000 + 7.0000i


» InMat = balance(a)

InMat =

   1.0000 + 1.0000i   4.0000 - 2.0000i   1.5000 - 0.5000i
   4.0000 + 2.0000i   4.0000             3.0000 + 4.0000i
        0 + 2.0000i   6.0000             1.0000 + 7.0000i

» InMat = hess(InMat)

InMat =

   1.0000 + 1.0000i   4.1079 - 1.3693i   1.3693 + 1.3693i
   4.3818 + 2.1909i   3.6667 + 0.8333i   4.9333 + 6.3000i
        0             3.0000 + 0.1667i   1.3333 + 6.1667i

» eigtst
   Undefined function or variable.
Symbol in question --^P eigtst

» eigentst

----- Main Menu      -----

      1) Input Matrix
      2) Specify Ctr
      3) Run Test
      4) Display Result
      5) Quit


 Select a menu number:
 Enter Iteration Count:
Ctr =

    25


Ctr =

    25

Press Enter To Continue

----- Main Menu      -----

      1) Input Matrix
      2) Specify Ctr
      3) Run Test
      4) Display Result
      5) Quit


 Select a menu number: Running.....
Iteration:

i =
```

```
     1


Xmat =

   1.0000 + 1.0000i
   4.3818 + 2.1909i
        0


Zmat =

     1
     0
     0


Sigma =

   4.4737 + 2.3694i


VSquare =

   65.0787


Hmat =

  -0.2697 + 0.0000i  -0.9640 - 0.0852i        0
  -0.9640 + 0.0852i   0.2624                  0
        0                  0             1.0000


Rmat =

  -4.3069 - 2.7548i  -4.5713 - 0.7464i  -4.5882 - 6.8624i
   0.1008 - 0.3038i  -2.8810 + 1.8886i  -0.1419 + 0.4500i
        0             3.0000 + 0.1667i   1.3333 + 6.1667i


Qmat =

  -0.2605 - 0.0000i  -0.9570 - 0.0846i        0
  -0.9570 + 0.0846i   0.2677 - 0.0000i        0
        0                  0             1.0000


Y =

   5.5601 + 1.0455i   2.6650 + 2.8009i  -4.5882 - 6.8624i
   2.5712 - 1.9719i  -0.8935 + 0.7879i  -0.1419 + 0.4500i
  -2.8852 + 0.0942i   0.8032 + 0.0446i   1.3333 + 6.1667i

Iteration:

i =

     2


Xmat =

   5.5601 + 1.0455i
   2.5712 - 1.9719i
  -2.8852 + 0.0942i


Zmat =

     1
     0
     0
```

```
Sigma =

   6.3926 + 0.0737i


VSquare =

  153.4983


Hmat =

  -0.8778 + 0.0000i  -0.3717 - 0.3446i   0.4480 + 0.0567i
  -0.3717 + 0.3446i   0.8632 - 0.0000i   0.0991 - 0.0710i
   0.4480 - 0.0567i   0.0991 + 0.0710i   0.8914 + 0.0000i


Rmat =

  -7.8138 - 1.1923i  -1.3785 - 2.3781i   4.4828 + 8.7437i
  -0.4866 + 0.0394i  -2.6442 + 0.5048i   4.5173 + 1.8744i
   0.3728 + 0.2239i   1.9243 + 1.1579i  -1.3021 + 2.7179i


Qmat =

  -0.6718 + 0.0000i  -0.3309 - 0.3068i   0.3988 + 0.0505i
  -0.3309 + 0.3068i   0.8782 - 0.0000i   0.0882 - 0.0632i
   0.3988 - 0.0505i   0.0882 + 0.0632i   0.9033 + 0.0000i


Y =

   8.6650 + 4.4258i   0.8522 + 1.7579i   0.7215 + 6.9056i
   2.9433 - 0.4854i  -1.8690 + 1.0303i   3.6832 + 1.8959i
  -1.6245 + 1.2065i   1.3486 + 0.9858i  -0.7960 + 2.5438i


Iteration:

i =

    25


Xmat =

   7.6043 + 4.1451i
   0.1410 + 0.3151i
  -0.1389 - 0.1881i


Zmat =

     1
     0
     0


Sigma =

  -7.6043 - 4.1451i


VSquare =

    0.1704


Hmat =

   1.0000                  0                  0
        0            -0.3988 + 0.0000i   0.9256 + 0.2026i
        0             0.9256 - 0.2026i   0.3581 - 0.0000i
```

```
Rmat =

   7.6043 + 4.1451i  -2.6219 - 6.2994i  -0.4115 - 5.0033i
  -0.1467 - 0.3279i   3.5471 - 1.2151i  -0.4863 - 0.6414i
   0.1446 + 0.1957i   0.0817 + 2.9607i   1.7685 + 3.2964i


Qmat =

   1.0000                  0                  0
        0            -0.3441 - 0.0000i   0.8895 + 0.1947i
        0             0.8895 - 0.1947i   0.3832 + 0.0000i


Y =

   7.6043 + 4.1451i  -0.4380 - 2.2024i  -1.2632 - 8.0309i
  -0.1467 - 0.3279i  -1.7781 - 0.0577i   3.2053 - 0.6359i
   0.1446 + 0.1957i   2.1868 + 1.5689i   0.1739 + 3.9125i


----- Main Menu      -----

      1) Input Matrix
      2) Specify Ctr
      3) Run Test
      4) Display Result
      5) Quit


 Select a menu number: The Final Result Is:

Result =

   7.6043 + 4.1451i  -0.4380 - 2.2024i  -1.2632 - 8.0309i
  -0.1467 - 0.3279i  -1.7781 - 0.0577i   3.2053 - 0.6359i
   0.1446 + 0.1957i   2.1868 + 1.5689i   0.1739 + 3.9125i

%Now, the result of 25 iterations is as follows:
%==========================================================================
Result =

   7.6043 + 4.1451i  -0.4380 - 2.2024i  -1.2632 - 8.0309i
  -0.1467 - 0.3279i  -1.7781 - 0.0577i   3.2053 - 0.6359i
   0.1446 + 0.1957i   2.1868 + 1.5689i   0.1739 + 3.9125i

» eig(a)

ans =

  -3.4786 + 0.5744i
   1.8179 + 3.4037i
   7.6607 + 4.0219i  <- Note that this is close to element (1,1) of the result

» test = [Result(2,2) Result(2,3); Result(3,2) Result(3,3)]

test =

  -1.7781 - 0.0577i   3.2053 - 0.6359i  ---> This is the two by two matrix
   2.1868 + 1.5689i   0.1739 + 3.9125i  |     in the lower right hand corner

» eig(test)

ans =
                                        ---> These are the two eigenvalues of the matrix
  -3.4530 + 0.5103i                     |    in the lower right hand corner.  They are also
   1.8487 + 3.3445i                     |    eigenvalues of the original matrix.

» save

Saving to: matlab.mat

» quit

 42652 flops.
```

The QR Shift Algorithm Implemented in ICECAP

Fred L. Trevino
EENG 799
Prof Gary I Lamont

```
: QRShift Test

Matrix C

 0.0000  1.0000  0.0000
 0.0000  0.0000  1.0000
 6.0000 -1.0000 -4.0000


Balanced Form of Matrix C

 0.0000  2.0000  0.0000
 0.0000  0.0000  1.0000
 3.0000 -1.0000 -4.0000


Hessenberg Form of Balanced Matrix C

 0.0000  0.0000  2.0000
 3.0000 -4.0000 -1.0000
 0.0000  1.0000  0.0000
TP 1
TP 2
TP 3
TP 3
TP 4
TP 6
TP 10
TP 12

its 1
nn: 3
================================
p:            0.2500
q:            0.0000
r:            0.7500
s:            1.3333
t:            0.0000
u:   0.55637508958790268E+0105
v:            0.0000
x:            0.00^
y:           -4.0000
z:            0.0000
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 18
TP 19
TP 20
TP 22
TP 23

its 1
nn: 3
================================
p:            0.0000
q:            0.0000
r:            0.7208
s:            0.7906
t:            0.0000
u:   0.55637508958790268E+0105
v:            0.0000
x:            1.3162
y:            0.0000
z:            0.9487
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
```

```
TP 22
TP 23

its 1
nn: 3
================================
p:            0.7208
q:            0.0000
r:            0.7208
s:            0.7906
t:            0.0000
u:   0.55637508958790268E+0105
v:            0.0000
x:            1.3162
y:            0.0000
z:            0.9487
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 22
TP 23

its 1
nn: 3
================================
p:            2.0000
q:            0.0000
r:            0.7208
s:            0.7906
t:            0.0000
u:   0.55637508958790268E+0105
v:            0.0000
x:            1.3162
y:            0.0000
z:            0.9487
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 24
TP 25

its 1
nn: 3
================================
p:           -0.6000
q:            0.0000
r:            0.7208
s:            0.7906
t:            0.0000
u:   0.55637508958790268E+0105
v:            0.0000
x:            1.3162
y:            0.0000
z:            0.9487
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 24
TP 25

its 1
nn: 3
================================
p:            3.0000
q:            0.0000
r:            0.7208
s:            0.7906
t:            0.0000
u:   0.55637508958790268E+0105
v:            0.0000
x:            1.3162
y:            0.0000
z:            0.9487
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
```

```
Eigenvalue 3            0.0000          0.0000
TP 24
TP 25

its 1
nn: 3
================================
p:            -1.8000
q:             0.0000
r:             0.7208
s:             0.7906
t:             0.0000
u:   0.55637508958790268E+0105
v:             0.0000
x:             1.3162
y:             0.0000
z:             0.9487
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 14

its 1
nn: 3
================================
p:             0.0000
q:             1.8000
r:             0.7208
s:             0.7906
t:             0.0000
u:   0.55637508958790268E+0105
v:             0.0000
x:             1.3162
y:             0.0000
z:             0.9487
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 16

its 1
nn: 3
================================
p:             0.0000
q:             1.8000
r:             0.0000
s:             0.7906
t:             0.0000
u:   0.55637508958790268E+0105
v:             0.0000
x:             1.3162
y:             0.0000
z:             0.9487
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 17

its 1
nn: 3
================================
p:             0.0000
q:             1.0000
r:             0.0000
s:             0.7906
t:             0.0000
u:   0.55637508958790268E+0105
v:             0.0000
x:             1.8000
y:             0.0000
z:             0.9487
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 18
```

```
TP 19
TP 21
TP 22
TP 22
TP 24
TP 24
TP 24
TP 26
TP 3
TP 3
TP 4
TP 6
TP 10
TP 12

its 2
nn: 3
================================
p:          -0.3060
q:           0.4113
r:          -0.2827
s:          11.1845
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:          -4.0000
y:          -0.6000
z:           0.6000
Eigenvalue 1          0.0000          0.0000
Eigenvalue 2          0.0000          0.0000
Eigenvalue 3          0.0000          0.0000
TP 18
TP 19
TP 20
TP 22
TP 23

its 2
nn: 3
================================
p:           1.4305
q:          -0.4614
r:           0.3172
s:          -0.5854
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           1.5227
y:          -0.7025
z:           0.4830
Eigenvalue 1          0.0000          0.0000
Eigenvalue 2          0.0000          0.0000
Eigenvalue 3          0.0000          0.0000
TP 22
TP 23

its 2
nn: 3
================================
p:          -0.5262
q:          -0.4614
r:           0.3172
s:          -0.5854
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           1.5227
y:          -0.7025
z:           0.4830
Eigenvalue 1          0.0000          0.0000
Eigenvalue 2          0.0000          0.0000
Eigenvalue 3          0.0000          0.0000
TP 22
TP 23
```

```
its 2
nn: 3
================================
p:          -0.4660
q:          -0.4614
r:           0.3172
s:          -0.5854
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           1.5227
y:          -0.7025
z:           0.4830
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 24
TP 25

its 2
nn: 3
================================
p:          -2.3056
q:          -0.4614
r:           0.3172
s:          -0.5854
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           1.5227
y:          -0.7025
z:           0.4830
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 24
TP 25

its 2
nn: 3
================================
p:          -0.5347
q:          -0.4614
r:           0.3172
s:          -0.5854
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           1.5227
y:          -0.7025
z:           0.4830
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 24
TP 25

its 2
nn: 3
================================
p:          -0.8321
q:          -0.4614
r:           0.3172
s:          -0.5854
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           1.5227
y:          -0.7025
z:           0.4830
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 14
```

```
its 2
nn: 3
================================
p:          -0.2603
q:           0.1412
r:           0.3172
s:          -0.5854
t:           0.0000
u:  0.5563750895879026 8E+0105
v:           0.0000
x:           1.5227
y:          -0.7025
z:           0.4830
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 16

its 2
nn: 3
================================
p:          -0.2603
q:           0.1412
r:           0.0000
s:          -0.5854
t:           0.0000
u:  0.5563750895879026 8E+0105
v:           0.0000
x:           1.5227
y:          -0.7025
z:           0.4830
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 17

its 2
nn: 3
================================
p:          -0.6484
q:           0.3516
r:           0.0000
s:          -0.5854
t:           0.0000
u:  0.5563750895879026 8E+0105
v:           0.0000
x:           0.4015
y:          -0.7025
z:           0.4830
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 18
TP 19
TP 21
TP 22
TP 22
TP 24
TP 24
TP 24
TP 26
TP 3
TP 3
TP 4
TP 6
TP 10
TP 12

its 3
nn: 3
================================
p:           0.8223
q:           0.1344
r:           0.0432
s:          37.4230
```

```
t:            0.0000
u:  0.55637508958790268E+0105
v:            0.0000
x:           -4.3027
y:           -0.4247
z:            0.7274
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 18
TP 19
TP 20
TP 22
TP 23

its 3
nn: 3
================================
p:            0.7514
q:            0.0811
r:            0.0261
s:            0.8344
t:            0.0000
u:  0.55637508958790268E+0105
v:            0.0000
x:            1.9856
y:            0.1611
z:            0.0518
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 22
TP 23

its 3
nn: 3
================================
p:            1.2018
q:            0.0811
r:            0.0261
s:            0.8344
t:            0.0000
u:  0.55637508958790268E+0105
v:            0.0000
x:            1.9856
y:            0.1611
z:            0.0518
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 22
TP 23

its 3
nn: 3
================================
p:            1.8097
q:            0.0811
r:            0.0261
s:            0.8344
t:            0.0000
u:  0.55637508958790268E+0105
v:            0.0000
x:            1.9856
y:            0.1611
z:            0.0518
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 24
TP 25

its 3
nn: 3
================================
```

```
p:          -1.7892
q:           0.0811
r:           0.0261
s:           0.8344
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           1.9856
y:           0.1611
z:           0.0518
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 24
TP 25

its 3
nn: 3
================================
p:           0.1380
q:           0.0811
r:           0.0261
s:           0.8344
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           1.9856
y:           0.1611
z:           0.0518
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 24
TP 25

its 3
nn: 3
================================
p:          -0.0545
q:           0.0811
r:           0.0261
s:           0.8344
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           1.9856
y:           0.1611
z:           0.0518
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 14

its 3
nn: 3
================================
p:           0.0371
q:           0.0156
r:           0.0261
s:           0.8344
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           1.9856
y:           0.1611
z:           0.0518
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 16

its 3
nn: 3
================================
p:           0.0371
```

```
q:            0.0156
r:            0.0000
s:            0.8344
t:            0.0000
u:  0.55637508958790268E+0105
v:            0.0000
x:            1.9856
y:            0.1611
z:            0.0518
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 17

its 3
nn: 3
================================
p:            0.7042
q:            0.2958
r:            0.0000
s:            0.8344
t:            0.0000
u:  0.55637508958790268E+0105
v:            0.0000
x:            0.0527
y:            0.1611
z:            0.0518
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 18
TP 19
TP 21
TP 22
TP 22
TP 24
TP 24
TP 24
TP 26
TP 3
TP 3
TP 4
TP 6
TP 10
TP 12

its 4
nn: 3
================================
p:           -0.9840
q:            0.0151
r:           -0.0010
s:          308.7020
t:            0.0000
u:  0.55637508958790268E+0105
v:            0.0000
x:           -3.6282
y:           -1.3963
z:            1.0246
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 18
TP 19
TP 20
TP 22
TP 23

its 4
nn: 3
================================
p:            1.0249
q:           -0.0077
r:            0.0005
s:           -0.9841
```

```
t:            0.0000
u:  0.5563750895879026 8E+0105
v:            0.0000
x:            1.9999
y:           -0.0153
z:            0.0010
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 22
TP 23

its 4
nn: 3
================================
p:            1.5475
q:           -0.0077
r:            0.0005
s:           -0.9841
t:            0.0000
u:  0.5563750895879026 8E+0105
v:            0.0000
x:            1.9999
y:           -0.0153
z:            0.0010
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 22
TP 23

its 4
nn: 3
================================
p:           -0.9831
q:           -0.0077
r:            0.0005
s:           -0.9841
t:            0.0000
u:  0.5563750895879026 8E+0105
v:            0.0000
x:            1.9999
y:           -0.0153
z:            0.0010
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 24
TP 25

its 4
nn: 3
================================
p:           -2.0252
q:           -0.0077
r:            0.0005
s:           -0.9841
t:            0.0000
u:  0.5563750895879026 8E+0105
v:            0.0000
x:            1.9999
y:           -0.0153
z:            0.0010
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 24
TP 25

its 4
nn: 3
================================
p:           -0.0247
q:           -0.0077
r:            0.0005
```

```
s:          -0.9841
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           1.9999
y:          -0.0153
z:           0.0010
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 24
TP 25

its 4
nn: 3
================================
p:          -0.0010
q:          -0.0077
r:           0.0005
s:          -0.9841
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           1.9999
y:          -0.0153
z:           0.0010
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 14

its 4
nn: 3
================================
p:           0.0002
q:          -0.0000
r:           0.0005
s:          -0.9841
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           1.9999
y:          -0.0153
z:           0.0010
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 16

its 4
nn: 3
================================
p:           0.0002
q:          -0.0000
r:           0.0000
s:          -0.9841
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           1.9999
y:          -0.0153
z:           0.0010
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 17

its 4
nn: 3
================================
p:           0.8760
q:          -0.1240
r:           0.0000
s:          -0.9841
t:           0.0000
```

```
u:  0.55637508958790268E+0105
v:            0.0000
x:            0.0002
y:           -0.0153
z:            0.0010
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 18
TP 19
TP 21
TP 22
TP 22
TP 24
TP 24
TP 24
TP 26
TP 3
TP 3
TP 4
TP 6
TP 10
TP 12

its 5
nn: 3
================================
p:           -0.9999
q:            0.0001
r:            0.0000
s:        69288.8960
t:            0.0000
u:  0.55637508958790268E+0105
v:            0.0000
x:           -3.1570
y:           -1.8431
z:            1.0001
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 18
TP 19
TP 20
TP 22
TP 23

its 5
nn: 3
================================
p:            1.0001
q:           -0.0000
r:           -0.0000
s:           -0.9999
t:            0.0000
u:  0.55637508958790268E+0105
v:            0.0000
x:            2.0000
y:           -0.0001
z:           -0.0000
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 22
TP 23

its 5
nn: 3
================================
p:            1.6997
q:           -0.0000
r:           -0.0000
s:           -0.9999
t:            0.0000
u:  0.55637508958790268E+0105
v:            0.0000
```

```
x:          2.0000
y:         -0.0001
z:         -0.0000
Eigenvalue 1          0.0000          0.0000
Eigenvalue 2          0.0000          0.0000
Eigenvalue 3          0.0000          0.0000
TP 22
TP 23

its 5
nn: 3
================================
p:          0.7813
q:         -0.0000
r:         -0.0000
s:         -0.9999
t:          0.0000
u:  0.55637508958790268E+0105
v:          0.0000
x:          2.0000
y:         -0.0001
z:         -0.0000
Eigenvalue 1          0.0000          0.0000
Eigenvalue 2          0.0000          0.0000
Eigenvalue 3          0.0000          0.0000
TP 24
TP 25

its 5
nn: 3
================================
p:         -2.0001
q:         -0.0000
r:         -0.0000
s:         -0.9999
t:          0.0000
u:  0.55637508958790268E+0105
v:          0.0000
x:          2.0000
y:         -0.0001
z:         -0.0000
Eigenvalue 1          0.0000          0.0000
Eigenvalue 2          0.0000          0.0000
Eigenvalue 3          0.0000          0.0000
TP 24
TP 25

its 5
nn: 3
================================
p:         -0.0001
q:         -0.0000
r:         -0.0000
s:         -0.9999
t:          0.0000
u:  0.55637508958790268E+0105
v:          0.0000
x:          2.0000
y:         -0.0001
z:         -0.0000
Eigenvalue 1          0.0000          0.0000
Eigenvalue 2          0.0000          0.0000
Eigenvalue 3          0.0000          0.0000
TP 24
TP 25

its 5
nn: 3
================================
p:          0.0000
q:         -0.0000
r:         -0.0000
s:         -0.9999
t:          0.0000
u:  0.55637508958790268E+0105
```

```
v:          0.0000
x:          2.0000
y:         -0.0001
z:         -0.0000
Eigenvalue 1          0.0000          0.0000
Eigenvalue 2          0.0000          0.0000
Eigenvalue 3          0.0000          0.0000
TP 14

its 5
nn: 3
================================
p:          0.0000
q:          0.0000
r:         -0.0000
s:         -0.9999
t:          0.0000
u:  0.55637508958790268E+0105
v:          0.0000
x:          2.0000
y:         -0.0001
z:         -0.0000
Eigenvalue 1          0.0000          0.0000
Eigenvalue 2          0.0000          0.0000
Eigenvalue 3          0.0000          0.0000
TP 16

its 5
nn: 3
================================
p:          0.0000
q:          0.0000
r:          0.0000
s:         -0.9999
t:          0.0000
u:  0.55637508958790268E+0105
v:          0.0000
x:          2.0000
y:         -0.0001
z:         -0.0000
Eigenvalue 1          0.0000          0.0000
Eigenvalue 2          0.0000          0.0000
Eigenvalue 3          0.0000          0.0000
TP 17

its 5
nn: 3
================================
p:          0.9625
q:          0.0375
r:          0.0000
s:         -0.9999
t:          0.0000
u:  0.55637508958790268E+0105
v:          0.0000
x:          0.0000
y:         -0.0001
z:         -0.0000
Eigenvalue 1          0.0000          0.0000
Eigenvalue 2          0.0000          0.0000
Eigenvalue 3          0.0000          0.0000
TP 18
TP 19
TP 21
TP 22
TP 22
TP 24
TP 24
TP 24
TP 26
TP 3
TP 3
TP 4
TP 6
TP 10
```

```
TP 12

its 6
nn: 3
================================
p:          -1.0000
q:           0.0000
r:          -0.0000
s:  6298606684.8862
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:          -3.0160
y:          -1.9840
z:           1.0000
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 18
TP 19
TP 20
TP 22
TP 23

its 6
nn: 3
================================
p:           1.0000
q:          -0.0000
r:           0.0000
s:          -1.0000
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           2.0000
y:          -0.0000
z:           0.0000
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 22
TP 23

its 6
nn: 3
================================
p:           1.7290
q:          -0.0000
r:           0.0000
s:          -1.0000
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           2.0000
y:          -0.0000
z:           0.0000
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 22
TP 23

its 6
nn: 3
================================
p:          -0.7146
q:          -0.0000
r:           0.0000
s:          -1.0000
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           2.0000
y:          -0.0000
z:           0.0000
```

```
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 24
TP 25

its 6
nn: 3
================================
p:          -2.0000
q:          -0.0000
r:           0.0000
s:          -1.0000
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           2.0000
y:          -0.0000
z:           0.0000
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 24
TP 25

its 6
nn: 3
================================
p:          -0.0000
q:          -0.0000
r:           0.0000
s:          -1.0000
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           2.0000
y:          -0.0000
z:           0.0000
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 24
TP 25

its 6
nn: 3
================================
p:          -0.0000
q:          -0.0000
r:           0.0000
s:          -1.0000
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           2.0000
y:          -0.0000
z:           0.0000
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 14

its 6
nn: 3
================================
p:           0.0000
q:          -0.0000
r:           0.0000
s:          -1.0000
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           2.0000
y:          -0.0000
z:           0.0000
```

```
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 16

its 6
nn: 3
================================
p:            0.0000
q:           -0.0000
r:            0.0000
s:           -1.0000
t:            0.0000
u:  0.55637508958790268E+0105
v:            0.0000
x:            2.0000
y:           -0.0000
z:            0.0000
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 17

its 6
nn: 3
================================
p:            0.9957
q:           -0.0043
r:            0.0000
s:           -1.0000
t:            0.0000
u:  0.55637508958790268E+0105
v:            0.0000
x:            0.0000
y:           -0.0000
z:            0.0000
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 18
TP 19
TP 21
TP 22
TP 22
TP 24
TP 24
TP 24
TP 26
TP 3
TP 3
TP 4
TP 6
TP 10
TP 12

its 7
nn: 3
================================
p:           -1.0000
q:            0.0000
r:            0.0000
s: 66626453394759628100.0000
t:            0.0000
u:  0.55637508958790268E+0105
v:            0.0000
x:           -3.0002
y:           -1.9998
z:            1.0000
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 18
TP 19
TP 20
TP 22
```

```
TP 23

its 7
nn: 3
================================
p:            1.0000
q:           -0.0000
r:           -0.0000
s:           -1.0000
t:            0.0000
u:   0.55637508958790268E+0105
v:            0.0000
x:            2.0000
y:           -0.0000
z:           -0.0000
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 22
TP 23

its 7
nn: 3
================================
p:            1.7320
q:           -0.0000
r:           -0.0000
s:           -1.0000
t:            0.0000
u:   0.55637508958790268E+0105
v:            0.0000
x:            2.0000
y:           -0.0000
z:           -0.0000
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 22
TP 23

its 7
nn: 3
================================
p:            0.7072
q:           -0.0000
r:           -0.0000
s:           -1.0000
t:            0.0000
u:   0.55637508958790268E+0105
v:            0.0000
x:            2.0000
y:           -0.0000
z:           -0.0000
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 24
TP 25

its 7
nn: 3
================================
p:           -2.0000
q:           -0.0000
r:           -0.0000
s:           -1.0000
t:            0.0000
u:   0.55637508958790268E+0105
v:            0.0000
x:            2.0000
y:           -0.0000
z:           -0.0000
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
```

```
TP 24
TP 25

its 7
nn: 3
================================
p:          -0.0000
q:          -0.0000
r:          -0.0000
s:          -1.0000
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           2.0000
y:          -0.0000
z:          -0.0000
Eigenvalue 1           0.0000          0.0000
Eigenvalue 2           0.0000          0.0000
Eigenvalue 3           0.0000          0.0000
TP 24
TP 25

its 7
nn: 3
================================
p:           0.0000
q:          -0.0000
r:          -0.0000
s:          -1.0000
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           2.0000
y:          -0.0000
z:          -0.0000
Eigenvalue 1           0.0000          0.0000
Eigenvalue 2           0.0000          0.0000
Eigenvalue 3           0.0000          0.0000
TP 14

its 7
nn: 3
================================
p:           0.0000
q:          -0.0000
r:          -0.0000
s:          -1.0000
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           2.0000
y:          -0.0000
z:          -0.0000
Eigenvalue 1           0.0000          0.0000
Eigenvalue 2           0.0000          0.0000
Eigenvalue 3           0.0000          0.0000
TP 16

its 7
nn: 3
================================
p:           0.0000
q:          -0.0000
r:           0.0000
s:          -1.0000
t:           0.0000
u:  0.55637508958790268E+0105
v:           0.0000
x:           2.0000
y:          -0.0000
z:          -0.0000
Eigenvalue 1           0.0000          0.0000
Eigenvalue 2           0.0000          0.0000
Eigenvalue 3           0.0000          0.0000
TP 17
```

```
its 7
nn: 3
================================
p:            1.0000
q:           -0.0000
r:            0.0000
s:           -1.0000
t:            0.0000
u:  0.55637508958790268E+0105
v:            0.0000
x:            0.0000
y:           -0.0000
z:           -0.0000
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 18
TP 19
TP 21
TP 22
TP 22
TP 24
TP 24
TP 24
TP 26
TP 3
TP 3
TP 6
TP 7

its 7
nn: 3
================================
p:            0.5003
q:            0.2500
r:            0.0000
s:            2.9997
t:            0.0000
u:  0.55637508958790268E+0105
v:            0.0000
x:           -3.0003
y:           -1.9997
z:            0.5000
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2            0.0000          0.0000
Eigenvalue 3            0.0000          0.0000
TP 8

its 7
nn: 3
================================
p:            0.5003
q:            0.2500
r:            0.0000
s:            2.9997
t:            0.0000
u:  0.55637508958790268E+0105
v:            0.0000
x:           -3.0003
y:           -1.9997
z:            1.0003
Eigenvalue 1            0.0000          0.0000
Eigenvalue 2           -2.0000          0.0000
Eigenvalue 3           -3.0000          0.0000
TP 2
TP 4
TP 5

its 0
nn: 0
================================
p:            0.5003
q:            0.2500
r:            0.0000
```

```
s:            2.9997
t:            0.0000
u:   0.55637508958790268E+0105
v:            0.0000
x:            1.0000
y:           -1.9997
z:            1.0003
Eigenvalue 1            1.0000          0.0000
Eigenvalue 2           -2.0000          0.0000
Eigenvalue 3           -3.0000          0.0000

its 0
nn: 0
================================
p:            0.5003
q:            0.2500
r:            0.0000
s:            2.9997
t:            0.0000
u:   0.55637508958790268E+0105
v:            0.0000
x:            1.0000
y:           -1.9997
z:            1.0003
Eigenvalue 1            1.0000          0.0000
Eigenvalue 2           -2.0000          0.0000
Eigenvalue 3           -3.0000          0.0000


Eigenvalues of Matrix C

 1.0000
-2.0000
-3.0000
```

Final Test of QR Shift For ICECAP-PC

Fred L. Trevino
EENG 799
Prof Gary I Lamont

```
: This is the first test matrix in Jordan Canonical Form

Matrix C

 0.0000  1.0000  0.0000
 0.0000  0.0000  1.0000
 6.0000 -1.0000 -4.0000


Eigenvalues of Matrix C

 1.00000000000000000
-3.00000000000000000
-2.00000000000000000

: The second test matrix is given in Numerical Recipes

Matrix E

 1.0000  2.0000   0.0000  0.0000  0.0000
-2.0000  3.0000   0.0000  0.0000  0.0000
 3.0000  4.0000  50.0000  0.0000  0.0000
-4.0000  5.0000 -60.0000  7.0000  0.0000
-5.0000  6.0000 -70.0000  8.0000 -9.0000


Eigenvalues of Matrix E

 50.00000000000000000
  2.00000000000000000 - 1.73205080756887730j
  2.00000000000000000 + 1.73205080756887730j
 -9.00000000000000000
  7.00000000000000000

: The third matrix is a complex matrix with distinct complex eigenvalues

Matrix A

 1.0000 + 1.0000j  4.0000 - 2.0000j  3.0000 - 1.0000j
 4.0000 + 2.0000j  4.0000            6.0000 + 8.0000j
 0.0000 + 1.0000j  3.0000            1.0000 + 7.0000j


Eigenvalues of Matrix A

-3.47855955887271427 + 0.57437430768745852j
 1.81789299597115922 + 3.40373402863058531j
 7.66066656290155505 + 4.02189166368195617j
```

LU Decompsition

Fred L. Trevino
EENG 799
Prof Gary I Lamont

Comment:
This is a test of the LU Decomposition Method. I will Decompose three matricies, multiply them back together and compare.

Matrix A

```
 0.000000000000000  1.000000000000000  0.000000000000000
 0.000000000000000  0.000000000000000  1.000000000000000
 6.000000000000000 -1.000000000000000 -4.000000000000000
```

The LU Decomposition is Given By:

L Component

```
 1.000000000000000  0.000000000000000  0.000000000000000
 0.000000000000000  1.000000000000000  0.000000000000000
 0.000000000000000  0.000000000000000  1.000000000000000
```

U Component

```
 6.000000000000000 -1.000000000000000 -4.000000000000000
 0.000000000000000  1.000000000000000  0.000000000000000
 0.000000000000000  0.000000000000000  1.000000000000000
```

The L and U Components Multiplied Together Equal:

Matrix B

```
 0.000000000000000  1.000000000000000  0.000000000000000
 0.000000000000000  0.000000000000000  1.000000000000000
 6.000000000000000 -1.000000000000000 -4.000000000000000
```

Matrix A

```
 0.000000000000000  1.000000000000000  0.000000000000000
 0.000000000000000  0.000000000000000  1.000000000000000
 6.000000000000000 -1.000000000000000 -4.000000000000000
```

Comment:
This was a Jordan Canonical Form Matrix

Comment:

==========

Comment:
The second test is to to a 5x5 Hilbert matrix

Matrix I

```
 1.000000000000000  0.500000000000000  0.333333333333333  0.250000000000000
0.200000000000000
 0.500000000000000  0.333333333333333  0.250000000000000  0.200000000000000
0.166666666666667
 0.333333333333333  0.250000000000000  0.200000000000000  0.166666666666667
0.142857142857143
 0.250000000000000  0.200000000000000  0.166666666666667  0.142857142857143
0.125000000000000
 0.200000000000000  0.166666666666667  0.142857142857143  0.125000000000000
0.111111111111111
```

The LU Decomposition is Given By:

L Component

```
 1.000000000000000  0.000000000000000  0.000000000000000  0.000000000000000
0.000000000000000
```

```
       0.200000000000000  1.000000000000000  0.000000000000000  0.000000000000000
0.000000000000000
       0.500000000000000  1.250000000000000  1.000000000000000  0.000000000000000
0.000000000000000
       0.333333333333333  1.250000000000000  0.533333333333333  1.000000000000000
0.000000000000000
       0.250000000000000  1.125000000000000  0.200000000000000  0.642857142857143
1.000000000000000
```

U Component

```
       1.000000000000000  0.500000000000000  0.333333333333333  0.250000000000000
0.200000000000000
       0.000000000000000  0.066666666666667  0.076190476190476  0.075000000000000
0.071111111111111
       0.000000000000000  0.000000000000000 -0.011904761904762 -0.018750000000000
-0.022222222222222
       0.000000000000000  0.000000000000000  0.000000000000000 -0.000416666666667
-0.000846560846561
       0.000000000000000  0.000000000000000  0.000000000000000  0.000000000000000
-0.000011337868481
```

The L and U Components Multiplied Together Equal:

Matrix J

```
       1.000000000000000  0.500000000000000  0.333333333333333  0.250000000000000
0.200000000000000
       0.500000000000000  0.333333333333333  0.250000000000000  0.200000000000000
0.166666666666667
       0.333333333333333  0.250000000000000  0.200000000000000  0.166666666666667
0.142857142857143
       0.250000000000000  0.200000000000000  0.166666666666667  0.142857142857143
0.125000000000000
       0.200000000000000  0.166666666666667  0.142857142857143  0.125000000000000
0.111111111111111
```

Matrix I

```
       1.000000000000000  0.500000000000000  0.333333333333333  0.250000000000000
0.200000000000000
       0.500000000000000  0.333333333333333  0.250000000000000  0.200000000000000
0.166666666666667
       0.333333333333333  0.250000000000000  0.200000000000000  0.166666666666667
0.142857142857143
       0.250000000000000  0.200000000000000  0.166666666666667  0.142857142857143
0.125000000000000
       0.200000000000000  0.166666666666667  0.142857142857143  0.125000000000000
0.111111111111111
```

The Determinant Of Matrix I is 0.000000000003749

Comment:
Note how poorly conditioned this matrix is. Yet I did not loose even a single significant digit

Comment:
==========

Comment:
The last test is with a complex matrix

Matrix C

```
       1.0000000000 + 2.0000000000j  4.0000000000 + 5.0000000000j  7.0000000000 +
3.0000000000j
       3.0000000000 + 4.0000000000j  7.0000000000 + 5.0000000000j  3.0000000000 +
5.0000000000j
       9.0000000000 + 4.0000000000j  3.0000000000 + 1.0000000000j  3.0000000000 +
6.0000000000j
```

The LU Decomposition is Given By:

L Component

```
 1.000000000000000                        0.000000000000000
0.000000000000000
 0.443298969072165 + 0.247422680412371j  1.000000000000000
0.000000000000000
 0.175257731958763 + 0.144329896907216j  0.769966722129784 + 0.245840266222962j
1.000000000000000
```

L Component

```
 9.0000000000 + 4.0000000000j  3.0000000000 + 1.0000000000j  3.0000000000 +
6.0000000000j
 0.0000000000                  5.9175257731 + 3.8144329896j  3.1546391752 +
1.5979381443j
 0.0000000000                  0.0000000000                  5.3040765391 -
0.4904328125j
```

The L and U Components Multiplied Together Equal:

Matrix D

```
 1.0000000000 + 2.0000000000j  4.0000000000 + 5.0000000000j  7.0000000000 +
3.0000000000j
 3.0000000000 + 4.0000000000j  7.0000000000 + 5.0000000000j  3.0000000000 +
5.0000000000j
 9.0000000000 + 4.0000000000j  3.0000000000 + 1.0000000000j  3.0000000000 +
6.0000000000j
```

Matrix C

```
 1.0000000000 + 2.0000000000j  4.0000000000 + 5.0000000000j  7.0000000000 +
3.0000000000j
 3.0000000000 + 4.0000000000j  7.0000000000 + 5.0000000000j  3.0000000000 +
5.0000000000j
 9.0000000000 + 4.0000000000j  3.0000000000 + 1.0000000000j  3.0000000000 +
6.0000000000j
```

Comment:
Again, I did not loose any significant digits in the process.

Inversion of Plant Matrix for MIMO QFT

Fred L. Trevino, Capt
EEE 799: Masters Thesis
Dr Gary I Lamont

The Matrix to be inverted is given by the following transfer functions:

MIMO Plant [1,1] Plant Matrix 1

$$\frac{1.0000}{s + 1.0000}$$

MIMO Plant [1,2] Plant Matrix 1

$$\frac{0.2000}{s^2 + 3.0000 + 2.0000}$$

MIMO Plant [2,1] Plant Matrix 1

$$\frac{0.5000}{s + 1.0000}$$

MIMO Plant [2,2] Plant Matrix 1

$$\frac{0.5000\ (\ s + 0.0000\ )}{s^2 + 3.0000 + 2.0000}$$

The Combined LU Decomposed Matrix is given by the following transfer functions:
Note that the diagonal ones of the Lower Triangular matrix are assumed

LUD Plant [1,1] L/U Matrix: 1

$$\frac{1.0000}{s + 1.0000}$$

LUD Plant [1,2] L/U Matrix: 1

$$\frac{0.2000}{s^2 + 3.0000 + 2.0000}$$

LUD Plant [2,1] L/U Matrix: 1

$$\frac{0.5000}{1.0000}$$

LUD Plant [2,2] L/U Matrix: 1

$$\frac{0.5000\ (\ s - 0.2000\ )}{s^2 + 3.0000 + 2.0000}$$

Now that the matrix is decomposed, we use forward and backsubstitution to process the inverse. We input the columns of the identity matrix one column at a time and get the inverse one column at a time. The following text are the results of the internal multiplications, divisions, etc showing how roots are internally cancelled and the growth of large order polynomials is prevented.

Forward Substitution Process==========

```
Forward Substitution Process================

*** Multiplication ***

First Operand: LUmat[ 2, 1]

 0.5000
 ------
 1.0000

Second Operand: BMat [ 1]

 1.0000
 ------
 1.0000

Result

 0.5000
 ------
 1.0000

*** Subtraction ***

First Operand

 0.0000
 ------
 1.0000

Second Operand

 0.5000
 ------
 1.0000

sum variable (sum = sum - a[i,j]*b[j])

-0.5000
 ------
 1.0000

Back Substitution Process================

Division
First Operand: LUmat[ 2, 2]

sum variable (sum = sum - a[i,j]*b[j])

-0.5000
 ------
 1.0000

LUD Plant [2,2]  L/U Matrix:  1

 0.5000 ( s  - 0.2000 )
 ----------------------
   2
  s + 3.0000s + 2.0000

Answer: Element of Q

            2
-1.0000 ( s + 3.0000s + 2.0000 )
--------------------------------
          s  - 0.2000

Back Substitution Process================

*** Multiplication ***

First Operand: LUmat[ 1, 2]

       0.2000
```

```
 2
s + 3.0000s + 2.0000

Second Operand: BMat [ 2]

                2
-1.0000 ( s + 3.0000s + 2.0000 )
-------------------------------
          s  - 0.2000

Result

  -0.2000
-----------
s  - 0.2000

*** Subtraction ***

First Operand

 1.0000
-------
 1.0000

Second Operand

  -0.2000
-----------
s  - 0.2000

sum variable (sum = sum - a[i,j]*b[j])

s + 0.0000
-----------
s  - 0.2000

Division

First Operand: LUmat[ 1, 1]

s + 0.0000
-----------
s  - 0.2000

Second Operand:

   1.0000
-----------
s  + 1.0000

Answer: Element of Q

 2
s + 1.0000s+ 0.0000
-------------------
   s  - 0.2000

Forward Substitution Process================

Forward Substitution Process================

Back Substitution Process================

Division
First Operand: LUmat[ 2, 2]

One

 1.0000
-------
 1.0000
```

```
LUD Plant [2,2]  L/U Matrix:  1

 0.5000 ( s  - 0.2000 )
 ----------------------
   2
  s + 3.0000s + 2.0000

Answer: Element of Q

                2
 2.0000 ( s + 3.0000s + 2.0000 )
 -------------------------------
           s  - 0.2000

Back Substitution Process================

*** Multiplication ***

First Operand: LUmat[ 1, 2]

       0.2000
 ----------------------
 2
s + 3.0000s + 2.0000

Second Operand: BMat [ 2]

                2
 2.0000 ( s + 3.0000s + 2.0000 )
 -------------------------------
           s  - 0.2000

Result

   0.4000
 ----------
s  - 0.2000

*** Subtraction ***

First Operand

 0.0000
 ------
 1.0000

Second Operand

   0.4000
 ----------
s  - 0.2000

sum variable (sum = sum - a[i,j]*b[j])

  -0.4000
 ----------
s  - 0.2000

Division
First Operand: LUmat[ 1, 1]

  -0.4000
 ----------
s  - 0.2000

Second Operand:

   1.0000
 ----------
s  + 1.0000

Answer: Element of Q

-0.4000 ( s  + 1.0000 )
```

$$\frac{}{s - 0.2000}$$

The Inverted Matrix is given by the following transfer functions:

Answer: Element of Q

$$\frac{s^2 + 1.0000s + 0.0000}{s - 0.2000}$$

Answer: Element of Q

$$\frac{-0.4000\ (s + 1.0000)}{s - 0.2000}$$

Second Operand: BMat [2]

$$\frac{-1.0000\ (s^2 + 3.0000s + 2.0000)}{s - 0.2000}$$

Second Operand: BMat [2]

$$\frac{2.0000\ (s^2 + 3.0000s + 2.0000)}{s - 0.2000}$$

The following is the resulting Q Matrix Answer:

q-Plant [1,1] Q Matrix: 1

$$\frac{s^2 + 1.0000s + 0.0000}{s - 0.2000}$$

q-Plant [1,2] Q Matrix: 1

$$\frac{-0.4000\ (s + 1.0000)}{s - 0.2000}$$

q-Plant [2,1] Q Matrix: 1

$$\frac{-1.0000\ (s^2 + 3.0000s + 2.0000)}{s - 0.2000}$$

q-Plant [2,2] Q Matrix: 1

$$\frac{2.0000\ (s^2 + 3.0000s + 2.0000)}{s - 0.2000}$$

Root Finder Test

Fred L. Trevino
EENG 799
Root Finding Test of IceCap-PC
IceCap-PC vs Matlab 3.26

```
ICECAP-PC
Polynomial A

GAIN  :   1.00000000000000000
          s^6      s^5      s^4       s^3       s^2       s^1       s^0
POLY  :  1.0000  12.0000  58.00000  144.00000  193.00000  132.00000  36.00000
ROOTS :  -3.00000000000000000
         -3.00000000000000000
         -2.00000000000000000
         -2.00000000000000000
         -1.00000000000000000
         -1.00000000000000000
Internal root representation accurate within:  3.40000000E-4932

MATLAB
e =
1    12    58   144   193   132    36
» roots(e)

ans =
-3.00000000000005 + 0.00000028052156i
-3.00000000000005 - 0.00000028052156i
-1.99999999999996 + 0.00000023148497i
-1.99999999999996 - 0.00000023148497i
-0.99999999999999 + 0.00000006852833i
-0.99999999999999 - 0.00000006852833i

ICECAP-PC
Polynomial A

GAIN  :   1.00000000000000000
          s^7      s^6      s^5      s^4      s^3      s^2       s^1       s^0
POLY  :  1.0000  13.0000  70.0000  202.0000 337.0000  325.0000  168.0000  36.0000
ROOTS :  -3.00000000000000000
         -3.00000000000000000
         -2.00000000000000000
         -2.00000000000000000
         -1.00004935264587402
         -0.99972993915088197
         -1.00022070820324401
Internal root representation accurate within:  2.23355772E-0006



ICECAP-PC
Polynomial A

GAIN  :    1.00000000000000000
          s^6      s^5      s^4       s^3       s^2       s^1       s^0
POLY  :  1.0000  18.0000  123.0000  396.0000  615.0000  450.0000  125.0000
ROOTS :  -5.00000000000000000
         -5.00000000000000000
         -5.00000000000000000
         -1.00035554842761348
         -0.99964451789855957
         -1.00000000000000000
Internal root representation accurate within:  7.50811614E-0006

MATLAB
» a = [1 18 123 396 615 450 125]
» roots(a)
ans =

-5.00006006048980
-4.99996996975510 + 0.00005201370898i
-4.99996996975510 - 0.00005201370898i
```

```
-1.00000494089214 + 0.00000855799746i
-1.00000494089214 - 0.00000855799746i
-0.99999011821573


ICECAP-PC
Polynomial A

GAIN  :   1.00000000000000000
          s^6      s^5       s^4       s^3       s^2        s^1       s^0
POLY  :  1.0000  10.0000  41.0000  88.0000  104.0000  64.0000  16.0000
ROOTS :  -2.00000000000000000
         -2.00000000000000000
         -2.00000000000000000
         -2.00000000000000000
         -1.00000000000000000
         -1.00000000000000000
Internal root representation accurate within:  3.40000000E-4932

» b = [1 10 41 88 104 64 16]
» roots(b)
ans =

-2.00024785812781 + 0.00024789014765i
-2.00024785812781 - 0.00024789014765i
-1.99975214187220 + 0.00024782611280i
-1.99975214187220 - 0.00024782611280i
-1.00000000000000 + 0.00000004785137i
-1.00000000000000 - 0.00000004785137i

ICECAP-PC
Polynomial A

GAIN  :    1.00000000000000000
          s^6      s^5       s^4        s^3        s^2         s^1         s^0
POLY  :  1.0000  21.0000  175.0000  735.00000 1624.0000  1764.0000  720.0000
ROOTS :  -6.00000000000000000
         -5.00000000000000000
         -4.00000000000000000
         -3.00000000000000000
         -2.00000000000000000
         -1.00000000000000000
Internal root representation accurate within:  3.40000000E-4932

» c = [1 21 175 735 1624 1764 720]
» roots(c)
ans =
-5.99999999999991
-5.00000000000039
-3.99999999999940
-3.00000000000039
-1.99999999999991
-1.00000000000001

ICECAP-PC
Polynomial A

GAIN  :  1.00000000000000000
         s^6      s^5      s^4       s^3       s^2       s^1      s^0
POLY  :  1.0000  6.0000  15.0000  20.0000  15.0000  6.0000  1.0000
ROOTS :  -1.00000000000000000
         -1.00000000000000000
         -1.00000000000000000
         -1.00000000000000000
         -1.00000000000000000
         -1.00000000000000000
Internal root representation accurate within:  3.40000000E-4932
```

```
MATLAB
» d = [1 6 15 20 15 6 1]
» roots(d)
ans =

-1.00331670554264
-1.00166155604821 + 0.00287235092887i
-1.00166155604821 - 0.00287235092887i
-0.99834164733085 + 0.00287789988059i
-0.99834164733085 - 0.00287789988059i
-0.99667688769924


ICECAP-PC
Polynomial A

GAIN  :  1.00000000000000000
         s^3                  s^2                  s^1                  s^0
POLY  :  1.00000000000000000  2.00000000000000000  3.00000000000000000
4.00000000000000000
ROOTS :  -0.17468540370464325-j1.54686890065397160
         -0.17468540370464325+j1.54686890065397160
         -1.65062919143938822
Internal root representation accurate within:  6.82119357E-0008

MATLAB
» f = [1 2 3 4]
» roots(f)
ans =

-1.65062919143939
-0.17468540428031 + 1.54686888723140i
-0.17468540428031 - 1.54686888723140i

ICECAP-PC
Polynomial A

GAIN  :  1.00000000000000000
         s^4                  s^3                  s^2                  s^1
s^0
POLY  :  1.0000  2.00000000000000000  3.00000000000000000  4.00000000000000000
5.00000000000000000
ROOTS :  -1.28781545162200928-j0.85789686668854613
         -1.28781545162200928+j0.85789686668854613
         +0.28781548142433167-j1.41609309864941254
         +0.28781548142433167+j1.41609309864941254
Internal root representation accurate within:  3.65869539E-0007

MATLAB
» g = [1 2 3 4 5]
» roots(g)
ans =
 0.28781547955765 + 1.41609308017191i
 0.28781547955765 - 1.41609308017191i
-1.28781547955765 + 0.85789675832849i
-1.28781547955765 - 0.85789675832849i
```

Root Finder Coefficient Reconstruction Error Test
Fred L. Trevino, Capt, USAF
Electrical Engineer

```
Unpolished Polynomial

Polynomial A
GAIN  :   1.0000
         s^6      s^5      s^4      s^3       s^2       s^1       s^0
POLY  :  1.0000  12.0000  58.0000  144.0000  193.0000  132.0000  36.0000
ROOTS :  -0.99999986114853990
         -1.00000013885151794
         -1.99999958484187777
         -2.00000041515827876
         -2.99999971614412451
         -3.00000028385566112
Internal root representation accurate within:  2.40238385E-0013 %

Unpolished Accuracy:  2.40238384741076E-0013

Polished Polynomial

Polynomial A
GAIN  :   1.0000
         s^6      s^5      s^4      s^3       s^2       s^1       s^0
POLY  :  1.0000  12.0000  58.0000  144.0000  193.0000  132.0000  36.0000
ROOTS :  -1.00000000000000000
         -1.00000000000000000
         -2.00000000000000000
         -2.00000000000000000
         -3.00000000000000000
         -3.00000000000000000
Internal root representation accurate within:  0.00000000E+0000 %

Polished Accuracy:  0.00000000000000E+0000

Choosing Polished Polynomial


=====================================================================

Unpolished Polynomial

Polynomial A
GAIN  :   1.0000
         s^7      s^6      s^5      s^4       s^3       s^2       s^1       s^0
POLY  :  1.0000  13.0000  70.0000  202.0000  337.0000  325.0000  168.0000  36.0000
ROOTS :  -0.99995061525371413
         -1.00002469237289833
         -1.00002469786131161
         -1.99991445853344107
         -2.00008554146667941
         -2.99995722634657145
         -3.00004276816538401
Internal root representation accurate within:  7.31758333E-0009 %

Unpolished Accuracy:  7.31758333094579E-0009

Polished Polynomial

Polynomial A
GAIN  :   1.0000
         s^7      s^6      s^5      s^4       s^3       s^2       s^1       s^0
POLY  :  1.0000  13.0000  70.0000  202.0000  337.0000  325.0000  168.0000  36.0000
ROOTS :  -1.00000114885965188
         -1.00000082939761701
         -0.99999965957871331
         -2.00000000000000000
         -2.00000000000000000
         -3.00000000000000000
         -3.00000000000000000
Internal root representation accurate within:  5.89621054E-0005 %
```

```
Polished Accuracy:  5.89621054182185E-0005

Choosing Unpolished Polynomial

: ==================================================================

Unpolished Polynomial

Polynomial A
GAIN  :    1.0000
         s^6      s^5       s^4        s^3        s^2        s^1        s^0
POLY  :  1.0000  18.0000  123.0000  396.0000  615.0000  450.0000  125.0000
ROOTS :  -0.99997979938543333
         -1.00001010026207655
         -1.00001010058202872
         -4.99893003491269068
         -5.00053498242888536
         -5.00053498242888536
Internal root representation accurate within:  4.30870321E-0006 %

Unpolished Accuracy:  4.30870321250360E-0006

Polished Polynomial

Polynomial A
GAIN  :    1.0000
         s^6      s^5       s^4        s^3        s^2        s^1        s^0
POLY  :  1.0000  18.0000  123.0000  396.0000  615.0000  450.0000  125.0000
ROOTS :  -0.99999951613993230
         -1.00000033103686999
         -0.99999984246064752
         -5.00000171802838821
         -5.00000021689256729
         -4.99999930827796170
Internal root representation accurate within:  7.71537733E-0006 %

Polished Accuracy:  7.71537733115779E-0006

==================================================================

Unpolished Polynomial

Polynomial A
GAIN  :   1.0000
         s^6      s^5       s^4       s^3       s^2        s^1       s^0
POLY  :  1.0000  10.0000  41.0000  88.0000  104.0000  64.0000  16.0000
ROOTS :  -0.99999959752956686
         -1.00000040247108108
         -1.99971085500699006
         -1.99971085500699006
         -2.00000024217795799
         -2.00057804780741396
Internal root representation accurate within:  1.00259883E-0006 %

Unpolished Accuracy:  1.00259883497114E-0006

Polished Polynomial

Polynomial A
GAIN  :   1.0000
         s^6      s^5       s^4       s^3       s^2        s^1       s^0
POLY  :  1.0000  10.0000  41.0000  88.0000  104.0000  64.0000  16.0000
ROOTS :  -1.00000000000000000
         -1.00000000000000000
         -2.00076234204481064
         -1.99937451021959366
         -2.00000000000000000
         -2.00000000000000000
Internal root representation accurate within:  1.09291077E-0003 %

Polished Accuracy:  1.09291076660156E-0003

Choosing Unpolished Polynomial
```

```
=====================================================================

Unpolished Polynomial

Polynomial A
GAIN  :    1.0000
         s^6      s^5       s^4        s^3        s^2         s^1         s^0
POLY  :  1.0000  21.0000  175.0000  735.0000  1624.0000  1764.0000  720.0000
ROOTS :  -0.99999999999999868
         -2.00000000000000659
         -2.99999999999998685
         -4.00000000000001295
         -4.99999999999999379
         -6.00000000000000114
Internal root representation accurate within:  1.59872116E-0013 %

Unpolished Accuracy:  1.59872115546023E-0013

Polished Polynomial

Polynomial A
GAIN  :    1.0000
         s^6      s^5       s^4        s^3        s^2         s^1         s^0
POLY  :  1.0000  21.0000  175.0000  735.0000  1624.0000  1764.0000  720.0000
ROOTS :  -2.00000000000000000
         -1.00000000000000000
         -4.00000000000000000
         -3.00000000000000000
         -6.00000000000000000
         -5.00000000000000000
Internal root representation accurate within:  0.00000000E+0000 %

Polished Accuracy:  0.00000000000000E+0000

=====================================================================

Unpolished Polynomial

Polynomial A
GAIN  :  1.0000
         s^6      s^5      s^4       s^3       s^2       s^1      s^0
POLY  :  1.0000  6.0000  15.0000  20.0000  15.0000  6.0000  1.0000
ROOTS :  -1.00000000000000000
         -1.00000000000000000
         -1.00000000000000000
         -1.00000000000000000
         -1.00000000000000000
         -1.00000000000000000
Internal root representation accurate within:  0.00000000E+0000 %

Unpolished Accuracy:  0.00000000000000E+0000

Polished Polynomial

Polynomial A
GAIN  :  1.0000
         s^6      s^5      s^4       s^3       s^2       s^1      s^0
POLY  :  1.0000  6.0000  15.0000  20.0000  15.0000  6.0000  1.0000
ROOTS :  -1.00000000000000000
         -1.00000000000000000
         -1.00000000000000000
         -1.00000000000000000
         -1.00000000000000000
         -1.00000000000000000
Internal root representation accurate within:  0.00000000E+0000 %

Polished Accuracy:  0.00000000000000E+0000

Choosing Polished Polynomial

 =====================================================================

Unpolished Polynomial
```

```
Polynomial A
GAIN  :  1.0000
         s^3      s^2      s^1      s^0
POLY  :  1.0000  2.0000  3.0000  4.0000
ROOTS :  -0.17468540428030588-j1.54686888723139627
         -0.17468540428030589+j1.54686888723139628
         -1.65062919143938823
Internal root representation accurate within:  2.36419161E-0017 %

Unpolished Accuracy:  2.36419160587147E-0017

Polished Polynomial

Polynomial A
GAIN  :  1.0000
         s^3      s^2      s^1      s^0
POLY  :  1.0000  2.0000  3.0000  4.0000
ROOTS :  -0.17468540428030588-j1.54686888723139624
         -0.17468540428030588+j1.54686888723139624
         -1.65062919143938822
Internal root representation accurate within:  2.19008839E-0016 %

Polished Accuracy:  2.19008838842072E-0016

Choosing Unpolished Polynomial

=================================================================

Unpolished Polynomial

Polynomial A
GAIN  :  1.0000
         s^4      s^3      s^2      s^1      s^0
POLY  :  1.0000  2.0000  3.0000  4.0000  5.0000
ROOTS :  -1.28781547955764792+j0.85789675832849048
         -1.28781547955764819-j0.85789675832849027
         +0.28781547955764808+j1.41609308017190785
         +0.28781547955764803-j1.41609308017190806
Internal root representation accurate within:  1.61971028E-0015 %

Unpolished Accuracy:  1.61971028480621E-0015

Polished Polynomial

Polynomial A
GAIN  :  1.0000
         s^4      s^3      s^2      s^1      s^0
POLY  :  1.0000  2.0000  3.0000  4.0000  5.0000
ROOTS :  -1.28781547955764797-j0.85789675832849028
         -1.28781547955764797+j0.85789675832849028
         +0.28781547955764797-j1.41609308017190794
         +0.28781547955764797+j1.41609308017190794
Internal root representation accurate within:  1.58293526E-0016 %

Polished Accuracy:  1.58293526465436E-0016

Choosing Unpolished Polynomial
```

Appendix C ICECAP-PC User's Manual

ICECAP - PC

Interactive	**C**ontrol	**E**ngineering
Computer	**A**nalysis	**P**ackage
for the	**P**ersonal	**C**omputer

Version 10.0 - MS-DOS

OFFERING:

time and frequency domains
z and w domains
root-locus, nyquist, and nichols
plots in color graphics
transfer function manipulation
matrix and polynomial operations

WITH APPLICATIONS TO:

conventional control
modern control
sampled-data systems
digital signal processing
MISO/MIMO Quantitative Feedback Theory (QFT)

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Air Force Institute of Technology
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Dayton, Ohio 45433-6583

cooperative copyrighted 1985-1992

ICECAP-PC 10.0 User's Manual

Ver 2.0

Rev. 12. 12/92

WELCOME to ICECAP-PC, an ongoing development of a public domain computer-aided design (CAD) package for students, faculty and practitioners of control engineering and digital signal processing with special emphasis on education. Source code and executable files are available. If you are interested in adding additional code or have suggestions for improvement please contact:

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Gary B. Lamont, Susan K. Mashiko, Gary C. Tarczynski, D. Gelopulos, Paul A. Moore, Wayne E. Bell, Vincent M. Parisi, Fred Trevino, Mark W. Schiller, Ken A. Crosby

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All references to MS-DOS in this document refer to MicroSoft DOS which is a registered trademark and copyrighted by MicroSoft Corporation.

Edited By: Gary B. Lamont , Wayne E. Bell, and Fred Trevino; 1992

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1 INTRODUCTION

1.1 What is ICECAP-PC

This is the User's Manual for the ICECAP-PC program which provides a windowed environment for control system design and analysis hosted on a personal computer. The system is menu driven and provides on-line help upon request.

1.2 General Information

This is a living document. It is designed to reflect the CAD program ICECAP-PC as it is currently implemented. If any changes are made to the software that affects the options available, this document will be changed to reflect those changes.

1.3 Who Should Read This Section

This section should be read by all first time users of ICECAP-PC. It provides general information about the operating system and hardware required to operate this CAD package, as well as general information about ICECAP-PC.

1.4 Operating Systems/Configuration/Directories

At the time of this publication the ICECAP-PC system consists of an installation program and a user interface program written in Borland's Turbo Pascal. The installation program is a simple batch process which unarchives ICECAP-PC to the user's harddrive. ICECAP-PC is distributed with system default settings that make it operational on any IBM PC 100% compatible machine with at least an 80286 CPU and 2 Meg of extended RAM. After being installed, the ICECAP-PC subdirectory will contain the executable file ICE.EXE, several device drivers, data files, two system files, and an optional SOURCE directory with the code in it. There will also be a subdirectory here called "NICSDATA". The data files inside NICSDATA are used for nichols chart (section 3.1.3.8) constant magnitude and angle curves. It is important that this subdirectory remain inside the ICECAP subdirectory and keep the same name "NICSDATA". If ICECAP-PC does not find this directory while drawing nichols charts, it will lock up--unless you turn the constant magnitude and angle options off (3.1.10).

ICECAP-PC is designed to operate with the MS-DOS disk operating system version 2.0 and later and is written in Borland Pascal 7.0. The DPMI DOS extension drivers are public domain and can be freely distributed with IECAP-PC. **NO MORE 640K BARRIER!!!** This DPMI driver can cause problems with some clones, so if your computer locks up while trying to start ICECAP-PC, read the documentation that is shipped with the DPMI drivers.

If you are using MS-DOS the following file must be on the disk that you boot the system with: CONFIG.SYS. The CONFIG.SYS file in the root directory of your hard

drive may contain many lines of commands. Open your CONFIG.SYS file using a text editor and be sure it contains these two lines as a minimum:

FILES = 25

If you make changes to your CONFIG.SYS file, remember to reboot before trying to run ICECAP-PC. Changes to your CONFIG.SYS file will not take effect until after you reboot the computer.

1.5 Hardware Required

ICECAP-PC is designed to operate on a hardware system that contains a minimum of 2 Meg of available extended RAM and a hard drive and an 80286 CPU or better. The use of a math coprocessor is highly recommended due to the large computational requirements of ICECAP-PC's mathematical algorithms. However, even without a math coprocessor, the PASCAL math coprocessor emulation software routines produce results quick enough to impress even non-coprocessor users.

There is an additional hardware requirement of an 80-column by 25-line monochrome monitor. The monitor is the means by which ICECAP-PC communicates with the user. ICECAP-PC can use color graphics for displays, so a color monitor does improve the human interface somewhat. ICECAP-PC graphs use standard graphic configurations (CGA, EGA, VGA, Hercules, etc.).

1.6 ICECAP-PC Commands

To execute ICECAP-PC the user should first make the ICECAP subdirectory current and type:

"ICECAP<CR>" (without quotes)

from the DOS prompt. ICECAP-PC will then display the first page of the "title slide", indicating that initialization is complete. If your screen is garbled with illegible characters, be sure your CONFIG.SYS file contains the call to ANSI.SYS as described in **Section 2.2**. The user is then prompted to enter a "carriage return" to continue. The second page of the "title slide" will then be displayed and the user will once again be prompted to enter a carriage return to continue.
Figure 1 displays the ICECAP-PC main menu window.

FILE	-	Perform file related options.
GRAPH	-	Display time response graphs, frequency response graphs, Nichols Charts, etc.
MATRIX	-	Perform matrix mathematical functions

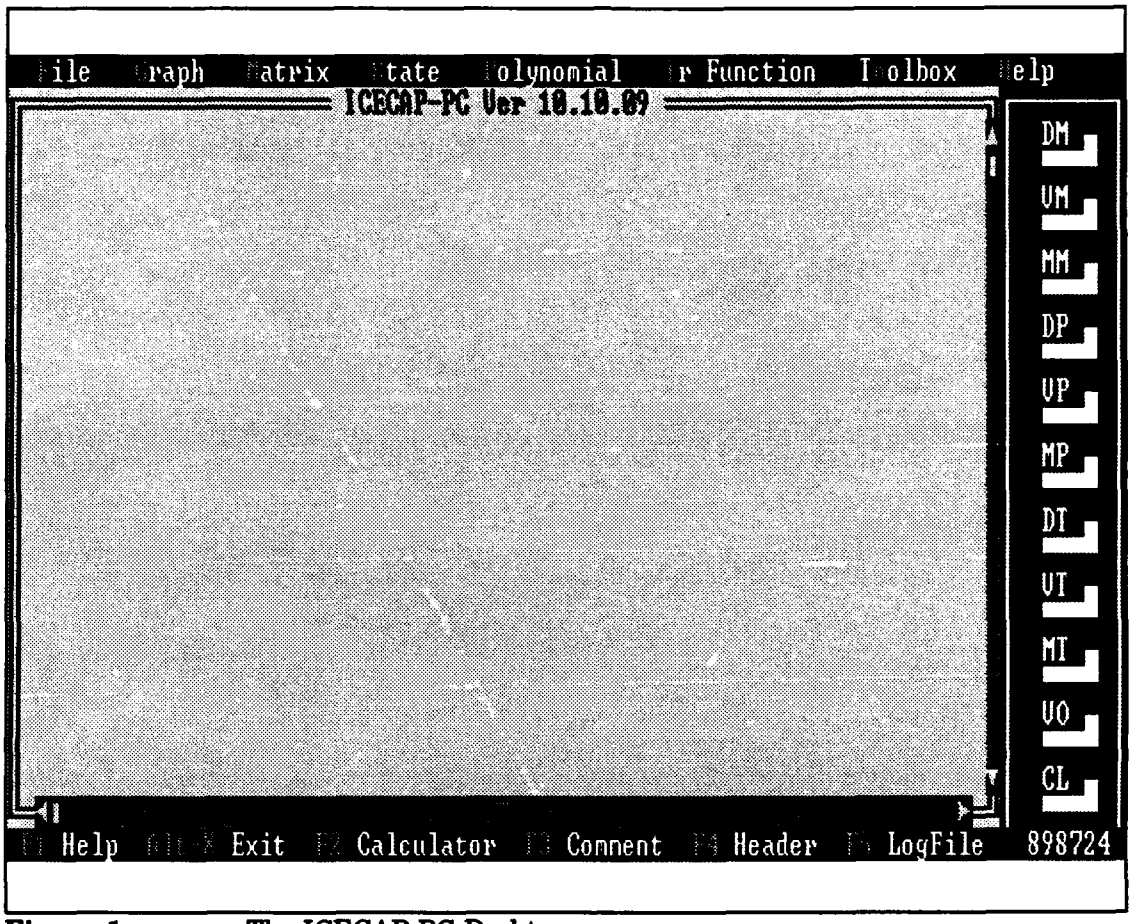


Figure 1 The ICECAP-PC Desktop

STATE	-	Perform state space operations
POLY	-	Perform polynomial operations
Tr FUNCTION	-	Perform transfer function operations
TOOLBOX	-	Call the advanced controls techniques toolboxes--currently available: DSP, MISO QFT, MIMO QFT.
HELP	-	Context Sensitive Help

1.7 Algorithms

ICECAP-PC uses several state-of-the-art algorithms to accomplish its control system functions. The root finder is based on Laguerre for finding rough roots. Laguerre

is a very stable 1st order approximation which does not require an initial estimate of the root locations, it also will converge to any types of roots (real, complex, single, or multiple). Bairstow is then used to polish the root estimates. Bairstow is an unstable 2nd order approximation which polishes roots in pairs (quadratic factors). Brent's method is used to polish the rough roots for cases of multiple roots. It polishes roots one at a time and is guaranteed to converge at least linearly if an initial interval is given within which the root lies.

The root locus algorithm is based on a Newton-Raphson technique for linear systems. It is among the most accurate and quick on the market today. The algorithm starts at a known point on each branch (the open loop poles and zeros) and then finds the next point on the branch which is delta away from the current point and within a delta of being an actual point on the locus. Breakaway points are calculated exactly. No a priori information is required about how the locus changes with increasing gain. Also, errors made in the routine are absolute and not cumulative--this is a very important goal for all algorithms implemented on digital computers.

1.8 Accuracies

Routines where accuracies or error terms are available, display this information along with the output. ICECAP-PC's global floating point representation is an extended real type which can represent 19-20 significant digits. Thus the absolute ceiling on accuracy is 19-20 significant digits.

1.9 Object-Oriented Technology

ICECAP-PC's user interface as well as the internal algorithms are fully object-oriented.

1.10 Testing Techniques

1.10.1 MACRO Files

This interface to ICECAP-PC is simple yet effective. The method is initiated from the DOS prompt by following the ICECAP command with the name of the desired macro file, for example:

ICECAP macrofilename<CR>

The Programmer's Manual contains information on the creation of macro files. Example macro files were installed with ICECAP-PC.

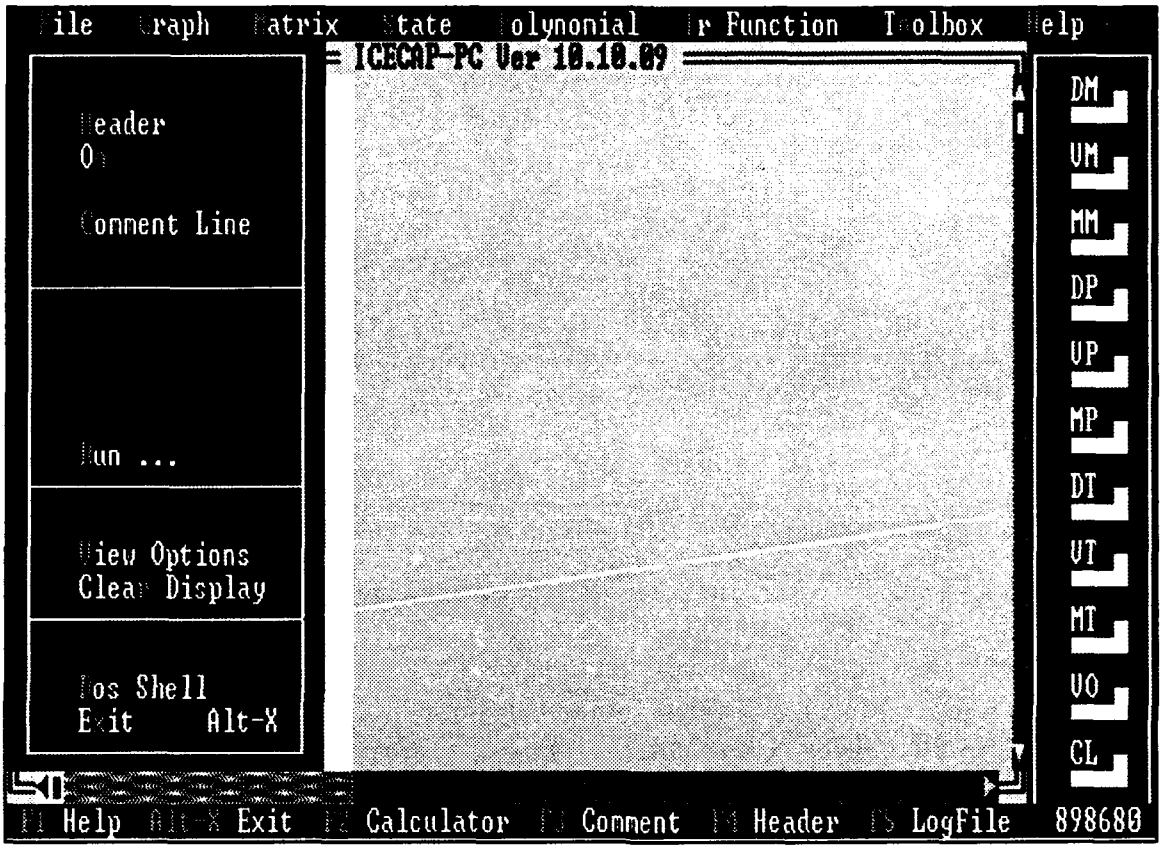
1.10.2 Test Cases

Each command in ICECAP-PC was validated using numerous exemplars for black box testing. All of these exemplars are maintained in macro files and are included with the ICECAP-PC installation.

1.10.3 Modular OOP

One of the advantages gained by porting ICECAP-PC to an object-oriented environment is the concept of inheritance. When a low level math object is written and validated, its validated abilities can be inherited by a higher level object. Thus when the higher level object uses these lower level math functions, they can be assumed to be correct, because the lower level object has been previously validated. The reason this is different from functional programming is that objects encapsulate, or protect, their data and methods. In a functional program, the higher level routine might contain a copy of the lower level procedure. This copy could have been changed slightly to match the variable names of the higher routine, or it could be out of date, etc. Inheriting objects is different. The higher level object has no control over the lower level object, it just sends a message to the lower level object requesting a function to be performed on a set of data. The lower level object then performs the required operations with no interaction from the higher level object; therefore, if the lower level object provided the correct output for a given input when it was validated in isolation, it will provide that same output for the same input when called by another object.

2 Administrative Functions



2.1 Session Files

Session files may be saved in order to periodically write all of the contents of ICECAP-PC memory files, 'tf&pol.dat', 'matrix.dat', 'bode.dat' and 'time.dat' 'qft_miso.dat' to user specified files. ICECAP-PC will provide prompts for the user name for each of the files. Just press <CR> for any files you do not wish to save. In later sessions you may use the RECOVER command to retrieve the information for reuse. This command is particularly useful when there is more than one user of ICECAP-PC or a single user is working on more than one design in parallel.

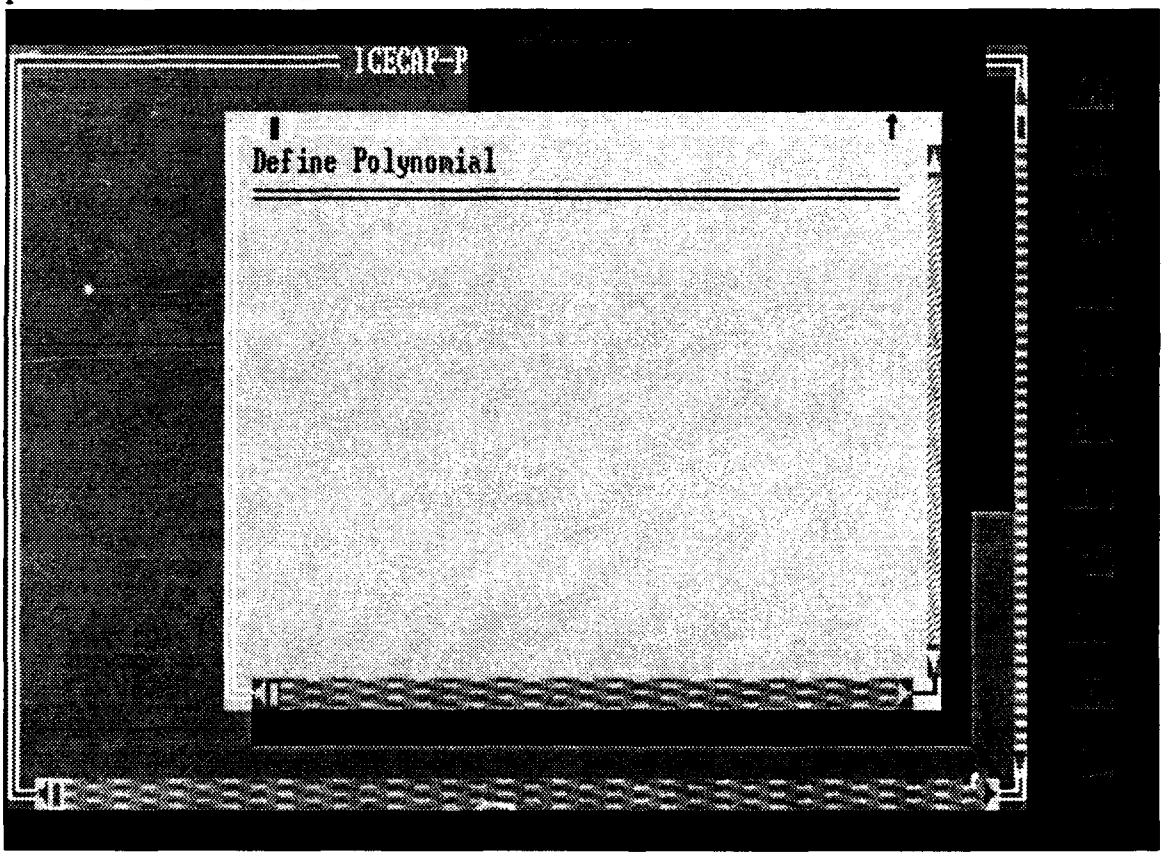
Session files can then be opened and the data files will be copied into ICECAP-PC memory so that you can continue a previous session at the point where you left off. The user data files were previously saved with the UPDATE command (Section 3.1.9). You may only RECOVER files that exist on the disk.

2.2 Log Files

While large data files, like frequency responses, are saved as separate files from within the full screen editor used to display them, the information displayed on the desktop can also be captured to a file. First the student information is entered into the header. Then the log file is turned on. During the session, comments can be entered and displayed on screen as well as in the log file.

2.3 Help

When you select a menu command or dialog box with the right mouse button, a detailed description of that command is presented. The dialogues are very similar to those presented in this manual.



2.4 About

This simple screen shows the current program information.

2.5 View Options

The appearance of numerical output is completely formattable. Numbers can be displayed in fixed decimal, or scientific notation. The number of significant digits displayed can also be adjusted. Note that the internal processing will still use maximum floating point accuracy, regardless of the number of digits displayed. 25 or 50 vertical lines can be displayed. 'i' or 'j' can be displayed as the complex letter.

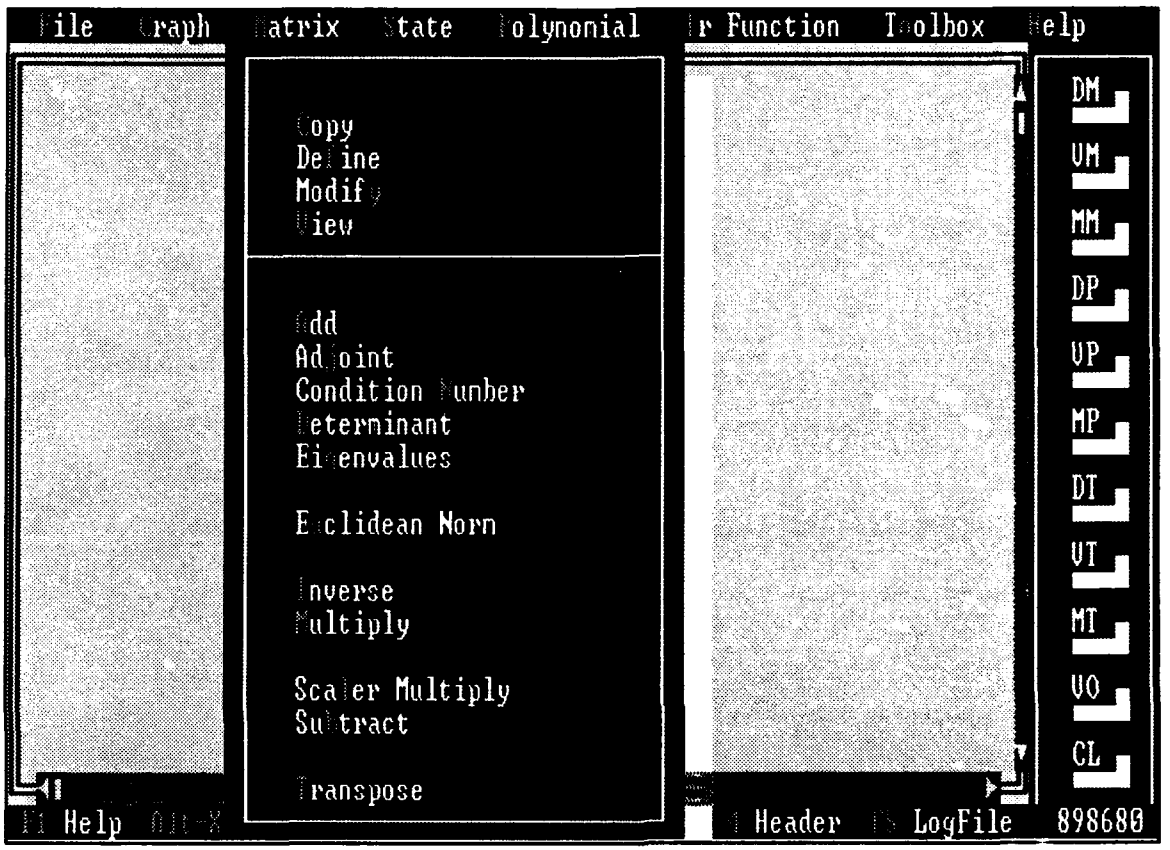
2.6 Shelling to DOS

If while working in ICECAP-PC, you need to briefly run another application, simply shell to DOS, run the application, exit the application, and type 'EXIT' at the DOS prompt to return to ICECAP-PC.

2.7 Exiting ICECAP-PC

The FILE - EXIT menu command or ALT-X is used to exit gracefully from ICECAP-PC. Information is always stored in the ICECAP-PC default session file to return you to this point in the next startup. If you desire to save this information in a user specified file, use the UPDATE command.

3 Matrix Functions



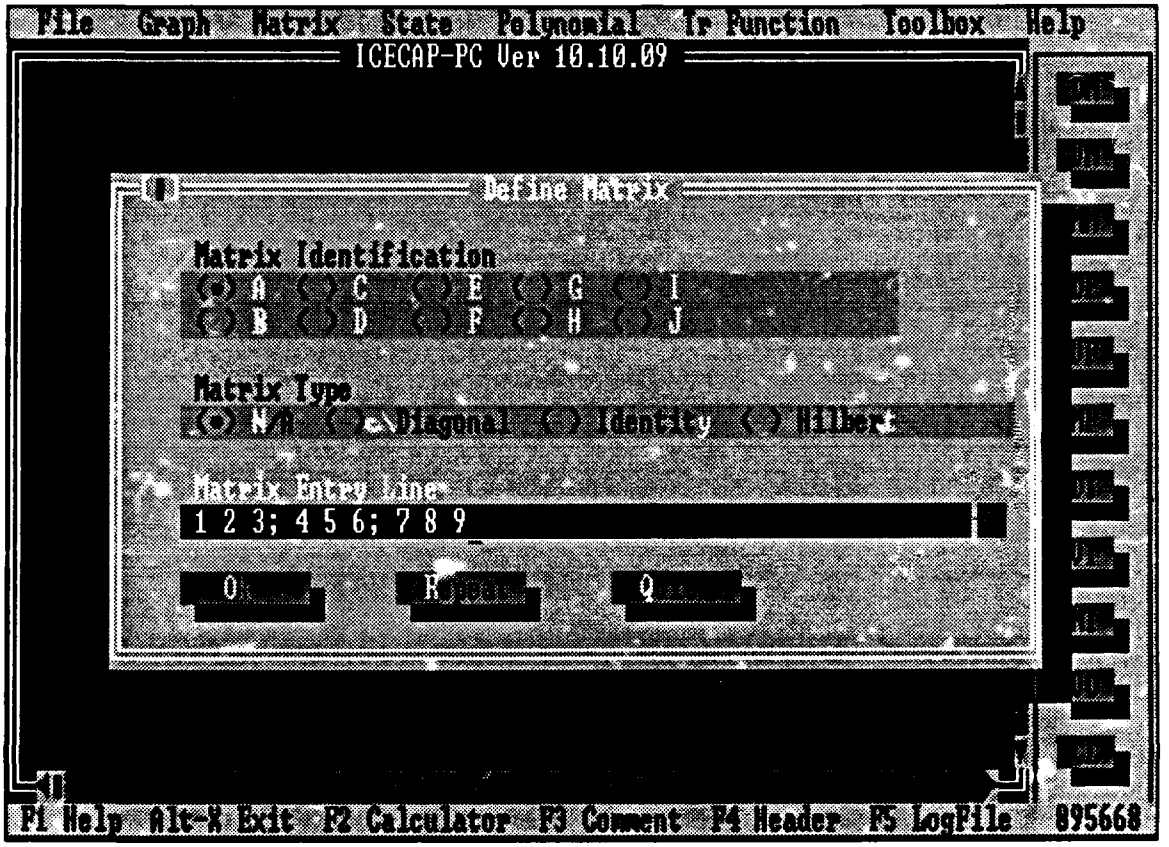
3.1 Copy Matrix

Copies one matrix to another.

3.2 Define Matrix

The Define Matrix dialog box contains a matrix selection radio button, matrix type radio button, and an inputline. Check which matrix you wish to define, check the type of matrix you wish to define, and enter the matrix elements on the input line. Examples are

Matrix Radio Button= 'A'
Type Radio Button = 'N/A'
Input Line = 1 2 3; 4 5 6; 7 8 9



Matrix Radio Button= 'B'
Type Radio Button = 'Diag'
Input Line = 1j2 3j4 5j6

Matrix Radio Button= 'C'
Type Radio Button = 'Identity'
Input Line = 3

3.3 Modify Matrix

The Modify Matrix dialog box contains a matrix selection radio button. Selection of a matrix results in a second dialog box on which to edit/redefine your selected matrix. Check the type of matrix you wish to define and modify or re-enter the matrix elements on the input line. Examples are

Matrix Radio Button= 'A'
Type Radio Button = 'N/A'
Input Line = 1 2 3; 4 5 6; 7 8 9

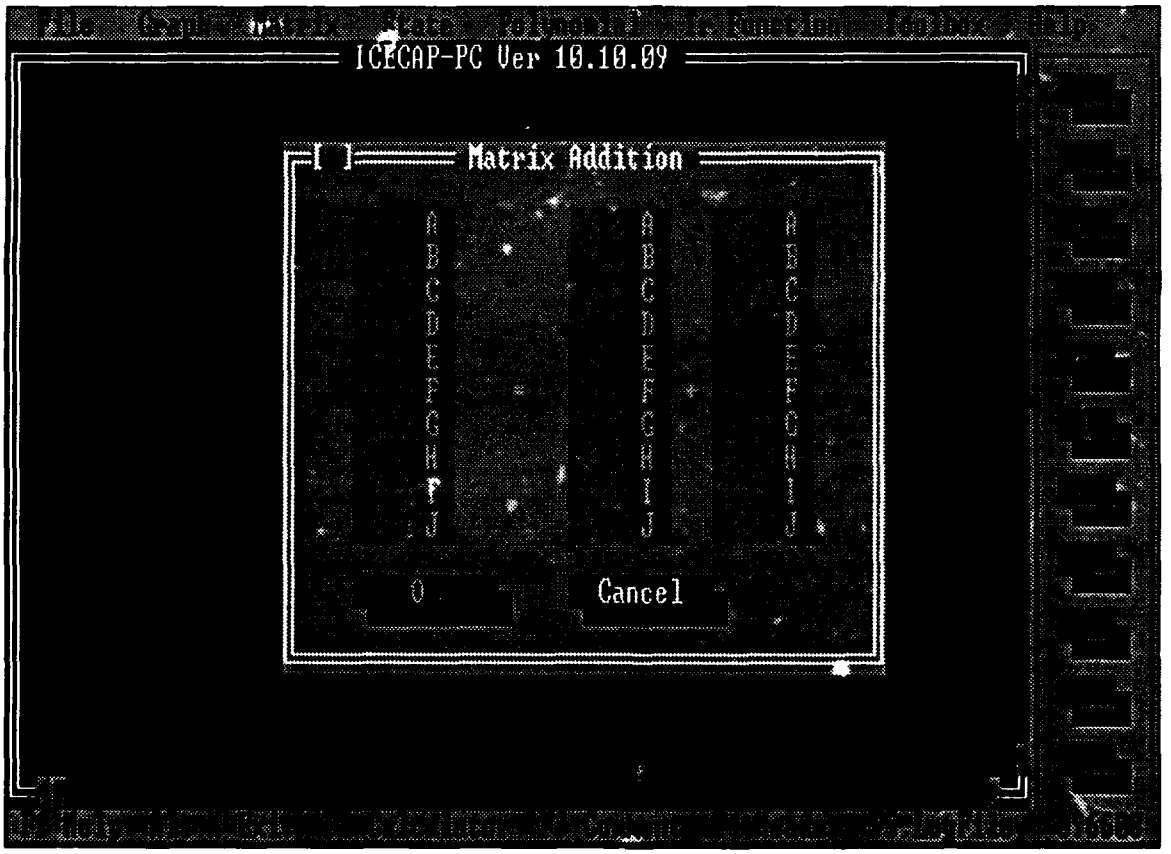
Matrix Radio Button= 'B'
Type Radio Button = 'Diag'
Input Line = 1j2 3j4 5j6

Matrix Radio Button= 'C'
Type Radio Button = 'Identity'
Input Line = 3

3.4 View Matrix

The View Matrix dialog box contains a matrix selection check box. Check the matrices you wish to view and press OK. The number of displayed decimal places and scientific notation may be selected with FILE-OPTIONS-VIEW OPTIONS.

3.5 Add Matrices



The Add Matrix dialog box contains three matrix selection radio buttons. The format of the selection is:

A = B + C

Check the resultant radio button and the two operand radio buttons then press OK to perform the operation. The resultant is displayed in the format chosen by the FILE-OPTIONS-VIEW OPTIONS setting.

3.6 Matrix Adjoint

The Matrix Adjoint dialog box contains two matrix selection check boxes. Check the matrices you wish to view and press OK. The format of the selection is:

A = Adjoint(B)

The adjoint matrix can be calcuated in two ways. First it is the transpose of the cofactor matrix. Second it is the inverse times the determinant. ICECAP-PC uses the second method. Select the resultant matrix on the left and the operand matrix on the right. The number of displayed decimal places and scientific notation may be selected with FILE-OPTIONS-VIEW OPTIONS.

3.7 Matrix Condition Number

The Matrix Condition Number dialog box contains a matrix selection check box. Check the matrix you wish to operate on and press OK. The format of the selection is:

Condition Number(B)

The condition number is calculated as $||B|| * ||B^{-1}||$.
Select the resultant matrix on the left and the operand matrix on the right.
The number of displayed decimal places and scientific notation may be selected with FILE-OPTIONS-VIEW OPTIONS.

3.8 Matrix Determinant

The Matrix Determinant dialog box contains two matrix selection check boxes. Check the matrices you wish to view and press OK. The format of the selection is:

A = Determinant(B)

ICECAP-PC uses LU Decomposition to calculate the matrix determinant. Select the resultant matrix on the left and the operand matrix on the right. The number of displayed decimal places and scientific notation may be selected with FILE-OPTIONS-VIEW OPTIONS.

3.9 Matrix Eigenvalues

The Matrix Eigenvalues dialog box contains a matrix selection check box. Check the matrix you wish to operate on and press OK. The format of the selection is:

Eigenvalues(B)

ICECAP-PC uses a three step process to calculate the eigenvalues. First, the matrix is balances to produce an equivalent matrix containing the same eigenvalues but with a lower norm. Second the matrix is converted to upper Hessenberg form using an orthogonal Householder transformation. Third, the eigenvalues are found using a double QR Shift algorithm. Select the resultant matrix on the left and the operand matrix on the right. The number of displayed decimal places and scientific notation may be selected with FILE-OPTIONS-VIEW OPTIONS.

3.10 Matrix Eigenvectors (The Modal Matrix)

The Matrix Eigenvectors dialog box contains a matrix selection check box. Check the matrix you wish to operate on and press OK. The format of the selection is:

Eigenvectors(B)

Select the resultant matrix on the left and the operand matrix on the right. The number of displayed decimal places and scientific notation may be selected with FILE-OPTIONS-VIEW OPTIONS.

3.11 Matrix Euclidean Norm

The Matrix Euclidean Norm dialog box contains a matrix selection check box. Check the matrix you wish to operate on and press OK. The format of the selection is:

Euclidean Norm(B)

Select the resultant matrix on the left and the operand matrix on the right. The number of displayed decimal places and scientific notation may be selected with FILE-OPTIONS-VIEW OPTIONS.

3.12 Matrix Hermite Normal Form

The Matrix Hermite Normal Form dialog box contains a matrix selection check box.

Check the matrix you wish to operate on and press OK. The format of the selection is:

Hermite Normal Form(B)

Select the resultant matrix on the left and the operand matrix on the right. The number of displayed decimal places and scientific notation may be selected with FILE-OPTIONS-VIEW OPTIONS.

3.13 Matrix Inverse

The Matrix Inverse dialog box contains two matrix selection check boxes. Check the matrices you wish to view and press OK. The format of the selection is:

A = Inverse(B)

Select the resultant matrix on the left and the operand matrix on the right. The number of displayed decimal places and scientific notation may be selected with FILE-OPTIONS-VIEW OPTIONS.

3.14 Matrix Multiplication

The Multiply Matrix dialog box contains three matrix selection radio buttons. The format of the selection is:

A = B X C

Check the resultant radio button and the two operand radio buttons then press OK to perform the operation. The resultant is displayed in the format chosen by the FILE-OPTIONS-VIEW OPTIONS setting.

3.15 Matrix Rank

The Matrix Rank dialog box contains a matrix selection check box. Check the matrix you wish to operate on and press OK. The format of the selection is:

Rank(B)

Select the resultant matrix on the left and the operand matrix on the right. The number of displayed decimal places and scientific notation may be selected with FILE-OPTIONS-VIEW OPTIONS.

.topic MatrixScalerMultiply=215
Matrix Scaler Multiplication

The Matrix Scaler Multiply dialog box contains two matrix selection check boxes. Check the matrices you wish to view and press OK. The format of the selection is:

A = Scaler Multiple(B)

Select the resultant matrix on the left and the operand matrix on the right. The number of displayed decimal places and scientific notation may be selected with FILE-OPTIONS-VIEW OPTIONS.

3.16 Matrix Subtraction

The Subtract Matrix dialog box contains three matrix selection radio buttons. The format of the selection is:

A = B - C

Check the resultant radio button and the two operand radio buttons then press OK to perform the operation. The resultant is displayed in the format chosen by the FILE-OPTIONS-VIEW OPTIONS setting.

3.17 Matrix Trace

The Matrix Trace dialog box contains two matrix selection check boxes. Check the matrices you wish to view and press OK. The format of the selection is:

A = Trace(B)

Select the resultant matrix on the left and the operand matrix on the right. The number of displayed decimal places and scientific notation may be selected with FILE-OPTIONS-VIEW OPTIONS.

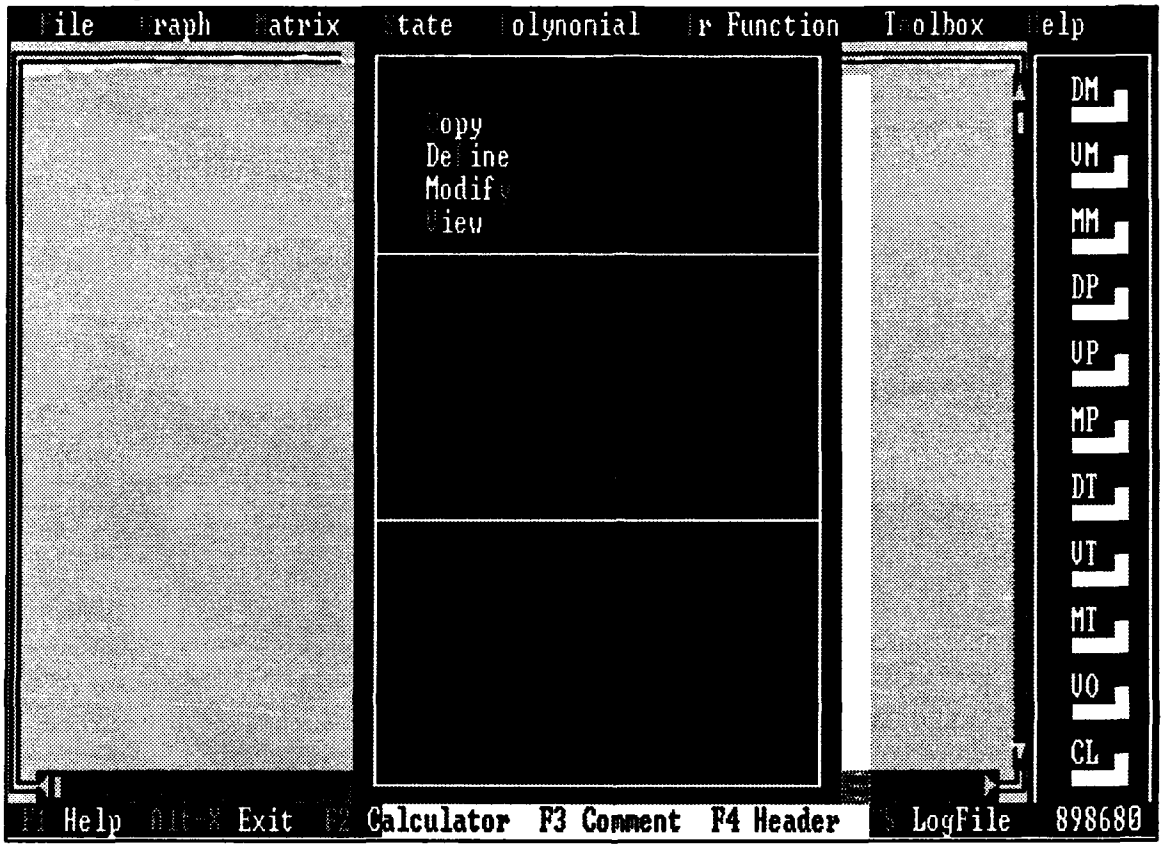
3.18 Matrix Transpose

The Matrix Transpose dialog box contains two matrix selection check boxes. Check the matrices you wish to view and press OK. The format of the selection is:

A = Transpose(B)

Select the resultant matrix on the left and the operand matrix on the right. The number of displayed decimal places and scientific notation may be selected with FILE-OPTIONS-VIEW OPTIONS.

4 System Functions



4.1 Defining Systems

4.2 Viewing Systems

4.3 Modifying

4.4 Copying

4.5 Controllability Matrix

The CNTABLE command determines if the system is controllable by generating and finding the rank of the hermite form. The user is prompted for the plant matrix and the control matrix.

4.6 Observability Matrix

The OBSABLE command determines if a system is observable by generating and finding the rank of the hermite form. The user is prompted for the plant matrix and the observation matrix.

4.7 Phase Variable Form

4.8 Observer Canonical Form

4.9 Observability Form

4.10 Controllability Form

4.11 Diagonal/Jordan Canonical Form

4.12 Tridiagonal Form

4.13 Hessenberg Form

4.14 Transform Domain

4.15 State Space to Transfer Function

The SSTOTF command generates the transfer function of a SISO state-space system. The user specifies the matrix location of the system and the target transfer function storage location. The specified system matrix should be in the form:

```
| A b |
| c d |
```

4.16 System Analysis Graphics

4.16.1 Time Response

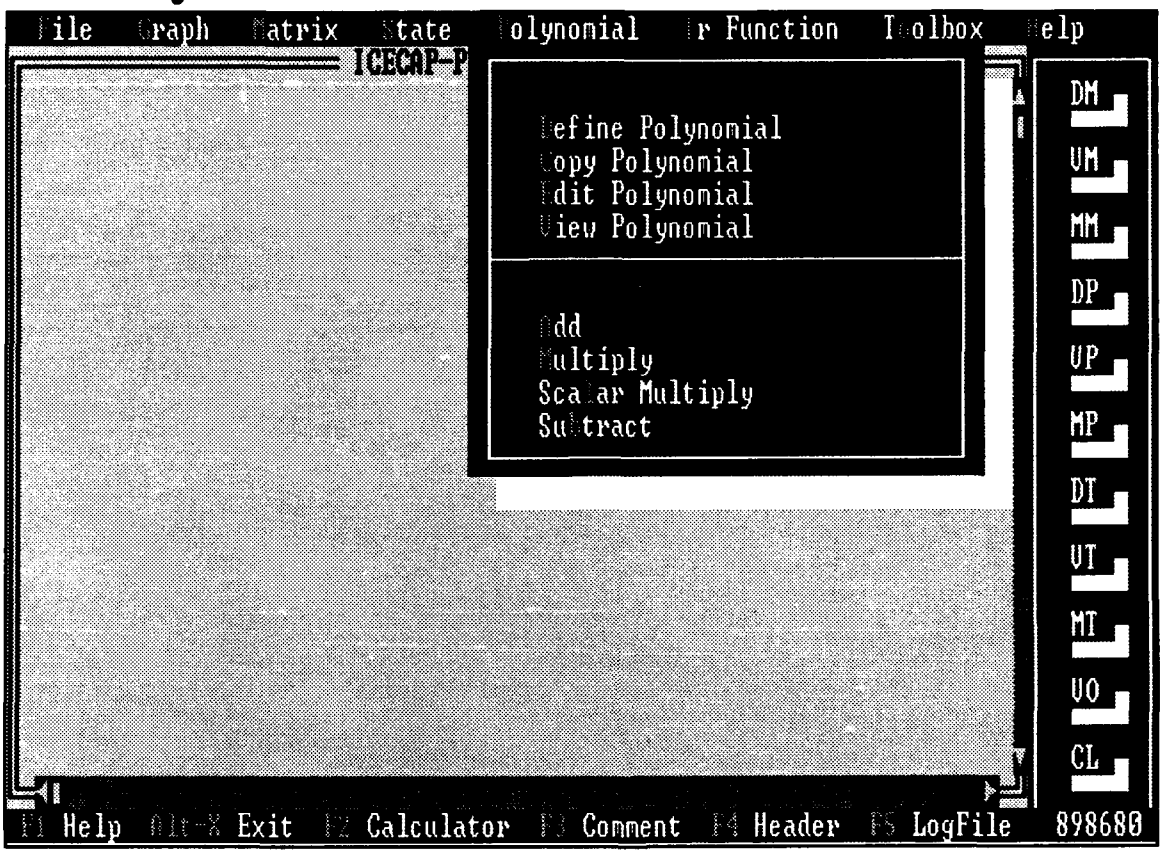
4.16.2 Frequency Response

4.16.3 Root Locus

4.16.4 Nichols Chart

4.16.5 Nyquist Plot

5 Polynomial Functions

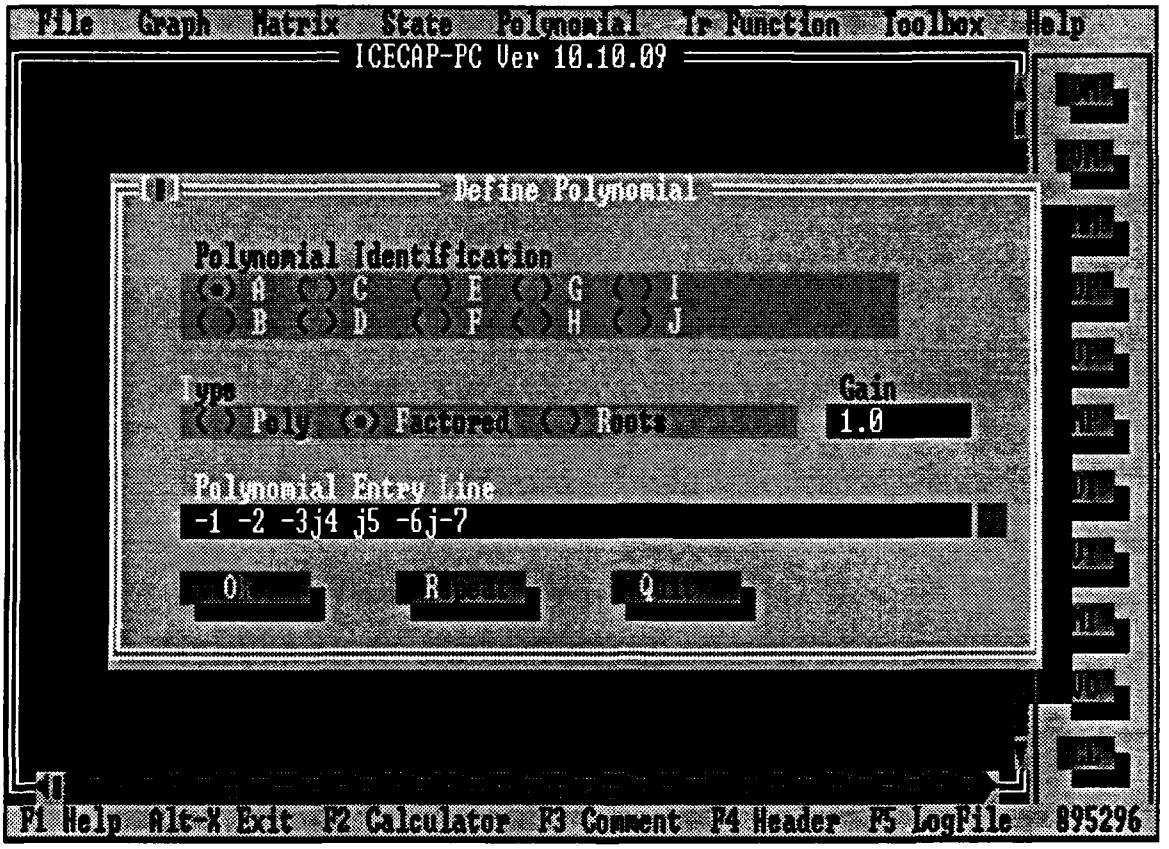


5.1 Defining Polynomials

There are two ways to define polynomials: polynomial format and factored format. Polynomial entry is done on an input line very similar to the most popular matrix/engineering programs with the exceptions that (1) complex factors may be entered directly and (2) brackets are not used to enclose the entry. Differentiation between the two forms is simply a matter of radio button selection. To enter a polynomial ($12.02s^3 - 4.32s^2 + 5s$) one would enter the following line:

12.02 -4.32 5 0

Note that the numbers are not encased by right and left brackets like other popular programs. After such entry, the polynomial is displayed on a scrollable screen in standard coefficient form. To enter a polynomial with five roots at -3±2j, -8, -1 and -9 with a gain of 1, one would enter the following:



-3j2 -8 -1 -9

Note the direct entry of the single complex variable. The entry of complex roots is always done with an i or j preceding the complex element with no spaces allowed. The entry of spaces in a complex number is taken to be a second root at an imaginary location. The entry of the complex conjugate is done automatically by the computer. Manual entry of the complex conjugate is allowed and will be detected by the program. After such entry, the polynomial is displayed on a scrollable screen in either factored form or in list form showing the gain and root locations of the polynomial as selected by the user.

5.2 Viewing Polynomials

Select all polynomials desired to be viewed and a format for displaying them.

5.3 Copying

Select the polynomial to be copied, and then the storage location to which to copy it to.

5.4 Adding

Select the radio buttons for the two polynomials you want added together and the location for the result. If you desire, you may add POLYA and POLYA together and store the result in POLYA.

5.5 Subtracting

Select the radio buttons for the two polynomials you want subtracted, in the order shown--left minus right--and the location for the result. If you desire, you may subtract POLYA from POLYA and store the result in POLYA.

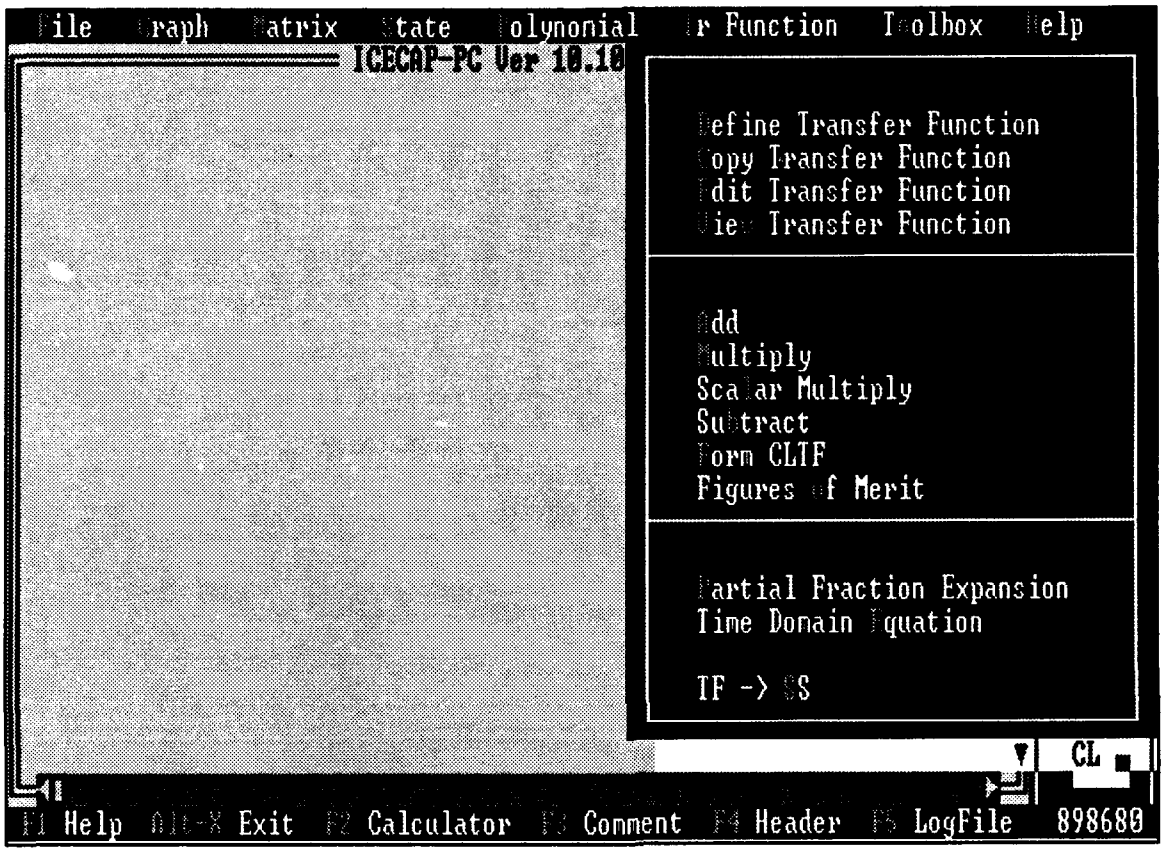
5.6 Multiplying

Select the radio buttons for the two polynomials you want multiplied and the location for the result. If you desire, you may multiply POLYA and POLYA and store the result in POLYA.

5.7 Scalar Multiplying

Select the polynomial you want to multiply by a gain factor, enter the gain factor value, and select a location for the result to be stored. Negative gain factors are allowed.

6 Transfer Function Functions



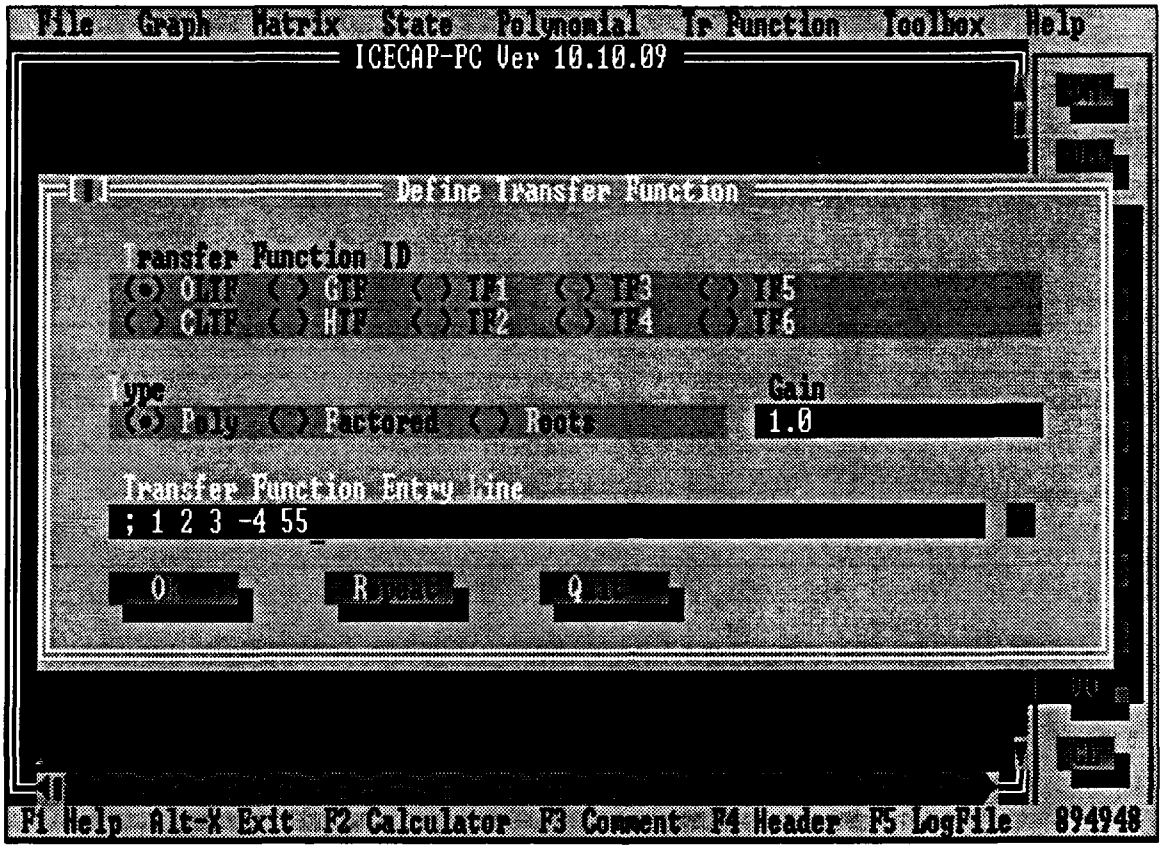
6.1 Defining Transfer Functions

There are two ways to define transfer functions: polynomial format and factored format. Transfer function entry is done on an input line very similar to the most popular matrix/engineering programs with the exceptions that (1) complex factors may be entered directly and (2) brackets are not used to enclose the entry. Differentiation between the two forms is simply a matter of radio button selection. To enter a transfer function $(12.02s^2 + 4.32s + 5) / (4s + 2)$ one would enter the following line:

12.02 4.32 5; 4 2

To enter a transfer function $1 / (4s + 2)$ one would enter the following line:

1 ; 4 2



Note that the numbers are not encased by right and left brackets like other popular programs. After such entry, the transfer function is displayed on a scrollable screen in standard coefficient form. To enter a transfer function with 3 zeros at -2, -5, and -7 and four poles -3±2j, -8, -1 and -9 with a gain of 1, one would enter the following:

-2 -5 -7; -3j2 -8 -1 -9

Note the direct entry of the single complex variable. The entry of complex is always done with an i or j preceding the complex element with no spaces allowed. The entry of spaces in a complex number is taken to be a second root at an imaginary location. The entry of the complex conjugate is done automatically by the computer. Manual entry of the complex conjugate is an error and results in an extra undesired root. After such entry, the transfer function is displayed on a scrollable screen in either factored form ()()()/()()() or in list form showing the gain and root locations of the numerator and denominator as selected by the user.

To enter a transfer function with no zeros and two poles at zero, one would enter the following line:

;0 0

6.2 Viewing Transfer Functions

Select all transfer functions desired to be viewed and a format for displaying them.

6.3 Copying

Select the transfer function to be copied, and then the transfer function location to which to copy it to.

6.4 Adding

Select the radio buttons for the two transfer functions you want added together and the location for the result. If you desire, you may add TF1 and TF1 together and store the result in TF1.

6.5 Subtracting

Select the radio buttons for the two transfer functions you want subtracted, in the order shown--left minus right--and the location for the result. If you desire, you may subtract TF1 from TF1 and store the result in TF1.

6.6 Multiplying

Select the radio buttons for the two transfer functions you want multiplied and the location for the result. If you desire, you may multiply TF1 and TF1 and store the result in TF1.

6.7 Scalar Multiplying

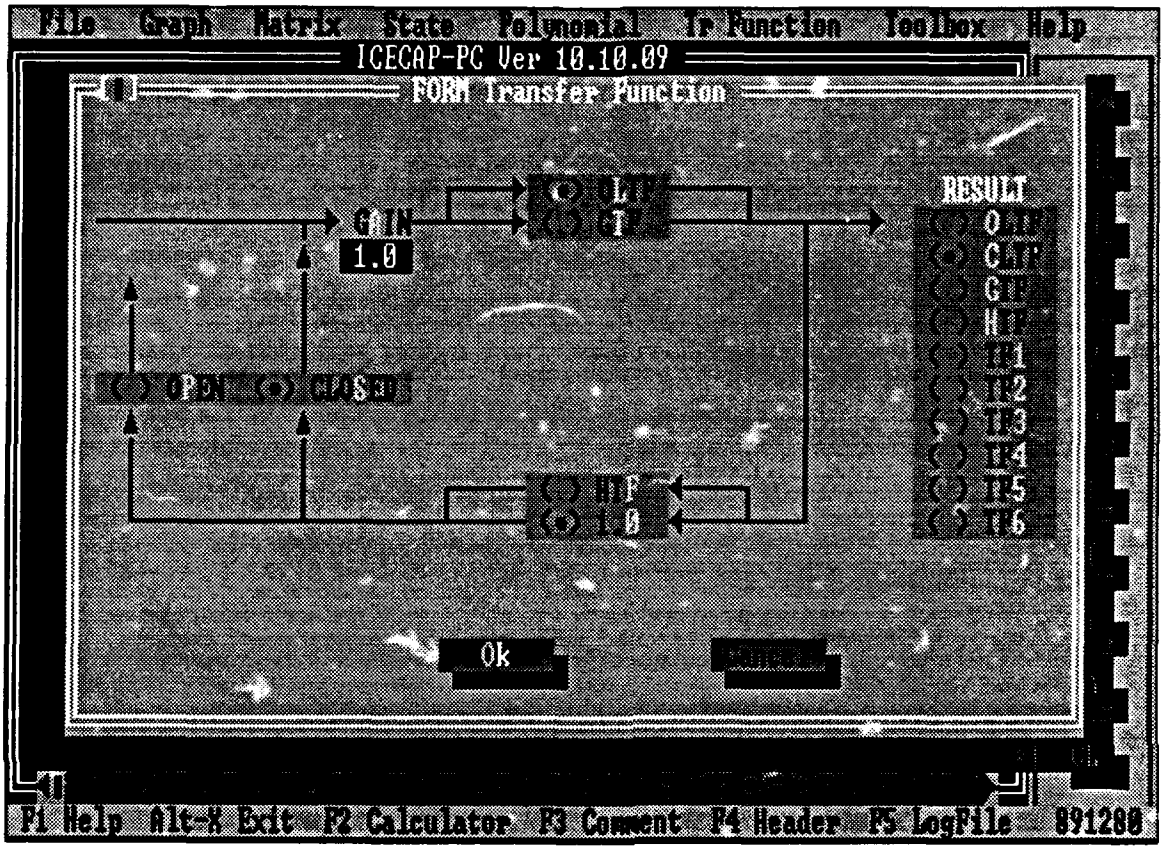
Select the transfer function you want to multiply by a gain factor, enter the gain factor value, and select a location for the result to be stored. Negative gain factors are allowed.

6.8 Form CLTF

The FORM command is used to produce the CLTF from either the OLTF or a combination of GFT and HFT. The formulas for producing the CLTF is as follows:

CLTF = (GAIN * GFT) / (1 + GAIN * GFT * HFT)
CLTF = (GAIN * OLTF) / (1 + GAIN * OLTF)
CLTF = GFT + HFT (In Parallel)

The FORM command will also form the OLTF from the GFT and the HTF. The formula for that operation is:



OLTF = GTF * HTF

6.9 Figures of Merit

This option generates the classical values of the time domain response using the specified transfer function and entered forcing function. The figures of merit include rise time, duplication time, peak time, settling time, peak value, and final value. An example display is:

ICECAP-PC Classical Figures of Merit

RISE TIME: TR= 1.2250784957E+00
DUPLICATION TIME:TD= 2.2257697620E+00
PEAK TIME: TP= 2.8909414644E+00
SETTLING TIME: TS= 3.8496676037E+00
PEAK VALUE: MP= 8.8716540772E-01

FINAL VALUE: FV= 8.4761565716E-01

6.10 Time Equation

This option displays the time-domain continuous or discrete equation terms for the specified transfer function and input (for the continuous case using the Heaviside partial-fraction expansion method). An example is:

*** Output Equation Terms for Specified Input ***

c(t)=

-0.203449 exp(-4.319476 t) sin(3.434581 t + 175.463663)

-1.697083 exp(-1.180524 t) sin(1.181357 t + 29.338792)

0.847616

6.11 Partial Fraction Expansion

This option displays the partial fraction coefficients of the specified transfer function with entered forcing function. The polar representations are also displayed. Available forcing function functions are impulse, step, ramp, pulse and sinusoidal. For example, a resulting display is:

ICECAP-PC Partial Fraction Expansion
CLTF

Numerator Coefficient	Corresponding Pole	Order
-8.04553E-03 + j-1.01406E-01	-4.31948E+00 + j 3.43458E+00	1
-8.04553E-03 + j 1.01406E-01	-4.31948E+00 + j -3.43458E+00	1
-4.15762E-01 + j 7.39706E-01	-1.18052E+00 + j 1.18136E+00	1
-4.15762E-01 + j-7.39706E-01	-1.18052E+00 + j -1.18136E+00	1
8.47616E-01 + j 0.00000E+00	0.00000E+00 + j 0.00000E+00	1

6.12 Transform Domain

This command permits a specific domain transfer function to be transformed into the desired domain using the following transformations:

z to s	Inverse Z transformation	-	INZ (impulse)
s to z	Tustin transformation	-	SZ/TUSTIN (bilinear)
w' to z	bilinear transformation	-	WPZ/BILIN

w to z bilinear transformation	-	WZ/BILIN
s to z z-transform	-	ZTRANS (impulse)
z to w' bilinear transformation	-	ZWP/BILIN
z to w bilinear transformation	-	ZW/BILIN

The user selects one of the above transformations and the specific transfer function he desires to transform. The result is placed into the selected transfer function's data file, overwriting the previous domain's data.

The technique to perform the INZ and ZTRANS symbolic transformations uses the partial fraction expansion approach.

Note that the ZTRANS exact Z transformation can transform an s-plane transfer function with a root of maximum multiplicity 10! When using ZTRAN, ICECAP will ask you if you want to add a Zero-order hold (ZOH). The INZ can transform a z-plane transfer function with a root of maximum multiplicity 2! The other transforms employ the standard bilinear transformation.

6.13 Transfer Function to State Space

The TFTOSS command generates the state space representation of a system using the phase variable technique. It is the inverse of the SSTOTF command.

6.14 Transfer Function Analysis Graphics

6.14.1 Time Response

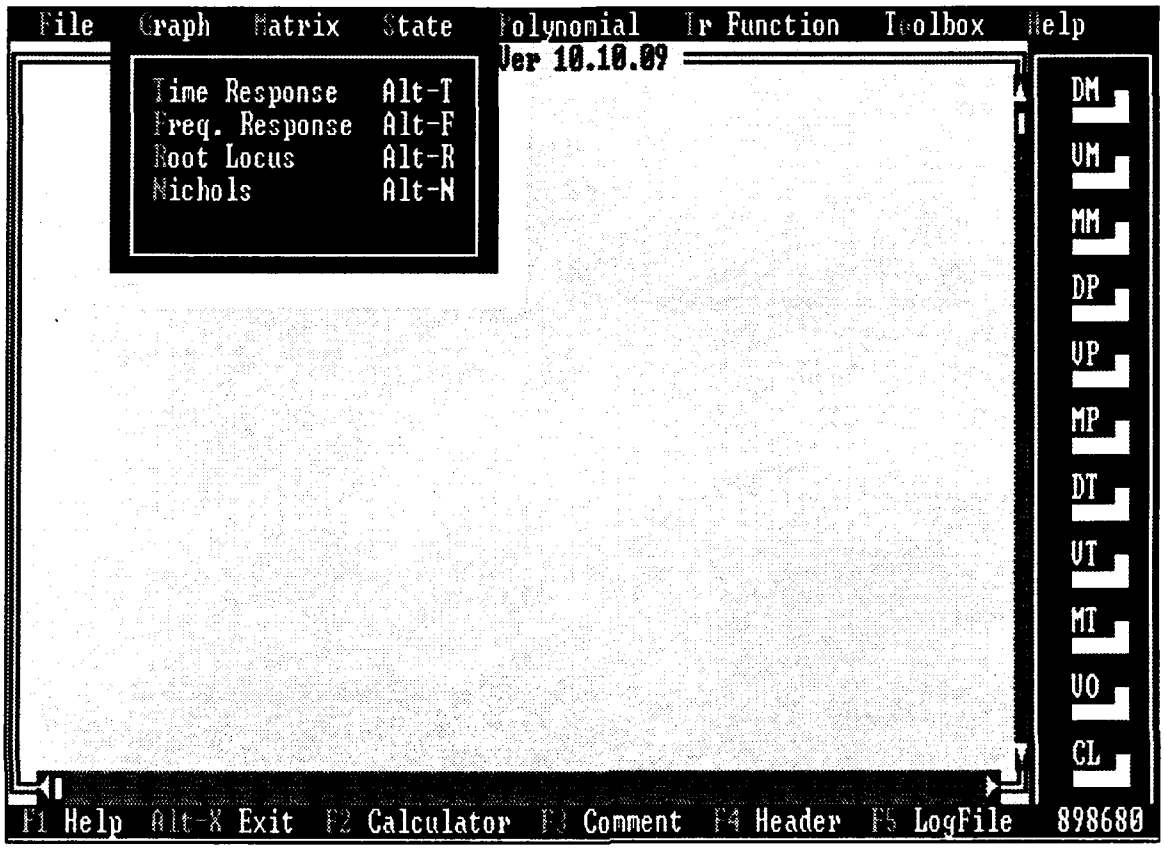
This option lists the time response of a specified s-plane transfer function with entered forcing function and time interval. The available forcing functions are impulse, step, ramp, pulse and sinusoidal.

Plotting Bounds: Users can enter their own plotting bounds as requested by the system.

Grid: The user can request a background (linear and log for bode plots or general plots).

6.14.2 Frequency Response

Given a continuous or discrete transfer function, the frequency response procedure calculates the magnitude and phase angle for a range of frequencies. The procedure gives the user a choice of units for frequency (radians/second or hertz), magnitude (normalized units or decibels), and phase angle (radians or degrees). A log frequency or linear frequency range can be selected. If log frequency is selected, the user is requested to enter the "number of cycles" and the "power of the starting frequency ", i.e. to begin at a frequency of 0.01, you want 10^{-2}, so enter -2 as the starting power. The user can also select linear frequency (omega). A specific step size (del) and range can be entered for



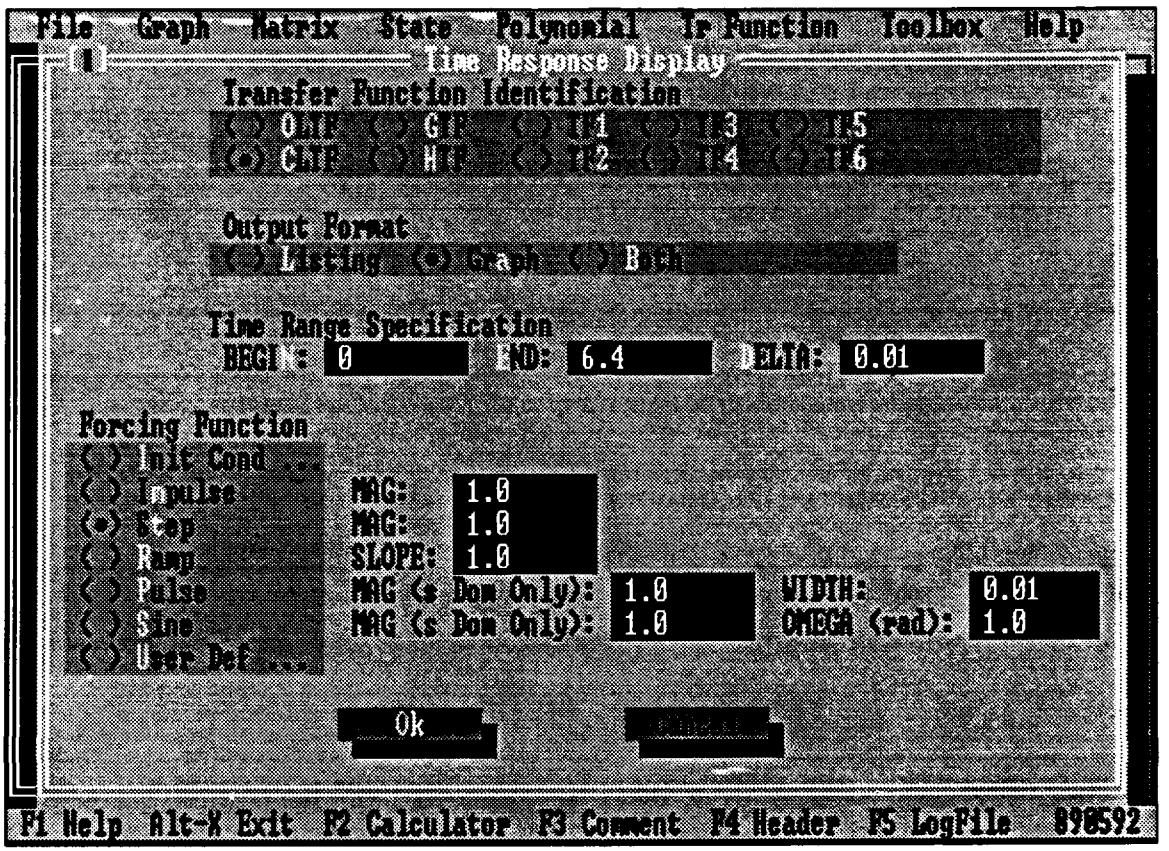
incrementing omega in the linear mode.

Once the frequency range and units are determined, the program automatically calculates the magnitude and phase angle for each value of omega then stores the points in a data file called BODE.DAT. The results are then displayed on the screen in a tabular form. The results will be graphically displayed if the user so requested on the dialog box.

NOTE: The frequency response procedure only calculates 640 data points. Therefore, if the user enters a frequency range and step size which produces over 640 points, the user is prompted to re-enter the range and step size.

6.14.3 Root Locus

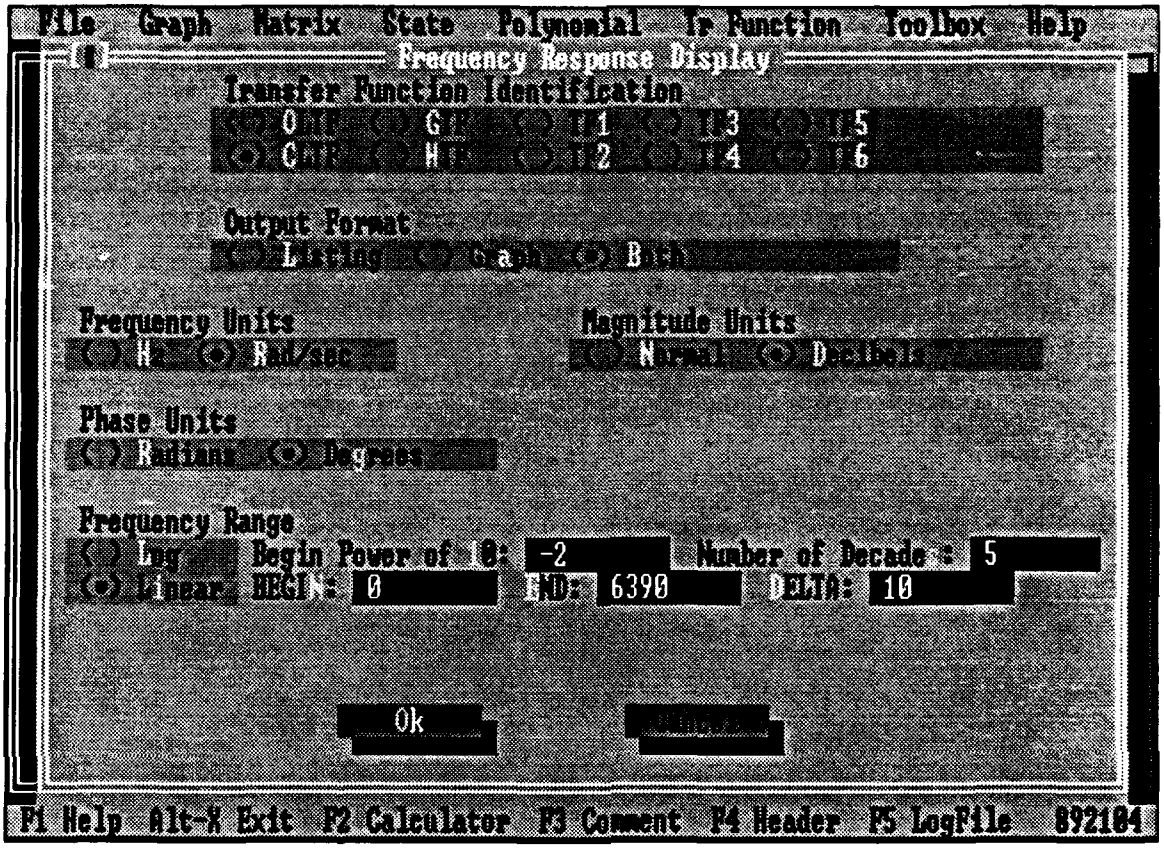
This displays the root locus of the specific transfer function. This command calculates all root locus branches over a specified region (s-plane, w-plane, z-plane) and displays the results as a graphical plot on the screen. It also displays a tabular listing of locus points if the user so desires. In addition, single-step root-locus plotting is available.



The area in which the root locus should be calculated is also requested. This region can be determined by one of two methods. The first method is to use an auto-scale algorithm. The second method requires the user to specify the region of interest. With the second method the user can select a different phaser increment for generating the root locus.

Once ICECAP-PC has a valid area it calculates the branches of the root locus and displays the points on the screen as a plot. Hash marks are provided on each axis at unit positions.

The root locus plotting boundaries are displayed in the lower right corner of the screen. Various lines on the screen are reserved for root locus algorithm processing information. The iteration number of the Newton Raphson algorithm is displayed as well as important information such as when the algorithm is calculating a break point. The line also contains information indicating where the Newton Raphson iteration step size changes. This normally occurs when there are two poles very close together. Also, the position and gain of each plotted point is dynamically presented in the lower left hand corner of the screen.



When the root locus plot is finished, press <CR> twice. The routine will ask the user if a tabular listing of the locus points is desired. If so desired, a tabular listing of the locus points, phaser value, damping factor and gain is listed on the screen for each branch. If there is more than one page of output, the routine will wait for the user to enter a carriage return before displaying more data.

Single-step root-locus is possible after the standard root-locus. Instead of entering two <CR>s as discussed in the previous paragraph, enter an "s" then a <CR>. The root-locus plot then proceeds one step each time you press <CR>. ICECAP-PC performs the single-step root-locus for the same range of data that was originally requested; however, it repeats the request for the second screen of data (plot title, zeta of interest).

When the root-locus plot is complete, the gain and root values are presented if you requested a zeta of interest, for example:

** GENERATION OF GAIN FOR A DAMPING RATIO (ZETA) OF INTEREST **

zeta = 7.1E-0001

Branch number	Locus Real	Locus Imag	Gain
1	-4.0000000000E+00	-4.0000000000E+00	0.0000000000E+00
2	-4.0000000000E+00	4.0000000000E+00	0.0000000000E+00
3	-1.1801669065E+00	-1.1805233708E+00	-2.3585638821E+00
4	-1.1801669065E+00	1.1805233708E+00	-2.3585638821E+00

Following this are the intersections of the root locus with the imaginary axis (stability range of gain); for example:

*** ROOT LOCUS CROSSING OF IMAGINARY AXIS ***
(Range of Gain for Stable System)

Branch number	Locus Real	Locus Imag	Gain
3	0.0	-2.9539E+0000	-9.2230E+0000
4	0.0	0.0000E+0000	0.0000E+0000
4	0.0	2.9539E+0000	-9.2230E+0000

FIGURE 5

6.14.4 Nichols Chart

Constant Mp curves and constant angle curves for the closed loop are also presented over the following ranges:

Mp in db	13,8,5,3,2,1,0,-1,-2,-3,-5,-8, -13,-22;
angle in degrees	-340,-320,-300,-280,-260,-240,-220,-200, -160,-140,-120,-100,-80,-60,-40,-20.

Displaying the constant Mp and angle curves is controlled by the SWITCH command (the constant Mp curves default to "on", the constant angle curves default to "off") (Fig. 4).

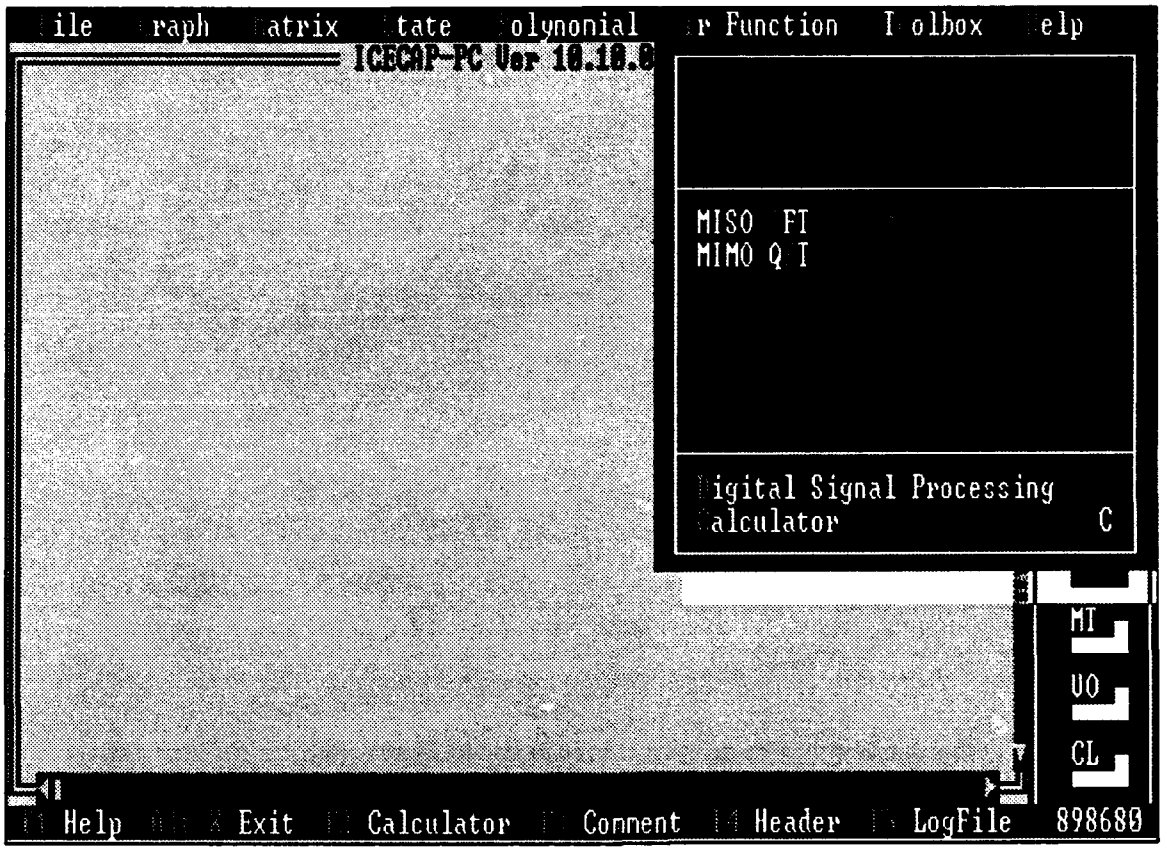
A Nichols chart display of the data in the BODE.DAT file as generated using the Frequency Response routine can be requested. Constant Mp curves and constant angle curves for the closed loop are also presented over the ranges as listed above.

Nyquist Plot

This option graphically displays the polar plot of the entered transfer function along with the associated gain margin and phase margin. Also, an optional plot title is requested. See example display of Fig. 6.

FIGURE 6

7 Toolboxes


ile
raph
atrix
tate
olynonial
r Function
I olbox
elp
ICECAP-PC Ver 10.10.0
MISO FT
MIMO Q I
igital Signal Processing
alculator
C
MI
UO
CL
Help
Exit
Calculator
Comment
Header
LogFile
898680

APPENDIX A. PRINTING

All printing of graphics can be accomplished by using a screen-dump package.

EGA terminals should use "EGADMP" (Part of "CHART 4" package). We distribute EGADMP configured to work with an EPSON printer. For laser printers we distribute LJEGADMP, which is configured for an HP. EGADMP can be reconfigured for other printers.

CGA terminals should use "GRAPHICS" under MS-DOS.

For VGA terminals use of a commercial package such as "GRAPPLUS" is suggested. The proper graphics and printer drivers must be installed as prescribed by each of those individual packages. If you have a VGA interface and do not own a commercial screen dump program, reprogramming your monitor as an EGA terminal will usually permit the EGADMP routine to execute properly.

APPENDIX B. IF PROBLEMS ARE ENCOUNTERED

The following is a brief list of actions to take when problems are encountered during execution of ICECAP-PC.

6.1 Errors During Initialization

Make sure all files required by the ICECAP-PC reside in the same disk directory as ICECAP-PC . Attempt to re-execute the program.

6.2 A "trashy" Title Slide Appears

1. Attempt to re-execute the program.

6.3 Graphics Display Problems

1. Since ICECAP-PC determines the type of graphic terminal interface (CGA, EGA, VGA,...) before plotting, the interface should be checked for proper switch selection (reference Turbo Pascal Graph Unit).

2. If the colors that are presented are not desired, change source code in ICECAP-PC graphics modules. (reference Turbo Pascal Graph Unit).

3. Try to obtain a .BGI file from Borland to drive your unique monitor.

6.4 System Hang Up

1. Read the documentation that was shipped with the new DPMI drivers.

6.5 Problem Report Form

Attached is a blank problem report form. Please copy and submit comments as appropriate to the indicated address or use electronic mail.

ICECAP-PC PROBLEM REPORT FORM

PROBLEM REPORT NUMBER: [do not specify]

DATE: _____.

ORIGINATOR: _____.

PROBLEM NAME: _____.

ERROR MESSAGE REPORTED: ERROR NUMBER: _____ LOCATION: _____.

MODULE(S) HAVING PROBLEM: _____.

PROBLEM DESCRIPTION: _____.

_____.

_____.

_____.

_____.

PROBLEM SERIOUSNESS: _____.

DIFFICULTY OF FIX: _____.

SUGGESTIONS FOR FIX: _____.

_____.

_____.

_____.

DISPOSITION: _____.

_____.

TO: Prof Gary B. Lamont AFIT/ENG
Wright-Patterson AFB OH 45433-6583
(ARPANET lamont@galaxy.afit.af.mil)

APPENDIX C. Theoretical Background of ICECAP-PC Algorithms

(in progress)

APPENDIX D. Basic Continuous Compensation Toolbox

This toolbox provides the student several template-style filters to use for control. The templates include Lead-Lag, Butterworth, and Chebychev filters. The student specifies the performance requirements and the plant, and the toolbox generates the proper filter parameters.

APPENDIX E. Nonlinear Modelling Toolbox

APPENDIX F. System Build Toolbox

APPENDIX G. Linear Quadratic Regulator/Gaussian/Compensator Toolbox

This toolbox provides the student with an LQR when he provides the plant and Q and R parameters. It also will provide an LQG estimator and the combination of the two into an LQ Compensator system.

The LQRCONT command solves the linear quadratic regulator problem by generating the solution to the Riccati equation (uses eigenvalue decomposition), determining the constant control gain and generating the closed-loop eigenvalues. The user is prompted for the plant, control and weighting matrices.

APPENDIX H. Kalman Filtering Toolbox

This toolbox is a port of Dr Maybeck's Matlab M-File program suite called KFEval. It allows the student to design Kalman filters.

APPENDIX I. H Infinite Toolbox

This toolbox allows the students to design controllers using the H Infinite method.

APPENDIX J. Eigenstructure Assignment Toolbox

This toolbox provides a matrix method for designing controllers.

APPENDIX K. Multi-Porter Method Toolbox

This toolbox provides a specific type of Eigenstructure Assignment called the Multi-Porter Method.

APPENDIX L. Digital Signal Processing Toolbox

(Major Development by D. Gelopulos, Valparaiso University)

A set of Pascal programs have been incorporated that provide elementary digital signal processing analysis and synthesis functions. The main DSP menu ICECAP provides looks like:

DEMOS DFT FFT FOURSERHELP

3.1.4.1 DEMOS

The DEMOS command permits the following variety of demonstrations:

1) Convolution
2) Fourier Series
3) Phase
4) Aliasing
5) DFT test data generation

The user is initially requested to enter a number corresponding to one of these demonstrations, which are described in the following paragraphs.

"Convolution Demonstration"

This program asks the user to specify a discrete unit pulse response and an input sequence. The program displays the response to each sample in the input sequence and shows how it combines with the response to all previous input samples to form the system response. The user may also request a record of the experiment which will be recorded in a disk file in the form of a convolution summation table. The user may name a file for saving the calculation of the convolution with respect to the response to each input sample as well as the total system response.

"Fourier Series Demonstration"

This Program Demonstrates The ability of the Fourier series to represent a square wave. This program displays a square wave, and a truncated, Fourier series of the wave. The square wave (red), its Fourier series (yellow) and the previously exhibited series (green) can all be displayed together for comparison. To see "Gibbs" phenomenon, use high resolution graphics and more than 50 harmonics. The user enters the number of harmonics he wishes to include after each display is produced. The user may also interrupt the display at any time to enter the harmonic number. Enter a "0" to terminate the execution.

"Phase Demonstration"

This demo generates a complex phasor rotation and the associated projection of its real and imaginary parts. The user enters four phasors (amplitude and phase), one at a time using amplitudes between 10 and 110.

"Aliasing Demonstration"

This Program Demonstrates The Aliasing of samples of a sinusoidal signal. The user enters a frequency. The program generates the alias signals, one at a time. The user must identify how many periods of a sinusoid to display, and how frequently it is sampled. The program displays the sine wave and an alias sinusoid which has the same values at sample times. Each time the program is re-run the next higher alias frequency is shown. The display is interrupted at each sample time for emphasis. To Terminate the program, press "E" at the END of a display.

"DFT Test Data Generation:"

The following Pascal program generates the dft test data. To run the program as is and generate the data as is, just choose option 5 from the DSP DEMO menu. However, if you want to generate a different set of test data, you could develop your own program based on this example. To develop your own program would require writing it and compiling and running it outside of ICECAP. Then run ICECAP and whenever it requests a filename for the DFT routines, enter the name of the file your program created.

```
program dft_data_generation;

var j, n: integer;  x, w1t, w2t, dw1t, dw2t : real;  out : text;

Begin
Clearscreen;
Writeln(' Please input desired DFT data file name ');
Reset(input);
Read(filename);
Assign( out, filename);
Rewrite( out );
Writeln( out, 'DFT test data: 5 sin(4 wo t) + 5 cos( 40 wo t )');
Writeln( out );
Writeln( out );
n    := 128;
w1t  := 0;
w2t  := 0;
dw1t := 8 * Pi / n;
dw2t := 80 * pi / n;
For j := 1 to n do
        Begin
                x   := 5 * ( sin( w1t ) + cos( w2t ) );
                w1t := w1t + dw1t;
                w2t := w2t + dw2t;
                Writeln( out, (j-1):5, x:12:4 )
        End;
Close( out );
End.    {end of program dft_data_generation}
```

3.1.4.2 FFT: CALCULATION OF FAST FOURIER TRANSFORM COEFFICIENTS

The samples to be Fourier transformed (to have the D.F.T. evaluated), should be listed in a sequential file, one sample per line. The first line should contain a one-line heading and the next two lines may have anything. The first sample should appear in line four.

To do an inverse D.F.T., the data file should have the following format: First line of the file should contain a one-line heading. Lines 2 & 3

can have anything. Line 4 has the real and imaginary part of the first spectrum point. Line 5 has the next point, etc.

Line numbers may precede a data point, and will be ignored if the file is declared by the user as "numbered" when asked by the program. The number of data points must be a power of two. Do NOT use a blank for a value of zero!

Data sets are limited to 4096 in length. A sample data file can be generated under DSP DEMO.

3.1.4.3 DFT: GENERATION OF D.F.T. COEFFICIENTS FOR SMALL DATA SETS

The form of the sequential data file is the same as that for the FFT.

Data sets are limited to 1024 in length because F.F.T. is NOT implemented in this program. It is intended to be transparent code for academic size problems. The DSP DEMOS option 5 can be used to generate a test file.

3.1.4.4 SERIES: CALCULATION OF FOURIER COEFFICIENTS

This procedure is programmed by the user to evaluate the wave for which the Fourier series is sought at "time = TIME". The general example calculates and graphically presents the series of a square wave which equals "1" for the first half period and "0" for the last half.

This program is interactive. It is necessary to reprogram a function to calculate the wave of interest. The user enters the period of the wave as well as the number of harmonics to be calculated. If you wish to save the response, enter a file name. If a file name is not entered, the Fourier series coefficients are listed in two forms: the trigonometric coefficients with An (cosine) and Bn (sine), and then the polar form of the phasors with "sine" as reference. The nominal time step selected by the user is trimmed so that an integer number of time steps fits exactly into one period.

Appendix D ICECAP-PC Programmer's Manual

ICECAP - PC

Version 10.0 - MS-DOS

Interactive **C**ontrol **E**ngineering **C**omputer **A**nalysis **P**ackage
for the **P**ersonal **C**omputer

Programmer's Manual v 1.0

Professor Gary B. Lamont
Department of Electrical and Computer Engineering
School of Engineering
Air Force Institute of Technology
Wright-Patterson AFB
Dayton, Ohio 45433-6583

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PREFACE

WELCOME to the Programmer's Manual for ICECAP-PC. ICECAP-PC is an ongoing development of a public domain computer-aided design (CAD) package for students, faculty and practitioners of control engineering and digital signal processing with special emphasis on education. Source code and executable files are available. If you are interested in adding additional code or have suggestions for improvement please contact:

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cooperative copyright (C) 1985, 1986, 1987, 1988, 1989, 1990,1991,1992 Gary B. Lamont, Susan K. Mashiko, Gary C. Tarczynski, D. Gelopulos, Paul A. Moore, Wayne E. Bell, Vincent M. Parisi, Fred Trevino, Mark W. Schiller, Ken A. Crosby

This public domain CAD package is intended for the main purpose of education and thus the executable code can be distributed freely. Any use of the package in support of written publications should be indicated as a reference. Changes to the public domain source code that improve and extend its capabilities are appreciated, however, all suggested changes should be communicated to the authors for updating and dissemination of the next official version.

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ICECAP-PC is written in Borland's$_{tm}$ Turbo PASCAL 6.0 and TurboVision, both of which are registered trademarks and copyrighted by Borland International, Inc. 1800 Green Hills Road, P.O. Box 660001, Scotts Valley, CA 95067-0001. The .BGI files distributed with our package are released to public access by Borland.

All references to MS-DOS in this document refer to Microsoft-DOS which is a registered trademark and copyrighted by MicroSoft$_{tm}$ Corporation.

SYSTEM REQUIREMENTS

ICECAP-PC is designed to work on MS-DOS$_{tm}$ 80286/80386/80486 computers with a minimum of 640 KB of RAM and 5MB of hard disk space. ICECAP-PC supports all graphics terminals including Hercules$_{tm}$, EGA and VGA. Operation is greatly enhanced with expanded memory and a math co-processor. Installation of ICECAP-PC and its QFT Toolbox is done automatically with a provided install procedure (see ICECAP-PC manual).

Edited By: Gary B. Lamont , Wayne E. Bell, and Fred Trevino; 1992

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1 Introduction

ICECAP-PC is fully object-oriented. In order to call one of its internal routines, one need only do the following:

(1) Fill the global record associated with the desired routine with the appropriate data.
(2) Send a message to the DeskTop invoking the desired object.

The message is formatted like this:

Message(DeskTop, evBroadCast, brDesiredRoutineName, nil);

The brDesiredRoutineName is the only variable element in this message. All the br commands and their associated routines are found in **Chapter 2**. If a routine has a global record for passing parameters associated with it, the global record is also listed along with the routines. Most of the global records further have associated with them transitional routines. These transitional routines make it easier to copy information from the global record of one routine to that of another. They must only be used when one is doing plots with multiple responses on the same plot. Typically, one must only call the main plot routine. For example, if one is currently working with the frequency response routine and wants to call a graphics plot of the response, one would summon the FreqDisplay routine with the following message:

Message(DeskTop, evBroadCast, brFreqDisplay, nil);

It is this ability to send anonymous messges to the Desktop, that makes object-oriented code so expandable. Future development will include expanding this macro-type language support for our code, making it more convenient and flexible for future programmers to use our package as a macro language or 4GL.

2 The Programmer's Guide

```
(*****************************************************************************)

{Unit Control}

 PROCEDURE TObjectControl.HandleEvent(var Event: TEvent);
 begin
  TView.HandleEvent(Event);
  If (Event.What = evBroadcast) then
     Case Event.Command of
       brGetMatrix, brMakeMatrix, brMatrixAdd, brMatrixAdjoint,
       brMatrixCondition, brMatrixCopy, brMatrixDeterm,
       brMatrixEigenvalues, brMatrixInverse, brMatrixModal,
       brMatrixModify, brMatrixSMultiply, brMatrixSubtract,
       brMatrixMultiply, brMatrixNorm, brMatrixTranspose,
       brTFPolyAdd, brTFPolyCopy, brPolyDefine, brPolyDisplay,
       brTFPolySubtract, brTFPolyMultiply, brTFPolySMultiply,
       brTFDefine, brTFDisplay, brTFFormCLTF, brTFtoSS, brTFPolyModify,
       brFreq2Plot, brDirectFreqResp, brOutputFreqFile, brFreqResponse,
       brTimePFE, brTimeFOM, brTimeEquation, brTimeResponse,
       brTime2Plot, brcalc_part, brdisp_part, brdirecttimeresp,
       brOutputTimeFile, brFOM, brOutputSpecFile,
       brGraphicsDialog, brFindMm, brPrepGraphMode, brInitGraphVars,
       brDrawGrid, brPositionGraphics, brScaleValues, brHandleLineType,
       brDrawPlotData, brHandleSpecialCases, brFinishGraphMode,
       brPlot_Display

        : Begin TObjectControl.ObjectControl(Event.Command); ClearEvent(Event); end;

     end;{case}
 end;
```

```
(*****************************************************************************)

{Unit MFreq}

 VAR
   ListOrGraph : Integer;

PROCEDURE TFreq.HandleEvent(var Event: TEvent);
begin
  TView.HandleEvent(Event);
  If (Event.What = evBroadcast) then
     Case Event.Command of
        brFreqResponse : Begin TFreq.FreqResponse; ClearEvent(Event); end;
        brFreq2Plot    : Begin TFreq.Freq2PlotRecord; ClearEvent(Event); end;
        brFreq2Nic     : Begin TFreq.Freq2NicPlotRecord; ClearEvent(Event); end;
        brDirectFreqResp : Begin TFreq.Direct_Freq_Resp; ClearEvent(Event); end;
        brOutputFreqFile : Begin TFreq.OutputFreqFile; ClearEvent(Event); end;
        brFreqDisplay    : Begin TFreq.freq_display; ClearEvent(Event); end;
        brNicholPlot     : Begin TFreq.NicholsPlot; ClearEvent(Event); end;
     end;{case}
end;
```

```
(*****************************************************************************)

{Unit MGlobals}

 {Global Constants}
 Max_ViewerSize  =  230; {10 Screens Of 23 Lines }
 Max_ViewerWidth = 256; {256 Columns            }
 Max_Rows = 12;
 Max_Cols = 13;
 Max_Cols1 = 13;   {we need a constant one more than the max order}
 Max_Degree = 20;
 Max_Degree1= 21; {needed for indexing coefficient arrays}
 MaxPlotGlb    = 640;       { added for graphics unit }
 MaxPlotGlb1   = 641;
 max_num_plots =  10;

Extended_complex  = record
 realpart : extended;
 imagpart : extended;
end;

Root_Poly_Type  = array[ 1..max_Degree] of extended_complex;
Coeff_Poly_Type = array[ 1..max_Degree] of extended;

Matrix = record
 name     : string;        {Holds Matrix Name}
 complex  : boolean;        {Used For Matrices}
 domain   : char;          {Used for domain s, w, or z that values were entered as}
 samp_per : extended;       {Used for discrete sampling period}
 num_rows : integer;        {Used For Matrices Degree}
 num_cols : integer;        {Used For Matrices Degree}
 element  : array[ 1..max_rows,0..max_cols] of extended_complex;
end;

Polynomial = record
 name     : string;        {Holds Poly Name}
 degree   : integer;
 gain     : extended;
 Factored : Root_Poly_Type;
 PolyForm : Coeff_Poly_Type;
end;
```

```
TransFunc = record
 name     : string;        {Holds TF Name}
 domain   : char;          {Used for domain s, w, or z that values were entered as}
 samp_per : extended;      {Used for discrete sampling period}
 num      : Polynomial;
 den      : Polynomial;
end;

PolyPtr    = ^Polynomial;
TFPtr      = ^TransFunc;
MatPtr     = ^Matrix;

  vectorarray = array[ 1..MaxPlotGlb1 ] of extended; {7k}
  Plot_Data_Type = Record
    DataFileName          : String;
    DataFile              : File of Extended;
    HorzValue,
    VertValue             : VectorArray;
    Grid,
    LastPlot              : Boolean;
    MaxHorzAxis,
    MaxVertAxis,
    MinHorzAxis,
    MinVertAxis           : Extended;
    Color,
    DisplayCount,
    LogOrLinear,
    Nichols,
    NormOrDec,
    NumDecade,
    NumPlot,
    NumPoint,
    PowerOfTen            : Integer;
    Palette               : PaletteType;
    GenTitle,
    HorzTitle,
    Title,
    VertTitle,
    Mm,
    Wm                    : String;
  end;
```

```
FreqRangeType = (LOW, MED, HIGH, USER);
Freq_Data_Type = Record
  TF          : TransFunc;
  DataFileName : String;
  DataFile     : File of Extended;
  FreqArray    : Array[1..MaxPlotGlb] of extended;
  FreqRange    : FreqRangeType;
  First,
  Final,
  Delta        : extended;
  HzOrRad,
  LogOrLinear,
  MagOrPhase,
  NormOrDec,
  NumDecade,
  NumPoint,
  PowerOfTen,
  RadOrDeg     : Integer
end;

Time_Data_Type = Record
  TF,
  FFTF          : TransFunc;
  ForceFuncType : Integer;
  DataFileName  : String;
  DataFile      : File of Extended;
  First,
  Final,
  Delta         : extended;
end;
bodtim    =  array[ 1..max_degree ] of extended;
```

```
VAR
{=========================================================================}

  AbortCode        : integer;
  bkc_blue         : boolean;
  choice           : string;
  ComplexLetter    : String[1];
  discrete_z,
  discrete_w       : boolean;
  DomainLetter     : String[1];
  FreqData         : ^Freq_Data_Type;
  GString          : String;
  MacroFile        : text;
  MacroFileName    : string[13];
  MacroFlag,
  MacroStop        : Boolean;
  Mats             : File of Matrix;
  omega_T          : extended;
  option           : string;
  PlotData         : ^Plot_Data_Type;
  PolyOne          : Polynomial;
  Polys            : File of Polynomial;
  PolyZero         : Polynomial;
  RealStr_Fixed    : Integer;
  RealStr_SCI      : Boolean;
  RightButtonDown  : boolean;
  spc              : array[1..20] of string[20];
  T                : extended;          (* sampling time *)
  tau              : extended;   {time delay - 12/23/89}
  TextMode         : Integer;
  TFDispFormat     : Integer;
  TFFileName       : String;
  TFInf            : TransFunc;
  TFOne            : TransFunc;
  TFs              : File of TransFunc;
  TFZero           : TransFunc;
  TimeData         : ^Time_Data_Type;
  TransFuncNames   : array[0..26] of string[7];
  VGACardType      : Integer;
  ViewString       : String;

CONST
  ComplexOne : extended_complex = (RealPart: 1.0; ImagPart: 0.0);
  ComplexZero: extended_complex = (RealPart: 0.0; ImagPart: 0.0);
  Infinity   : extended         = 1e1000;
  rcer       : extended         = 1e-8;
  ZeroVal    : extended         = 1e-100;
```

```
(*****************************************************************************)

{Unit MIceGrap}

 PROCEDURE TIceGraph.HandleEvent(var Event: TEvent);
 begin
  TView.HandleEvent(Event);
  If (Event.What = evBroadcast) then
    Case Event.Command of
      brGraphicsDialog     : Begin TIceGraph.GraphicsDialog;     ClearEvent(Event); end;
      brFindMm             : Begin TIceGraph.FindMm;             ClearEvent(Event); end;
      brPrepGraphMode      : Begin TIceGraph.PrepGraphMode;      ClearEvent(Event); end;
      brInitGraphVars      : Begin TIceGraph.InitGraphVars;      ClearEvent(Event); end;
      brDrawGrid           : Begin TIceGraph.drawgrid;           ClearEvent(Event); end;
      brPositionGraphics   : Begin TIceGraph.PositionGraphics;   ClearEvent(Event); end;
      brScaleValues        : Begin TIceGraph.ScaleValues;        ClearEvent(Event); end;
      brHandleLineType     : Begin TIceGraph.HandleLineType;     ClearEvent(Event); end;
      brDrawPlotData       : Begin TIceGraph.DrawPlotData;       ClearEvent(Event); end;
      brHandleSpecialCases : Begin TIceGraph.HandleSpecialCases; ClearEvent(Event); end;
      brFinishGraphMode    : Begin TIceGraph.FinishGraphMode;    ClearEvent(Event); end;
      brPlot_Display       : Begin TIceGraph.plot_display;       ClearEvent(Event); end;
    end;{case}
 end;
```

```
(*****************************************************************************)

{Unit MMath}

var
 year        : word;
 month       : word;
 day         : word;
 day_of_week : word;
 datestring  : string;
 days        : string;
 years       : string;
 months      : string;

  {General Routines For All}
  FUNCTION    ConditionExt(Y: extended): Extended;
  PROCEDURE   Display (Msg: String);
  FUNCTION    Exist(File_Name : string): boolean;
  PROCEDURE   FileView (Filename : String);
  FUNCTION    FormatNumber (Num: extended_complex; Complex: boolean): string;

  {Matrix Specific Routines - Possibly Move}
  PROCEDURE   ConditionMatrix (var SomeMatrix: Matrix; InitMat : Boolean);

  {General Math Routines}
  PROCEDURE   AddComplex (A,B: extended_complex; var Y: extended_complex);
  FUNCTION    AddExt (A,B: extended): extended;
  FUNCTION    AModB(num1 : extended; num2 : extended) : extended;
  FUNCTION    Arc_Tangent (y, x:extended):extended;
  FUNCTION    AxSignB(num1 : extended; num2 : extended) : extended;
  PROCEDURE   ComplexQuadratic (a,b,c: extended_complex;
                    var Root1, Root2: extended_complex);
  FUNCTION    ConvertToReal (TempStr: String; Var AbortCode : Integer)
                  : Extended;
  PROCEDURE   ComplexSqrt(A: extended_complex; var B: extended_complex);
  PROCEDURE   Disp_date;
  PROCEDURE   DivideComplex (A,B: extended_complex; var Y: extended_complex);
  PROCEDURE   EqualComplex (var Y : extended_complex; A, B : extended);
  FUNCTION    Exp10 (x: extended): extended;
  FUNCTION    Ftor(x : integer): extended;
  FUNCTION    IsZero(A: extended): boolean;
  FUNCTION    IsZero_Com(A: extended_complex): boolean;
  FUNCTION    Log10_ext(x:extended): extended;
  {?} function magcomplex(real1,imag1,real2,imag2 : real):real;
  FUNCTION    Magnitude_ext (A: extended_complex): extended;
  PROCEDURE   MultiplyComplex (A,B: extended_complex;
                    var Y: extended_complex);
```

```
PROCEDURE   MultiplyReal (A,B: extended_complex; var Y: extended_complex);
PROCEDURE   Polar_ext(var realpart: extended; var imagpart: extended;
            var radius: extended; var theta : extended );
FUNCTION    Raise_pwr(number : extended; pwr : integer) : extended;
FUNCTION    RaiseLongIntToPower(i : Word;j:integer) : LongInt;
PROCEDURE   SubtractComplex (A,B: extended_complex;
                var Y: extended_complex);
{ft}  FUNCTION SubtractExt (A,B: extended): extended;
FUNCTION    Tan (angle:extended):extended;
```

```
(*****************************************************************************)

{Unit MPTFMath}

 type
  MakePolyType = Record
    PolyName_RadioButton : word;
    PolyType_RadioButton : word;
    GainLine             : String;
    InputLine            : String;
  end;

  {Administrative Routines}

  PROCEDURE  CompletePoly(PolyORFact:char; var HalfPoly : Polynomial;
                var AbortCode:Integer);
  PROCEDURE  CompleteTF(var NewTF : TransFunc; var AbortCode:Integer);
  PROCEDURE  ConditionPoly (var SomePoly : Polynomial; NewPoly : Boolean);
  PROCEDURE  ConditionTF (var SomeTF : TransFunc; NewTF : Boolean);
  PROCEDURE  DisplayPoly (var Poly: Polynomial);
  PROCEDURE  DisplayTF (var TF: TransFunc);
  PROCEDURE  InverseParseLine(var Poly : MatPtr; TypeChar : char;
                var InputLine : String);
  PROCEDURE  InverseParsePoly(var Poly : Polynomial; TypeChar : char;
                var InputLine : String);
  PROCEDURE  InverseParseTF(var TF : TransFunc; TypeChar : char;
                var InputLine : String);
  PROCEDURE  ParseLine (TheInput: String;  VAR OutMatrix : Matrix;
               AbortCode : Integer);
  PROCEDURE  ParsePoly (TheInput: String;  VAR OutPoly : Polynomial;
               AbortCode : Integer);
  PROCEDURE  ParseTF (TheInput: String;  VAR OutTF : TransFunc;
              AbortCode : Integer);
  PROCEDURE  RetrievePoly (var OldPoly : Polynomial; Stor_Loc: Integer);
  PROCEDURE  RetrieveTF (var OldTF : TransFunc; Stor_Loc: Integer);
  PROCEDURE  StorePoly (var NewPoly: Polynomial; Stor_Loc: Integer);
  PROCEDURE  StoreTF (var NewTF : TransFunc; Stor_Loc: Integer);

  {Polynomial Math Routines}

  PROCEDURE  DefineTFGuts (var NewTF : TFPtr; MakeTFData : MakePolyType;
                TFList : PView);
  FUNCTION   magnitude( omega : extended; num_poly,
               denom_poly : polynomial ) : extended;
  PROCEDURE  PAdd (var PolyA, PolyB, PolyC: Polynomial;
             var AbortCode: Integer);
```

```
PROCEDURE  PDivide (var N1, D1, N1_Simplified, D1_Simplified
                : Polynomial; var Abortcode : Integer);
FUNCTION   phase_angle( omega : extended; num_poly,
                  denom_poly : polynomial ) : extended;
PROCEDURE  PMult (var PolyA, PolyB, PolyC: Polynomial;
               var AbortCode: Integer);
PROCEDURE  PScalarMult (number : extended; var PolyA,
                  PolyB : Polynomial; var AbortCode : Integer);
PROCEDURE  PSubtract (var PolyA, PolyB, PolyC: Polynomial;
                 var AbortCode : Integer);
PROCEDURE  RootCancel (var N1, D1, N1_Simplified, D1_Simplified
                  : Polynomial; var AbortCode : Integer);
PROCEDURE  TFAdd(var TFA, TFB, TFC : TransFunc; var AbortCode:Integer);
PROCEDURE  TFDivide(var TFA, TFB, TFC : TransFunc;
               var AbortCode:Integer);
PROCEDURE  TFMult(var TFA, TFB, TFC : TransFunc; var AbortCode:Integer);
PROCEDURE  TFScalarMult(ANumber : extended; var TFA, TFB : TransFunc;
                  var AbortCode : Integer);
PROCEDURE  TFSubtract(var TFA, TFB, TFC : TransFunc;
                 var AbortCode : Integer);

(*****************************************************************************)

{Unit MRoots}

 PROCEDURE Bairstow(VAR ThePoly: Polynomial; VAR b,c: extended; eps: extended);
 FUNCTION  BrentsMethod(ThePoly: Polynomial; x1,x2,tol: extended): extended;
 PROCEDURE BuildFromRoots(var ReturnPoly : polynomial);
 PROCEDURE EvalThePoly(var ThisPoly: Polynomial; ForThisX: extended; var Ans, dp:
extended);
 PROCEDURE Laguer(VAR a: Root_Poly_Type; m: integer; VAR x: Extended_Complex);
 PROCEDURE LaguerreDriver(VAR ThePoly: Polynomial);
 FUNCTION  NewtRap (var ThisPoly: Polynomial; x1 ,x2 ,xacc: extended): extended;
 PROCEDURE PolDiv(var u: Coeff_Poly_Type; n: Integer; v: Coeff_Poly_Type; nv: Integer; var q,r:
Coeff_Poly_Type);
 PROCEDURE Root_Accuracy (var Poly: Polynomial; var RtErrBound:extended);
 PROCEDURE RootFinder(var ThePoly : Polynomial);
 PROCEDURE SortRoots (var Poly : Polynomial);
```

```
(*****************************************************************************)

{Unit MsgBox}

 { Message box classes }

  mfWarning      = $0000;      { Display a Warning box }
  mfError        = $0001;      { Dispaly a Error box }
  mfInformation  = $0002;      { Display an Information Box }
  mfConfirmation = $0003;      { Display a Confirmation Box }

 { Message box button flags }

  mfYesButton    = $0100;      { Put a Yes button into the dialog }
  mfNoButton     = $0200;      { Put a No button into the dialog }
  mfOKButton     = $0400;      { Put an OK button into the dialog }
  mfCancelButton = $0800;      { Put a Cancel button into the dialog }

  mfYesNoCancel  = mfYesButton + mfNoButton + mfCancelButton;
                       { Standard Yes, No, Cancel dialog }
  mfOKCancel     = mfOKButton + mfCancelButton;
                       { Standard OK, Cancel dialog }

 { MessageBox displays the given string in a standard sized      }
 { dialog box. Before the dialog is displayed the Msg and Params }
 { are passed to FormatStr. The resulting string is displayed    }
 { as a TStaticText view in the dialog.                          }

 function MessageBox(Msg: String; Params: Pointer; AOptions: Word): Word;

 { MessageBoxRec allows the specification of a TRect for the     }
 { message box to occupy.                                        }

 function MessageBoxRect(var R: TRect; Msg: String; Params: Pointer;
  AOptions: Word): Word;

 { InputBox displays a simple dialog that allows the user to     }
 { type in a string.                                             }

 function InputBox(Title: String; ALabel: String; var S: String;
  Limit: Byte): Word;
```

```
(*****************************************************************************)

{Unit MTime}

 PROCEDURE TTime.HandleEvent(var Event: TEvent);
 begin
  TView.HandleEvent(Event);
  If (Event.What = evBroadcast) then
    Case Event.Command of
      brTimePFE        : Begin TTime.PFE;              ClearEvent(Event); end;
      brTimeFOM        : Begin TTime.FigureOfMerit;    ClearEvent(Event); end;
      brTimeEquation   : Begin TTime.Equation;         ClearEvent(Event); end;
      brTimeResponse   : Begin TTime.TimeResponse;     ClearEvent(Event); end;
      brTime2Plot      : Begin TTime.Time2PlotRecord;  ClearEvent(Event); end;
      brcalc_part      : Begin TTime.Calc_Part;        ClearEvent(Event); end;
      brdisp_part      : Begin TTime.Disp_Part;        ClearEvent(Event); end;
      brdirecttimeresp: Begin TTime.Direct_Time_Resp; ClearEvent(Event); end;
      brOutputTimeFile: Begin TTime.OutputTimeFile;   ClearEvent(Event); end;
      brFOM            : Begin TTime.FOM;              ClearEvent(Event); end;
      brOutputSpecFile: Begin TTime.OutputSpecFile;   ClearEvent(Event); end;
    end;{case}
 end;
```

```
(*************************************************************************)

  Assign(polys, 'POLYS.DAT');
     For i := 0 to 9 do begin
        Poly.Name := 'Polynomial ' + Chr(65+i);

(*************************************************************************)

  TFFileName := 'TFS.DAT';
  Assign(TFs, TFFileName);
     For i := 0 to 9 do begin
        TF.Name := TransFuncNames[i];
        TF.Num.Name := TransFuncNames[i] + ' Numerator';
        TF.Den.Name := TransFuncNames[i] + ' Denominator';
   TransFuncNames[0] := 'OLTF';
   TransFuncNames[1] := 'CLTF';
   TransFuncNames[2] := 'GTF';
   TransFuncNames[3] := 'HTF';
   TransFuncNames[4] := 'TF1';
   TransFuncNames[5] := 'TF2';
   TransFuncNames[6] := 'TF3';
   TransFuncNames[7] := 'TF4';
   TransFuncNames[8] := 'TF5';
   TransFuncNames[9] := 'TF6';

(*************************************************************************)

  TFFileName := 'MISO.DAT';
  Assign(TFs, TFFileName);
     For i := 0 to 1 do begin
        TF.Name := TransFuncNames[i];
        TF.Num.Name := TransFuncNames[i] + ' Numerator';
        TF.Den.Name := TransFuncNames[i] + ' Denominator';
  TransFuncNames[0] := 'QFTTRL';
  TransFuncNames[1] := 'QFTTRU';
  TransFuncNames[2] := 'DISTF';
  TransFuncNames[3] := 'LZERO';
  TransFuncNames[4] := 'GCONTR';
  TransFuncNames[5] := 'FILTER';
  TransFuncNames[6] := 'FCTF';
  TransFuncNames[7] := 'QFTTF1';
  TransFuncNames[8] := 'QFTTF2';
  TransFuncNames[9] := 'QFTTF3';
  TransFuncNames[10] := 'QFTTF4';
  TransFuncNames[11] := 'QFTTF5';
  TransFuncNames[12] := 'QFTTF6';
  TransFuncNames[13] := 'QFTTF7';
```

```
  TransFuncNames[14] := 'QFTTF8';
  TransFuncNames[15] := 'QFTTF9';
  TransFuncNames[16] := 'QFTTF10';
  TransFuncNames[17] := 'QFTTF11';
  TransFuncNames[18] := 'QFTTF12';
  TransFuncNames[19] := 'QFTTF13';
  TransFuncNames[20] := 'QFTTF14';
  TransFuncNames[21] := 'QFTTF15';
  TransFuncNames[22] := 'QFTTF16';
  TransFuncNames[23] := 'QFTTF17';
  TransFuncNames[24] := 'QFTTF18';
  TransFuncNames[25] := 'QFTTF19';
  TransFuncNames[26] := 'QFTTF20';

(*****************************************************************************)

  Assign(mats, 'MATRICES.DAT');
     For i := 0 to 9 do begin
        Mat.Name := 'Matrix ' + Chr(65+i);

f(*****************************************************************************)

{How to do a Freq Response}
   FreqData.DataFileName := 'FREQ.DAT';
   Choice := 'FREQ/RESP';
   Message(DeskTop, evBroadCast, brDirectFreqResp, nil);
   {Generate the report file and display it}
   If (ListOrGraph <> 1) then begin
      Assign(Output, 'FREQ.REP');
      Rewrite(Output);
      Message(DeskTop, evBroadCast, brOutputFreqFile, nil);
      Close(Output);
      Assign(Output, '');
      Rewrite(Output);
      fileview('FREQ.REP');
   end;
   {Display the graph}
   if (ListOrGraph > 0) then begin
      Message(DeskTop, evBroadCast, brFreqDisplay, nil);
   end;
```

```
(*****************************************************************************)

{How to do a MultiTime Response}
  TimeData.DataFileName := 'QFTTRUT.DAT';
  Choice := 'TIME/RESP';
  Message(DeskTop, evBroadCast, brDirectTimeResp, nil);
  If (ListOrGraph <> 1) then begin
    option := 'QFTTRU';
    Message(DeskTop, evBroadCast, brOutputTimeFile, nil);
  end;
  {Now do the Figures of Merit}
  Message(DeskTop, evBroadCast, brFOM, nil);
  If (ListOrGraph <> 1) then begin
    Message(DeskTop, evBroadCast, brOutputSpecFile, nil);
    Close(Output);
    Assign(Output, '');
    Rewrite(Output);
    fileview('TIMESPEC.REP');
  end;
  if ListOrGraph > 0 then begin
    PlotData.NumPlot := 2;
    TimeData.DataFileName := 'QFTTRUT.DAT';
    PlotData.DisplayCount := 1;
    Message(DeskTop, evBroadCast, brTime2Plot, nil);
    PlotData.LastPlot := FALSE;
    Message(DeskTop, evBroadCast, brplot_display, nil);
    TimeData.DataFileName := 'QFTTRLT.DAT';
    PlotData.DisplayCount := 2;
    Message(DeskTop, evBroadCast, brTime2Plot, nil);
    PlotData.LastPlot := TRUE;
    Message(DeskTop, evBroadCast, brplot_display, nil);
  end;

(*****************************************************************************)
```

Appendix E QFT Toolbox User's Manual

ICECAP - PC

Version 10.0 - MS-DOS

Interactive **C**ontrol **E**ngineering **C**omputer **A**nalysis **P**ackage
for the **P**ersonal **C**omputer

QFT TOOLBOX

Quantitative Feedback Theory (QFT)

User's Manual v 2.0

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PREFACE

WELCOME to the QFT Toolbox of ICECAP-PC. This Toolbox includes both multiple-input multiple-output (MIMO) and multiple-input single output (MISO) models in both continuous and discrete domains. ICECAP-PC is an ongoing development of a public domain computer-aided design (CAD) package for students, faculty and practitioners of control engineering and digital signal processing with special emphasis on education. Source code and executable files are available. If you are interested in adding additional code or have suggestions for improvement please contact:

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cooperative copyright (C) 1985, 1986, 1987, 1988, 1989, 1990,1991,1992 Gary B. Lamont, Susan K. Mashiko, Gary C. Tarczynski, D. Gelopulos, Paul A. Moore, Wayne E. Bell, Vincent M. Parisi, Fred Trevino, Mark W. Schiller, Ken A. Crosby

This public domain QFT-CAD package is intended for the main purpose of education and thus the executable code can be distributed freely. Any use of the package in support of written publications should be indicated as a reference. Changes to the public domain source code that improve and extend its capabilities are appreciated, however, all suggested changes should be communicated to the authors for updating and dissemination of the next official version.

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ICECAP-PC is written in Borland's$_{tm}$ Turbo PASCAL 6.0 and TurboVision, both of which are registered trademarks and copyrighted by Borland International, Inc. 1800 Green Hills Road, P.O. Box 660001, Scotts Valley, CA 95067-0001. The .BGI files distributed with our package are released to public access by Borland.

All references to MS-DOS in this document refer to Microsoft-DOS which is a registered trademark and copyrighted by MicroSoft$_{tm}$ Corporation.

QFT Notation as used in ICECAP-PC is consistent with [Houpis, 1992c].

SYSTEM REQUIREMENTS

ICECAP-PC is designed to work on MS-DOS$_{tm}$ 80286/80386/80486 computers with a minimum of 640 KB of RAM and 5MB of hard disk space. ICECAP-PC supports all graphics terminals including Hercules$_{tm}$, EGA and VGA. Operation is greatly enhanced with expanded memory and a math co-processor. Installation of ICECAP-PC and its QFT Toolbox is done automatically with a provided install procedure (see ICECAP-PC manual).

Edited By: Gary B. Lamont , Wayne E. Bell, and Fred Trevino; 1992

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1 Introduction

One objective of ICECAP-PC, as well as its associated toolboxes, is to provide a 4th generation language (4GL) interface for control engineering students and practitioners. This 4GL interface allows ICECAP-PC's functions and operations to be used as an end product within its window-based desktop environment, or as an object-oriented macro language for new user products called toolbox extensions. The window-based desktop interface provides pull-down menus, speed-buttons, mouse support, *hot keys* and on-line, context-sensitive HELP, all of which combines to make ICECAP-PC very user friendly as well as effective!

ICECAP-PC and the QFT toolbox was developed using Borland's$_{tm}$ object-oriented TurboVision language (a 4GL) under Turbo Pascal. Top pull-down menu selections produce dialog boxes from which the user defines an operation. The pull-down menu is always accessible providing a truly *event-driven* and nimble interface. System parameters are quickly modified with recall of past inputs providing efficient interactive analysis and synthesis of the controller. The QFT toolbox is invoked from the ICECAP-PC main menu by selecting either the *Toolbox - MIMO QFT* or *Toolbox - MISO QFT* menu options.

The overviews of the MIMO and MISO model QFT design techniques are presented in the following chapters. For supporting theoretical studies please consult references. Note that ω is used in place of $j\omega$ simply to keep equations less cluttered. A complete design example is given at the end of the manual.

2 The MISO QFT Toolbox

2.1 The MISO QFT Problem

Consider designing a practical, linear, time-invariant feedback controller for a plant model with uncertainty in parameter and disturbance. The QFT method, developed by Dr Isaac Horowitz, quantitatively defines the problem in the form of (1) a set {P} of possible plants, (2) sets $\{T_R\}$ of acceptable command or tracking input/output relations, and (3) sets $\{T_D\}$ of acceptable disturbance input/output relations. The design objective is to guarantee that the control ratio, T_R= **Y/R**, is a member of $\{T_R\}$ for all P in {P}. Although this technique can be used for a variety of system structures, ICECAP only emphasizes structured uncertainty including non-minimum phase models.

The QFT design (QFD) approach is a frequency domain technique that provides robust performance despite plant uncertainties and disturbances. The general model has three inputs: a tracking input **R**(s), a plant disturbance D_1 and a measurement disturbance D_2 as shown in **Figure 1**.

ICECAP-PC currently handles only the case of plant disturbance D_1. **P** is the symbol for

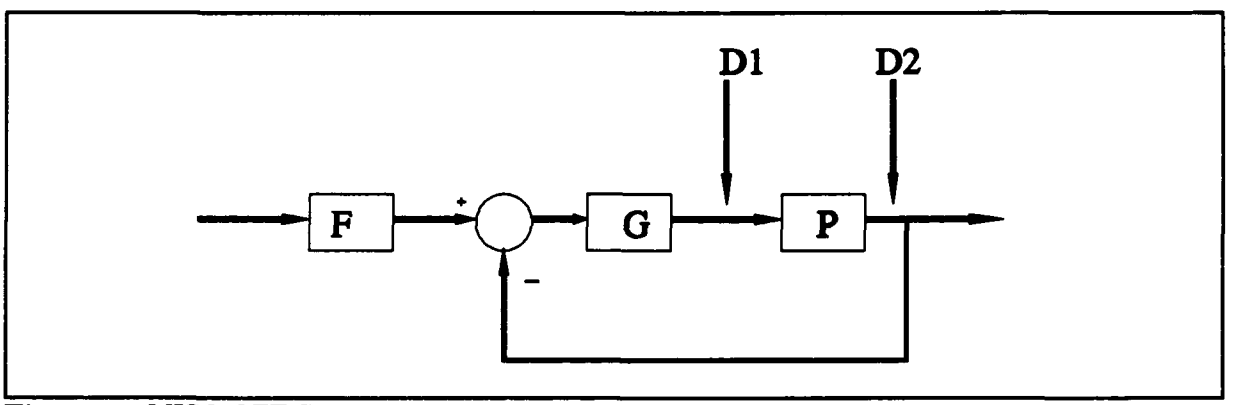


Figure 1: MISO QFT System

the plant matrix, **G** is the compensator to be designed and **F** is a pre-filter that also requires design. **L = GP** is defined as the loop transmission (open-loop transfer function). If only **G** as a design parameter is available, it is called a single degree of freedom control loop. If **F** is added, two degrees of freedom are available. Thus, the QFT method is a two degree of freedom design.

This approach has sufficient generality for modelling a variety of systems. The closed-loop transfer function for a tracking input is by definition

$$T_R(s) = \frac{FGP}{1 + GP} = \frac{FL}{1 + L} \tag{1}$$

$$L = PG \text{ is Loop Transmission}$$

To design a controller, various closed-loop performance bounds are specified which must be satisfied for all plant variations. The various specifications are generally given in terms of the frequency responses of tracking and disturbance transfer functions. So to begin the design, ICECAP accepts four categories of design specifications: a plant variation model, tracking specifications, stability specifications, and disturbance specifications. Each of these are introduced in the following.

2.1.1 Plant Model Specifications. Due to Plant Uncertainty, there is a set {P} of plants. Consider, for example, a second-order plant model with the following variations:

$$P = \frac{k}{As^2 + Bs + C}$$
$$\begin{aligned} A &= [1\text{-}4] \\ B &= [2\text{-}6] \\ C &= [10\text{-}20] \\ k &= [50\text{-}84] \end{aligned} \tag{2}$$

The set {P} of plants consists of all possible combinations of plant variations which could be a very large number of specific plants.

2.1.2 Tracking Specification. The closed loop tracking transfer function for plant P_j is given by

$$\delta_r(\omega) = B_U(\omega) - B_L(\omega) \tag{3}$$

where all T_{Rj} responses (one for each plant) must lie between the $B_U$and $B_L$specifications and where the maximum tracking error is defined as [D'Azzo, 1988:429, 692] There are two methods of deriving δ_R. In the first method, the time domain tracking specifications (M_p-max, M_p-min, T_s-max, T_s-min, etc.) lead to two transfer functions, T_{RU} and T_{RL}, which describe the upper and lower bounds permitted in both time and frequency domains. δ_R is then defined as the difference between the frequency responses $\delta_R = B_U(\omega) - B_L(\omega) = T_{RU}(\omega) - T_{RL}(\omega)$. In the second method, $B_L(\omega)$ and $B_U(\omega)$ are input directly in the frequency domain as a set of data points.

Successful QFT design is enhanced if $\delta_R(\omega)$ monotonically increases with frequency. Using the augmented model [D'Azzo, 1988:693], this is accomplished for high frequencies by adding a zero to T_{RU} and a pole to T_{RL} at ω_h.

If the MISO tracking relationships are part of a larger MIMO problem, the allowable operation area between the tracking bounds B_U and B_L must be constricted to account for the tracking responses of other plant elements modeled as disturbance inputs to the MISO loop. Currently, this is done manually off line and is not addressed directly in ICECAP-PC.

2.1.3 Stability Specifications (Phase Margin, Gain Margin). The constraint on the distance from the -1+j0 point is given by [Yaniv, 2; D'Azzo, 309]

$$|1 + GP_j| \geq x \tag{4}$$

where $x \leq 1$ is a chosen parameter. A larger x for a given frequency results in a smaller steady state sinusoidal error. Another parameter, chosen to reduce the oscillatory nature of the design, is given by: [D'Azzo, 1988:312]

$$\left|\frac{GP_j}{1 + GP_j}\right| \leq y \tag{5}$$

For an equivalent second order system, larger values of y result in smaller values of zeta. Note that y is not equivalent to M_m because **F** is not being considered yet.

These equations relate to the desired gain margin, phase margin, maximum magnitude and M_L contour (Nichols plot) as given by the following.

$$\begin{aligned} gm &= \frac{1}{1 - x} \\ \gamma &= 180° - 2\cos^{-1}\left(\frac{x}{2}\right) \end{aligned} \tag{6}$$

Given a set {P} of all possible plants, the stability specifications describe the region in the frequency domain that none of the plants P in {P} should violate. In the QFT design technique, the set of {P} plants form a frequency domain template, or a region of possible responses over the parameter variation range. All plants P in {P} must remain outside the stability margins in the QFT design. Phase margin (γ), gain margin (gm), maximum magnitude (M_m), and M_L contour are all mathematically related and each can be derived from the other for a second order or equivalent second order system as shown in **Equation (7)**.

2.1.4 Disturbance Specification. The disturbance transfer functions for the two disturbance inputs of **Figure 1** are given by the relations of **Equations (8) and (9)**. [D'Azzo, 1988:446] $T_D(\omega)$ is the upper disturbance bound defined in the specifications. Recent QFT designers have begun to define $T_D(\omega)$ as a constant (i.e -20db) rather than a transfer function. Using a constant allows for both easier and more conservative design.

Plant Disturbance D_1

$$\begin{aligned} T_{D_{1_j}} &= \frac{P_j}{1 + L_j} \quad \forall P_j \in \{P\} \\ \left| T_{D_{1_j}}(\omega) \right| &< \left| T_D(\omega) \right| \end{aligned} \tag{8}$$

$$gm = -20 Log_{10} \frac{M_m}{1 - M_m}$$

$$M_L = 20 Log_{10} \frac{10^{-\frac{gm}{20}}}{1 + 10^{-\frac{gm}{20}}} \tag{7}$$

$$M_p \approx M_m = e^{\frac{Ln 10 M_L}{20}} = \frac{10^{-\frac{gm}{20}}}{1 - \frac{gm}{20}}$$

$$\gamma = 180° - \cos^{-1}\sqrt{1 - 10^{-\frac{M_L}{10}}}$$

Measurement Disturbance D_2

$$T_{D_{2_j}} = \frac{1}{1 + L_j} \quad \forall P_j \in \{P\} \tag{9}$$

$$\left| T_{D_{2_j}}(\omega) \right| < \left| T_D(\omega) \right|$$

2.2 *The MISO QFT Design Process*

As mentioned previously, the objective of the QFT technique is to find a **G** and **F** to guarantee that the closed-loop response is within prescribed limits of the various bounds despite plant uncertainty and disturbance inputs as represented in the set notation. The ICECAP-PC QFT package closely follows the design procedure specified by Dr Horowitz and Dr Houpis. [Horowitz, 1981; D'Azzo, 1988:728]. This procedure is summarized as follows:

1. Synthesize upper and lower tracking response transfer functions $\mathbf{T}_{RU}$ and $\mathbf{T}_{RL}$ to meet minimum and maximum specifications.
2. Synthesize the upper disturbance response transfer function $\mathbf{T}_D$
3. Define a set of plants $\{P_j\}$ from all possible $\{P\}$ such that the frequency response of the set $\{P_j\}$ defines the perimeter of all possible frequency responses of $\{P\}$.
4. Select a representative nominal plant P_o from the set $\{P_j\}$. Normally, the best selection is the plant which represents the lower-left point (most negative angle, smallest magnitude) of the template as seen on a Nichols chart.
5. Determine the disturbance bounds $\mathbf{B}_D(\omega)$ on the loop transmission $L_0(\omega)$.
6. Determine the tracking bounds $\mathbf{B}_R(\omega)$.
7. Define the composite bounds as the most restrictive of the bounds determined in steps 6 and 7.

8. Design the loop transmission $L_0(\omega)$ for the nominal plant $P_0(\omega)$ to meet, as closely as possible, the composite bounds determined in step 7.
9. Synthesize the prefilter $F(\omega)$.
10. Simulate system behavior to verify correct design.

At the conclusion of the design process, a formatted report is available upon user request. This is an ASCII text file containing all pertinent design process results. The file is easily edited with any number of text editors. Note that the editor integrated into ICECAP-PC will not open the file because this simple editor is limited to files smaller than 64K.

ICECAP-PC QFT allows one to access the various phases of design (File, Specs, Plant, Disturbance, Templates Bounds, L-Zero, Filter, Simulation) through pull down menus. **Figure 2** shows the MISO QFT toolbox menuing system. It is similar to that of the main ICECAP-PC program.

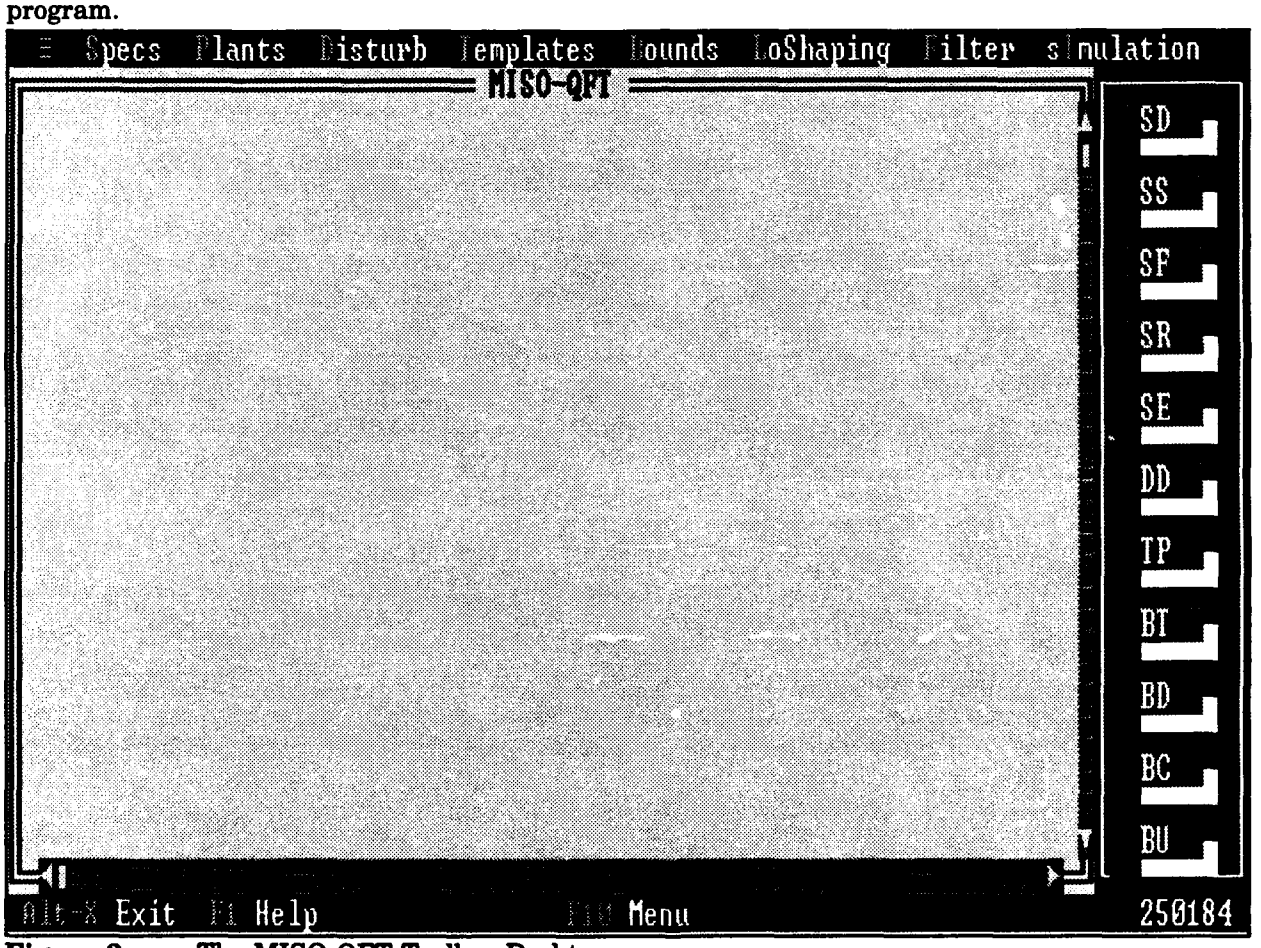


Figure 2 The MISO QFT Toolbox Desktop

The various menu items, corresponding to the high-level design steps, are initiated by using the arrow keys, mouse or control keys. For example, the introductory menu can be accessed by pressing the first letter of the desired menu selection. For example, the **SPECS** menu is pulled down by **S**. **F1** or the right mouse button displays a window with help information at the selected level. Although a detailed step-by-step example could be provided, the use of the keys or mouse is self-evident. The QFT MISO example in **Chapter 3** details each step of the design process as implemented in the ICECAP-PC QFT Toolbox.

Note that during the design process, it is helpful to develop a commented log file of the unfolding design. ICECAP-PC provides this capability allowing the user to open a text log file and enter comments at any point of the design. This would be separate from the **REPORT** option found at the end of the design process.

2.2.1 File Operations. ICECAP-PC data files are generated and stored in binary format allowing rapid access to large amounts of data. On the other hand, all output files such as time and frequency response data, etc. are stored in ASCII form to allow easy interface to other graphics programs. Additionally, ICECAP-PC will soon be able to read ASCII files generated from other popular engineering programs. Such files will be checked for proper structure before the import process begins. ICECAP-PC sessions can be saved and recalled by user defined names thus returning the engineer to the place he left off during an interrupted design process. At the end of the design process, a printed report of the file contents presents the complete design record. Also of importance is the ability of the MISO QFT toolbox to read the separate MISO loop files created by the MIMO toolbox. These files are opened as sessions within the MISO toolbox.

2.2.2 QFD Specifications. Three operational domains are available consisting of the continuous and discrete domains (s, z and w). Specifications in each case are defined in either the time domain or frequency domain.

A priori synthesized tracking specifications can either be input as s-plane transfer functions or frequency domain data. For transfer function input, the upper tracking function bound ($\mathbf{T}_{RU}$) and the lower tracking function bound ($\mathbf{T}_{RL}$) are interactively synthesized or manually entered using the standard ICECAP-PC transfer function input. Transfer functions, in general, are entered in one of two forms: factored (gain, zeros and poles) or polynomial (gain and coefficients). The time domain ($\mathbf{T}_{RU}$, $\mathbf{T}_{RL}$) or frequency domain specifications ($\delta_R(\omega)$) can be presented in a table or in graphical form as requested. The frequency domain data can be directly entered as magnitude limits (max and min) vs. frequency.

Selection from the **SPEC** pull-down menu, **Figure 3**, produces a palette of options, each of which result in a dialog box that defines specific actions. The options include system domain (s, z, or w), time-domain or frequency domain tracking and disturbance specification input.

2.2.2.1 Time Domain Tracking Specifications. Enter $\mathbf{T}_{RU}(s)$ and $\mathbf{T}_{RL}(s)$ bounds for step response tracking operations. Usually these bounds are defined in terms of transfer functions that are synthesized from time domain specifications such as rise time, settling time, overshoot (the conventional figures of merit). Alternately, you may synthesize the bounds interactively with the QFT toolboxes.

2.2.2.2 Frequency Domain Tracking Specifications. Enter $\mathbf{T}_{RU}(\omega)$ and $\mathbf{T}_{RL}(\omega)$ bounds for the frequency range of interest. These usually are generated in transfer function. $\delta_R(\omega)$ is the difference between $\mathbf{T}_{RU}(\omega)$ and $\mathbf{T}_{RL}(\omega)$. It is desirable that $\mathbf{T}_{RU}$ and $\mathbf{T}_{RL}$ be synthesized such that δ_R increases with frequency after $\mathbf{T}_{RU}$ crosses the 0 dB line. An increasing δ_R permits an effective high frequency design technique. δ_R can also be found from a given set of lower, $\mathbf{B}_L(\omega)$

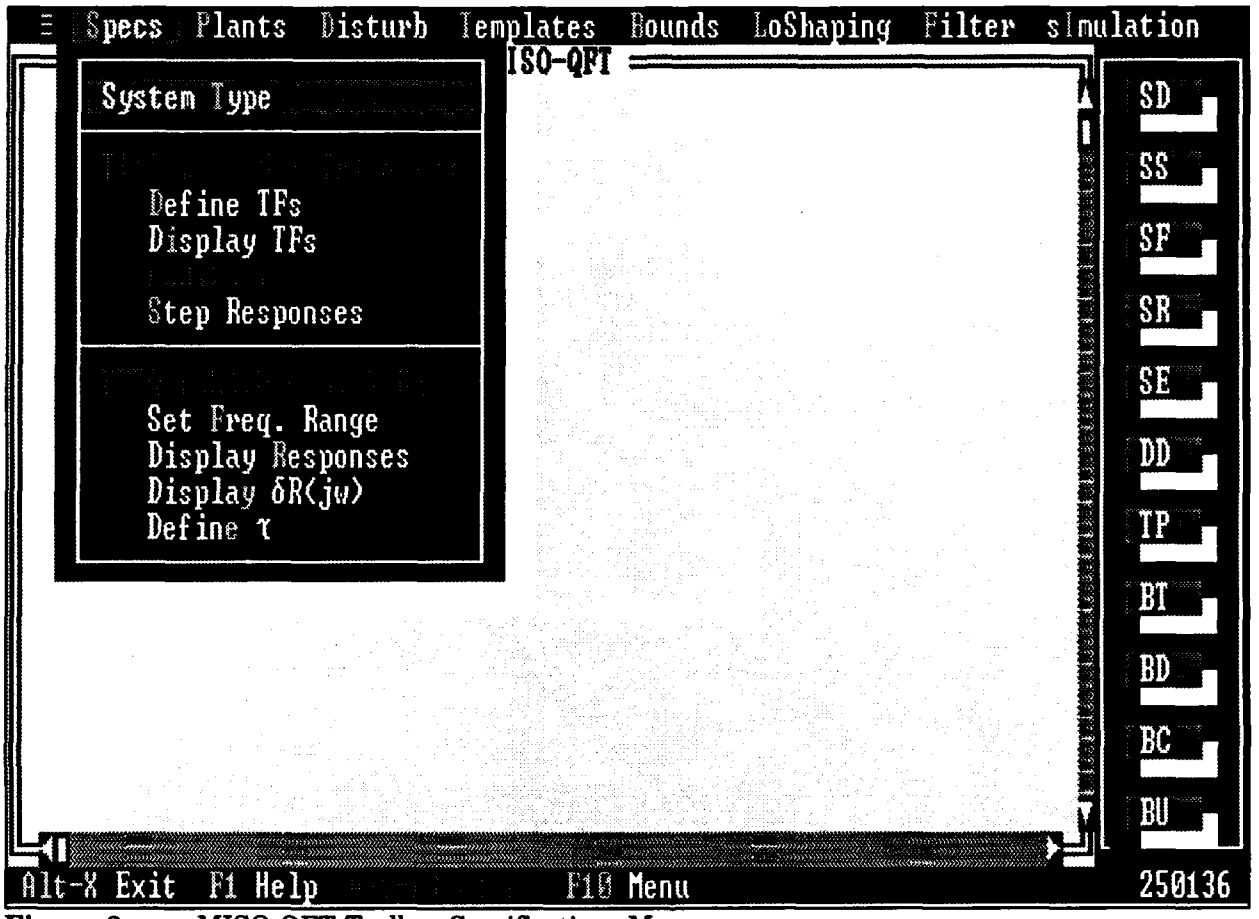


Figure 3 MISO QFT Toolbox Specifications Menu

and upper, $\mathbf{B}_U(\omega)$, bounds which are given for a finite number of frequencies [See **Equation (3)**]. Two other values that need consideration are the frequency at which $\mathbf{B}_U(\omega)$ is -12dB (ν_{hR}) and the frequency at which $\mathbf{B}_U$ crosses the 0 dB line (ν_{zR}).

The discrete frequencies chosen are at the user's discretion. Normally the frequency range of interest is defined by the region two octaves below ν_{zR} and two octaves above ν_{hR}. Inside of this region, frequencies are normally chosen an octave apart. The magnitudes are entered in dB and frequencies in rad/sec. For ultra-high frequencies, see Section 4.2.

2.2.2.3 Stability Bound Specifications (Phase & Gain Margin). Stability bounds are entered in one of three ways. Since stability bounds (phase margin, gain margin, tangent M_L contour, and peak overshoot) are mathematically related, entry of any one initiates automatic computation of the others. Entry of phase margin, peak overshoot, and tangent M_L contour is allowed, however computation of these three from a given gain margin is error prone since phase margin is very sensitive to changes in gain margin. Therefore entry of gain margin is not provided.

2.2.2.4 Disturbance Specifications. The disturbance specifications can also be input as a synthesized transfer function but usually are defined as a constant magnitude bound

(dB) or $|T_D(\omega)|$ in the frequency domain for the plant disturbance and for the measurement disturbance. Entry of disturbance bounds are done exactly as the tracking bounds.

2.2.3 Plant Model Descriptions. Plant model parameter variations can be entered in four ways:

1. Individual Models - plant TFs encompassing the variations are entered separately.
2. Variation Models -
   (a) Nominal plant tf and parameter coefficient variations are entered.
   (b) Nominal plant tf and parameter pole/zero/gain variations are entered.
3. Plant Frequency Domain Models - frequency domain data is entered for each specified plant. (in progress)

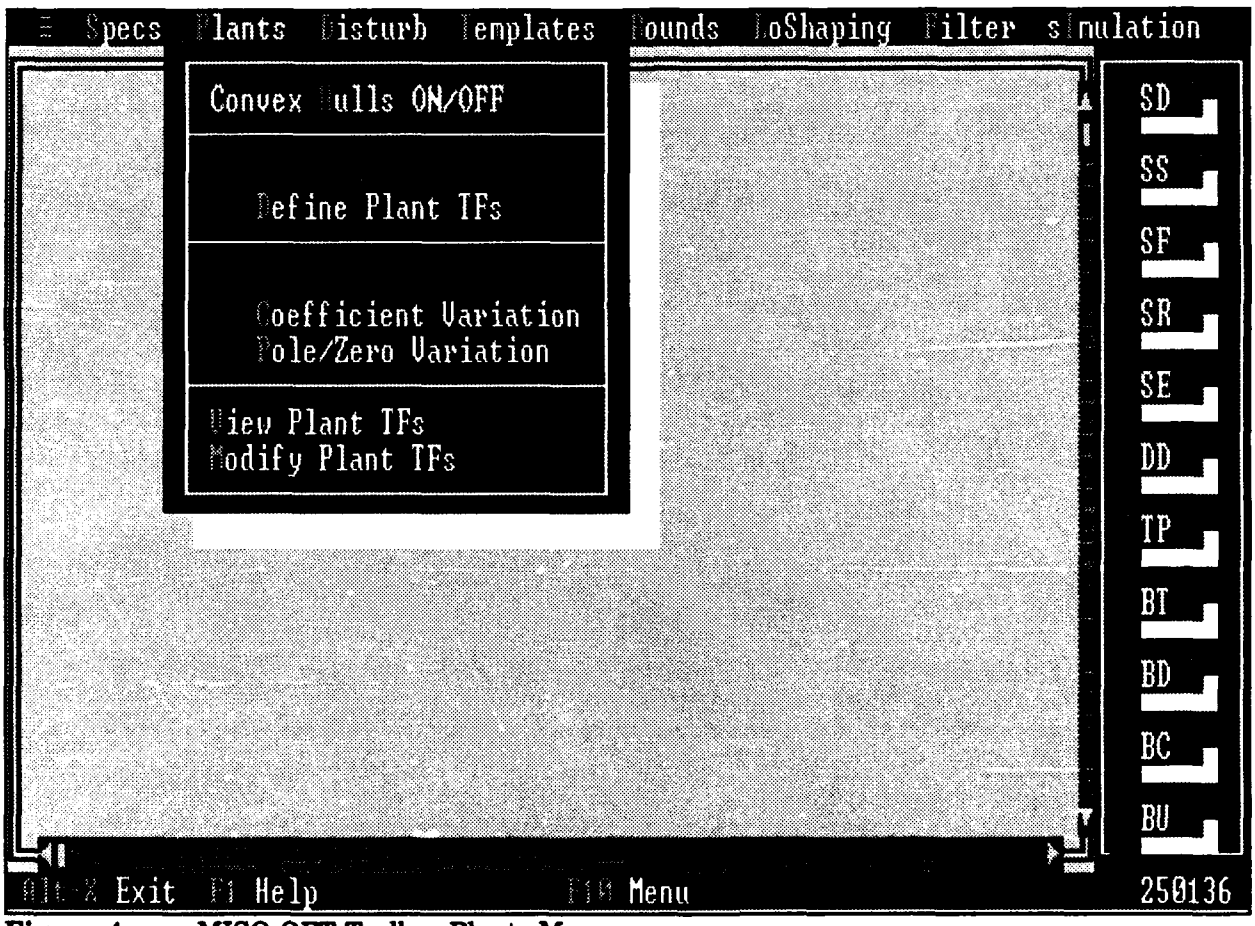


Figure 4 MISO QFT Toolbox Plants Menu

As can be seen from **Figure 4**, currently the first two methods are available within ICECAP_PC. With approach (1), the number of plants is first defined and then each plant is entered separately by specifying the gain and the zeros and poles in factored or unfactored form using the standard ICECAP-PC input dialogue (order,gain, pole/zero-factored or coefficients-polynomial). Each plant transfer function can be displayed and checked for proper entry. Although not yet implemented, the user will have the ability to import plant models from external ASCII files in a future release.

Approach (2a) requests the entry of the maximum and minimum for each numerator and denominator coefficient. Currently the number of possible parameter variations is limited to four because of memory size.

Approach (2b) requests the variation (max,min) in each zero, in each pole and in the plant gain. The user is requested to answer the following question concerning the polynomial form: "Do you desire the transfer function roots (zeros/poles) to be represented as [s/a +1] or [s+a] for real roots or as $[s^2/(a^2 + w^2) + 2as/(a^2 + w^2) + 1]$ or $[s^2 + 2as + a^2 + w^2]$?"

Observe that a user of this package can build a program that uses symbols to characterize the coefficients or roots of the transfer function as related to some physical model. These symbols can then be instantiated with specific values to generate the specific plants. In this way, the QFT toolbox could be used to interactively design controllers for a variety of models in a given application (automotive spring control, engine control, vehicle control, etc.).

2.2.3.1 Plant Transfer Function Models. First enter the number of plants to be input (note that the 'tab' function highlights each section of the window). The plants are then entered using the standard ICECAP-PC transfer function input dialog (num order, denom order, num gain, zeros, denom gain, poles) for each factored form.

2.2.3.2 Plant Parameter Variations. A nominal transfer function is entered with nominal parameters. The number of plant variations is requested. Then the positive variation of each parameter (gain, zero, pole or coefficient) is entered in turn. The variation could be thought of as a uniform or a normal distribution. Depending upon the number of plants requested, a finite number (<= 625) of plant cases are defined.

2.2.4 Disturbance Models. Plant disturbance models are entered using the standard ICECAP-PC format. The measurement disturbance model is not yet implemented. Gain is entered in real units not db.

2.2.5 Plant Template Generation. Because of plant uncertainty there exists a set of complex numbers $\{P(\omega)\}$ for any frequency ω which are defined as *plant templates*. If individual plants are entered, then the package generates all the frequency domain points for each plant at a given frequency. This data is then sorted by frequency to develop templates of uncertain plant response. The graphical structure of each template (one at each frequency) can also be displayed on the Nichols chart.

If the plant variation ranges are entered, then the package generates a *convex hull* around all the frequency domain points and selects only those point on the boundary of the hull for representing the templates. This process reduces the number of plants since the maximum number of possible plants using the variation method is 625. This hull or template can also be displayed as a table or graphically on the Nichols chart.

2.2.6 Bounds. The tracking and disturbance bounds are generated in a similar manner. However, in most cases, the disturbance bounds are generated from the disturbance

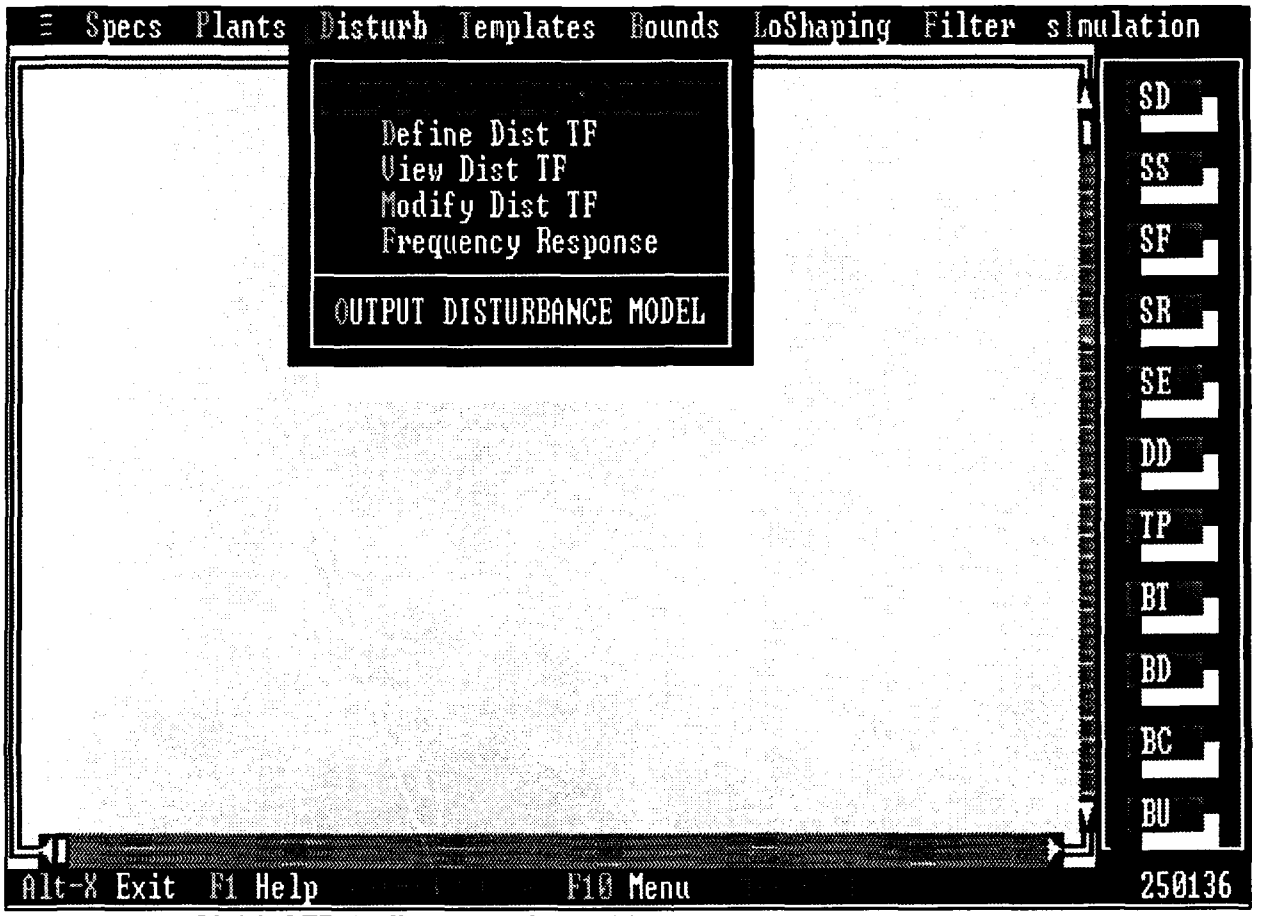


Figure 5 MISO QFT Toolbox Disturbance Menu

specification of a constant over all frequencies. Various templates are usually generated for discrete values of frequency ω an octave apart. From the templates,the tracking bound $\mathbf{B}_R(\omega)$ and disturbance bound $\mathbf{B}_D(\omega)$ are generated. From $\mathbf{B}_R(\omega)$ and $\mathbf{B}_D(\omega)$, a composite or optimal bound $\mathbf{B}_o(\omega)$ is generated.

2.2.6.1 Tracking Bounds Generation. From the templates,the plant bound $\mathbf{B}_R(\omega)$ and disturbance bound $\mathbf{B}_D(\omega)$ are generated using a selection of two methods (manual, automatic). The manual process of graphically determining the $\mathbf{B}_R(\omega)$ bound on the loop transmission is accomplished using the following steps which involve the movement of the various plant templates and the selection of a nominal plant:

1. Translate (do not rotate) the plant template for a specific frequency ω to a major angle division on the Nichols chart.
2. Using the constant M contours on the Nichols chart determine the max and min values of $\mathbf{T}_R(\omega)$ corresponding to the max and min values of M covered by the template, where $\delta_M(\omega)$ = max M - min M.

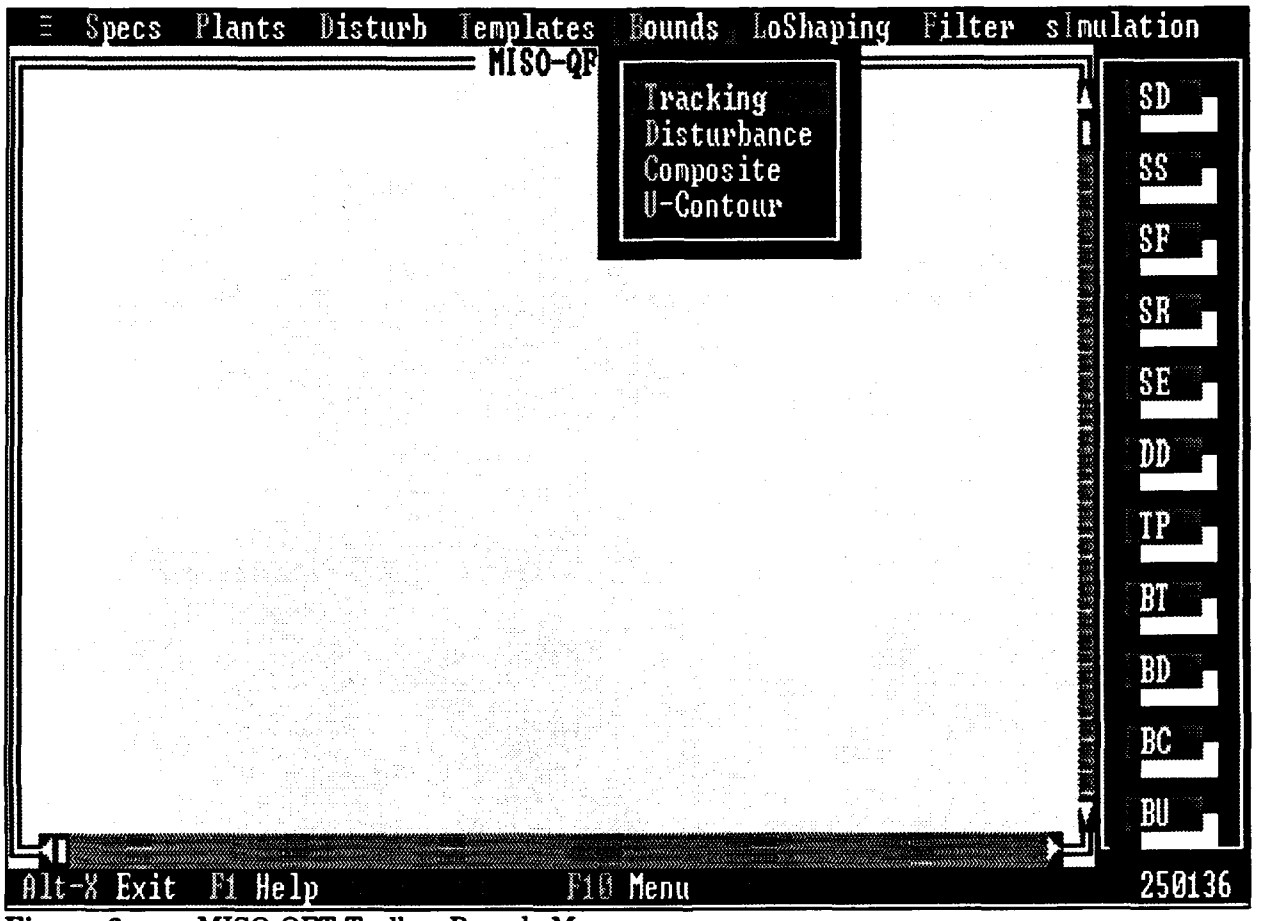


Figure 6 MISO QFT Toolbox Bounds Menu

3. Move the template vertically up and down the Nichols chart until the difference, $\delta_M(\omega)$, is equal to $\delta_R(\omega)$. At that point the position of the nominal plant is a point on the bound $\mathbf{B}_R(\omega)$. Usually the nominal plant is selected as the lower left point of the template for each frequency. Thus, for the specific frequency this point position represents the bound of plant performance in order to meet the specifications.
4. Translate the template to the next major angle division and repeat step 2 until the template becomes tangent to the U-contour.
5. Draw a point through all points to construct $\mathbf{B}_R(\omega)$, the tracking bound on $L_0(\omega)$, for the specific frequency ω.
6. Repeat steps 1 to 5 for a discrete number of frequencies over the frequency band of interest.

The above algorithm for generating $\mathbf{B}_R(\omega)$ is what has been implemented in this QFD - CAD package for the automated process (note that this is the same algorithm implemented in the original VAX ICECAP QFT package).

An educational interactive $\mathbf{B}_R(\omega)$ generation mode is also available using movable templates on the Nichols Chart. Templates are entered for Nichols Chart display as tp#.dat. Template movement is possible with the use of the arrow keys. δ_R and δ_m are displayed so that the student can move the template to the point where $\delta_R \le \delta_m$. Points on the $\mathbf{B}_R(\omega)$ curve at a given frequency are stored with the press of the 'insert' key. The 'return' key provides exit from interactive bounds generation.

2.2.6.2 Disturbance Bound Generation. The plant disturbance bound $\mathbf{B}_D(\omega)$ is determined by finding the minimum value of $L_0(\omega)$ that satisfies the following relation:

$$\left|\frac{P_0(\omega)}{\delta_3(\omega)}\right| < \left|\frac{P_0(\omega)}{P(\omega)+L_0(\omega)}\right| \qquad \textbf{Eq 10}$$

across the range of plant uncertainty embodied in $P(\omega)$. The tracking bounds can be listed and graphed.

For the measurement disturbance the associated disturbance bound is found from the inequality using basically the same method:

$$\left|\frac{P_0(\omega)}{\delta_3(\omega)\cdot P(\omega)}\right| < \left|\frac{P_0(\omega)}{P(\omega)+L_0(\omega)}\right| \qquad \textbf{Eq 11}$$

2.2.6.3 Composite Bound Generation. The combined or composite bound $\mathbf{B}_o$ is generated by comparing the tracking and disturbance bounds and defining the highest boundary at each major angle division for a select number of frequencies which are an octave apart. All bounds can be displayed on a Nichols chart for the synthesis of L_0 in the next step. See Section 4.2 for information on the U-Contour.

2.2.6.4 U-Contours for Ultra-High Frequency. To help ensure that the synthesized loop transmission L_0 does not yield unstable roots or stable roots of the closed loop system close to the imaginary axis, an additional constraint is imposed. This constraint is expressed as $|\mathbf{L}/(1 + \mathbf{L})| < M_L$ (the $\delta_2(\omega)$ constant) for all ω and all plant variations. In some cases this results in an *ash can* structure. The synthesized loop transmission must not penetrate this region on the Nichols chart.

The U-Contour or ultra-high frequency bound (UHFB) can be displayed in a table, graph and Nichols chart for the desired frequency range. It is based upon the desired phase angle and the maximum variation of magnitude at high frequencies.

2.2.7 Loop Transmission Design. In order to develop the loop transmission, the Loop transmission, L_0, can be generated using a variety of techniques: manual, interactive, or automatic. The *loop shaping* is accomplished by keeping the value of $L_0(\omega)$ above the composite bound $\mathbf{B}_o$ at each distinct frequency while not violating the U-contour.

Currently, no CAD algorithm for completely automated design has been implemented. An initial L_0 is selected and then modified by adding zeros and poles to meet the above criteria. A

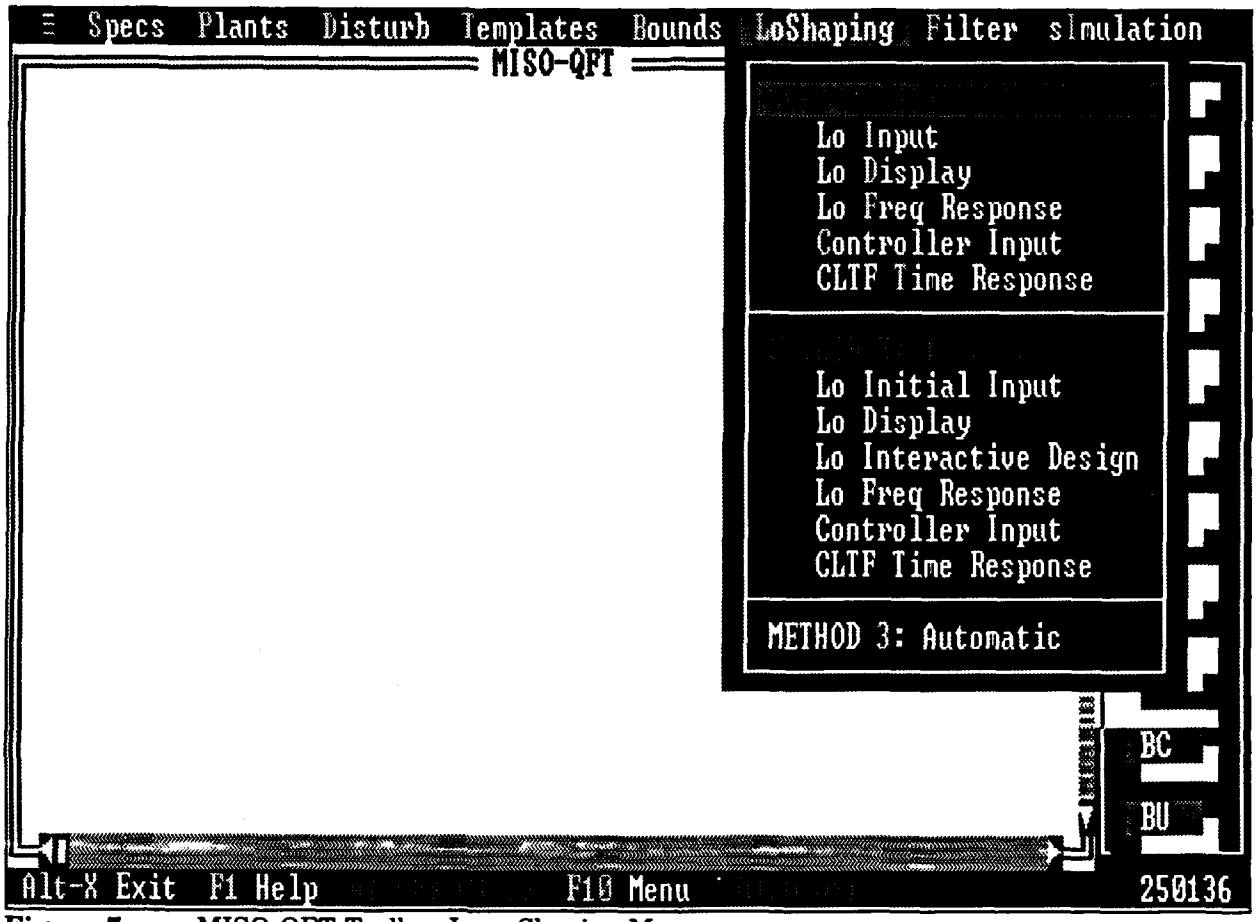


Figure 7 MISO QFT Toolbox Loop Shaping Menu

good initial L_0 is the nominal plant P_0 itself. Using the nominal plant results in a minimum order controller. The nominal plant is normally selected as the plant in the lower left corner of the templates on the Nichols chart. Although, any plant--even a different one from the set of plant variations--may be chosen.

2.2.7.1 Loop Transmission - Manual Design. The controller can be designed manually using the Nichols chart and the resulting transfer function entered as indicated. This is accomplished by fitting a curve between the composite bounds and the specific M_L contour specified by the stability criteria on the Nichols chart. If the designed controller satisfies the bounds, then the closed-loop system output should be within the tracking tolerances as well as reject the disturbances within the required specification. This performance requirement can be analyzed by doing a closed-loop time or frequency domain analysis of the design. If not within specifications then a filter (prefilter) must be designed (step 8).

The designer inputs the L_0, the loop transmission transfer function from the manual design process. The manual design process consists of starting with an initial form such as plant P_0. Then determining if it meets the bound specifications. This is easily accomplished by either using a Nichols chart or a Bode diagram. In a Bode diagram, the composite bounds, $\mathbf{B}_0(\omega)$, give the

necessary magnitude and angle conditions for which L_0 must be designed. Overdesign is minimized by placing L_0 as close as possible to the bound. Zeros and poles are added to $L_0(\omega)$ in order to meet and approach the composite bound. The U-contour corresponds to the phase margin bound on the Bode diagram while the composite bound $\mathbf{B}_o(\omega)$ on the Nichols chart defines the amplitude bound.

2.2.7.2 Loop Transmission - Interactive Design. After entering an initial $L_0(\omega)$, additional poles and zeros are added interactively. After each addition/subtraction of poles and zeros, an updated graph is generated. A recommended process is to locate the frequency at which the worst violation of the $\mathbf{B}_o(\omega)$ bounds occurs. After finding this frequency, install one zero in $L_0(\omega)$ for each 12 dB of violation at a frequency 1 octave (approx) below the violation frequency. An equal number of poles also needs to be installed 1 octave below this frequency to offset the zeros. Repeat this process until the $\mathbf{B}_o(\omega)$ bounds are met while remaining outside and in close proximity to the U-Contour to achieve minimum overdesign.

Poles are entered with 'shift p' and zeros are entered with 'shift z' commands. Entering the 'return key' updates the Nichols chart with the new poles and zeros and stores the data to file. Use of the 'esc key' exits the procedure.

2.2.7.3 Loop Transmission - Automated Design. An automated design of loop transmission is under current development. This process will provide the necessary tools for the user to define a desired $L_0(\omega)$ at a distinct set of frequencies, a loop transmission order constraint, and a cost function such as a weighted least squares solution. The optimization process generates the transfer function coefficients that minimize the cost function.

2.2.7.4 The Controller. From L_0 and the nominal plant, the compensator **G** is generated from the equation $L_o = G * Po$. This **G** is then employed as the robust controller. The CLTF time responses can be generated for checking the design.

2.2.8 Filter Generation. The design of the controller **G** only guarantees the frequency responses for any given P in {P} lies within a δ_R without regard to the actual position of δ_R in the frequency domain. A prefilter translates the magnitude progression to lie between $\mathbf{B}_U$ and $\mathbf{B}_L$ frequency responses [D'Azzo, 1988:725].

In order to meet the original tracking frequency specifications for $\mathbf{T}_R(\omega) = \mathbf{F} \cdot L_o(\omega)/(1 + L_0(\omega))$, a filter is employed to position the frequency domain closed-loop response within the desired envelope of $\mathbf{T}_{RU}(\omega)$ and $\mathbf{T}_{RL}(\omega)$. In some cases this is only a gain. The process consists of the following 4 steps:

1. Place the nominal point of the plant template TP(ω) on the point $L_0(\omega)$. Determine T_{max} and T_{min} at that point using the M-contours. The entire perimeter (each plant) of the template must be inspected in order to determine the true T_{min} and T_{max} because the curvilinear nature of the M_L Contour can be deceptive.
2. Obtain the values of $\mathbf{T}_{RU}$ and $\mathbf{T}_{RL}$ for various frequencies ω.
3. From the values obtained in steps 1 and 2, plot $[\mathbf{T}_{RU} - T_{max}]$ and $[\mathbf{T}_{RL} - T_{min}]$ vs ω. These values are the upper and lower bounds on the filter (prefilter). The command Calculate Filter Transfer function generates this table.
4. Synthesis a filter that lies within the frequency plots by the use of straight line approximations. For a step forcing function, the following limit as s goes to zero (or time goes to infinity) must be satisfied:

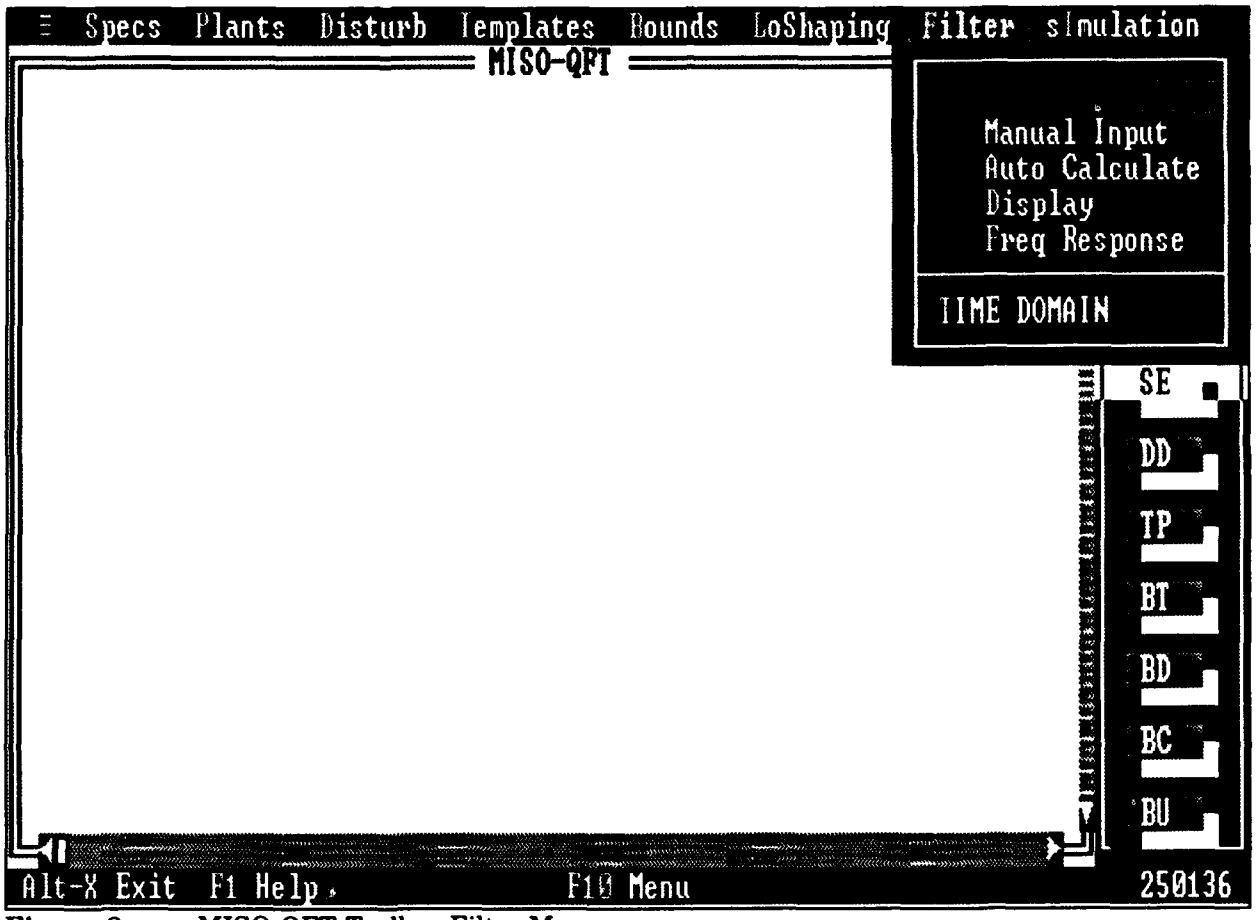


Figure 8 MISO QFT Toolbox Filter Menu

$$\lim_{s \to \infty} [F(s)] = 1$$

Filter Input: The filter transfer function is entered based upon manual synthesized design. The Filter can be Displayed and a Frequency Response generated.

2.2.9 Closed-Loop Simulation. The closed-loop system with the Filter, **F**, and the Controller, **G**, is simulated (step-input) for each plant and each disturbance to ascertain if the system meets the original specifications. Table and graphical data are presented as requested for the time and frequency domains. Non-linear function will be added in the future as appropriate.

2.2.9.1 Simulation in the Time Domain. Again the ICECAP-PC simulated input type (step, impulse, sine wave, ramp, user defined, random signal) is requested over the range of time entered for tracking and disturbances. This data can then be displayed using a table or the graph selection for up to ten data sets. They can also be compared to time domain specifications.

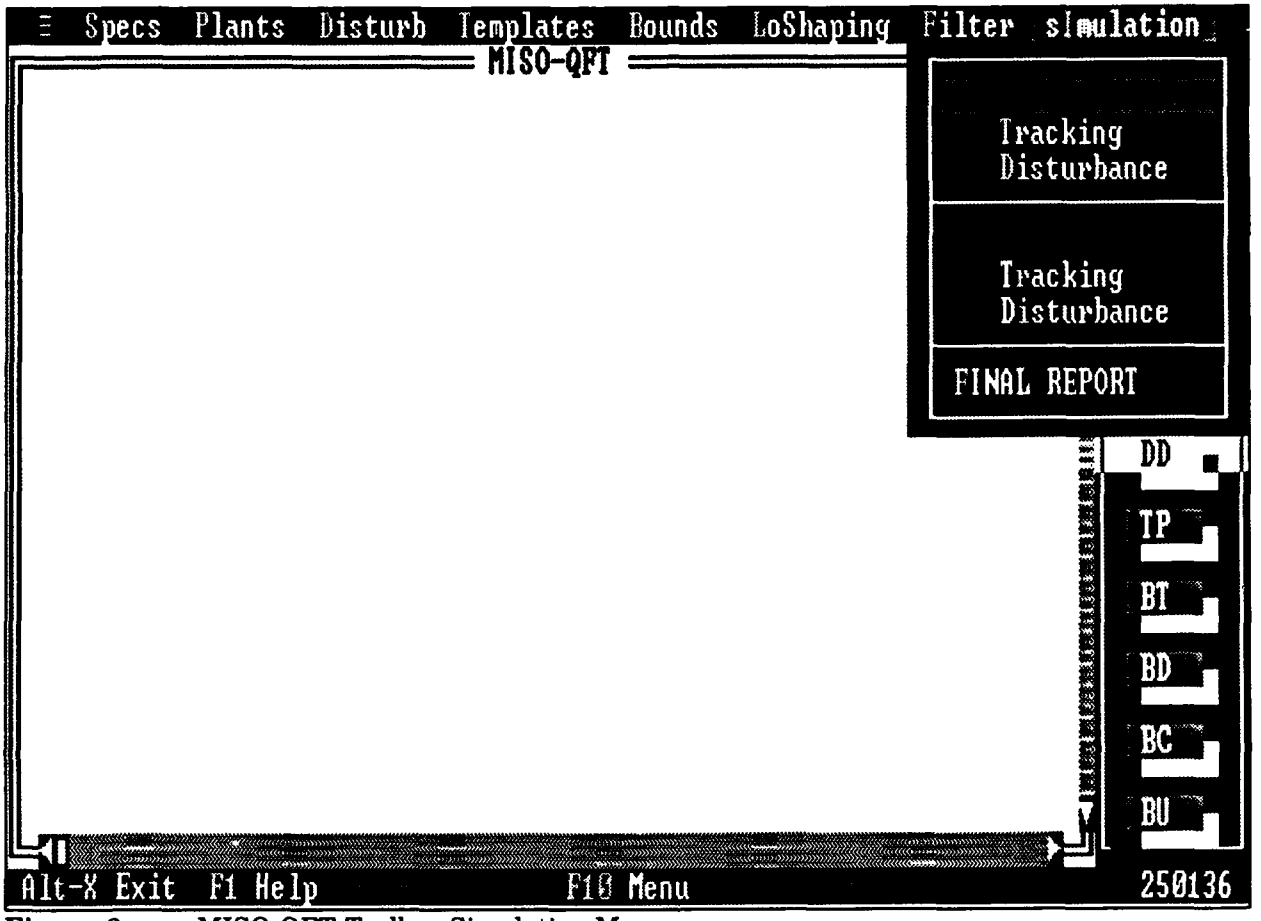


Figure 9 MISO QFT Toolbox Simulation Menu

2.2.9.2 Simulation in the Frequency Domain. The frequency domain data (table and graph) is presented over the range of frequency entered using standard ICECAP-PC deluge for tracking and disturbance models. This data can then be displayed using the graph selection for up to ten data sets. They can also be compared to frequency domain delta specifications.

2.2.9.3 The Report. A text file suitable for editing is generated using the various data files from each step as appropriate to the selected process for identifying the plant variations. Graphical presentations can be printed using screen dumps and then incorporated into the printed report.

2.3 The MISO QFT User Interface

2.3.1 The Desktop. The window-based desktop of the MIMO QFT Toolbox has been completely described by the previous sections.

2.3.2 Help. The operation of the context-sensitive help system is identical to that of the main ICECAP-PC package.

2.3.3 The Toolbar. The operation of the toolbar is identical to that of the main ICECAP-PC package.

2.3.4 The Status Line. The operation of the status line is identical to that of the main ICECAP-PC package.

3 The MIMO QFT Toolbox

3.1 *The MIMO QFT Design Process*

The QFT MIMO synthesis problem requires conversion into a number of MISO single-loop feedback problems in which parameter uncertainly, external disturbances, and performance tolerances are derived from the original MIMO problem. The combined solutions to these MISO single-loop problems achieve the desired performance for the MIMO plant. The basic approach is a point-wise frequency domain MISO synthesis technique. A 3x3 MIMO feedback structure is shown in **Figure 10**.

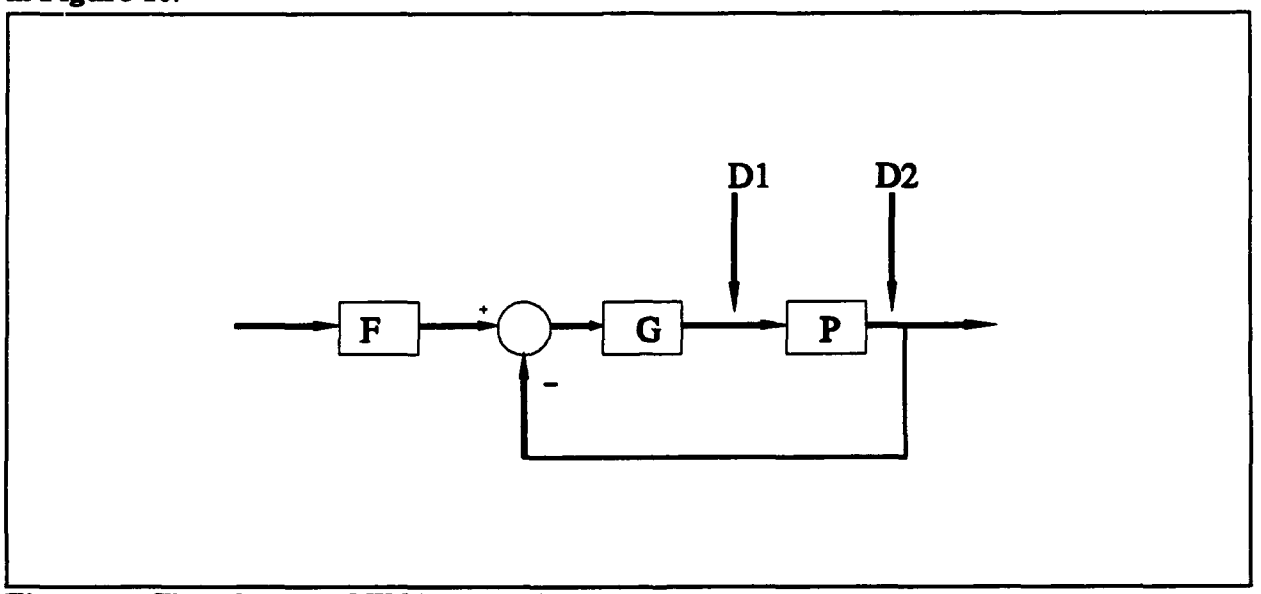


Figure 10: Three by three MIMO Design Structure

Plant models for **Figure 10** are developed in one of two formats: differential equation form and state space form. The general state-space model is manipulated as follows:

The state-space model representation for a LTI MIMO system is given by

$$X'(t) = AX(t) + BU(t) \qquad (12)$$
$$Y(t) = CX(t)$$

where **X** is an m vector, **Y** is an n vector and **U** is an r vector. **A**,**B**, and **C** are constant matrices of the proper dimension.

The plant transfer-function matrix **P**(s) is defined in state space form as

$$P(s) = C[sI - A]^{-1}B \tag{13}$$

When the system of **Figure 10** is defined in differential equation form, we start with the following relations:

$$\begin{aligned} a_1(s)y_1(s) + b_1(s)y_2(s) + c_1(s)y_3(s) &= d_1u_1(s) + e_1u_2(s) + f_1u_3(s) \\ a_2(s)y_1(s) + b_2(s)y_2(s) + c_2(s)y_3(s) &= d_2u_1(s) + e_2u_2(s) + f_2u_3(s) \\ a_3(s)y_1(s) + b_3(s)y_2(s) + c_3(s)y_3(s) &= d_3u_1(s) + e_3u_2(s) + f_3u_3(s) \end{aligned} \tag{14}$$

This set of differential equations can be represented in matrix notation as

$$\begin{vmatrix} a_1(s) & b_1(s) & c_1(s) \\ a_2(s) & b_2(s) & c_2(s) \\ a_3(s) & b_3(s) & c_3(s) \end{vmatrix} Y(s) = \begin{vmatrix} d_1 & e_1 & f_1 \\ d_2 & e_2 & f_2 \\ d_3 & e_3 & f_3 \end{vmatrix} U(s) \tag{15}$$

which yields the following:

$$\begin{aligned} M(s)Y(s) &= NU(s) \\ Y(s) &= M^{-1}NU(s) \\ Y(s) &= P(s)U(s) \\ P(s) &= M^{-1}N \end{aligned} \tag{16}$$

This plant transfer function matrix $\mathbf{P}(s) = [p_{ij}(s)]$ is a member of the set $\mathbf{P} = \{P(s)\}$ of possible plant matrices which are functions of the uncertain plant parameters. If the equivalent plant matrix **P** resulting from the three matrices is not square, a weighting matrix ω can be used to form an effective square plant; however, the use of a weighting matrix is not implemented in the ICECAP-PC MIMO QFT toolbox.

In CACSD practice, one of three explicit methods can be used to define the region of plant uncertainty. The first is based upon the physical modeling of various plants representing the variety of possible plants. The second includes the selection of only a finite set of **P** matrices, representing the extreme boundaries of plant pole/zero uncertainty. The third considers the variations in plant coefficients by considering a preselected number of plants to represent the maximum variations. A convex hull is then closed around these plants to derive the minimum number of plant models to represent the variation.

An mxm MIMO closed-loop system can be represented by three mxm transfer function matrices, **F**, **G**, and **P**. There are m^2 closed-loop system transfer functions $t_{ij}(s)$ (transmissions)

contained within its system transmission matrix or system tracking matrix. $\mathbf{T}_R(s) = \{t_{ij}(s)\}$, relates the outputs $y_i(s)$ to the inputs $r_j(s)$, that is, $y_i(s) = t_{ij}(s)r_j(s)$. In a quantitative problem statement there are tolerance bounds on each $t_{ij}(s)$, giving a set of m^2 acceptable regions $T_{ij}(s)$ which are to be specified in the design, thus $t_{ij}(s) \varepsilon T_{ij}(s)$ and $\mathbf{T}(s) = \{T_{ij}(s)\}$. These regions may also be directly given in the frequency domain.

The following system equations define the input/output relation of **Figure 10**:

$$\begin{aligned} Y &= Px \\ x &= GU \\ U &= FR - Y \end{aligned} \tag{17}$$

In these equations G(s) is the matrix of compensator transfer functions and is often simplified so that it is diagonal. F(s) is the matrix of refilter transfer functions which may also be a diagonal matrix. The combination of these equations yields a 2 degree-of-freedom feedback structure

$$Y = [I + PG]^{-1}\, PGFr \tag{18}$$

where the system tracking control ratio relating r to y is

$$T_R = [I + PG]^{-1} PGF \tag{19}$$

The disturbance model is given as

$$T_D = [I + PG]^{-1} P = \{d_{ij}\} \tag{20}$$

The MIMO design objective is to determine a F and G for all plants in {P} such that

(1) the closed-loop control ratio is stable and
(2) the norm of $t_{ij}(\omega)$ is bounded: $a_{ij}(\omega) \le t_{ij}(\omega) \le b_{ij}(\omega)$ for $\omega \le \omega$
(3) the disturbance, **Equation (20)**, is bounded (disturbance rejection).

A linear mapping from a MIMO system structure results in m^2 MISO equivalent systems, each with two inputs and one output. One input is designated as a *desired* tracking input and the other as a disturbance input. To develop this mapping consider the inverse of the plant matrix represented by

$$P^{-1} = \begin{vmatrix} p^*_{11} & p^*_{12} & \cdots & p^*_{1m} \\ p^*_{21} & p^*_{22} & \cdots & p^*_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ p^*_{m1} & p^*_{m2} & \cdots & p^*_{mm} \end{vmatrix} \tag{21}$$

The m^2 effective plant transfer functions are formed by defining

$$q_{ij} \equiv \frac{1}{p_{*_{ij}}} \tag{22}$$

A **Q** matrix is defined as:

$$P^{-1} = \begin{vmatrix} q_{11} & q_{21} & \cdots & q_{1m} \\ q_{21} & q_{22} & \cdots & q_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ q_{m1} & q_{m2} & q_{m3} & q_{mm} \end{vmatrix} = \begin{vmatrix} p^*_{11} & p^*_{12} & \cdots & p^*_{1m} \\ p^*_{21} & p^*_{22} & \cdots & p^*_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ p^*_{m1} & p^*_{m2} & \cdots & p^*_{mm} \end{vmatrix} \tag{23}$$

where $\mathbf{P} = [p_{ij}]$, $\mathbf{P}^{-1} = [p^*_{ij}] = [1/q_{ij}]$, and $\mathbf{Q} = [q_{ij}] = [1/p^*_{ij}]$.
the matrix $\mathbf{P}^{-1}$ is partitioned to form

$$P^{-1} = [p^*_{ij}] = [\frac{1}{q_{ij}}] = \Lambda + B \tag{24}$$

where $\Lambda = \{\lambda_{ii}\}$ is the diagonal part and $\mathbf{B} = \{b_{ij}\}$ is the off-diagonal component of $\mathbf{P}^{-1}$. Thus, $\lambda_{ii} = 1/q_{ii} - p_{ii}$, $b_{ij} = 1/q_{ij} = p_{ij}$ for $i \neq j$. Pre-multiplying **Equation (19)** by $\mathbf{P}^{-1}[\mathbf{I} + \mathbf{PG}]$ yields

$$\begin{aligned} P^{-1}[I + PG]T_R &= P^{-1}[I + PG][I + PG]^{-1}PGF \\ [P^{-1} + G]T_R &= GF \end{aligned} \tag{25}$$

If we let $\mathbf{P}^{-1} = \Lambda + \mathbf{B}$ where Λ contains the diagonal terms and **B** contains the off diagonal terms, **Equation (25)** becomes

$$
\begin{aligned}
&[\Lambda + B + G]T_R = GF \\
&[\Lambda + G]T_R = GF - BT \\
&T_R = [\Lambda + G]^{-1}[GF - BT]
\end{aligned}
\tag{26}
$$

Each of the m^2 matrix elements on the right side of **Equation (26)** can be interpreted as a MISO problem. A fixed point mapping based on Schauder's fixed point theorem [D'Azzo, 1988:699] is defined by $Y(T_R)$ as:

$$
Y(T_R) = [\Lambda + G]^{-1}[GF - BT] \tag{27}
$$

where $G = \{g_{ij}\}$ is assumed to be diagonal and each member of T_R is from the acceptable set $\{T_R\}$. If this mapping has a fixed point, i.e., $T_R \in \{T_R\}$ such that $Y(T_R) = \{T_R\}$, then this T_R is a solution of **Equation (26)**.

The control ratios for the desired tracking of the inputs by the corresponding outputs for each feedback loop of **Equation (27)** have the form

$$
y_{ii} = w_{ii}(v_{ij} + d_{ij}) = y_{r_i} + y_{d_{ij}} \tag{28}
$$

where

$$
\begin{aligned}
w_{ii} &= \frac{q_{ii}}{1 + g_{ii}q_{ii}} \\
v_{ij} &= g_{ij}f_{ii}
\end{aligned}
\tag{29}
$$

The interaction between the loops has the form

$$
d_{ij} = -\sum_{k \neq i} \frac{t_{kj}}{q_{ik}} \qquad k = 1,2,\cdots,m \tag{30}
$$

and appears as a *disturbance* input in each of the feedback loops.

3.2 *The MIMO QFT User Interface*

Figure 11 shows the MIMO QFT toolbox desktop.

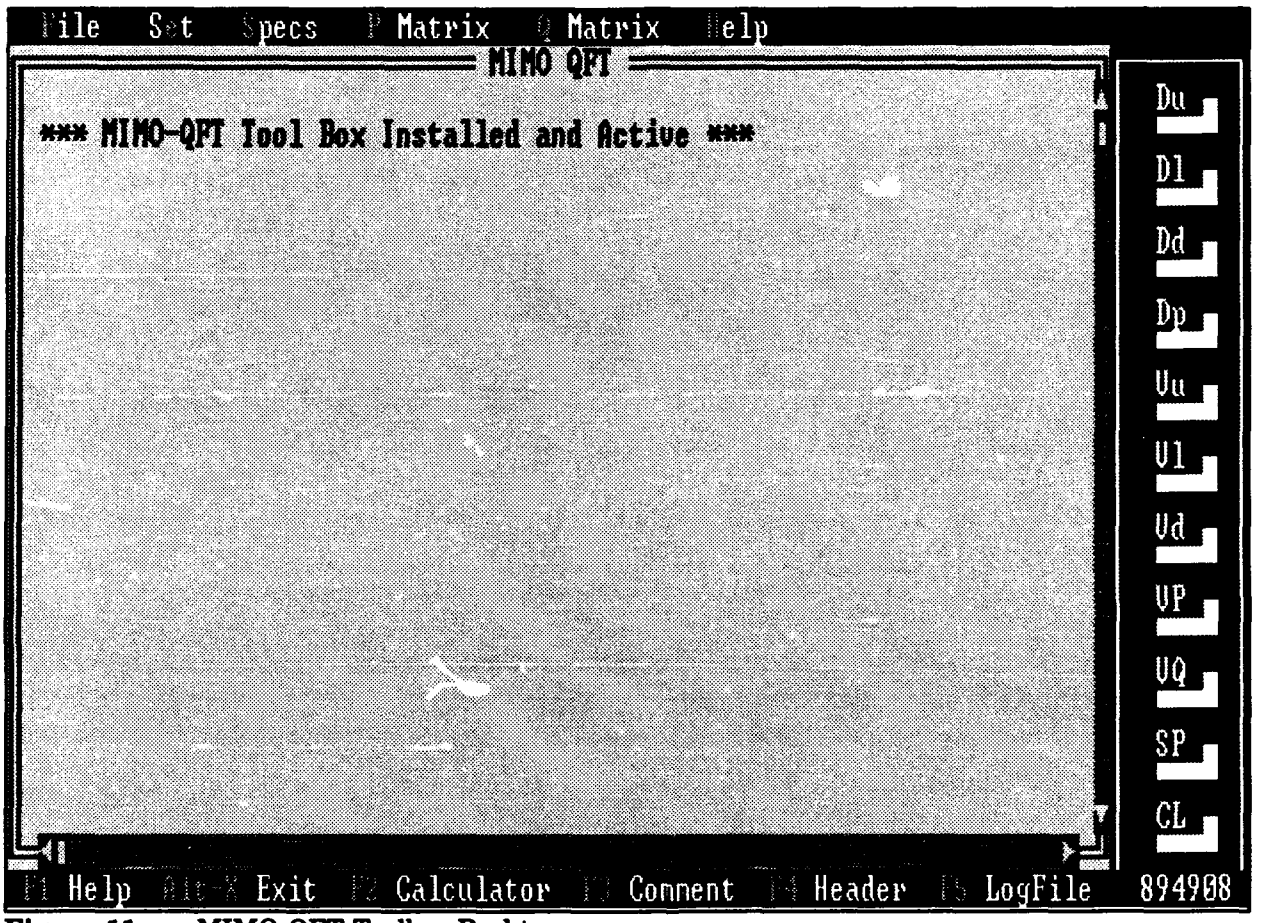


Figure 11 MIMO QFT Toolbox Desktop

The heart of the MIMO-QFT toolbox interface is the dialog box which is a pop-up window containing input lines, radio buttons, and check boxes. *Input lines* allow text entry such as comment lines and transfer function definitions. ICECAP-PC input lines contain history windows by which past inputs are recalled and edited with mouse or the down arrow. *Checkboxes* are a multiple selection tools consisting of brackets that are checked when selected ([X][ ][X]). For example, if the user desires to see or define any number of transfer functions at the same time he may do so by selecting from among a 5x5 array of checkboxes. *Radiobuttons* are singular selection tools consisting of parenthesis that are dotted when selected [( )(·)( )]. For example, when the user is allowed to select from one and only one frequency range, he makes his selection on a checkbox.

The MIMO QFT toolbox allows the design of systems up to 5x5 in dimension. It provides up to 20 plant cases of the **P** matrix. Thus, the file structure is conceptually a 5x5 p_{ij} transfer function matrix 20 levels deep with each level containing a plant case **P**. The toolbox stores a $\mathbf{T}_{RU}$, $\mathbf{T}_{RL}$, $\mathbf{T}_D$, $\mathbf{L}_0$, **G**, and FCTF for each transfer function element.

There are two ways to define transfer function elements and matrices: polynomial format and factored format. Transfer function entry is done on an input line very similar to the most popular matrix/engineering programs with the exceptions that 1) complex factors may be entered directly and 2) brackets are not used to enclose the entry. Differentiation between the two forms is simply a matter of radio button selection. To enter a transfer function $(12.02s^2 + 4.32s + 5) / (4s + 2)$ one would enter the following line:

12.02 4.32 5; 4 2

Note that the numbers are not encased by right and left brackets like other popular programs. After such entry, the transfer function is displayed on a scrollable screen in standard coefficient form. To enter a transfer function with 3 zeros at -2, -5, and -7 and four poles -3±2j, -8, -1 and -9 with a gain of 1, one would enter the following:

-2 -5 -7; -3j2 -8 -1 -9

Note the direct entry of the single complex variable. The entry of complex is always done with an i or j preceding the complex element with no spaces allowed. The entry of spaces in a complex number is taken to be a second root at an imaginary location. The entry of the complex conjugate is done automatically by the computer. Manual entry of the complex conjugate is an error and results in an extra undesired root. After such entry, the transfer function is displayed on a scrollable screen in either factored form ()()()/()()() or in list form showing the gain and root locations of the numerator and denominator as selected by the user. Several p_{ij} (in fact all of the **P** matrix) can be defined at one time by simple checkbox selection from among a 5x5 array of elements that indicate which p_{ij} is to be defined.

The heart of the MIMO process is the accurate calculation of $\mathbf{P}^{-1}$ and its decomposition into MISO equivalent loops. The MIMO QFT toolbox uses the LU Decomposition process to find $\mathbf{P}^{-1}$ and **Q**. LU Decomposition offers several advantages over the classical Adj/Det technique.

1. It provides a single general method for the inversion of all **P**
2. Root cancellation occurs at very low orders preventing the growth of unnecessarily large order polynomials.
3. Because of this, root finding is much simpler and more accurate and root cancellation can be done with far tighter constraints than any other technique.
4. There is no need to factor out common denominators and numerators in **P**. These are canceled internally with no loss of accuracy.

LU Decomposition also provides quick and accurate calculation of **P** matrix determinant so that the engineer can inspect the **P** matrix for singularity and for non-minimum phase conditions.

The MIMO QFT process as implemented in ICECAP-PC follows the following menu and process structure:

3.2.1 File.

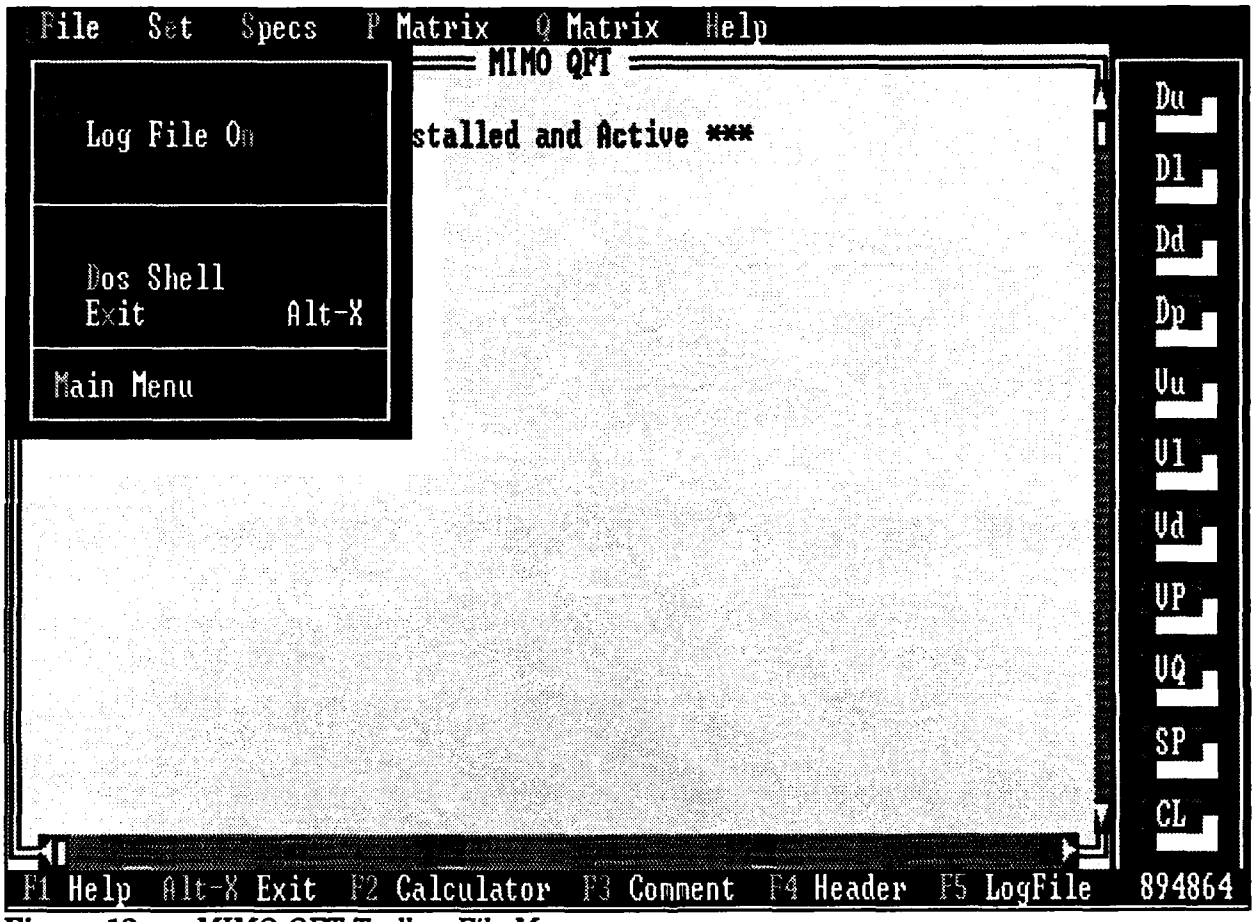


Figure 12 MIMO QFT Toolbox File Menu

Log File On: Activates the ICECAP-PC log file. All subsequent information displayed to screen is also sent to the log file. The log file is a text file named LOGFILE.TXT and as such can be viewed, printed or edited with any good text editor.

Log File Off: Turns log file off.

DOS Shell: Provides Temporary exit to DOS. Once in the DOS environment, return to the ICECAP-PC MIMO QFT program is initiated with the 'Exit' DOS command. Caution: Do not attempt to edit an active log file by using this option.

Exit: Exits the ICECAP-PC MIMO QFT toolbox.

3.2.2 Set.

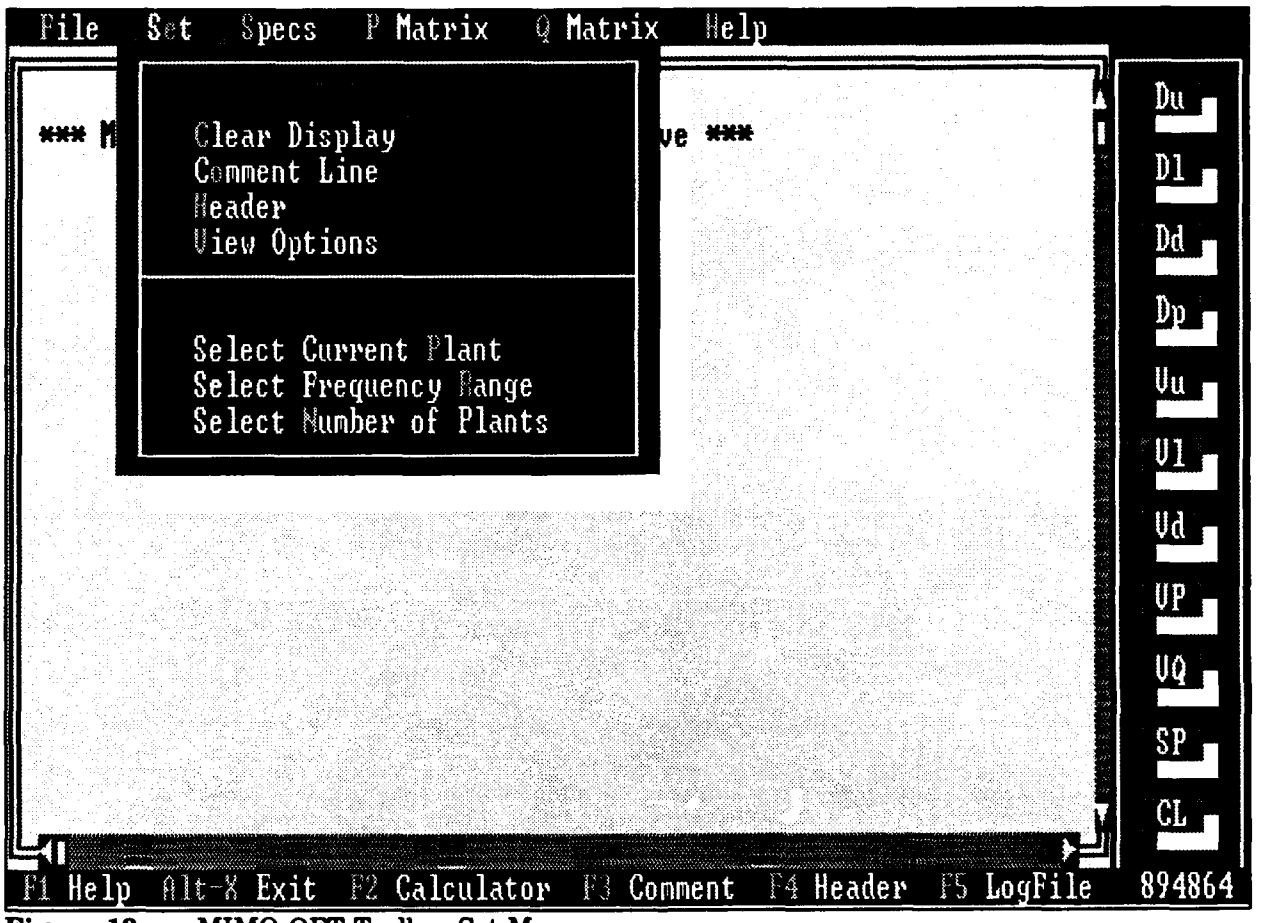


Figure 13 MIMO QFT Toolbox Set Menu

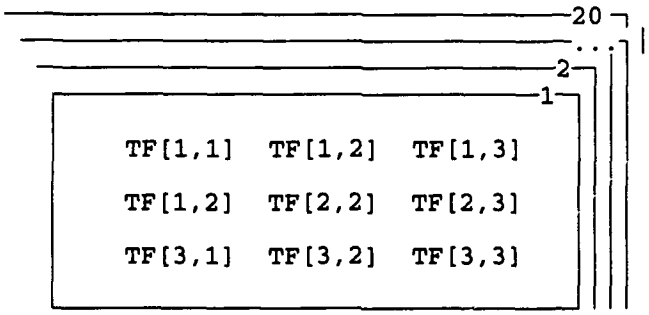
Clear Display: Clears the screen.

CommentLine: Presents direct entry of comments into the design session. Comments can be up to 132 characters long. If the log file is active, comments are also sent to it.

Header: Provides a dialog box to record the user/student name, title and other header information that should appear on top of log files. The header information is saved to disk and recalled each time the log file is turned on with the header option enabled.

View Options: Allows user to customize the session including the selection of high resolution screens, Number of decimal places displayed, fixed decimals or scientific notation display selection, and complex letter (i or j) selection.

Select Current Plant: Provides selection of the current plant and plant dimension. The MIMO-QFT toolbox allows up to 20 plant matrix definitions for both P and Q matrices. Each plant is a transfer function matrix. The complete plant set of 1-20 plants defines the region of plant parameter uncertainty.



Select Frequency Range: The MIMO-QFT toolbox provides three frequency ranges each containing 16 frequencies 1 octave apart. Plant templates are generated over the selected frequency range. The three ranges are:

1) .015 - 512 Rad/Sec
2) .500 - 16,000 Rad/Sec
3) 4096.000 - 134,000,000 Rad/Sec

Select Number Of Plants: Provides selection of the number of plants used in the MIMO QFT design process. The user can select from 1-20 plants used. Plant template generation depends on the proper setting of this option.

3.2.3 Specs.

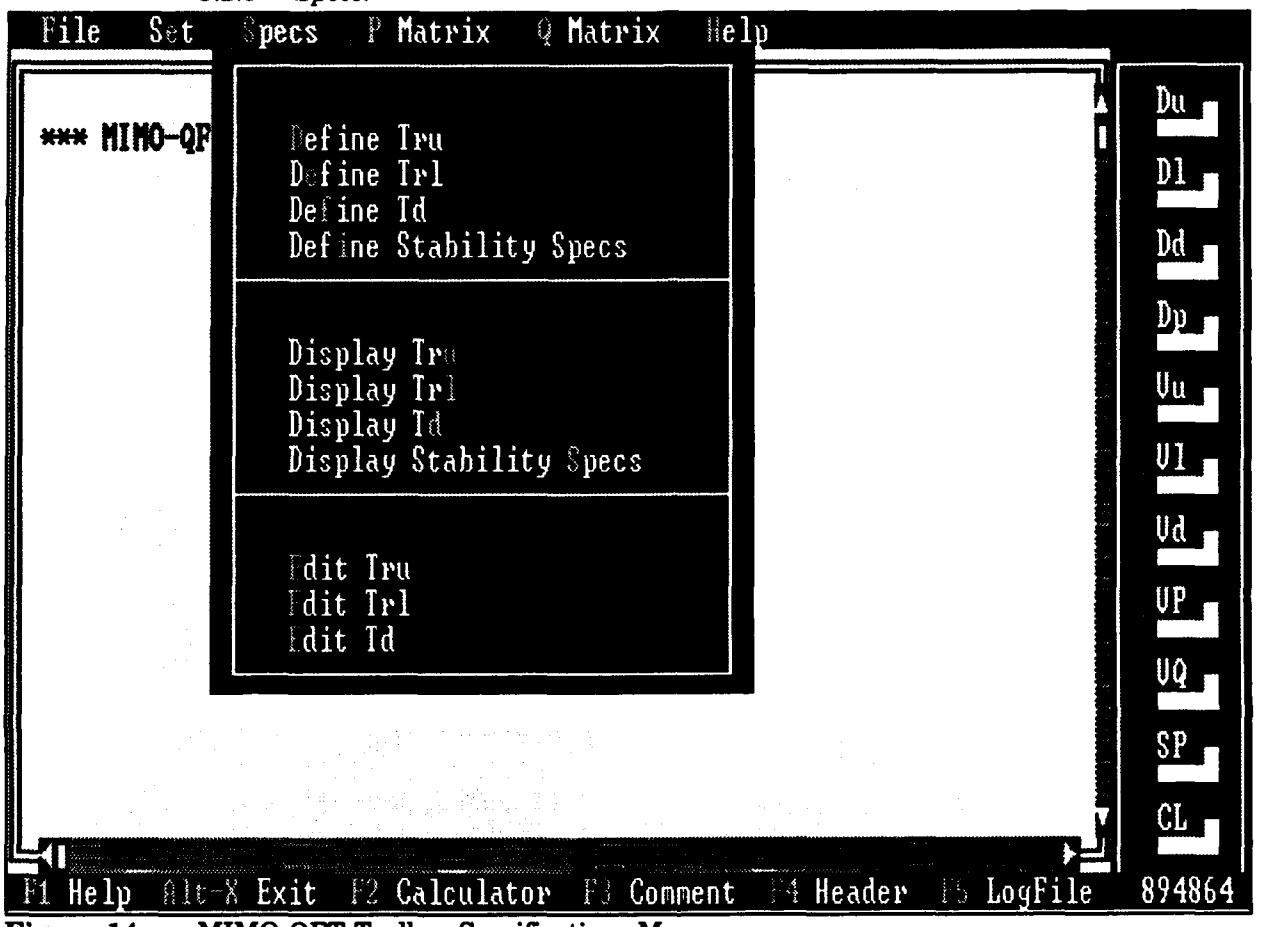


Figure 14 MIMO QFT Toolbox Specifications Menu

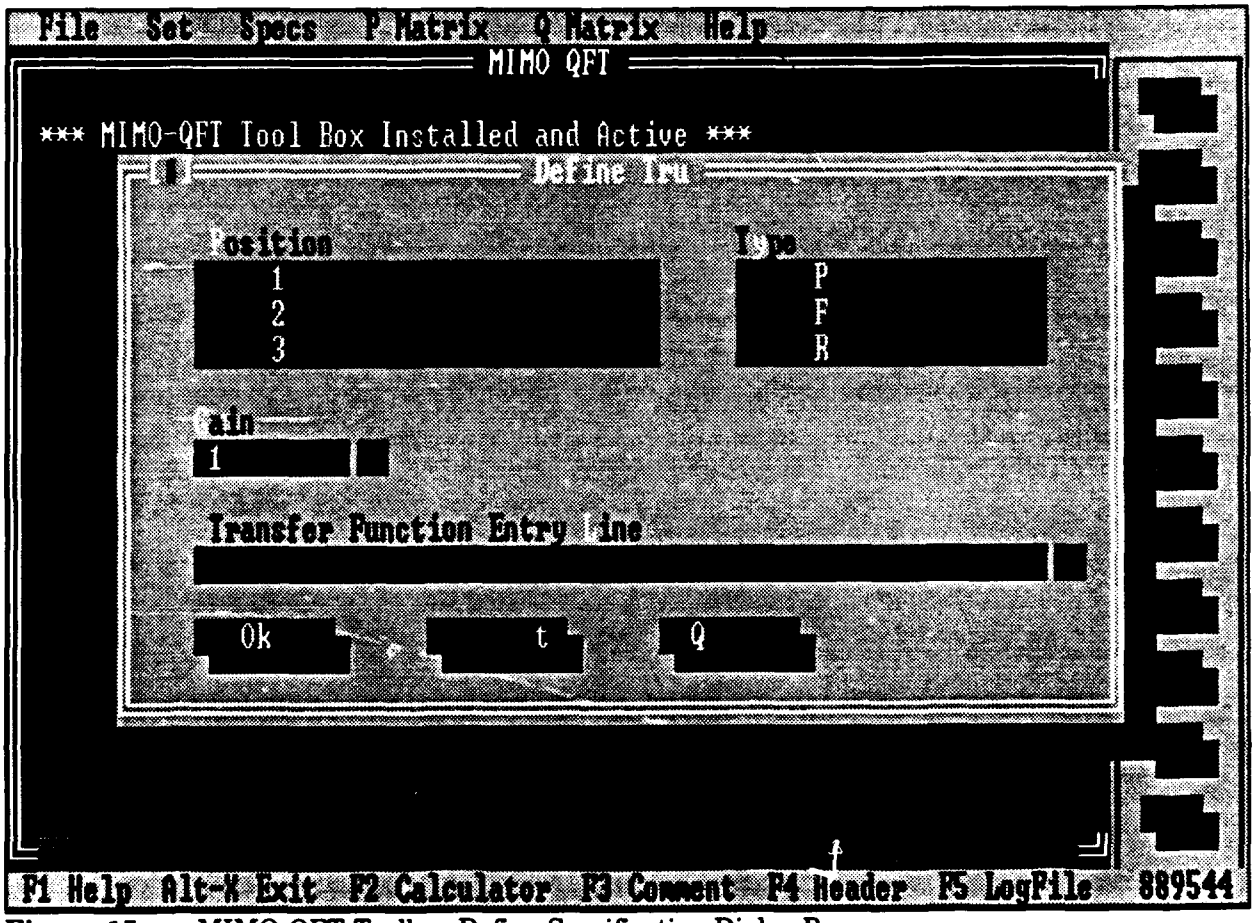


Figure 15 MIMO QFT Toolbox Define Specification Dialog Box

Define T_{RU}: Define the upper tracking response transfer function (T_{RU}) for transfer function elements of the plant matrix. T_{RU} is normally defined element by element on an individual basis, however, several transfer function elements may have the same T_{RU}. Therefore, T_{RU} can be defined for several elements at a time by simply checking the appropriate boxes. Transfer function input can be in either polynomial or factored form as shown below.

To enter this: s^2+3s+5 / s^3+6s^2+7s+8
Check Poly :
And Type This: 1 3 5; 1 6 7 8

To enter this : (s+4)(s+6) / (s+8)(s-4+j2)(s-4+j2)
Check Factored:
Type this : -4 -6; -8 4j2
Note that the complex conjugate is automatically entered

Display T_{RU}: Display T_{RU} for any p_{ij} element/elements desired.

Edit T_{RU}: Edit T_{RU} for any transfer function element of the plant matrix.

Define T_{RL}: Define the lower tracking response transfer function (T_{RL}) for transfer function elements of the plant matrix. T_{RL} cannot be defined for off-diagonal elements. T_{RL} is normally defined element by element on an individual basis, however, several transfer function elements may have the same T_{RL}. Therefore, T_{RL} can be defined for several diagonal elements at a time by simply checking the appropriate boxes. Transfer function input can be in either polynomial or factored form as shown below.
To enter this: s^2+3s+5 / s^3+6s^2+7s+8
Check Poly :
And Type This: 1 3 5; 1 6 7 8

To enter this : (s+4)(s+6) / (s+8)(s-4+j2)(s-4+j2)
Check Factored:
Type this : -4 -6; -8 4j2
Note that the complex conjugate is automatically entered

Display T_{RL}: Display T_{RL} for any p_{ij} element(s) desired. Since T_{RL} is undefined for off-diagonal elements, the display of such T_{RL} is disallowed.

Edit T_{RL}: Edit T_{RL} for any transfer function element of the plant matrix.

Define T_D: Define the disturbance tracking response transfer function (T_D) for transfer function elements of the plant matrix. T_D is normally defined element by element on an individual basis, however, several transfer function elements may have the same T_D. Therefore, T_D can be defined for several elements at a time by simply checking the appropriate boxes. Transfer function input can be in either polynomial or factored form as shown below. However, it is common practice to simply define T_D as some constant (i.e., .1 for -20db)

To enter this: s^2+3s+5 / s^3+6s^2+7s+8
Check Poly :
And Type This: 1 3 5; 1 6 7 8

To enter this : (s+4)(s+6) / (s+8)(s-4+j2)(s-4+j2)
Check Factored:
Type this : -4 -6; -8 4j2
Note that the complex conjugate is automatically entered

Display T_D: Display T_D for any p_{ij} element(s) desired.

Edit T_D: Edit T_D for any transfer function element in the plant matrix.

Define Stability Specs: Stability specifications may be defined as either a phase margin (γ), a M_L contour, or a peak overshoot(M_p). Specifications are entered one for each row in the

design and multiple rows may be define simultaneously. The entry of gain margin is specifically disallowed because 1) the sensitivity of phase margin with respect to gain margin and 2) the ill conditioned nature of calculating the phase margin given a gain margin which is error prone. Using any definition provided results in the printing of all specs.

Display Stability Specs: Display stability specifications for any number of row(s) of the **P** matrix. The display will show phase margin, peak overshoot, Ml contour, and gain margin.

3.2.4 Plants.

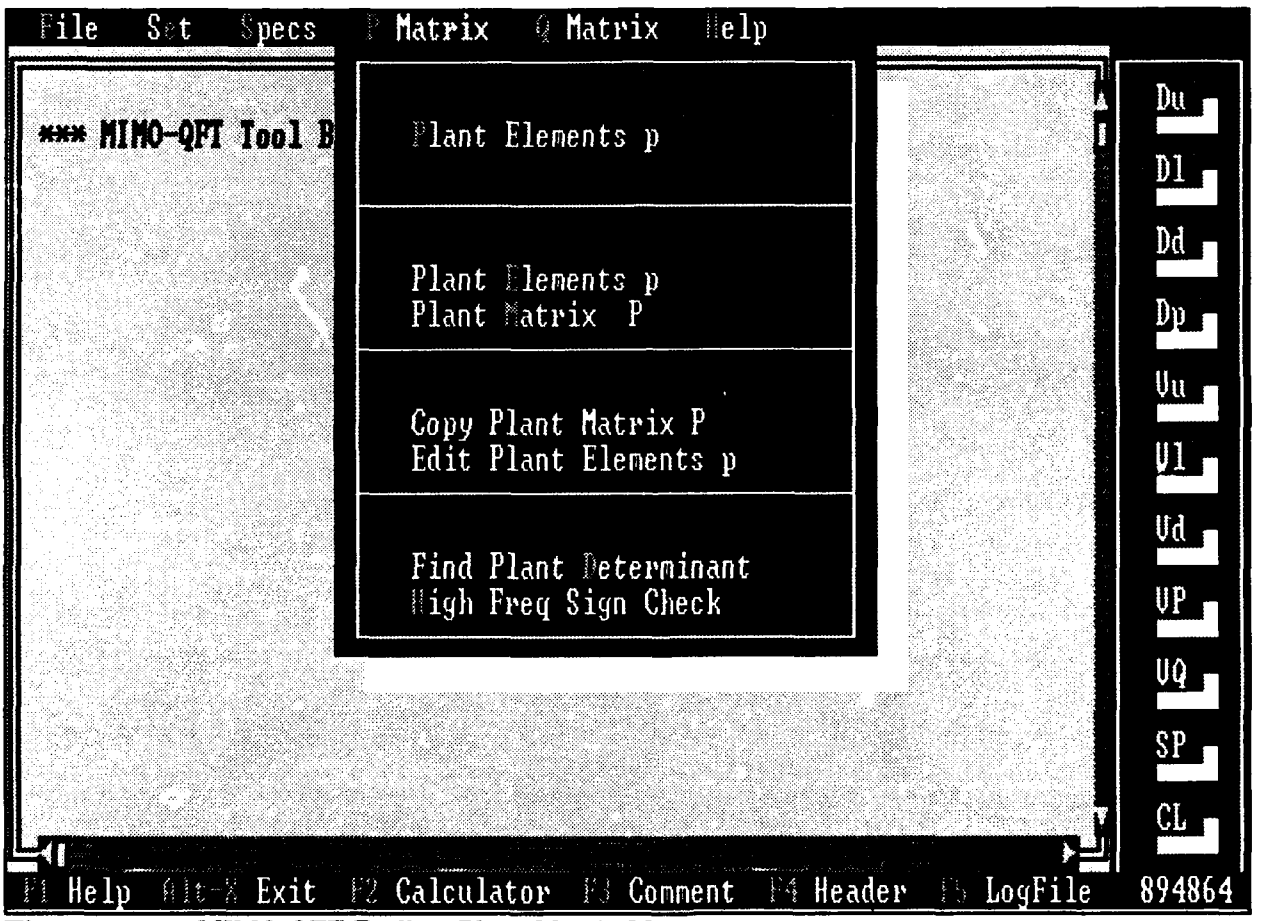


Figure 16 MIMO QFT Toolbox Plant Matrix Menu

Define Plant Elements p: Define the plant transfer function p_{ij} for transfer function elements of the plant matrix P. p_{ij} is normally defined element by element on an individual basis, however, several transfer function elements may have the same definition. Therefore, p_{ij} can be defined for several elements at a time by simply checking the appropriate boxes. Transfer function input can be in either polynomial or factored form as shown below. The current **P** is indicated in the dialog box and may be set using the *Select*

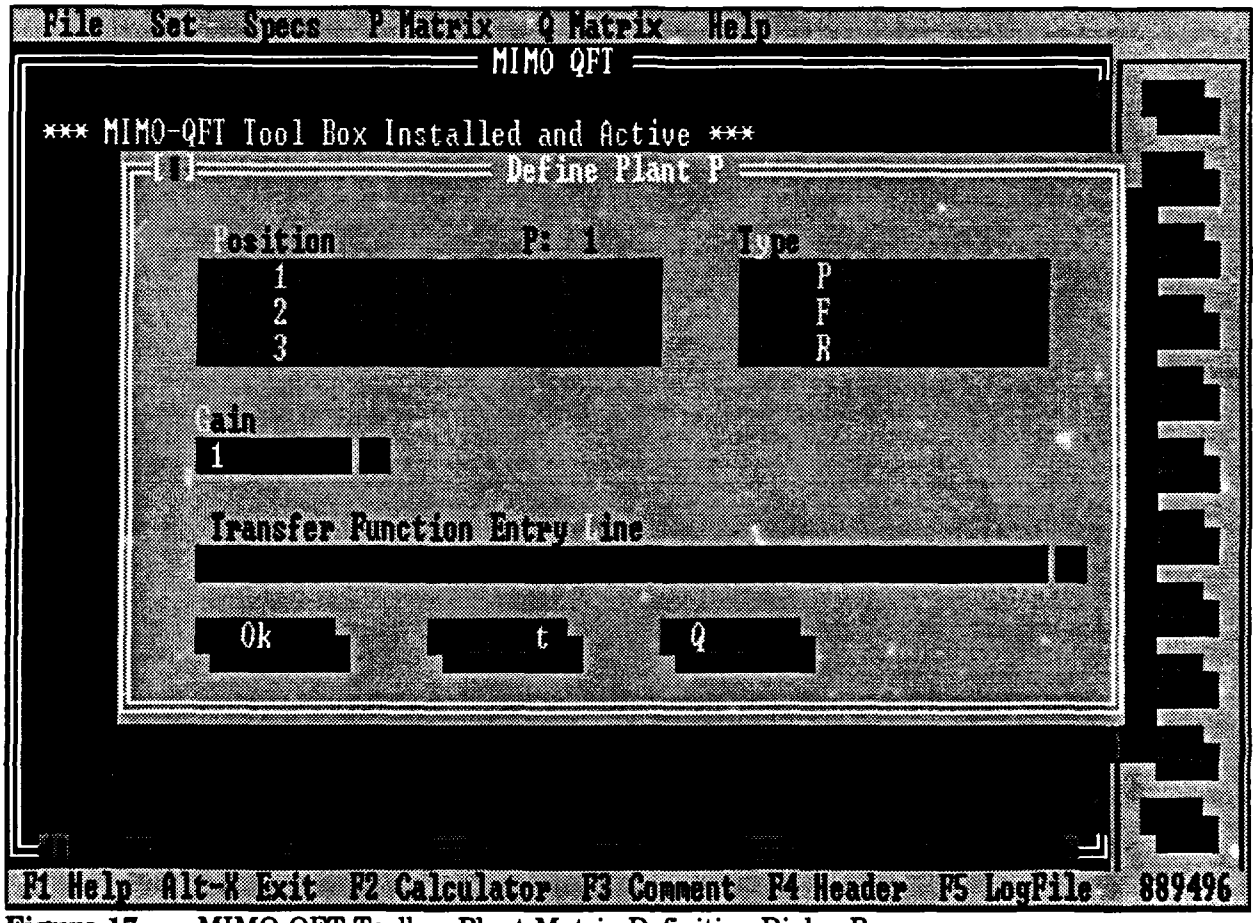


Figure 17 MIMO QFT Toolbox Plant Matrix Definition Dialog Box

Current Plant option.

To enter this: s^2+3s+5 / s^3+6s^2+7s+8
Check Poly :
And Type This: 1 3 5; 1 6 7 8

To enter this : (s+4)(s+6) / (s+8)(s-4+j2)(s-4+j2)
Check Factored:
Type this : -4 -6; -8 4j2
Note that the complex conjugate is automatically entered

Define Plant Variation: Provides an automated method for generating 20 plant cases. The user defines two transfer functions at the minima and maxima in variation for any given plant p_{ij}. Entry is allowed in polynomial or factored form by selection. The MIMO-QFT toolbox will automatically generate 125 plant cases for each plant element p_{ij}, envelop these plants (p_{ij}) with a convex hull, and choose 20 plants on its perimeter.

Copy Plant Matrix P:

Display Plant Elements p: Provides for the display of 1-25 plants p_{ij} in a given plant **P** as selected in *Select Current Plant* (described above).

Display Plant Matrix P: Allows the rapid display of all p_{ij} in a given plant case **P**. This is a separate menu item from the *Display Plants* option because the selection of several p_{ij} in a matrix can be a time consuming task. Radio button selection allows selection of the desired plant case and **P** dimension.

Edit Plant Elements p:

Find Plant Determinant: Calculates and displays the determinant for a selected **P**. **P** is chosen via radiobutton selection. In the QFT design process, all **P** must be checked for non-singularity and for minimum phase conditions. Calculation of the determinant is via LU Decomposition.

High Freq Sign Check: Calculates and displays the sign of diagonal elements p_{ii} of **P** for all plant **P** cases.

3.2.5 Q Matrix.

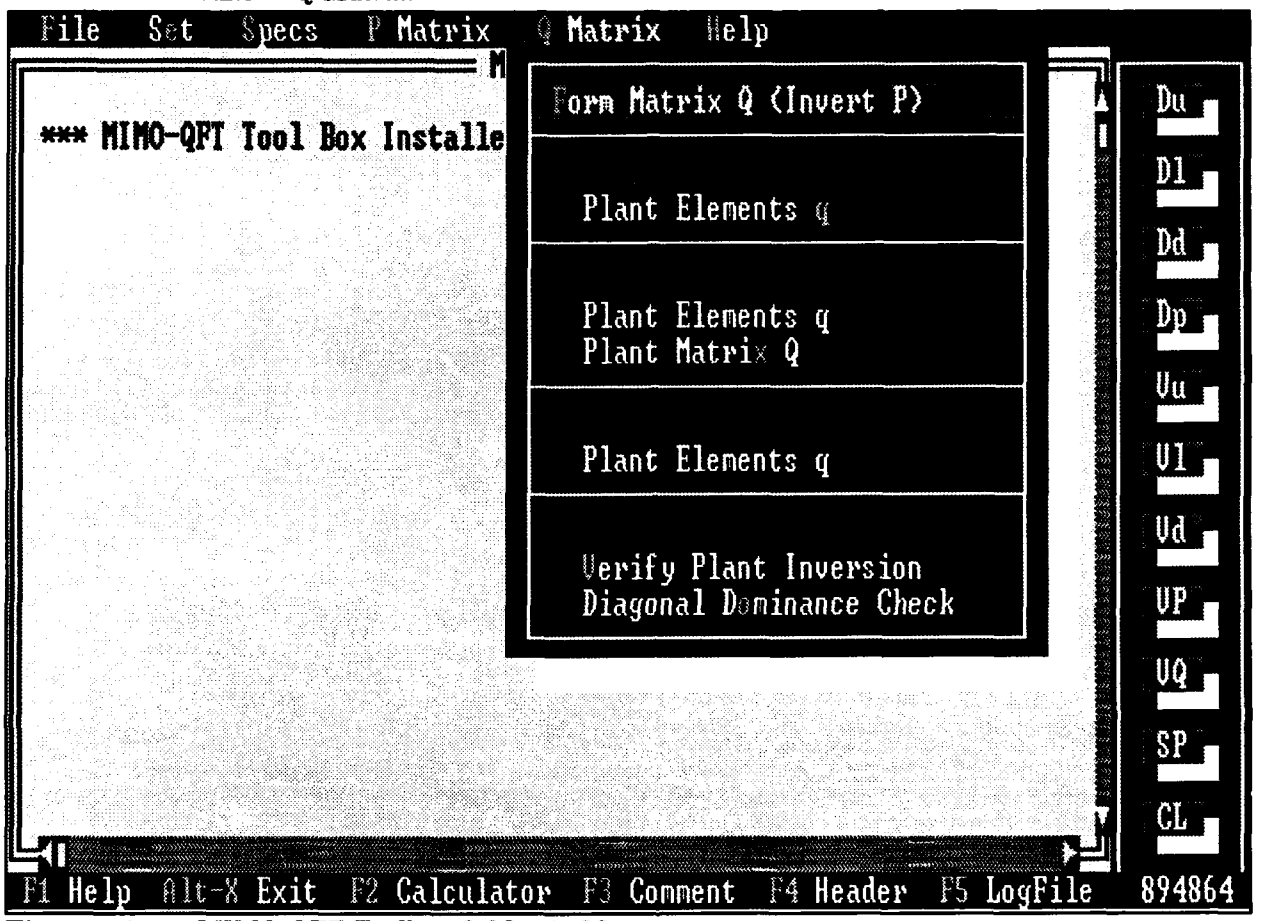


Figure 18 MIMO QFT Toolbox Q Matrix Menu

Define Plant Elements q: Define the plant transfer function q_{ij} for transfer function elements of the plant matrix Q. THE DIRECT DEFINITION OF **Q** IS AN ALTERNATIVE TO THE NORMAL INVERSION OF **P**. q_{ij} is normally defined element by element on an individual basis, however, several transfer function elements may have the same definition. Therefore, q_{ij} can be defined for several elements at a time by simply checking the appropriate boxes. Transfer function input can be in either polynomial or factored form as shown below. The current **P** is indicated in the dialog box and may be set using the *Select Current Plant* option.

To enter this: s^2+3s+5 / s^3+6s^2+7s+8
Check Poly :
And Type This: 1 3 5; 1 6 7 8

To enter this : (s+4)(s+6) / (s+8)(s-4+j2)(s-4+j2)

Check Factored:
Type this : -4 -6; -8 4j2
Note that the complex conjugate is automatically entered

Form Q Matrix: Inverts the selected matrix **P** via LU decomposition and then reciprocates the elements of $\mathbf{P}^{-1}$ to form the matrix **Q**.

Verify Plant Inversion: Multiplies **P** x $\mathbf{P}^{-1}$ in order to verify the accuracy of the inversion process. Ideally in the absence of zero roundoff error, the result will be an identity matrix. In practice, finite roundoff error is detected via this process. Scientific notation display should be used with this option to detect low levels of roundoff.

Check Diagonal Dominance: Calculates the magnitude of each P in a selected **P** via L^Hospitals rule and displays the result along with an analysis as to the diagonal dominance of the plant **Q**. A dialog box provides radiobutton selection among 20 **Q**.

Display Plant Elements q: Provides a dialog box with checkbox input for the display of 1-25 plants q_{ij} in a given plant **Q** as selected in *Select Current Plant* (described above).

Display Plant Matrix Q: Allows the rapid display of all q_{ij} in a given plant case **Q**. This is a separate menu item from the *Display Plants* option because the selection of several q_{ij} in a matrix can be a time consuming task. Radio button selection allows selection of the desired plant case and **Q** dimension.

Edit Plant Elements q:

4 *Design Examples*
4.1 MIMO QFT Design Example

Students Name
Teachers Name
Class

: This log provides demonstration of the entry modes and operation of
: MIMO-QFT toolbox functions and operation.

: Step 1: Define T_{RU}, T_{RL}, and T_D for plant P. Only plant P1 is shown below:
: Note that in this example, T_{RU} and T_{RL} are the same for all rows.

MIMO T_{RU} [1,1]

$$\frac{1.8896\ (s + 12.0000)}{(s + 2.2857 \pm j4.1775)}$$

MIMO T_{RU} [2,2]

$$\frac{1.8896\ (s + 12.0000)}{(s + 2.2857 \pm j4.1775)}$$

MIMO T_{RU} [3,3]

$$\frac{1.8896\ (s + 12.0000)}{(s + 2.2857 \pm j4.1775)}$$

: T_{RU} for off diagonal elements is defined for all off diagonal plants as:

MIMO T_{RU} [1,2]

$$\frac{0.1000}{1.0000}$$

MIMO T_{RU} [1,3]

$$\frac{0.1000}{1.0000}$$

MIMO T_{RU} [2,1]

$$\frac{0.1000}{1.0000}$$

MIMO T_{RU} [2,3]

$$\frac{0.1000}{1.0000}$$

MIMO T_{RU} [3,1]

$$\frac{0.1000}{1.0000}$$

MIMO T_{RU} [3,2]

$$\frac{0.1000}{1.0000}$$

: T_{RL} is only defined for diagonal elements:

MIMO T_{RL} [3,3]

$$\frac{11600.0000}{(s + 4.0000)(s + 4.0000)(s + 7.2500)(s + 100.0000)}$$

MIMO T_{RL} [3,3]

$$\frac{11600.0000}{(s + 4.0000)(s + 4.0000)(s + 7.2500)(s + 100.0000)}$$

MIMO T_{RL} [3,3]

$$\frac{11600.0000}{(s + 4.0000)(s + 4.0000)(s + 7.2500)(s + 100.0000)}$$

: If definition of T_{RL} for off diagonal is attempted, the following results:

T_{RL} Undefined for Off Diagonal Transfer Function Element [1, 2]

: T_D is defined at .1 for all plants p(ij)

MIMO T_D [1,1]

$$\frac{0.1000}{1.0000}$$

MIMO T_D [1,2]

$$\frac{0.1000}{1.0000}$$

MIMO T_D [1,3]

$$\frac{0.1000}{1.0000}$$

MIMO T_D [2,1]

$$\frac{0.1000}{1.0000}$$

MIMO T_D [2,2]

$$\frac{0.1000}{1.0000}$$

MIMO T_D [2,3]

$$\frac{0.1000}{1.0000}$$

: Stability bounds are defined as followed:

Stability Bounds for Row 1

```
Phase Margin:     40.0000°
Gain Margin:       4.3116 db
ML Contour:        3.8387 db
Mp :               1.5557

Stability Bounds for Row  2

Phase Margin:     35.0000°
Gain Margin:       3.9378 db
ML Contour:        4.8282 db
Mp :               1.7434

Stability Bounds for Row  3

Phase Margin:     35.0000°
Gain Margin:       3.9378 db
ML Contour:        4.8282 db
Mp :               1.7434
```

: Plant Case P_1 is defined as follows:

```
MIMO Plant [1,1]  Plant Matrix 1

        2.0000 (s + 3.0000)
-----------------------------------------
(s + 2.0000)(s + 0.0000)(s + 5.0915)

MIMO Plant [1,2]  Plant Matrix 1

       -10.1961 (s + 3.0000)
-----------------------------------------
(s + 2.0000)(s + 0.0000)(s + 5.0915)

MIMO Plant [1,3]  Plant Matrix 1

        5.4902 (s + 3.0000)
-----------------------------------------
(s + 2.0000)(s + 0.0000)(s + 5.0915)

MIMO Plant [2,1]  Plant Matrix 1

       -10.1961 (s + 3.0000)
-----------------------------------------
(s + 2.0000)(s + 0.0000)(s + 5.0915)

MIMO Plant [2,2]  Plant Matrix 1

 -2.3529 (s - 17.0000)(s + 3.0000)
-----------------------------------------
(s + 2.0000)(s + 0.0000)(s + 5.0915)

MIMO Plant [2,3]  Plant Matrix 1

  5.8824 (s + 0.3333)(s + 3.0000)
-----------------------------------------
(s + 2.0000)(s + 0.0000)(s + 5.0915)

MIMO Plant [3,1]  Plant Matrix 1

        5.4902 (s + 3.0000)
-----------------------------------------
(s + 2.0000)(s + 0.0000)(s + 5.0915)

MIMO Plant [3,2]  Plant Matrix 1

  5.8824 (s + 0.3333)(s + 3.0000)
-----------------------------------------
(s + 2.0000)(s + 0.0000)(s + 5.0915)

MIMO Plant [3,3]  Plant Matrix 1
```

```
  -4.7059 (s + 1.8889)(s + 3.0000)
 ---------------------------------
 (s + 2.0000)(s + 0.0000)(s + 5.0915)
 : Inspection of the Determinant of P1 reveals it is non-singular and minimum phase
 Determinant of Plant Matrix  1
            -47.0588 (s + 3.0000)(s + 3.0000)(s + 3.0000)
 ---------------------------------------------------------------------------------------
(s + 2.0000)(s + 2.0000)(s + 2.0000)(s + 0.0000)(s + 0.0000)(s + 0.0000)(s + 5.0915)
 Matrix Q will contain minimum phase elements upon P inversion

 : The Q matrix is formed via LU Decomposition and is :
 q-Plant [1,1]  Q Matrix:  1
        2.0000
 ---------------------
 (s + 2.0000)(s + 0.0000)
 q-Plant [1,2]  Q Matrix:  1
  3.0000 (s + 3.0000)
 ---------------------
 (s + 2.0000)(s + 0.0000)
 q-Plant [1,3]  Q Matrix:  1
  1.0000 (s + 3.0000)
 ---------------------
 (s + 2.0000)(s + 0.0000)
 q-Plant [2,1]  Q Matrix:  1
  3.0000 (s + 3.0000)
 ---------------------
 (s + 2.0000)(s + 0.0000)
 q-Plant [2,2]  Q Matrix:  1
  5.0000 (s + 3.0000)
 ---------------------
 (s + 2.0000)(s + 0.0000)
 q-Plant [2,3]  Q Matrix:  1
  4.0000 (s + 3.0000)
 ---------------------
 (s + 2.0000)(s + 0.0000)
 q-Plant [3,1]  Q Matrix:  1
  1.0000 (s + 3.0000)
 ---------------------
 (s + 2.0000)(s + 0.0000)
 q-Plant [3,2]  Q Matrix:  1
  4.0000 (s + 3.0000)
 ---------------------
 (s + 2.0000)(s + 0.0000)
 q-Plant [3,3]  Q Matrix:  1
  10.0000 (s + 3.0000)
 ---------------------
 (s + 2.0000)(s + 0.0000)
```

```
: The inversion process can be checked by multiplying P x inv P
Identity[ 1, 1]
 1.0000E+0000
 ------------
 1.0000E+0000
Identity[ 1, 2]
 0.0000E+0000
 ------------
 1.0000E+0000
Identity[ 1, 3]
   1.6263E-0019
 ---------------
(s +  5.0915E+0000)
Identity[ 2, 1]
-4.3368E-0019 (s +  4.7624E+0008)
 ---------------------------------
       (s +  5.0915E+0000)
Identity[ 2, 2]
 1.0000E+0000
 ------------
 1.0000E+0000
Identity[ 2, 3]
   7.2810E-0011
 ---------------
(s +  5.0915E+0000)
Identity[ 3, 1]
   4.6623E-0011
 ---------------
(s +  5.0915E+0000)
Identity[ 3, 2]
  -2.9216E-0011
 ---------------
(s +  5.0915E+0000)
Identity[ 3, 3]
 1.0000E+0000
 ------------
 1.0000E+0000
 : This accuracy will be improved with more sophistication in the algorithm but is
 acceptable for now
: The next step is to check the diagonal dominance of the Q matrix
Transfer Function Magnitudes at ω = ∞
 0.0E+0000   0.0E+0000   0.0E+0000
 0.0E+0000   0.0E+0000   0.0E+0000
 0.0E+0000   0.0E+0000   0.0E+0000
Diagonal Dominance Test Passed For Q Plant  1
```

: Since Q is diagonally dominant, this Q is ready for MISO manipulation.

: Q1 (1,1) is now shown to be

q-Plant [1,1] Q Matrix: 1

$$\frac{2.0000E+0000}{(s + 2.0000E+0000)(s + 0.0000E+0000)}$$

: Solution of this MISO problem is now given in the following section.

4.2 MISO QFT Design Example

This discussion is based upon the QFT design approach (see qft tool box) and the report file (QFT_REPORT.TXT) that contains the qft design data files that can be generated from the qft toolbox.

Step 1. Specifications:

A second order plant is modeled as

Plant tf = ka / s(s + a) with variations 1 < k < 5, 2 < a < 10

The tracking response specifications are

for upper tracking bound T_{RU} - M_m = 1.2 (1.58dB - overshoot)
- t_s = 1.65 sec (settling time)
for lower tracking bound T_{RL} - t_s = 1.65 sec (settling time)

The plant disturbance specification is

max output value to unit step - $|T_D|$ = 0.1 (-20 dB);

For a M_p = 1.2, zeta = 0.4559 and for t_s = 1.65, ω_n = 5.3169. Thus, a Ts was selected as 1.75 with ts < Ts and zeta = 0.48 with ω_n = 4.7619 resulting in the following T_{RU} (qfttru):

```
 ** Upper Tracking Transfer Function - qfttru **

 Numerator:          order = 1
  constant/gain =    1.889600
   polynomial                                  roots
    1.000000                          -12.000000   j  0.000000
   12.000000

 Denominator:        order = 2
  constant/gain =    1.000000
   polynomial                                  roots
    1.000000                          -2.285700   j -4.177500
    4.571400                          -2.285700   j  4.177500
   22.675931
```

In a similar trial and error process, T_{RL} evolved as

```
 ** Lower Tracking Transfer Function - qfttrl **

 Numerator:          order = 1
  constant/gain =    1.1600E4
   polynomial                                  roots
    1.000000

 Denominator:        order = 4
  constant/gain =    1.00000
   polynomial                                  roots
   1.00000E+0000              -4.00000E+0000   j 0.00000E+0000
        1.15250E+0002         -4.00000E+0000   j 0.00000E+0000
        1.59900E+0003         -7.25000E+0000   j 0.00000E+0000
        7.51600E+0003         -1.00000E+0002   j 0.00000E+0000
        1.16000E+0004
```

** Time domain tracking specifications - qfttrut

Time	Magnitude
0.00	0.000000
1.00	1.060103
2.00	1.004076
3.00	0.998920
4.00	1.000034
5.00	0.999972
6.00	0.999967
7.00	0.999968
8.00	0.999968
9.00	0.999968
10.00	0.999968

The desired T_{RU} model specifications are achieved as shown:

RISE TIME:	TR=	2.99722818757E-0001
DUPLICATION TIME:	TD=	3.98639562532E-0001
PEAK TIME:	TP=	6.54828325989E-0001
SETTLING TIME:	TS=	1.65130077524E+0000
PEAK VALUE:	MP=	1.19723535520E+0000
FINAL VALUE:	FV=	9.99967774642E-0001

Similarly, t_s for T_{RL} is 1.65.

The frequency domain specifications at the frequencies of interest (observe that selecting these frequencies is an iterative process although octave values are suggested as a minimum):

** Freq domain tracking specifications - qfttruf

Frequency	Magnitude	Phase
0.50	0.058664	-3.433671
1.25	0.359712	-9.197165
2.50	1.270365	-23.060350
5.00	0.581211	-73.185940
10.00	-9.666784	-109.602844
20.00	-18.898683	-107.343144
30.00	-23.253644	-102.916918
35.00	-24.785234	-101.344557
40.00	-26.073534	-100.086578
80.00	-32.421198	-95.248695

** Freq domain tracking specifications - qfttrlf

Frequency	Magnitude	Phase
0.50	-0.155383	-18.481695
1.25	-0.937225	-45.206616
2.50	-3.354850	-84.468469
5.00	-9.873879	-140.135077
10.00	-21.877692	-196.165662
20.00	-37.819826	-238.764487
30.00	-48.111949	-257.923966
35.00	-52.151961	-264.547541
40.00	-55.705826	-270.106893
80.00	-75.101888	-297.756713

** Freq domain tracking error spec - qftdelr (δ_R)

Frequency	Magnitude	Phase
0.50	0.214047	15.048024
1.25	1.296937	36.009451
2.50	4.625216	61.408118
5.00	10.455090	66.949137
10.00	12.210908	86.562818
20.00	18.921143	131.421343
30.00	24.858305	155.007048
35.00	27.366726	163.202984
40.00	29.632293	170.020315
80.00	42.680690	202.508018

The magnitude values should always be increasing for increasing frequency.

Step 2. Plant model variations:

Six plants were chosen to represent the plant variation model. The coefficient variation or pole/zero variation model could have been entered instead.

```
  ** QFT Plant Explicit Plant Models -  6

  QFTTF1

 Numerator:          order = 0
  constant/gain =    2.000000
   polynomial                                  roots
    1.000000

 Denominator:        order = 2
  constant/gain =    1.000000
   polynomial                                  roots
    1.000000                             0.000000   j  0.000000
    2.000000                            -2.000000   j  0.000000
    0.000000

  QFTTF2

 Numerator:          order = 0
  constant/gain =   10.000000
   polynomial                                  roots
    1.000000

 Denominator:        order = 2
  constant/gain =    1.000000
   polynomial                                  roots
    1.000000                             0.000000   j  0.000000
    2.000000                            -2.000000   j  0.000000
    0.000000

  QFTTF3

 Numerator:          order = 0
  constant/gain =   30.000000
   polynomial                                  roots
    1.000000

 Denominator:        order = 2
  constant/gain =    1.000000
   polynomial                                  roots
    1.000000                             0.000000   j  0.000000
    6.000000                            -6.000000   j  0.000000
    0.000000

  QFTTF4

 Numerator:          order = 0
  constant/gain =   50.000000
   polynomial                                  roots
    1.000000

 Denominator:        order = 2
  constant/gain =    1.000000
   polynomial                                  roots
    1.000000                             0.000000   j  0.000000
   10.000000                           -10.000000   j  0.000000
    0.000000

  QFTTF5

 Numerator:          order = 0
  constant/gain =   10.000000
   polynomial                                  roots
    1.000000
```

```
 Denominator:        order = 2
  constant/gain =    1.000000
   polynomial                                  roots
    1.000000                              0.000000   j  0.000000
   10.000000                            -10.000000   j  0.000000
    0.000000

  QFTTF6

 Numerator:          order = 0
  constant/gain =    6.000000
   polynomial                                  roots
    1.000000

 Denominator:        order = 2
  constant/gain =    1.000000
   polynomial                                  roots
    1.000000                              0.000000   j  0.000000
    6.000000                             -6.000000   j  0.000000
    0.000000


Step 3.  Disturbance model:

  ** Disturbance Transfer Function Spec - distf **

 Numerator:          order = 0
  constant/gain =    0.100000
   polynomial            roots
    1.000000

  Denominator:        order = 0
  constant/gain =    1.000000
   polynomial                                  roots
    1.000000


 ** Freq domain disturbance specifications - distff

   Frequency       Magnitude         Phase
      0.50        -20.000000        0.000000
      1.25        -20.000000        0.000000
      2.50        -20.000000        0.000000
      5.00        -20.000000        0.000000
     10.00        -20.000000        0.000000
     20.00        -20.000000        0.000000
     30.00        -20.000000        0.000000
     35.00        -20.000000        0.000000
     40.00        -20.000000        0.000000
     80.00        -20.000000        0.000000

In order to generate the high frequency u-contour,
   V = Pmax - Pmin  is generated.

          ** QFT U-Contour Parameters **

  frequency         Pmax(dB)        Pmin(dB)       V(dB)

     0.50000         19.98916         5.75731       14.23185
     1.25000         11.97387        -3.37030       15.34417
     2.50000          5.75731       -12.04544       17.80275
     5.00000         -0.96910       -22.58278       21.61368
    10.00000         -9.03090       -34.14973       25.11883
    20.00000        -19.03090       -46.06381       27.03291
    30.00000        -25.56303       -53.08351       27.52048
    35.00000        -28.12412       -55.75628       27.63216
    40.00000        -30.36629       -58.07264       27.70635
    80.00000        -42.21153       -70.10571       27.89418

      U-Contour V Height =    27.894180    or    28 db
```

ML-Contour = 3.84 dB for a phase margin of 40 degrees

Step 4. Plant template generation:

The plant templates are developed from the six plants. Figure B.1 depicts graphical the 10 templates.

** Plant Templates for Specified Frequencies

tp1.dat

Frequency	Magnitude	Phase
0.50	5.757311	-104.036243
0.50	19.736711	-104.036243
0.50	19.969945	-94.763642
0.50	19.989156	-92.862405
0.50	6.009756	-92.862405
0.50	5.990545	-94.763642
0.50	5.757311	-104.036243

** Plant Templates for Specified Frequencies

tp2.dat

Frequency	Magnitude	Phase
1.25	-3.370301	-122.005383
1.25	10.609100	-122.005383
1.25	11.856680	-101.768289
1.25	11.973866	-97.125016
1.25	-2.005534	-97.125016
1.25	-2.122720	-101.768289
1.25	-3.370301	-122.005383

Fig B.1

** Plant Templates for Specified Frequencies

tp3.dat

Frequency	Magnitude	Phase
2.50	-12.045439	-141.340192
2.50	1.933961	-141.340192
2.50	5.325358	-112.619865
2.50	5.757311	-104.036243
2.50	-8.222090	-104.036243
2.50	-8.654042	-112.619865
2.50	-12.045439	-141.340192

** Plant Templates for Specified Frequencies

tp4.dat

Frequency	Magnitude	Phase
5.00	-22.582780	-158.198591
5.00	-8.603380	-158.198591
5.00	-2.290273	-129.805571
5.00	-0.969100	-116.565051
5.00	-14.948500	-116.565051
5.00	-16.269673	-129.805571
5.00	-22.582780	-158.198591

** Plant Templates for Specified Frequencies

tp5.dat

Frequency	Magnitude	Phase
10.00	-34.149733	-168.690068
10.00	-20.170333	-168.690068
10.00	-11.792964	-149.036243
10.00	-9.030900	-135.000000
10.00	-23.010300	-135.000000
10.00	-25.772364	-149.036243
10.00	-34.149733	-168.690068

** Plant Templates for Specified Frequencies

tp6.dat

Frequency	Magnitude	Phase
20.00	-46.063814	-174.289407
20.00	-32.084414	-174.289407
20.00	-22.873040	-163.300756
20.00	-19.030900	-153.434949
20.00	-33.010300	-153.434949
20.00	-36.852440	-163.300756
20.00	-46.063814	-174.289407

** Plant Templates for Specified Frequencies

tp7.dat

Frequency	Magnitude	Phase
30.00	-53.083509	-176.185925
30.00	-39.104109	-176.185925
30.00	-29.712758	-168.690068
30.00	-25.563025	-161.565051
30.00	-39.542425	-161.565051
30.00	-43.692159	-168.690068
30.00	-53.083509	-176.185925

** Plant Templates for Specified Frequencies

tp8.dat

Frequency	Magnitude	Phase
35.00	-55.756280	-176.729512

35.00	-41.776880	-176.729512
35.00	-32.346087	-170.272421
35.00	-28.124120	-164.054604
35.00	-42.103520	-164.054604
35.00	-46.325487	-170.272421
35.00	-55.756280	-176.729512

** Plant Templates for Specified Frequencies

tp9.dat

Frequency	Magnitude	Phase
40.00	-58.072644	-177.137595
40.00	-44.093243	-177.137595
40.00	-34.636608	-171.469234
40.00	-30.366289	-165.963757
40.00	-44.345689	-165.963757
40.00	-48.616008	-171.469234
40.00	-58.072644	-177.137595

** Plant Templates for Specified Frequencies

tp10.dat

Frequency	Magnitude	Phase
80.00	-70.105713	-178.567904
80.00	-56.126313	-178.567904
80.00	-46.605535	-175.710847
80.00	-42.211533	-172.874984
80.00	-56.190933	-172.874984
80.00	-60.584935	-175.710847
80.00	-70.105713	-178.567904

Step 5. Bounds (tracking, disturbance, composite):

The tracking bounds are achieved using the specified geometric approach which results in the following frequency tables for the 10 frequencies of interest.

** Tracking Bounds for Specified Frequencies

trb1.dat

Frequency	Magnitude	Phase
0.50	30.366686	0.000000
0.50	30.366686	-10.000000
0.50	29.866686	-20.000000
0.50	29.866686	-30.000000
0.50	29.116686	-40.000000
0.50	28.116686	-50.000000
0.50	27.116686	-60.000000
0.50	25.366686	-70.000000
0.50	22.866686	-80.000000
0.50	19.616686	-90.000000
0.50	18.116686	-100.000000
0.50	21.116686	-110.000000
0.50	24.866686	-120.000000
0.50	27.116686	-130.000000
0.50	28.616686	-140.000000
0.50	29.616686	-150.000000
0.50	30.116686	-160.000000
0.50	30.616686	-170.000000
0.50	30.616686	-180.000000

** Tracking Bounds for Specified Frequencies

trb2.dat

Frequency	Magnitude	Phase
1.25	14.158996	0.000000
1.25	13.908996	-10.000000
1.25	13.408996	-20.000000

1.25	12.721496	-30.000000
1.25	12.158996	-40.000000
1.25	11.971496	-50.000000
1.25	11.533996	-60.000000
1.25	10.908996	-70.000000
1.25	10.033996	-80.000000
1.25	8.846496	-90.000000
1.25	7.471496	-100.000000
1.25	7.283996	-110.000000
1.25	8.971496	-120.000000

** Tracking Bounds for Specified Frequencies

trb3.dat

Frequency	Magnitude	Phase
2.50	1.357881	0.000000
2.50	1.076631	-10.000000
2.50	0.670381	-20.000000
2.50	0.139131	-30.000000
2.50	-0.485869	-40.000000
2.50	-1.204619	-50.000000
2.50	-1.923369	-60.000000
2.50	-2.345244	-70.000000
2.50	-2.829619	-80.000000
2.50	-3.313994	-90.000000
2.50	-3.657744	-100.000000
2.50	-3.720244	-110.000000
2.50	-3.907744	-120.000000

** Tracking Bounds for Specified Frequencies

trb4.dat

Frequency	Magnitude	Phase
5.00	-9.496843	0.000000
5.00	-9.809343	-10.000000
5.00	-10.153093	-20.000000
5.00	-10.496843	-30.000000
5.00	-10.824968	-40.000000
5.00	-11.153093	-50.000000
5.00	-11.449968	-60.000000
5.00	-11.715593	-70.000000
5.00	-11.934343	-80.000000
5.00	-11.981218	-90.000000
5.00	-11.817155	-100.000000
5.00	-11.067155	-110.000000
5.00	-10.379655	-120.000000

** Tracking Bounds for Specified Frequencies

trb5.dat

Frequency	Magnitude	Phase
10.00	-11.639968	0.000000
10.00	-11.843093	-10.000000
10.00	-12.061843	-20.000000
10.00	-12.280593	-30.000000
10.00	-12.499343	-40.000000
10.00	-12.702468	-50.000000
10.00	-12.905593	-60.000000
10.00	-13.061843	-70.000000
10.00	-13.202468	-80.000000
10.00	-13.311843	-90.000000
10.00	-13.272780	-100.000000
10.00	-13.147780	-110.000000
10.00	-12.444655	-120.000000

** Tracking Bounds for Specified Frequencies

trb6.dat

Frequency	Magnitude	Phase
20.00	-21.967134	0.000000
20.00	-22.154634	-10.000000
20.00	-22.264009	-20.000000
20.00	-22.295259	-30.000000
20.00	-22.248384	-40.000000
20.00	-22.123384	-50.000000
20.00	-21.920259	-60.000000
20.00	-21.639009	-70.000000
20.00	-21.310884	-80.000000
20.00	-20.912446	-90.000000
20.00	-20.474946	-100.000000
20.00	-20.014009	-110.000000
20.00	-19.326509	-120.000000

** Tracking Bounds for Specified Frequencies

trb7.dat

Frequency	Magnitude	Phase
30.00	-35.676283	0.000000
30.00	-35.863783	-10.000000
30.00	-35.895033	-20.000000
30.00	-35.707533	-30.000000
30.00	-35.363783	-40.000000
30.00	-34.801283	-50.000000
30.00	-34.051283	-60.000000
30.00	-33.082533	-70.000000
30.00	-31.926283	-80.000000
30.00	-30.582533	-90.000000
30.00	-29.113783	-100.000000
30.00	-27.582533	-110.000000
30.00	-26.098158	-120.000000

** Tracking Bounds for Specified Frequencies

trb8.dat

Frequency	Magnitude	Phase
35.00	-56.928155	0.000000
35.00	-57.178155	-10.000000
35.00	-57.178155	-20.000000
35.00	-56.928155	-30.000000
35.00	-56.178155	-40.000000
35.00	-55.428155	-50.000000
35.00	-54.178155	-60.000000
35.00	-52.428155	-70.000000
35.00	-49.928155	-80.000000
35.00	-46.428155	-90.000000
35.00	-41.303155	-100.000000
35.00	-35.803155	-110.000000
35.00	-31.365655	-120.000000

The disturbance bounds are achieved using the specified geometric approach which results in the following frequency tables for the 10 frequencies of interest.

** Disturbance Bounds for Specified Frequencies

db1.dat

Frequency	Magnitude	Phase
0.50	4.841138	-10.000000
0.50	4.866419	-20.000000
0.50	4.932439	-30.000000
0.50	5.022113	-40.000000
0.50	5.132764	-50.000000
0.50	5.261063	-60.000000
0.50	5.403127	-70.000000
0.50	5.554625	-80.000000
0.50	5.710920	-90.000000

```
     0.50          5.867215       -100.000000
     0.50          6.190783       -110.000000
     0.50          6.990566       -120.000000
     0.50          7.250768       -123.521237

** Disturbance Bounds for Specified Frequencies

db2.dat

  Frequency       Magnitude         Phase
     1.25         -5.818170       -10.000000
     1.25         -5.883702       -20.000000
     1.25         -5.882905       -30.000000
     1.25         -5.799389       -40.000000
     1.25         -5.476635       -50.000000
     1.25         -5.099829       -60.000000
     1.25         -4.680040       -70.000000
     1.25         -4.230305       -80.000000
     1.25         -3.765184       -90.000000
     1.25         -3.300063      -100.000000
     1.25         -2.850329      -110.000000
     1.25         -2.430539      -120.000000
     1.25         -2.292340      -123.521237

** Disturbance Bounds for Specified Frequencies

db3.dat

  Frequency       Magnitude         Phase
     2.50        -17.831487       -10.000000
     2.50        -18.133736       -20.000000
     2.50        -18.301196       -30.000000
     2.50        -18.332603       -40.000000
     2.50        -18.227750       -50.000000
     2.50        -17.987368       -60.000000
     2.50        -17.610768       -70.000000
     2.50        -16.966317       -80.000000
     2.50        -16.202078       -90.000000
     2.50        -14.493796      -100.000000
     2.50        -12.649904      -110.000000
     2.50        -11.053478      -120.000000
     2.50        -10.557684      -123.521237

** Disturbance Bounds for Specified Frequencies

db4.dat

  Frequency       Magnitude         Phase
     0.50         -3.468183       -10.000000
     0.50         -3.544164       -20.000000
     0.50         -3.592646       -30.000000
     0.50         -3.612203       -40.000000
     0.50         -3.602262       -50.000000
     0.50         -3.563115       -60.000000
     0.50         -3.495909       -70.000000
     0.50         -3.331169       -80.000000
     0.50         -2.909641       -90.000000
     0.50         -2.488113      -100.000000
     0.50         -2.080328      -110.000000
     0.50         -1.699344      -120.000000
     0.50         -1.573820      -123.521237

** Disturbance Bounds for Specified Frequencies

db5.dat

  Frequency       Magnitude         Phase
     0.50        -16.829739       -10.000000
     0.50        -16.967571       -20.000000
     0.50        -17.032351       -30.000000
     0.50        -17.022558       -40.000000
```

```
     0.50        -16.938420        -50.000000
     0.50        -16.781924        -60.000000
     0.50        -16.556893        -70.000000
     0.50        -16.269100        -80.000000
     0.50        -15.926364        -90.000000
     0.50        -15.475263       -100.000000
     0.50        -14.839083       -110.000000
     0.50        -14.203693       -120.000000
     0.50        -13.403941       -123.521237

** Disturbance Bounds for Specified Frequencies

db6.dat

  Frequency       Magnitude         Phase
     0.50        -45.452773        -10.000000
     0.50        -45.591908        -20.000000
     0.50        -45.493507        -30.000000
     0.50        -45.153305        -40.000000
     0.50        -44.556190        -50.000000
     0.50        -43.674382        -60.000000
     0.50        -42.464581        -70.000000
     0.50        -40.865973        -80.000000
     0.50        -38.807586        -90.000000
     0.50        -36.252094       -100.000000
     0.50        -33.312533       -110.000000
     0.50        -30.336900       -120.000000
     0.50        -29.356833       -123.521237
```

The composite bounds--the combination of the tracking and disturbance bounds--are as follows:

```
** Composite Bounds for Specified Frequencies

cb1.dat

  Frequency       Magnitude         Phase
     0.50         30.366686        -10.000000
     0.50         30.366686        -20.000000
     0.50         29.866686        -30.000000
     0.50         29.866686        -40.000000
     0.50         29.116686        -50.000000
     0.50         28.116686        -60.000000
     0.50         27.116686        -70.000000
     0.50         25.366686        -80.000000
     0.50         22.866686        -90.000000
     0.50         19.616686       -100.000000
     0.50         18.116686       -110.000000
     0.50         21.116686       -120.000000
     0.50         24.866686       -123.521237

** Composite Bounds for Specified Frequencies

cb2.dat

  Frequency       Magnitude         Phase
     1.25         14.158996        -10.000000
     1.25         13.908996        -20.000000
     1.25         13.408996        -30.000000
     1.25         12.721496        -40.000000
     1.25         12.158996        -50.000000
     1.25         11.971496        -60.000000
     1.25         11.533996        -70.000000
     1.25         10.908996        -80.000000
     1.25         10.033996        -90.000000
     1.25          8.846496       -100.000000
     1.25          7.471496       -110.000000
     1.25          7.283996       -120.000000
     1.25          8.971496       -123.521237

** Composite Bounds for Specified Frequencies
```

cb3.dat

Frequency	Magnitude	Phase
2.50	1.357881	-10.000000
2.50	1.076631	-20.000000
2.50	0.670381	-30.000000
2.50	0.139131	-40.000000
2.50	-0.485869	-50.000000
2.50	-1.204619	-60.000000
2.50	-1.923369	-70.000000
2.50	-2.345244	-80.000000
2.50	-2.829619	-90.000000
2.50	-3.313994	-100.000000
2.50	-3.657744	-110.000000
2.50	-3.720244	-120.000000
2.50	-3.907744	-123.521237

** Composite Bounds for Specified Frequencies

cb4.dat

Frequency	Magnitude	Phase
5.00	-3.468183	-10.000000
5.00	-3.544164	-20.000000
5.00	-3.592646	-30.000000
5.00	-3.612203	-40.000000
5.00	-3.602262	-50.000000
5.00	-3.563115	-60.000000
5.00	-3.495909	-70.000000
5.00	-3.331169	-80.000000
5.00	-2.909641	-90.000000
5.00	-2.488113	-100.000000
5.00	-2.080328	-110.000000
5.00	-1.699344	-120.000000
5.00	-1.573820	-123.521237

** Composite Bounds for Specified Frequencies

cb5.dat

Frequency	Magnitude	Phase
10.00	-11.639968	-10.000000
10.00	-11.843093	-20.000000
10.00	-12.061843	-30.000000
10.00	-12.280593	-40.000000
10.00	-12.499343	-50.000000
10.00	-12.702468	-60.000000
10.00	-12.905593	-70.000000
10.00	-13.061843	-80.000000
10.00	-13.202468	-90.000000
10.00	-13.311843	-100.000000
10.00	-13.272780	-110.000000
10.00	-13.147780	-120.000000
10.00	-12.444655	-123.521237

** Composite Bounds for Specified Frequencies

cb6.dat

Frequency	Magnitude	Phase
20.00	-21.967134	-10.000000
20.00	-22.154634	-20.000000
20.00	-22.264009	-30.000000
20.00	-22.295259	-40.000000
20.00	-22.248384	-50.000000
20.00	-22.123384	-60.000000
20.00	-21.920259	-70.000000
20.00	-21.639009	-80.000000
20.00	-21.310884	-90.000000
20.00	-20.912446	-100.000000
20.00	-20.474946	-110.000000

20.00	-20.014009	-120.000000
20.00	-19.326509	-123.521237

** Composite Bounds for Specified Frequencies

cb7.dat

Frequency	Magnitude	Phase
30.00	-35.676283	0.000000
30.00	-35.863783	-10.000000
30.00	-35.895033	-20.000000
30.00	-35.707533	-30.000000
30.00	-35.363783	-40.000000
30.00	-34.801283	-50.000000
30.00	-34.051283	-60.000000
30.00	-33.082533	-70.000000
30.00	-31.926283	-80.000000
30.00	-30.582533	-90.000000
30.00	-29.113783	-100.000000
30.00	-27.582533	-110.000000
30.00	-26.098158	-120.000000
30.00	-24.738783	-130.000000
30.00	-23.473158	-140.000000
30.00	-21.215345	-150.000000
30.00	-19.879408	-160.000000
30.00	-19.066908	-170.000000

** Composite Bounds for Specified Frequencies

cb8.dat

Frequency	Magnitude	Phase
35.00	-56.928155	0.000000
35.00	-57.178155	-10.000000
35.00	-57.178155	-20.000000
35.00	-56.928155	-30.000000
35.00	-56.178155	-40.000000
35.00	-55.428155	-50.000000
35.00	-54.178155	-60.000000
35.00	-52.428155	-70.000000
35.00	-49.928155	-80.000000
35.00	-46.428155	-90.000000
35.00	-41.303155	-100.000000
35.00	-35.803155	-110.000000
35.00	-31.365655	-120.000000
35.00	-28.240655	-130.000000
35.00	-26.037530	-140.000000
35.00	-24.342217	-150.000000
35.00	-21.318780	-160.000000
35.00	-20.139092	-170.000000
35.00	-19.600030	-180.000000

Step 6. Loop transmission design:

The loop transmission is designed to have a phase angle above gamma - 180 = -140 over the region of frequency 3 to 40 rad/sec which prohibits L_o from penetrating the u-contour. Also, L_o was designed to have a magnitude greater than the bounds at the specified discrete frequencies. The bode plot provided by the qft tool box reflects this characteristic. In addition, the angle contributions are determined as each new pole or zero is add in the L_o design process using the bode plot. An iterative design technique is employed starting with

$$L_o(s) = Po/s = 2/s(s+2)$$

The resulting L_o meeting the bounding criteria using the QFD approach is

** Loop Transmission - L_o **

```
Numerator:          order = 4
 constant/gain = 701766.000000
  polynomial                                  roots
       1.00                              -0.010000   j  0.000000
```

```
    10562.0                              -12.000000   j  0.000000
  5626705.62                            -550.000000   j  0.000000
 66056266.00                          -10000.000000   j  0.000000
   660000.00

 Denominator:        order = 7
  constant/gain =    1.000000
   polynomial                                  roots
             1.0                     0.000000   j  0.000000
          8727.00                        0.000000   j  0.000000
      51772450.00                       -2.000000   j  0.000000
    16238510000.00                    -125.000000   j  0.000000
  1257270000000.00             -200.000000   j  0.000000
  2450000000000.00            -4200.000000   j -5600.000000
          0.000000                   -4200.000000   j  5600.000000
          0.000000
```

The zero at -10000 was added to decrease the gain. The complex pole has a zeta of 0.6 and a wn = 7000 rad/sec

The following frequency response can be check for achieving the desired bounds:

** Freq domain Loop Transmission - lof

Frequency	Magnitude	Phase
0.10	45.564071	-98.160021
1.10	23.592022	-114.803398
2.10	15.989122	-128.097662
3.10	10.663229	-134.869957
4.10	6.586885	-137.915513
5.10	3.339406	-138.960580
9.10	-5.072261	-136.351593
10.10	-6.499835	-135.269468
19.10	-14.389152	-128.424274
20.10	-14.963042	-128.047181
29.10	-18.955878	-126.971790
30.10	-19.310471	-127.041855
34.10	-20.614006	-127.574123
35.10	-20.915351	-127.760558
39.10	-22.041838	-128.673153
40.10	-22.306226	-128.936752

Figure B.2 presents the combined curves for the composite bounds, L_o and the U-contour

Step 7. Controller G generation:

Using L_o and the nominal plant Po, the controller is generated

** Controller - Gcontr **

```
 Numerator:          order = 4
  constant/gain = 701766.000000
   polynomial                                  roots
    1.000000                              -0.010000   j  0.000000
  10562.010000                           -12.000000   j  0.000000
  5626705.620000                        -550.000000   j  0.000000
  66056266.000000                     -10000.000000   j  0.000000
  660000.000000
```

Fig B.2

```
Denominator:        order = 5
 constant/gain =    2.000000
  polynomial                                  roots
            1.000000                      0.000000   j  0.000000
         8725.000000                   -125.000000   j  0.000000
     51755000.000000                   -200.000000   j  0.000000
   16135000000.000000                 -4200.000000   j-5600.000000
 1225000000000.000000                 -4200.000000   j 5600.000000
            0.000000
```

The CLTFs with G and each plant can be generated and analyzed for a unit step input.

Step 8. Filter generation:

** QFT Data for Filter Generation **

frequency	Tmax	Tmin	T_{RU}	T_{RL}	T_{RU}-Tmax	T_{RL}-Tmin
0.50	0.05	0.00	0.06	-0.16	0.01	-0.16
1.25	0.29	0.00	0.36	-0.94	0.07	-0.94
2.50	1.14	0.01	1.27	-3.35	0.13	-3.36
5.00	3.56	-0.02	0.58	-9.87	-2.97	-9.85
10.00	2.36	-3.74	-9.67	-21.88	-12.03	-18.13
20.00	0.98	-14.00	-18.90	-37.82	-19.88	-23.82
30.00	1.11	-18.72	-23.25	-48.11	-24.37	-29.39
35.00	1.06	-20.42	-24.79	-52.15	-25.85	-31.74
40.00	1.03	-21.87	-26.07	-55.71	-27.11	-33.84
80.00	1.31	-29.82	-32.42	-75.10	-33.73	-45.28

The filter was design to *fit* between the values of the last two columns of the previous table. Using a trail and error procedure, the following filter tf was developed:

** Prefilter - filter **

```
Numerator:          order = 1
 constant/gain = 116.667000
  polynomial                                  roots
   1.000000                            -18.000000   j  0.000000
  18.000000

Denominator:        order = 3
 constant/gain =    1.000000
  polynomial                                  roots
   1.000000                             -3.000000   j  0.000000
  83.000000                            -10.000000   j  0.000000
 940.000000                            -70.000000   j  0.000000
 2100.000000
```

Observe that filter frequency data at the specified frequencies is within the desired magnitude band.

** Freq domain Filter Data - filterd

Frequency	Magnitude	Phase
2.50	1.142266	0.005701
5.00	3.555355	-0.023358
10.00	2.359959	-3.743955
20.00	0.982747	-13.995255
30.00	1.111816	-18.724763
35.00	1.064837	-20.416449
40.00	1.033052	-21.867131
80.00	1.306490	-29.822368

Step 9. Simulation (time and frequency domains):

*** Tracking Simulation ***

Observe that frequency domain responses are within the desired tracking tolerances specified by T_{RU} and T_{RL}. Figure B.3 presents the 6 variations. The simulations for Plant 1 are shown in the following tables:

** Frequency Domain Tracking Simulations - simf#

simf1.dat

Frequency	Magnitude	Phase
0.00	0.004601	0.000000
1.00	-0.299118	-24.962418
2.00	-0.979253	-47.659076
3.00	-1.653054	-68.522305
4.00	-2.186886	-90.022440
5.00	-2.885382	-114.795202
10.00	-16.505601	-205.594432
20.00	-34.408601	-231.877907
30.00	-43.727907	-241.745678
40.00	-50.185303	-250.958689
50.00	-55.297283	-260.066176
60.00	-59.636560	-268.824671
70.00	-63.468612	-277.061248
80.00	-66.934951	-284.701878
90.00	-70.119377	-291.733938
100.00	-73.075825	-298.177534

**** Disturbance Simulation ***

Observe that time domain unit step responses are within the desired disturbance tolerance specified by td. Figure B.4 depicts the six variations. The following list is for plant 1 time domain simulation.

Fig B.3

Fig B.4

** Time Domain Disturbance Simulation - dsimt#

dsimt1.dat

Time	Magnitude
0.00	-0.000000
1.00	0.049418
2.00	0.051887
3.00	0.051440
4.00	0.050916
5.00	0.050407
6.00	0.049905
7.00	0.049408
8.00	0.048917
9.00	0.048430
10.00	0.047948

Observe that frequency domain responses are within the desired disturbance tolerance specified by td.

** Frequency Domain Disturbance Simulations - dsimf#

dsimf1.dat

Frequency	Magnitude	Phase
0.10	-25.568491	4.995521
1.10	-25.339810	-7.540779
2.10	-24.848301	-16.181341
3.10	-24.084997	-26.969107
4.10	-23.199018	-41.781977
5.10	-22.642605	-62.204749
10.10	-31.735471	-142.160328
20.10	-45.244328	-165.337401
30.10	-52.592365	-170.916968
40.10	-57.703980	-173.558937
50.10	-61.641599	-175.130722
60.10	-64.850193	-176.178110
70.10	-67.560114	-176.923008
80.10	-69.906538	-177.474652
90.10	-71.975765	-177.894259

****

Conclusions - Thus a robust controller has been designed, analyzed and simulated for the given second-order system with plant coefficient variation and plant disturbances.

(This example was based upon the work of Dennis Trosen in the AFIT course EENG660 as taught by Professor Houpis)

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13. ABSTRACT (Maximum 200 words)

This thesis is a continuation of the ICECAP-PC research project conducted under Prof. Gary B. Lamont at the Air Force Institute of Technology. It is an ongoing development of a public domain Computer Aided Design package for Control Engineering and Digital Signal Processing students, faculty and practitioners with a special emphasis on education. This investigation begins with the software maintenance task of restructuring, debugging, and testing the functional version of ICECAP-PC 9.0. The continuous, traditional portions are then ported to a new object-oriented program structure which is the primary focus of this effort. New interactive graphics capabilities are then added as well as new procedures for the time and frequency response plots. All basic math algorithms are rewritten to be more accurate within a contemporary personal computer ennvironment. Finally, using a program extension concept called a toolbox, a Multiple-Input-Single-Output (MISO) Quantitative Feedback Theory (QFT) toolbox is created. This toolbox allows manual, interactive, and automatic QFT design for continuous, linear, time invariant MISO control system problems.

14. SUBJECT TERMS

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