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Report No. ONR-109

Research on Computer Aided Design for Maintainability

Douglas M. Towne
Mark C. Johnson

BEHAVIORAL TECHNOLOGY LABORATORIES
Department of Psychology
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The report summarizes the operation of the performance model which generates projected diagnostic sequences for sample failures; it presents a complete example of a maintainability analysis of a system; and it discusses the current application of the technique within an intelligent tutoring system.

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The report summarizes the operation of the performance model which generates projected diagnostic sequences for sample failures; it presents a complete example of a maintainability analysis of a system; and it discusses the current application of the technique within an intelligent tutoring system.

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Nicholas Bond, Anthony Mason, and Michael Fehling contributed in significant ways to the formulation of the performance model; Richard Mishler and William Corwin were responsible for conducting and analysing the experimental studies conducted throughout the project.

We also thank Martin Tolcott, formerly of the Office of Naval Research, for his support and encouragement in performing this work.

TABLE OF CONTENTS

LIST OF FIGURES

SECTION I. INTRODUCTION

This report is for research performed under contract N00014-80-C-0493. The research is part of a multi-disciplinary program concerned with design for maintainability. The objective of this component has been to investigate generalized methods for measuring and predicting maintainability characteristics of an equipment as a consequence of its internal structure and of the design of the man-machine interface.

Background

In recent years we have been concerned with understanding the ways expert diagnosticians conduct fault isolation activities as a function of their knowledge, the constraints present in the maintenance environment, and the architecture of the system design. A key outcome of this research has been the development of a generic (device-independent) model of troubleshooting behavior which can be applied to a wide range of specific equipments (Towne, 1984, 1986). The model, termed PROFILE, generates a detailed sequence of testing actions required to isolate any fault of interest. When standard times are retrieved for each of the detailed maintenance actions, a total time to diagnose and repair is obtained. Doing this over a large sample of representative failures produces a distribution of corrective maintenance times which provide a measure of the likely corrective maintenance workload implied by the system design and the maintenance conditions.

When provided complete data about the internal design of a system, PROFILE's troubleshooting sequences are near-optimal, and appear very much like those of expert maintenance technicians. Exhaustive studies (Towne, Johnson, & Corwin, 1982, 1983) comparing PROFILE performance to that of actual technicians have yielded some insights into the ways in which poorer maintainers differ from experts. The studies showed that varying the precision of fault effect knowledge in the model produced variations in diagnostic performance very much like those observed in human technician samples, whereas varying the troubleshooting strategy effectiveness did not. As a result of these findings, PROFILE has been configured to accept either perfect fault-effect data, to produce near optimal fault isolation sequences, or somewhat degraded data, to simulate the performance of a more typical technician population.

Applications

PROFILE can be applied in at least the following five ways:

- to evaluate an equipment design for its maintainability characteristics;
- to support an intelligent maintenance training system that can evaluate a learner's diagnostic strategies and can recommend preferred approaches;
- to generate fault isolation strategies to be provided in technical documentation or to be executed as automated tests;
- to determine the workload implications of various repair policies;
- to assist in the identification of actual failures in the field.

To date, PROFILE has been applied experimentally in the first two of these ways. These will be described in sections III and IV, following an updated summary of PROFILE operation in Section II. Section V presents conclusions.

SECTION II. SYSTEM SUMMARY

PROFILE is a form of expert system whose rules have been generalized and built into the model, rather than expressed as domain-specific data. The primary advantages of following the generic approach are (1) the cost and effort of capturing the necessary system-specific data are kept modest, (2) the quality of diagnostic prescriptions generated by PROFILE are not dependent upon an individual expert's skill, attention to detail, and recall abilities (in specifying a particular diagnostic approach), (3) the process can be used to generate diagnostic sequences under widely varying conditions, including student-created conditions and conditions of interest to a designer, and (4) the analyses are consistent and repeatable as they are not subject to individual differences in troubleshooting style. These advantages have come at the cost of conducting research leading to the characterization of diagnostic performance in a generalized manner.

Organization of the Model

The organization of the model is a highly structured set of generic troubleshooting rules and associated metrics computed by specialized functions. The rules and metrics were developed over a period of several years, and were the result of extensive experimental observations of human diagnostic performance and of studies of alternative diagnostic strategies (Towne, Fehling, and Bond, 1981). The model performs three basic functions at each step of a corrective maintenance problem: (1) test selection, (2) test "performance", and (3) symptom interpretation. Test performance within the model involves recording that the selected test would be done by the simulated maintenance expert and updating internal records of the symptom information obtained and the state of the system. The selection-performance-interpretation cycle is repeated until the true failure is identified and resolved. The organization of the data and processes is shown in Figure 1.

The specifications for a particular equipment are contained in the *design specifications*, in Figure 1. The remainder of the system consists of generic fault isolation processes (the test selector, the test performer, and the test interpreter), some subordinate utility functions (time calculator and test value calculator), plus working memory which reflects current suspicion levels and the current state of the internally-simulated equipment.

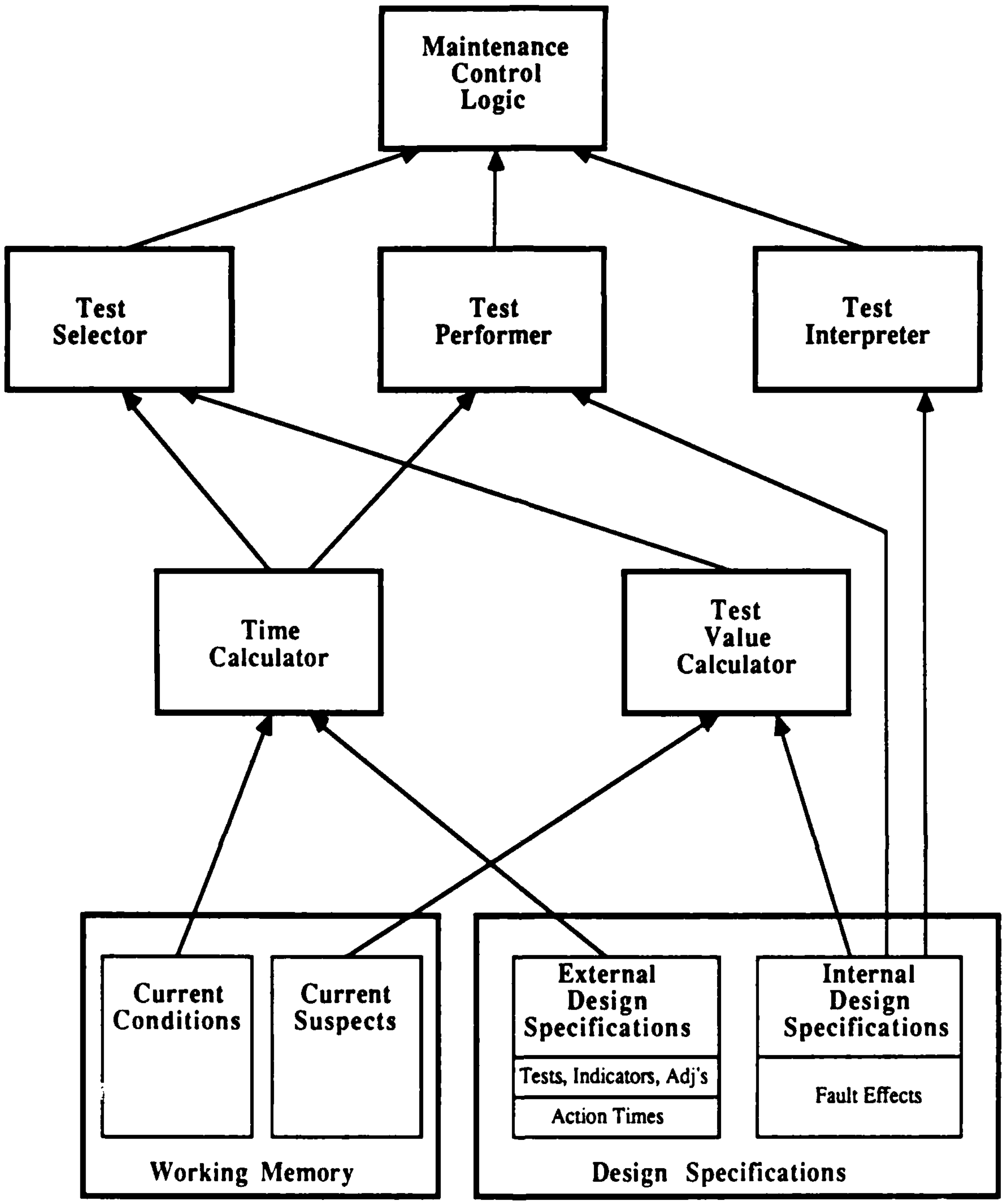


Figure 1. PROFILE System Organization.

Test Selection

The model considers any action which can yield new information to be a test, thus front panel tests, use of test equipment at internal test points, adjustments, and replacing suspected components are all candidates for performance at each stage of a problem. To select the next diagnostic action, the test selector function shown in Figure 1 first computes the time required to perform each possible action and the expected utility of each.

The *time calculator* function determines those actions which must be performed to accomplish the test under consideration and the time those actions will take. The determination of required actions includes a search algorithm for selecting those actions which will transition the system from its current state to the state required for performing the test under consideration. The *test value calculator* examines the fault-effect data to determine what information would be obtained from each test outcome. After these two utility functions have yielded their results, for all available tests, the test selector chooses that one which minimizes the expected time to identify the fault. This is done by finding the minimum of the term:

[TEST TIME + EXPECTED COMPLETION TIME]

where TEST TIME is the time to perform the test (which is conditional upon the current state of the system) and EXPECTED COMPLETION TIME is the best estimate of the time to complete the diagnosis *following the test*. By selecting the test which minimizes this expression, the model is finding the test which produces the most gain, assuming that only one more test will be made. This heuristic is a form of suboptimization which allows rapid computation of excellent diagnostic approaches. Because the exploration of solution possibilities is not exhaustive, however, the generated diagnostic sequences are not guaranteed to be optimal.

Because test performance times and expected test utilities can change radically following any single action, these measures must be recomputed at each stage of a fault isolation sequence. Furthermore, a sizable sample of failures must be analyzed to provide a reliable indication of the expected maintenance workload. As a result, the analysis process is highly compute-bound.

The scheme described above for selecting tests represents a slight revision of the algorithm reported earlier. The process used until recently selected that test which maximizes the ratio of new information (about the source of the failure) to test time. This metric almost always produces rational decisions, but encounters a scaling problem (see Appendix A) which could yield irrational decisions in some extreme cases. A further disadvantage of the ratio is that it could not be used to select replacements or tests just prior to replacements, called "direct" tests. As a result, two additional rules were previously required for these special needs.

While the revised algorithm yields results identical to the earlier one in most cases, this newer formulation avoids the scaling problems and it can be used to select all tests and replacements. Thus the PROFILE model is now simpler and somewhat more elegant than before, and it functions appropriately within all ranges of time and cost.

Test Performance

The model simulates the performance of the selected test by (1) adding the time to perform the test to the cumulative time to resolve the problem, and (2) retrieving from the fault-effect data the symptom which the "actual" (assumed) fault would yield. This symptom is passed to the test interpreter function for assessment.

Test Interpretation

The test interpreter function scans the fault-effect data to determine the significance of the test symptom, and it revises the current suspicion levels of the possible faults by considering the similarities between the symptoms received and those possible from each malfunction.

Phases of a Diagnostic Problem

While the cycle of selecting, performing, and interpreting tests is carried out repeatedly by the model, this occurs under three somewhat different conditions: (1) initially in a fault isolation process, prior to the observation of any abnormal indications, (2) when the selected test does not involve replacement of a suspected part, and (3) when the selected test does involve replacement of a suspected part.

Figure 2 reflects these three basic phases, each of which involves the test selector, test performer, and test interpreter, however their particular operation changes somewhat depending upon the phase of the diagnostic process. While the search for abnormality is always done first in a problem, PROFILE may shift between testing and replacing multiple times in a problem, as described below.

Search for Abnormality

The upper loop in Figure 2 reflects a search by PROFILE for some abnormal symptom. This causes the model to begin troubleshooting by testing major critical functions, each of which involves as much of the system as possible. During this phase the test selector implements a rule of searching the fault effect data for the test which maximizes the probability of detecting an abnormality. In information-theory terms, as applied later in a problem, a test which meets this criterion is often a poor test for fault identification purposes, but is an effective test for getting started.

When PROFILE starts a fault-isolation process, the probability (suspicion level) of each RU is set according to its generic reliability. In this manner, the inherent failure likelihoods of components initially tend to draw PROFILE's testing toward unreliable areas of the system. Generally, the reliability information is simply that related to each generic component in the system. If component reliabilities change drastically in a particular system configuration, however, they may be revised to reflect the impacts.

If all major functions of the equipment are found to be normal, then the diagnosis ends with *no evidence of failure*. This diagnosis sequence provides a measure of the time and maintenance actions required to check out a functioning system (one of the most common maintenance situations at the depot level). If, however, some abnormal function is observed, then the model shifts to the standard cycle of selecting tests based upon minimization of expected completion time.

Test performance

The middle section of the flow diagram is the main cycle in which the test selector, test performer, and test interpreter operate to select tests and update suspicion levels. When the selected test does not involve replacement of a suspected unit, the cyclic execution of the three functions continues without interruption.

Replacement

Invariably in a diagnostic problem in which some failure does exist, PROFILE will find that a lower expected completion time is achieved from replacing some suspected part than from performing another "conventional" test. This occurs because the current suspicion level of the part has reached a level, from completed tests, which warrants its replacement followed by a "confirming" test to see if the abnormality disappears. Because the replacement plus confirming check provide some new information (about one particular part), it is considered a test, and is evaluated for potential value in exactly the same way as are other tests.

Because the information value of a replacement is usually very low, and the time cost is often high, PROFILE rarely selects a replacement until it has performed more informative tests. Adjustments followed by confirming tests, are somewhat more attractive in general, as they usually do not involve extensive disassembly. Replacements are further penalized with the cost of the spare part being replaced, so that replacements are not often performed until there is high certainty that the failure has been identified. This rule is weakened, however, when time pressure, as specified by a user parameter, is extreme. In this case expensive components and subassemblies may be replaced by PROFILE in its effort to minimize restoration time without regard for the associated consumption of spares. In all cases, more expensive spares are less likely to be replaced than cheaper ones, all other factors being equal.

Upon choosing to replace a part, the model sets the part's suspicion level to zero; it adds on the time to accomplish the replacement and any associated shut-down, disassembly, reassembly, and restart operations; and then it investigates the advisability of also replacing other associated parts which share a high suspicion level and are easily accessed at this time. If PROFILE finds that further replacements make sense from a time minimization standpoint, it will also call for replacing these, usually inexpensive, components as a group, without further intervening tests. This is called "gang replacement".

Following replacement of one or more parts, the model selects a "confirming test" (see the lowest portion of Figure 2), which is the quickest previously-performed test which yielded an abnormal symptom. If the confirming test is now normal, the repair is completed. Otherwise, further testing continues.

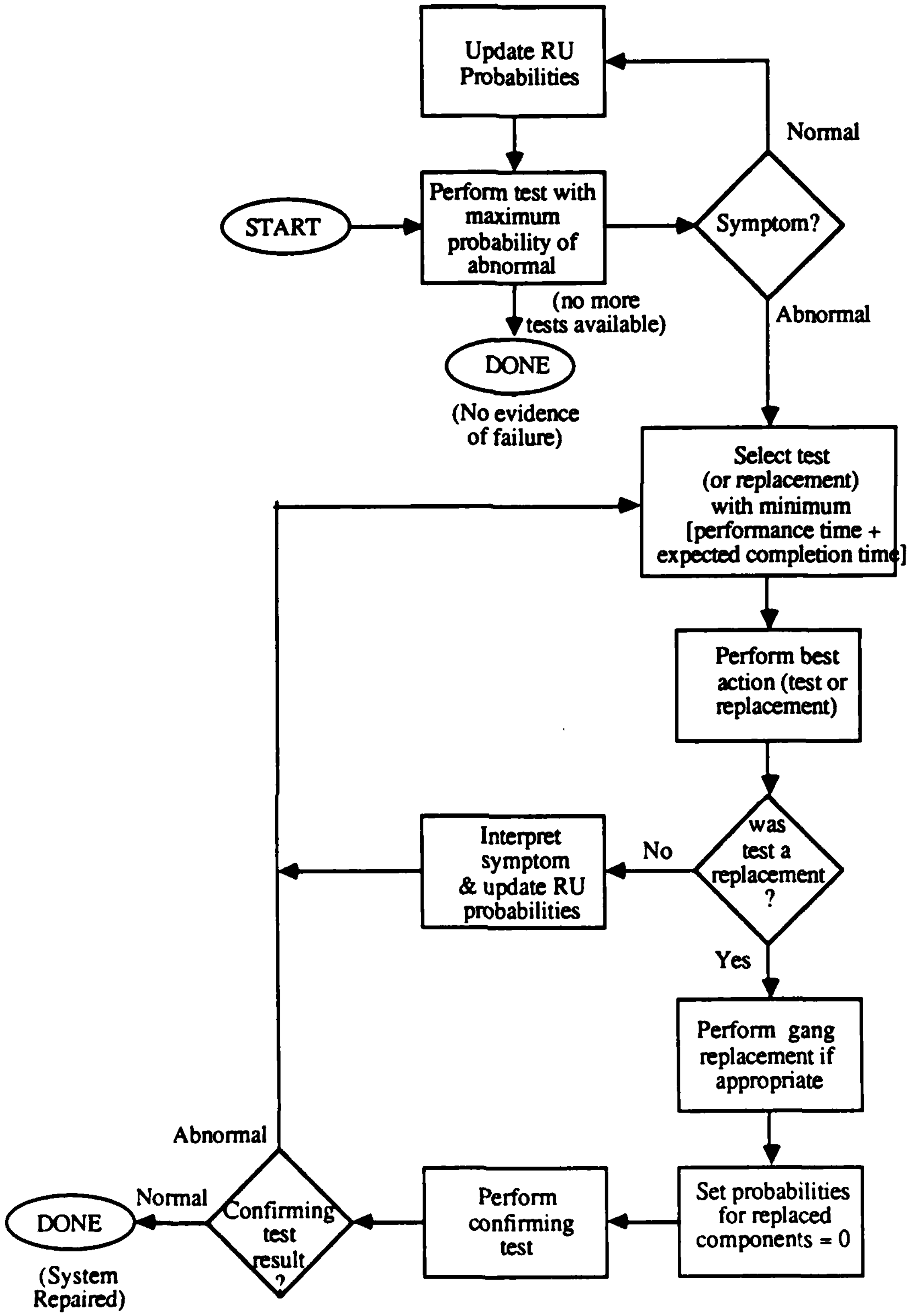


Figure 2. PROFILE Diagnostic Logic.

Behaviors of the Model

The simple expression for test value given above yields surprisingly diverse diagnostic behaviors under differing situations. As just mentioned it drives the diagnostic model toward efficient performance, with which an expert would agree. In addition to avoiding costly replacements, as discussed above, PROFILE exhibits these characteristics as well:

a. it generally performs front-panel checks prior to calling for test equipment usage, since the first use of test equipment involves a considerable set-up time cost. Once a particular test equipment has been used, PROFILE prefers its use to other equipments, since further testing with it is economical.

b. if 'known-good' spares are available for short-term substitution, it will use these if the time to swap them in and out is low, since the cost of using these spares is considered to be negligible.

c. it can 'profit' from past field experience, if component reliabilities are maintained to reflect their true values. All other factors being equal, PROFILE will pursue the testing of less reliable areas of a system.

d. it recognizes tests which produce outcomes which can be more easily interpreted, in terms of relating the symptoms received to the possible causes. As a result, it tends to generate testing sequences which are lower in cognitive difficulty than would a process only concerned with maximizing information

Because there is uncertainty (for a human maintainer and for the PROFILE test selector) about what symptom will actually be obtained when a test is performed, the model will at times select a test which turns out to provide little new information even though it had the *potential* of providing considerable new information. Furthermore, PROFILE may at times replace units which are not the actual faulty unit. When this is done, however, it can be shown that making the replacement was a rational decision considering the cost of further testing versus the suspicion level of the unit, its time to replace, and its cost.

Cognitive Time

PROFILE computes the total manual time to perform a diagnostic sequence by summing predetermined standard times of all the operations which are required to perform the generated sequence. These times can be produced using conventional industrial engineering techniques such as synthetically assembling times from basic micromotions or performing timed studies of the particular operations.

Detailed studies of diagnostic performance (Towne, 1985) revealed a relatively reliable measure of cognitive time as a function of the manual times of the individual operations and of the number of testing operations. In general, it was found that cognitive time preceding a test increases when the associated manual time increases, although the cognitive time quickly reaches an asymptotic value. Furthermore, a component was identified which was related solely to the number of tests required to resolve a problem, possibly reflecting some aspects of problem difficulty. Comparing the empirically-derived projections to the actual mean cognitive times over thirty different problems yielded a multiple R of 0.755 ($F=37.082$; d.f.=2,26).

Since the empirical formulation was derived from this same data, we can only know for sure that the function is relatively significant for this body of data. It is encouraging, however, that the function relates well to each of the three individual experimental studies comprising the thirty problems in the data. The cognitive time function has been added to the model so that distributions of total projected performance time (cognitive plus manual) are provided as well as distributions for manual time alone.

Cognitive Difficulty

Research during the contract period also endeavored to explore promising avenues for measuring the variables affecting cognitive difficulty during fault diagnosis. This formidable area becomes somewhat penetrable when the diagnostic sequences generated by PROFILE are used as the basis for investigating the information processing which may accompany those projected performances. If the PROFILE-generated performance for a particular fault is somewhat representative of that human technicians would perform, then the symptom information and fault-effect data which are involved in selecting and interpreting tests become rather well-defined. While the processes actually performed are not known, the PROFILE rule-base and execution process may be sufficiently realistic to provide a primitive basis for assessing cognitive workload.

SECTION III. APPLICATION OF PROFILE TO ANALYSIS OF DESIGN

When used as a design analysis tool, PROFILE generates explicit testing sequences to isolate and repair each of a sample of failures, it accumulates the estimated time to perform each diagnostic sequence, and it keeps track of the reasons for excessive fault resolution time Among its summary values reported to the user are the following (Towne and Johnson, 1984):

a. the distribution of repair times, with mean time to repair;

b. an analysis of the utilities of all indicators and test points. This can highlight maintenance features which are redundant or of marginal value, considering their production cost;

c. an analysis of false replacements, indicating those components which are likely to be consumed in quantities greater than their failure rates would indicate. This also focuses attention on needs for additional indicators and test points, to discriminate between parts which produce identical symptoms under the current design;

d. a summary of the types and frequencies of maintenance actions required to resolve the sample of faults, and the proportion of time spent performing those functions.

Figure 3 illustrates the general design process as it would currently be carried out with PROFILE support. Upon developing a design which meets the functional requirements of the system, the designer enters schematic diagrams representing the system architecture. Following this, a repetitive cycle is followed involving the analysis of maintainability characteristics and the correction or improvement of maintainability weaknesses. Because PROFILE is not now integrated with a commercial CAD/CAE (computer aided design/computer aided engineering) system, the accomplishment of the functional design and the entry to PROFILE are required to be two separate steps. The preparation of special PROFILE diagrams will become unnecessary when it can be integrated into a commercial CAE system. Work is in progress to embed the PROFILE model in the MentorGraphics IDEA CAE system.

Extracting Required Inputs From Design Specifications

To operate upon a particular system, PROFILE requires the following information:

a. a list of the replaceable units (RU's) in the system, along with their interconnections;

b. a list of possible test points and indicators;

c. the disassembly sequences required to gain access to internal parts and test points;

d. the physical groupings of components into modules, boards, units, etc.

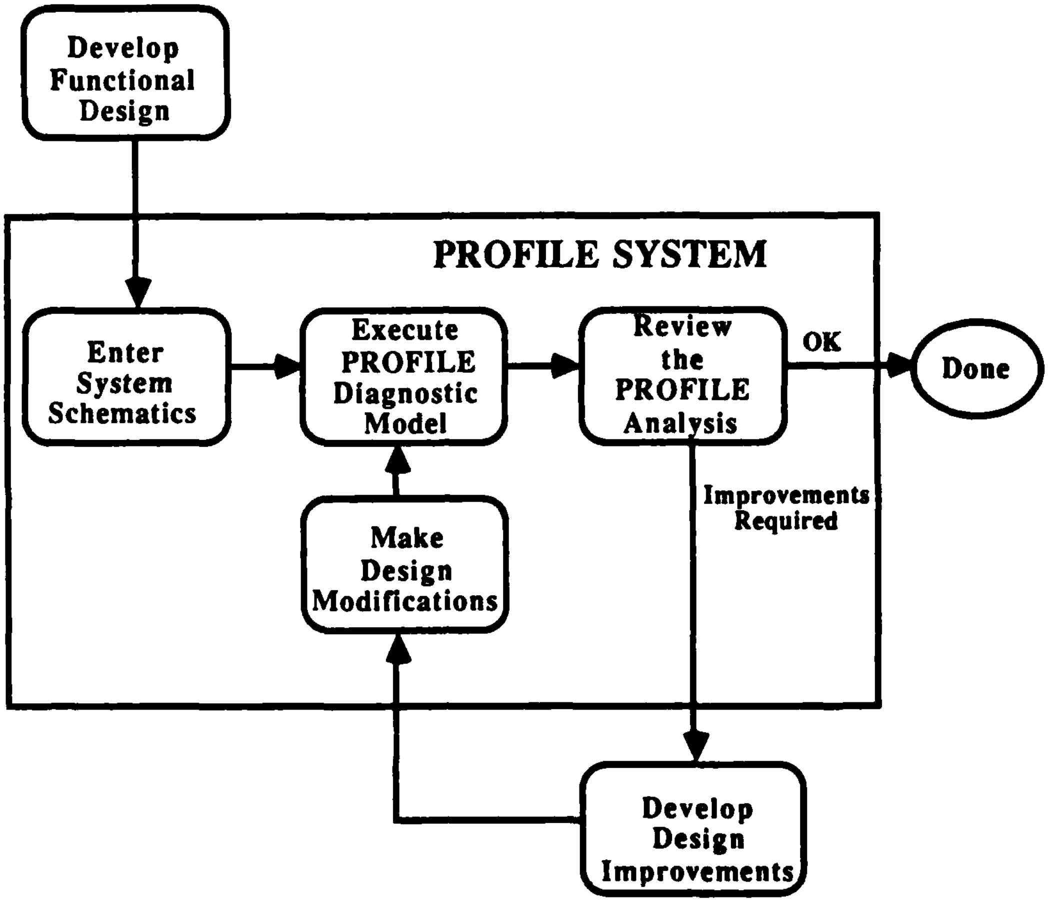


Figure 3. The PROFILE-Supported Design Process

A long-term objective of the research has been to develop ways to extract these data items from the representations built up during the computer-aided design process. A special graphics interface was developed to facilitate experimentation with PROFILE in a design setting, and to determine the feasibility of developing a general interface between it and commercial CAE systems. This suite of programs allows a designer to (1) enter system schematics in block diagram form and to provide the generic identification of each element, and (2) execute a system simulation which automatically introduces failures into the system and computes the effects of those failures at the indicators and test points. Included in this resource is a prototype library of generic objects, containing representative costs, reliabilities, and replacement times.

The identification of system components is made in terms of *generic parts* whose characteristics have been predefined in a library of system components. The generic description for a part specifies its approximate reliability, cost, and *the fixed portion* of the time to replace (assuming that obstructing parts have been removed). A second library, a standard task library, contains standard times to perform common maintenance tasks such as making various test readings, setting up test equipment, and removing and replacing various types of fasteners. By combining the fixed replacement times with the times to remove and replace various fasteners, according to the disassembly requirements specified for the equipment, PROFILE computes the times to access, test, and replace internal parts.

Providing the system-specific data to PROFILE is a relatively straightforward task which does not require a diagnostic expert. Systems which have been designed using a commercial CAD/CAE system can be readily analyzed by PROFILE, as the bulk of necessary data are present within the captured schematic diagrams (although there is currently no interface between these commercial systems and PROFILE). One type of design information must usually be added, as it is rarely captured within CAD/CAE processes. This is a specification of the manner in which the functional units are packaged, i.e., the order in which parts must be disassembled to gain access to internal parts.

While this experimental graphics interface is not as sophisticated as commercial CAE systems, it does provide a self-contained approach to specifying and analyzing system designs. There are many powerful CAE systems which perform the two necessary functions for supporting PROFILE analysis: (1) capturing system schematics, and 2) simulating faults. Systems exist for capturing and simulating both analog and digital technologies, although the majority of CAE resources are devoted to specification and analysis of digital systems. The great majority of these system simulators are also based upon some version of SPICE (Nagel & Pederson, 1973; Nagel, 1975). It is clear that PROFILE can be tailored to communicate with the 'design file' created by most of these systems. The design file contains the system-specific specifications of the interconnections and component types. It is our intention to create the interface between one of the leading CAE packages to operate in conjunction with PROFILE.

A Sample Application

Appendix B presents a complete application of PROFILE to an infrared (IR) transmitter/receiver system built for the purpose of obtaining realistic diagnosis and repair data. An earlier report (Towne, Johnson, and Corwin, 1983) presents the maintenance time predictions and actual observations. Appendix B presents the inputs to PROFILE in the graphical form which was developed after the original study and the maintainability analyses.

SECTION IV. A TRAINING APPLICATION

We are currently using PROFILE within the Intelligent Maintenance Training System (IMTS), a computer-based training system whose function is to interact in intelligent ways with learners who are practicing troubleshooting (Towne, 1987; Towne, Munro, Pizzini, and Surmon, 1987). The approach used in the IMTS for relating the graphical appearance of an object to its role and state within a particular system was heavily influenced and inspired by work on a simulation system called STEAMER (Hollan, Hutchins, and Weitzman, 1984;Hollan, 1983). STEAMER allows experts to construct interfaces between existing simulations of particular systems to graphical "objects" which display their response to system conditions. When attached to a particular system by a content-expert, the objects determine how they react to their inputs and how they appear under any condition. Thus, as a student alters the system configuration, by setting switches, the intelligent objects respond and appear appropriately.

Our objectives have been (1) to produce an object editor and a system editor which can be used by non-programmers to create new objects and systems, (2) to develop a system simulator which will respond correctly as a learner alters switches and attaches simulated test equipment, and (3) to embed PROFILE into this simulation environment to intelligently assess the learner's diagnostic approach.

Graphics-based Specification for Training Applications

For analysis of designs and generation of diagnostic specifications it is not important that the fault simulator create graphic representations of the symptoms resulting at each test point or of the operational states of the elements. For training purposes, however, the graphic representation of fault effects and system function is critically important.

The system used to create the graphics and fault information required for training is shown in Figure 4. The system includes 1) an *object construction editor* for defining generic objects (both their ***graphic*** appearance and their ***functions***), 2) a *system construction editor* for combining the generic objects into specific system diagrams, and 3) a *fault simulator* capable of determining the symptoms produced by each possible fault. These elements form a type of CAD/CAE system, but one which can also support training.

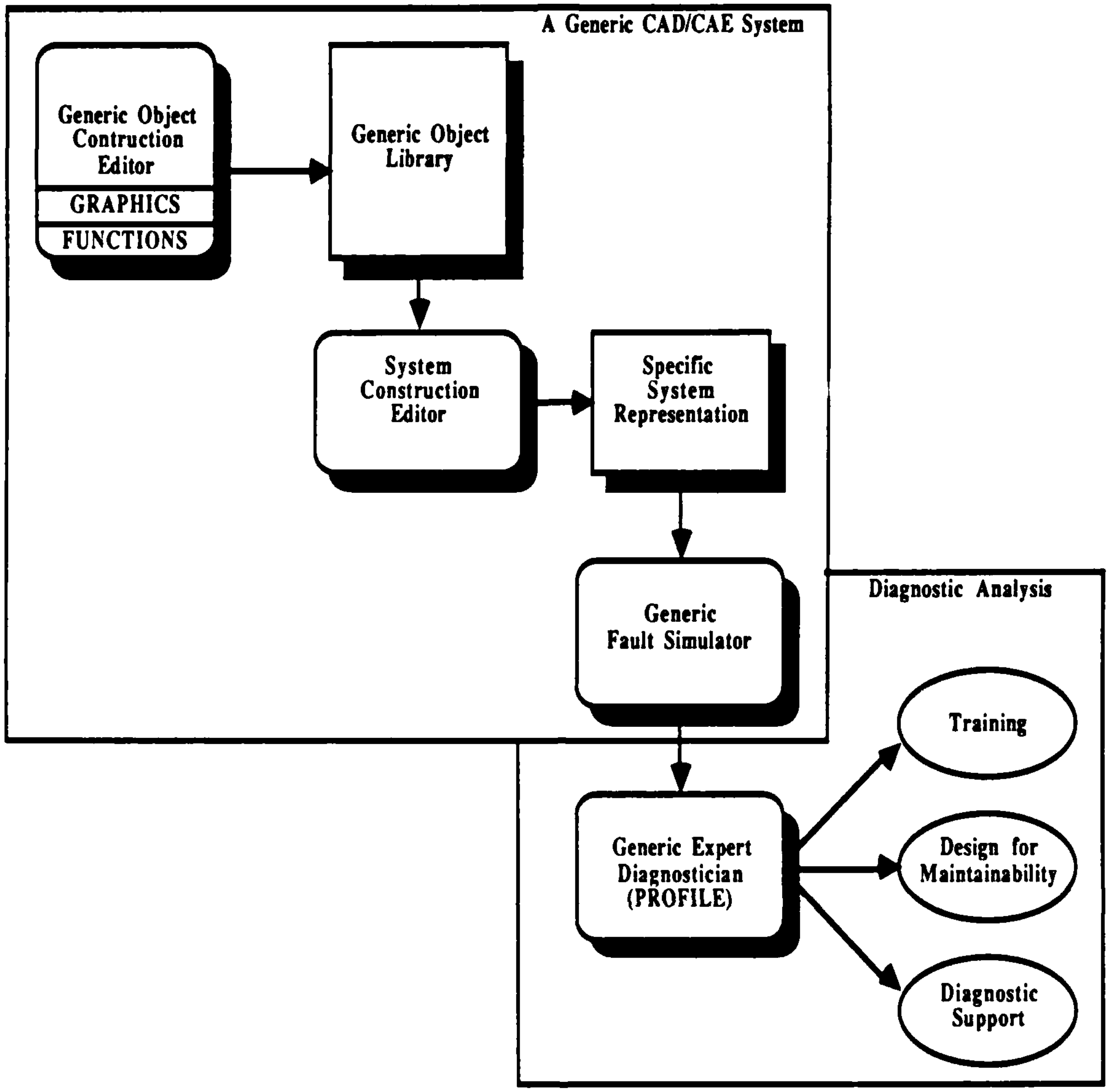


Figure 4. Simulation Composition System

Creating New Objects

If the simulation author finds that the existing library of generic objects lacks a required object, he or she constructs it using an object editor. This involves constructing the graphic representations for the part in its possible states, and entering rules which govern its behavior. The rules for an object are of two types (1) *system condition* rules, which state the conditions which cause an object to enter its various states, and (2) *performance effect* rules, which state what operations the object performs in each of its states. Figure 5 illustrates a two-state object with the system conditions and performance effects for each state. This object, a Caliper Brake, is in the BRAKE-OFF condition if the pressure at the input port (A) is less than 200 psi or if more than 50 pounds of pressure is exerted at the brake pads (port B). When in this state, the object exerts no force at the brake pads.

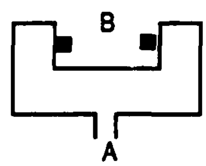
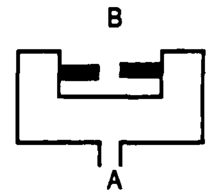
State Name	BRAKEOFF	BRAKEON
Graphic		
System Condition	((A < 200) OR (B > 50))	((A >= 200) AND (B < 50))
Performance Effects	(B ← 0)	(IF (A >= 200) THEN (B ← 50) ELSE (B← 5))

Figure 5. Graphics and Rules for a Two-state Object

Constructing New Simulations for Training

The content-expert constructs a specific system simulation (and all associated training interactions) by simply selecting (with a mouse) appropriate objects from the library and positioning them on the screen, using a special graphics editor. While the author must be certain that each object selected actually operates as the real object in the system, the job of constructing the simulation is primarily one of subdividing a big system into separate screens, or drawings, and then producing each individual diagram in the editor provided with the IMTS. As the objects are positioned, the editor detects the connections between elements, and it retains the connectivity data in a file. While the connectivity data are necessary to computing how a system will behave under a current condition, these data are a small part of the intelligence used to simulate the system behaviors. The IMTS uses the connectivity information plus the behavior rules of each object involved to determine the *nature of the signal conversions*, and hence the particular appearance of system indicators and associated test equipment.

Once all the individual diagrams have been created, and outputs from one diagram have been linked to inputs to others, the representation is completed. IMTS can now select and insert practice malfunctions for each student, it can accept and display the results of student testing actions, it can monitor each learner providing individualized assistance, and it can demonstrate expert diagnostic strategies as required.

SECTION V. CONCLUSIONS

The PROFILE model has been found to generate troubleshooting behaviors very similar to those of qualified technicians working with adequate training, facilities, and time to resolve single, persisting failures. The experimental applications indicate that use of the technique can sense the maintainability implications of a wide range of design alternatives including those concerning packaging, modularization, test point provisions, front panel design, and extent of automated test facilities. The formalization of a generalized fault isolation process has also shown that not all false replacements are the result of poor technician decisions, and that a substantial portion of such replacements may be the result of rational decision making in the face of an imperfect design or demanding conditions in the maintenance environment. Application of the model also verifies what field technicians already know -- that under conditions of inadequate time, test equipment, or training a rational person may be forced to resort to radically different diagnostic approaches. There is some analytical evidence that the resulting degradation in diagnostic performance does not occur gracefully, i.e., that even small deficits in necessary resources may demand major shifts in approach. Generally this shift must be toward a drastic limiting of testing operations in favor of substitution of large units of hardware.

Perhaps the greatest potential for future research lies with exploring the maintenance performance implications of reduced technician knowledge, as a result of reduced training and experience. Some equipment designs might be relatively tolerant to reduced proficiency levels while others could conceal catastrophic implications which become known only when the system is deployed. System A in Figure 6 below is one which is relatively insensitive to skill and knowledge deficits. While MTTR increases as proficiency decreases, the change is relatively gradual. System B, however, can only be maintained well by fully qualified technicians. Fault isolation of such a system, by anyone other than an expert, will involve either great consumption of time or great consumption of spare parts.

If the two systems are compared under conditions of fully qualified technicians, then system B appears to be superior. There is growing evidence that systems involving highly automated test and diagnostic functions offer repair time profiles something like that of system B. If a mission requirement demands an MTTR which can only be achieved with fully qualified technical skills, then it is crucial that the associated personnel skill levels be realized long before deployment.

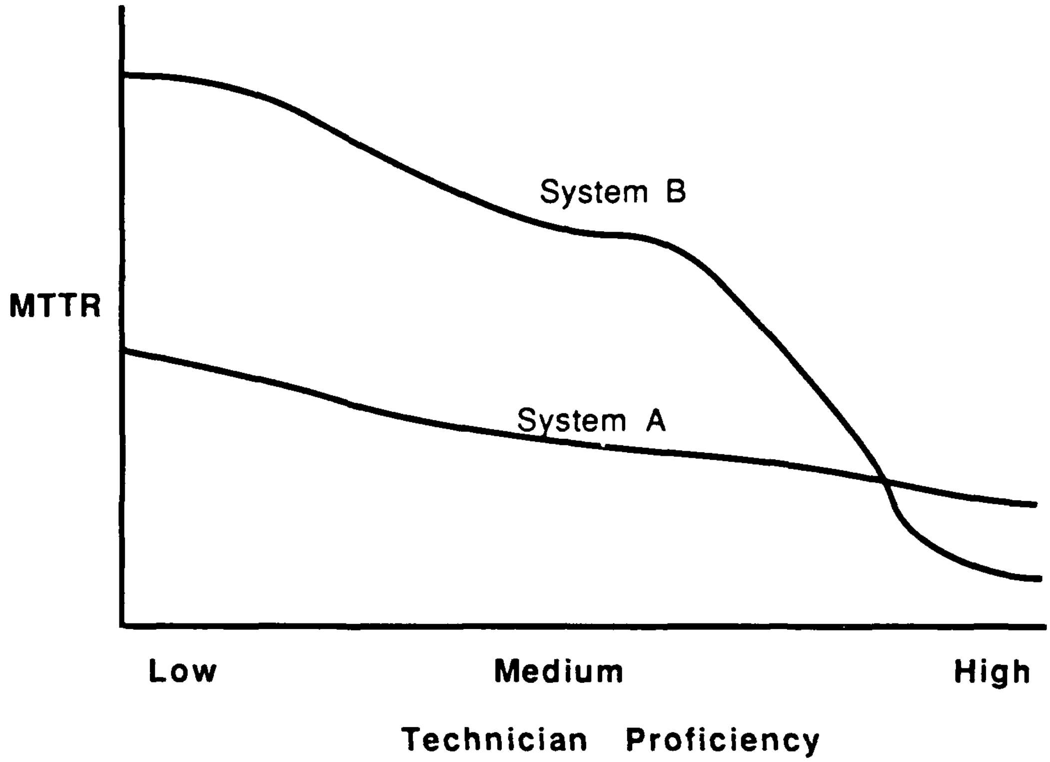


Figure 6. MTTR versus Technician Proficiency for Two System Designs

Of course some would say that the resolution to the problem is simply to adequately train the necessary people and assign them to the maintenance of the system. While this is always a reasonable attitude, the systems which supply trained people to the field are also complex and are also subject to imperfections, thus it makes sense to consider the likelihood of personnel deficits in the design stage.

The major practical obstacle to introducing quantitative maintainability analysis into the design process has to do with the need to (1) sufficiently integrate the analysis process into the CAD/CAE systems that the designer is not hampered by the tools when they are not in use, and (2) minimize the additional activities (beyond those required to produce the functional design) which are required to support maintainability assessment. Ideally, the designer should be unaware of the maintainability analysis process during the early phases of design in which the system is taking form, and not be required to tend to satisfying data requirements before the data are available. To accomplish this will require that the majority of design information required by PROFILE be automatically extracted from the design file created by the commercial CAD/CAE systems.

In fact it appears that the graphical schematic capture routines of such systems, along with their system simulation routines, may provide virtually all the user interface features required. The MentorGraphics CAE system (IDEA) provides the capability to associate user-defined properties to the parts entered at the schematic capture stage. This would allow for assigning the design-dependent information required, such as assembly/disassembly priority and possibly design-dependent reliability data.

The second practical problem which will persist is overcoming excessive compute delays. The two most promising avenues for doing this appear to be (1) the inevitable increase in raw compute speed from faster computer processors, and (2) finding more efficient search processes for selecting tests. The latter of these almost certainly will require a deeper understanding of the process human diagnosticians employ when directing their testing performance.

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APPENDIX A

Improvements to the Test Selection Process

Previous versions of the PROFILE model selected the next test in a sequence as the test which maximized amount of new information contributed by the test divided by the time to perform it. New information is the reduction in uncertainty , ΔU, resulting from the test calculated as U - U' where U is the system uncertainty *prior* to the test, and U' is system uncertainty *following* the test. System uncertainty is measured as Σ (p_i log p_i) , where the p_i are the probabilities of each of the i possibilities, which sum to 1.0. Uncertainty is zero when one of the probabilities is 1.0 and it is maximized when the probabilities are distributed equally among all the possibilities.

For example, suppose a system consists of 100 replaceable units (RU's), and the current probability (based on symptoms already received) that RU1 is failed is .98, while the probability of each of the remaining 99 RU's is 0.0002 (0.02/99). The system uncertainty at this point of the problem is therefore (using logarithms to the base 2):

$$\Sigma p_i \log p_i = (.98) \log .98 + 99 (.0002) \log (.0002) = -0.02857 - 0.24332 = -0.27189$$

Suppose there are no more conventional tests, thus we must resort to replacement to finish the problem. The uncertainty which would result from replacing RU1 (and repeating one of the tests previously yielding an abnormal) is

$$0.98 \times 0 + .02 \times 99 \times .010 \log .010 = 0 - 0.13156 = -0.13156$$

and the uncertainty reduction would be $\Delta U = -0.27189 - (-0.13156) = 0.140$

whereas the uncertainty resulting from replacing any one of the other RU's would be
$.98 \log .98 + .0002 \times 0 + 98 \times .0002 \log .0002 = -0.02857 + 0 -0.24086 = -0.26943$
and the uncertainty reduction would be $-0.27189 - (-0.26943) = -.00246$

Now if the time to replace RU1 is 600 seconds, then ΔU/T for replacing RU1 is

$.140/600 = 0.00023$

If the time to replace any of the other RU's is 10 seconds, then ΔU/T for one of them is .00246/10 = .000246

Thus the prior rule would replace each of the RU's 2, 3, ..., 100 before finally replacing RU1.

Yet the expected time to solve the problem with this strategy is
.0002 x 10 + ..0002 x 20 + ..0002 x 30 + ..0002 x 40 + ... + .0002 x 990 + .98 x (990 + 600) = 1570 seconds

whereas the strategy of replacing RU1 first has the expected solution time of
.98 x 600 + .0002 x 610 + .0002 x 620 + ... + .0002 x 1590 = 610 seconds

In this case, the old measure was heavily influenced by the 60 to 1 ratio of test time for replacing RU1 compared to replacing any of the others. This same ratio could have been encountered if the replacement of RU1 required 60 seconds and the others required 1 second, in which case PROFILE would have passed up making a one-minute replacement of a part with a .98 chance of being the malfunction in favor of replacing parts in 1 second with .0002 chance of being correct.

In actuality, RU1 should be replaced first even if its time is as much as 4,900 (.98/.0002) times as long as the other RU's replacement times.

Under the new test selection rule, replacements are performed in descending order of probability per "time-cost" ratio (P/T). Note, "time-cost" is a function of replacement time, confirming test time, and dollar cost of the RU. This strategy can be shown to minimize expected (average) repair time. RU 1 has a P/T ratio of .0016 (=.98/600), while each of the other RU's have a P/T ratio of 0.00002 (=0.0002/10). Hence RU 1 would be replaced first, and then successively each of the other RU's, until the system was found to be operational. In fact, RU 1 would be replaced first unless the other RU time-costs were less than 0.12 seconds (600/ (0.98 / 0.0002)), in which case replacing each of the other RU's first would be the optimal strategy.

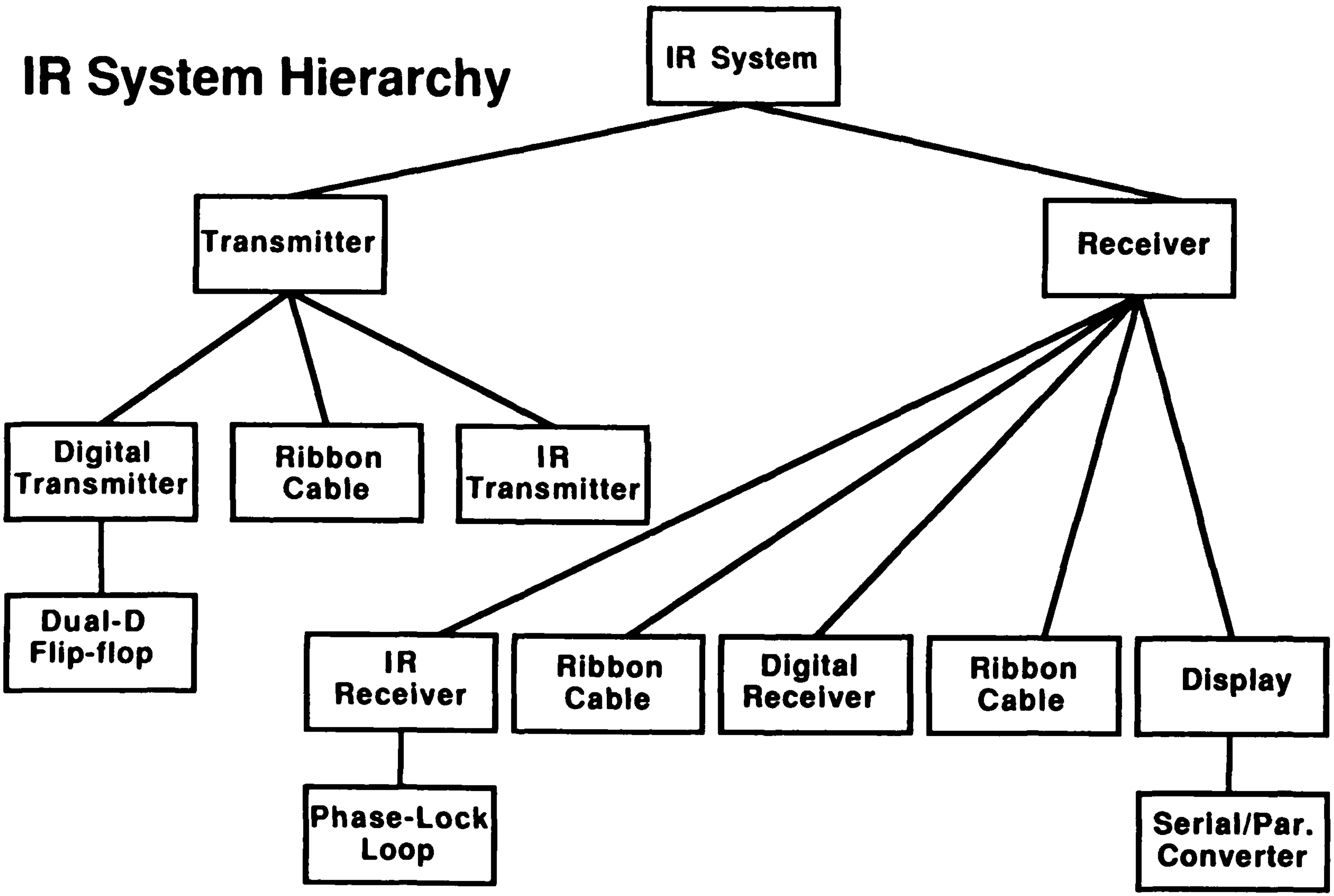
APPENDIX B

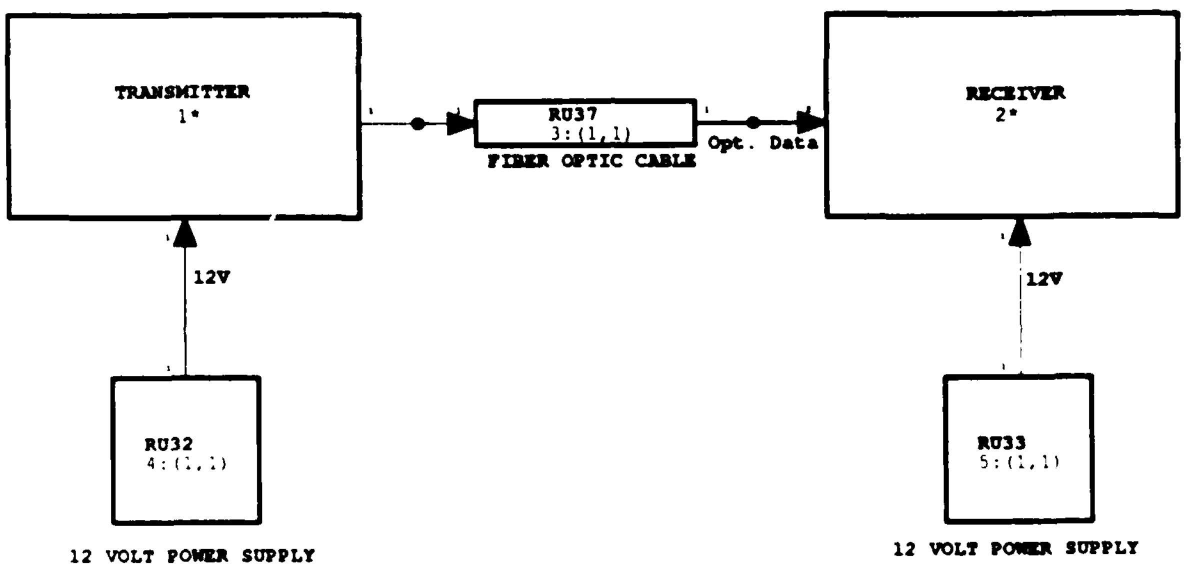
Maintainbility Analysis of an Ifrared Transmitter/Receiver

Figure B-1 presents the organization of the infrared (IR) Transmitter/receiver. Each of the fourteen blocks in this figure represent a diagram entered to PROFILE. Figures B-2 through B-15 are those fourteen graphic representations of the IR system.

Figures B-16 through B-23 are the PROFILE analyses of the design of the system.

IR System Hierarchy





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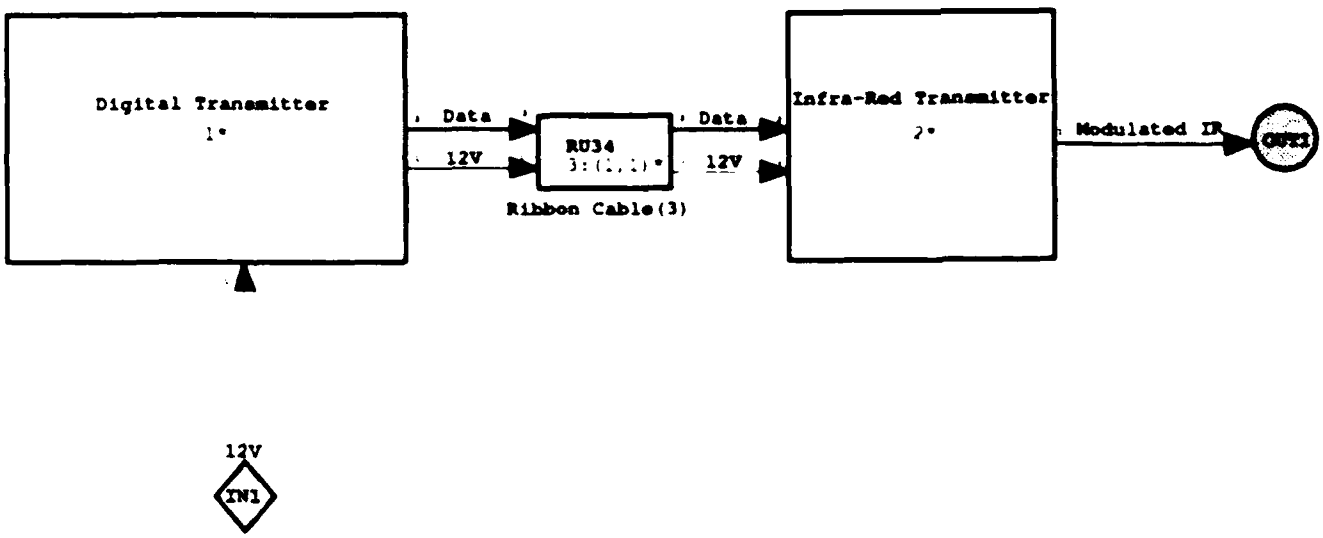
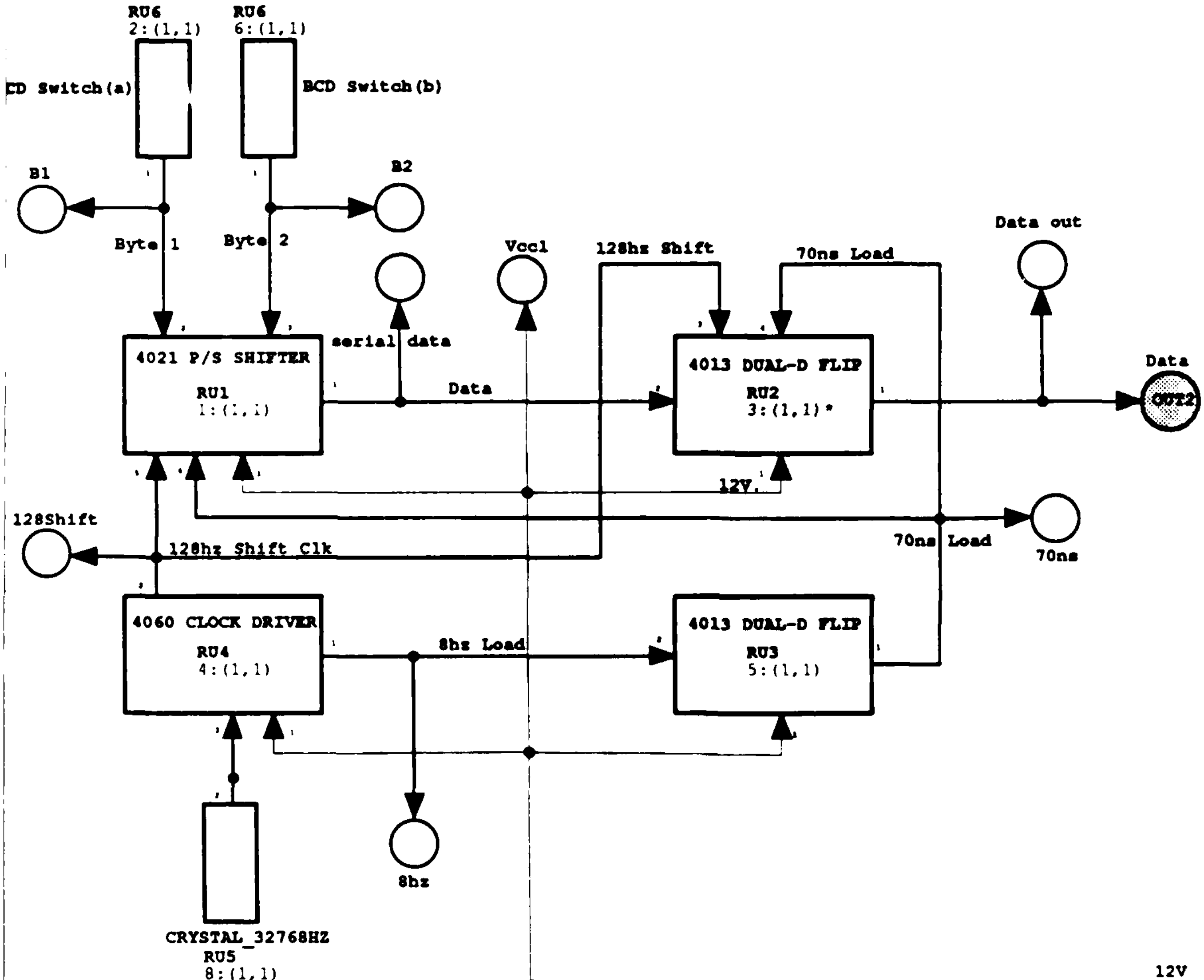


TRANSMITTER



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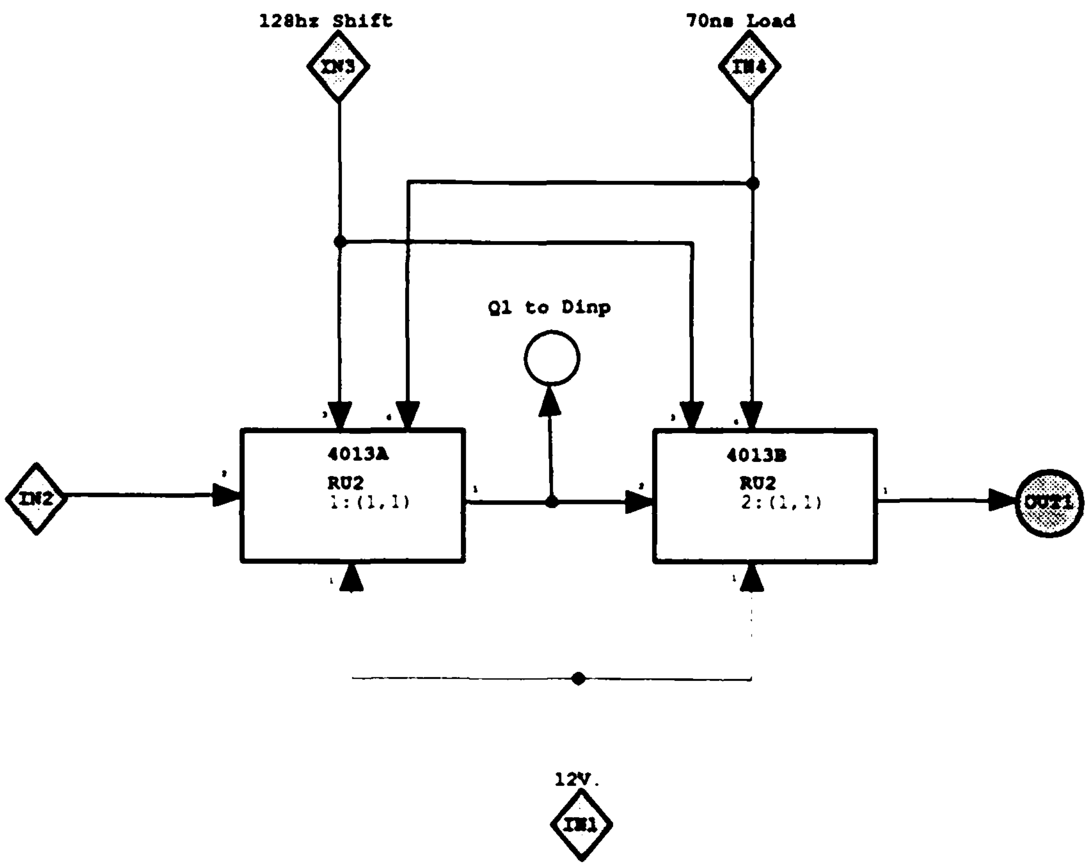
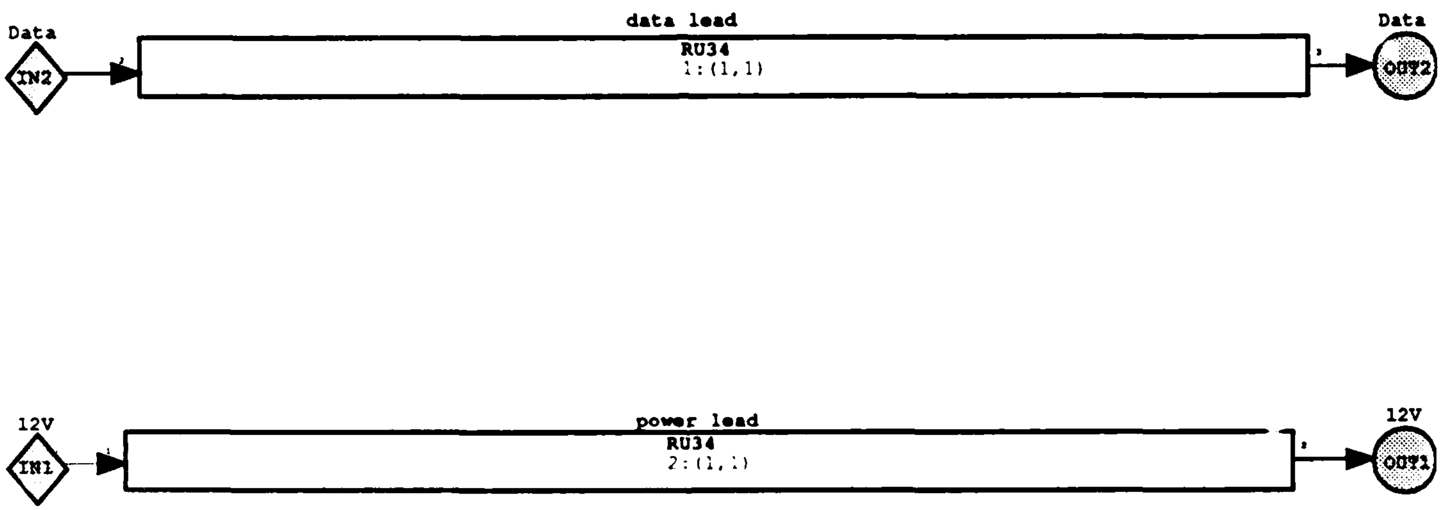
TRANSMITTER/Digital Transmitter

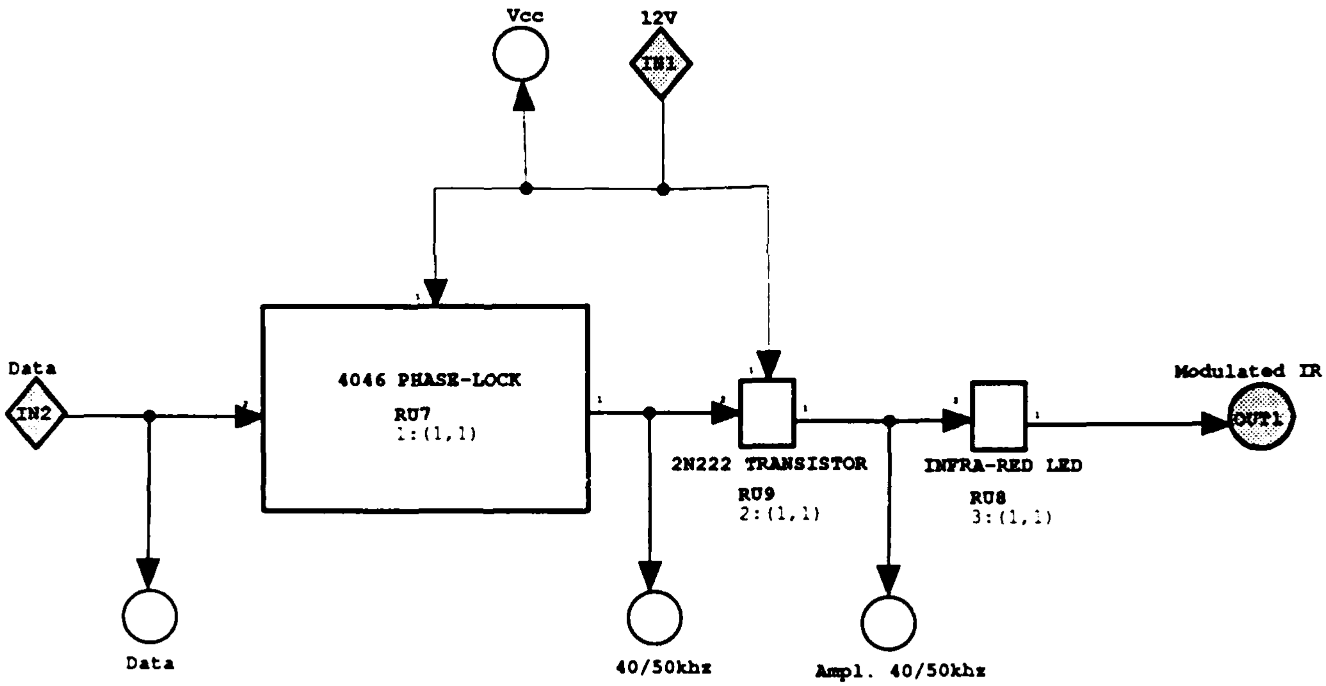


TRANSMITTER/Digital Transmitter/4013 DUAL-D FLIP



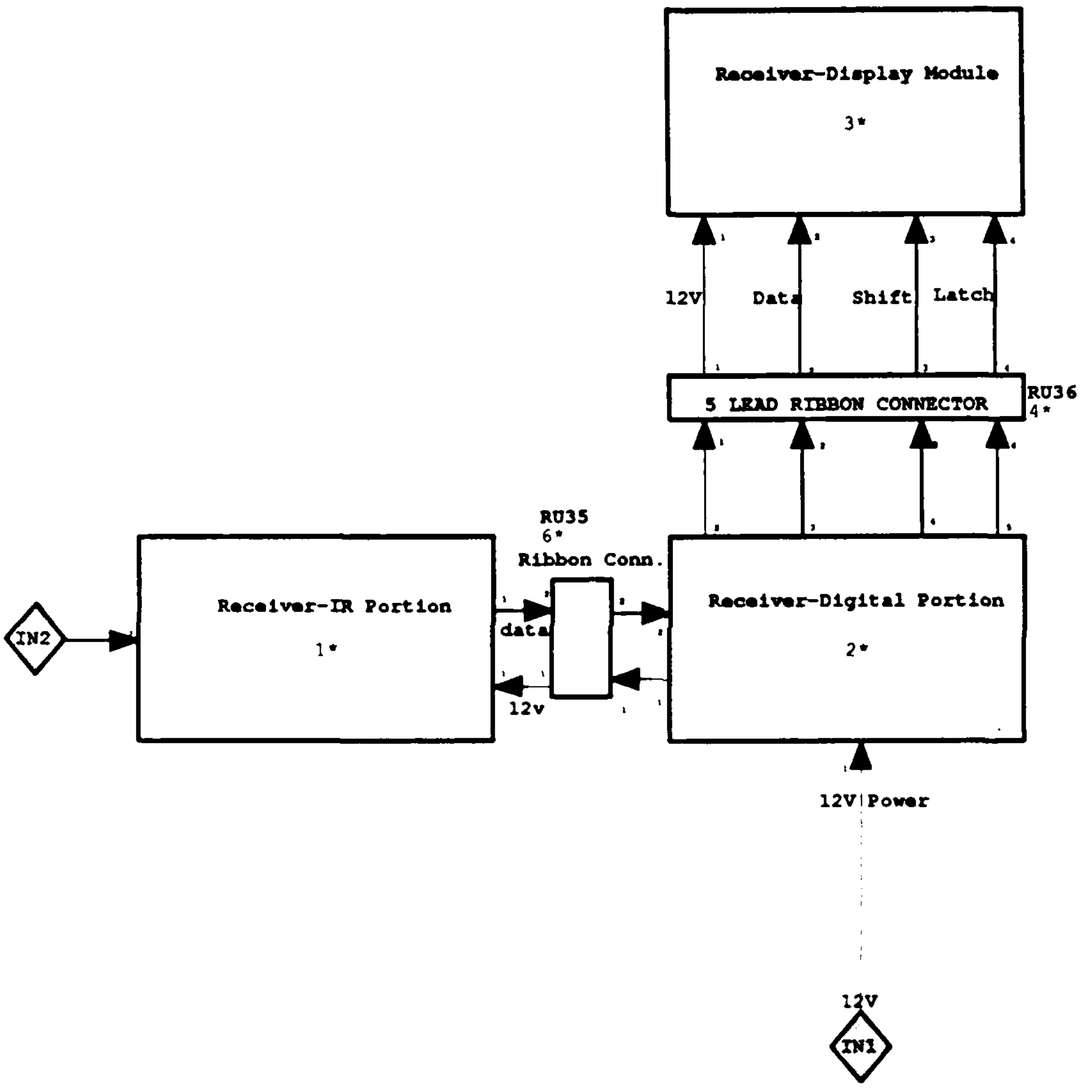
File:data/system.1.3

TRANSMITTER/Ribbon Cable(3)



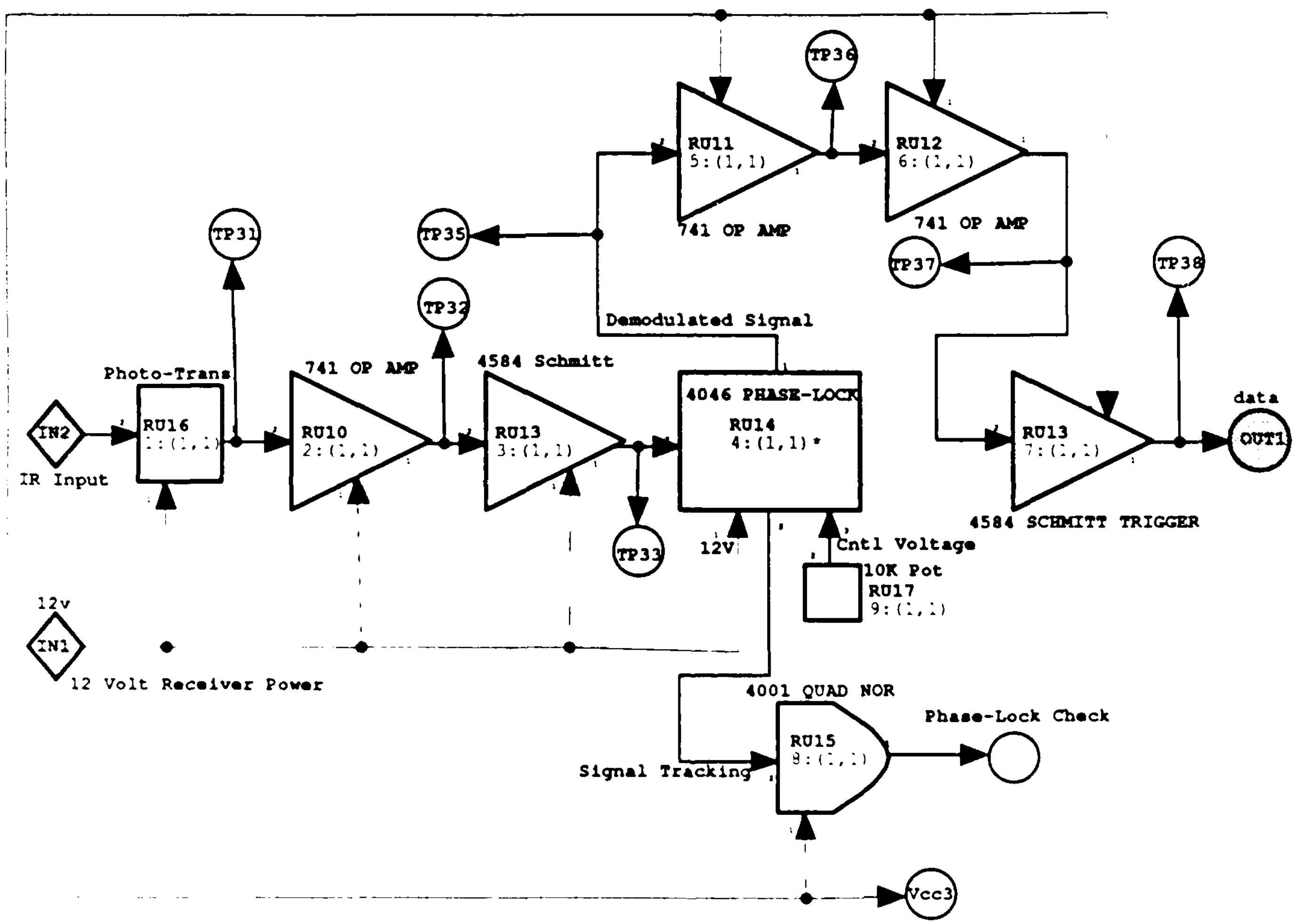
File:data/system.1.2

TRANSMITTER/Infra-Red Transmitter

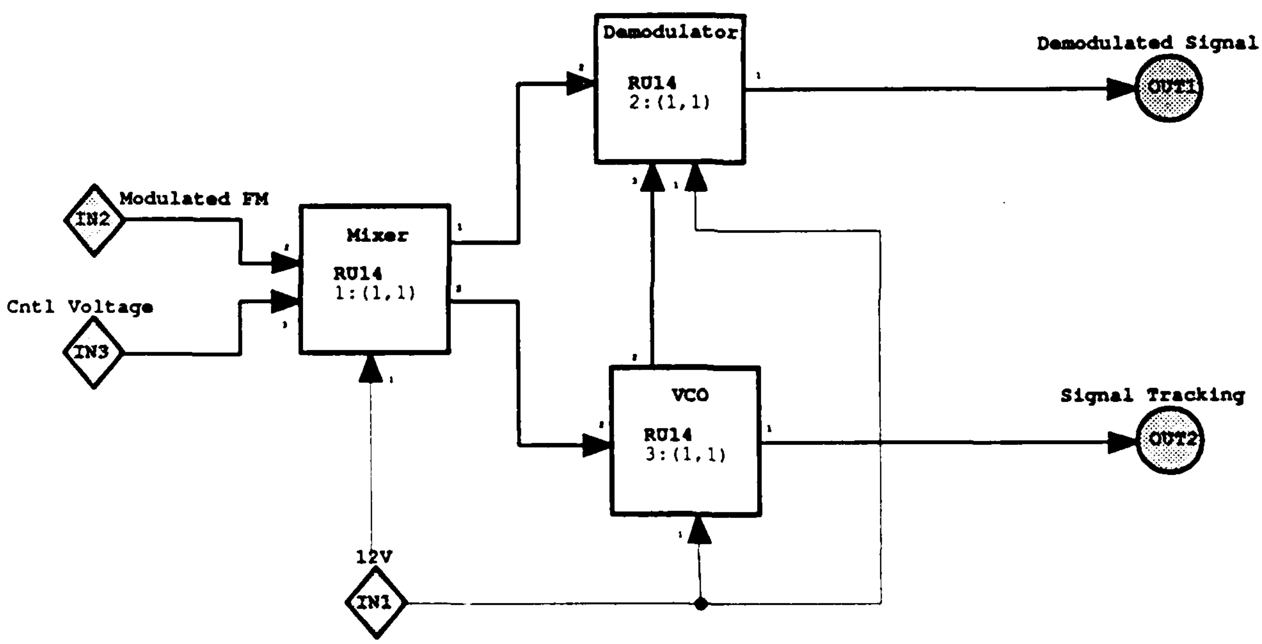


Receiver-Display Module
3*
12V
Data
Shift
Latch
5 LEAD RIBBON CONNECTOR
RU36
4*
RU35
6*
Ribbon Conn.
Receiver-IR Portion
1*
IN2
data
12v
Receiver-Digital Portion
2*
12V Power
12V
IN1

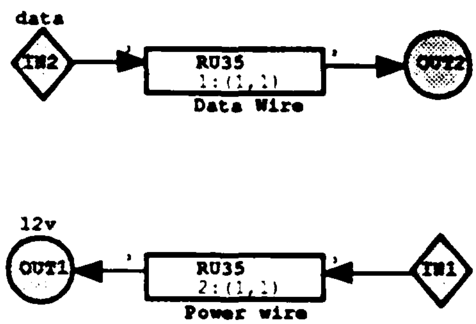
RECEIVER



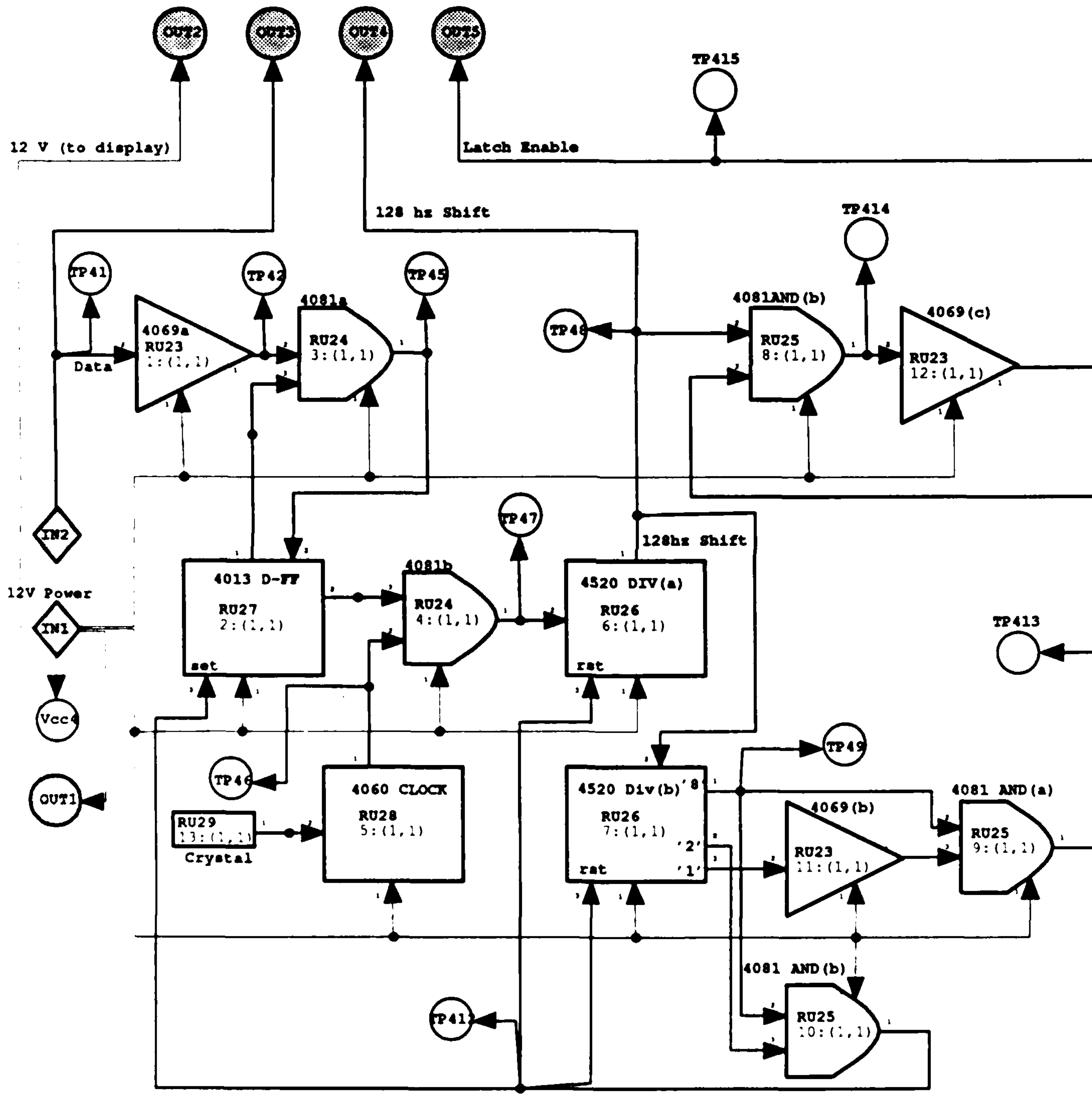
RECEIVER/Receiver-IR Portion



File:data/system.2.1.4 RECEIVER/Receiver-IR Portion/4046 PHASE-LOCK



RECEIVER/Ribbon Conn.



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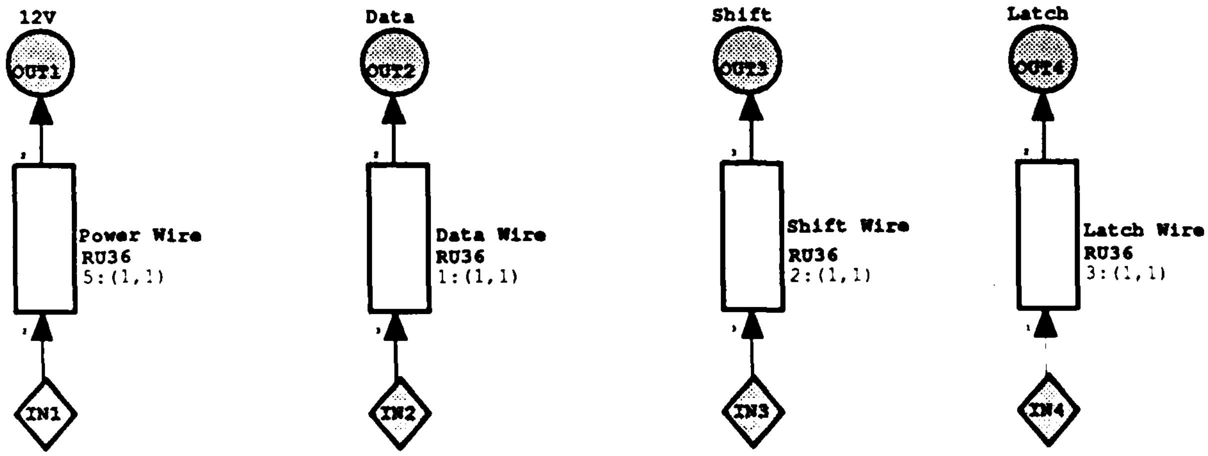
RECEIVER/Receiver-Digital Portion



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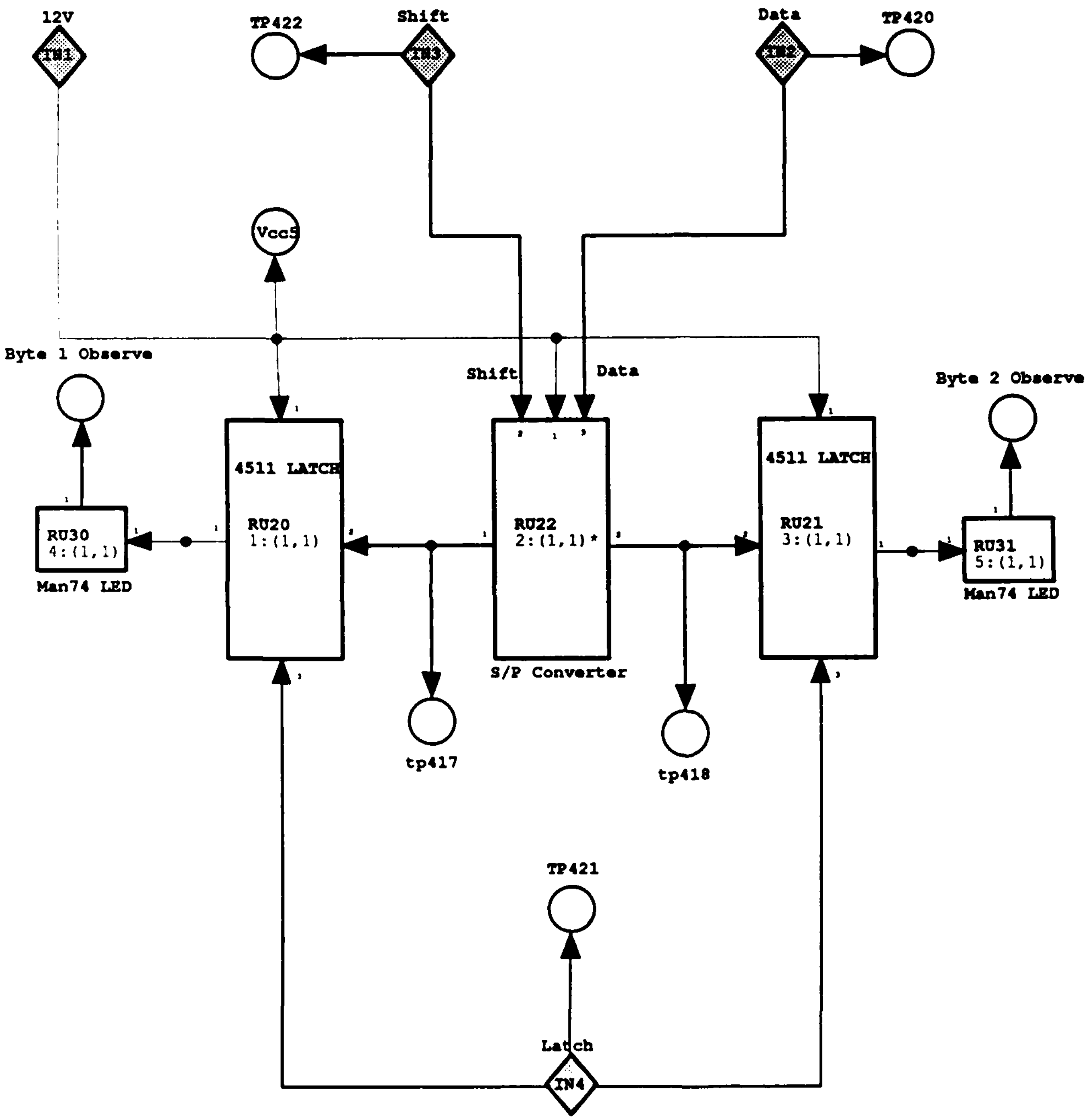
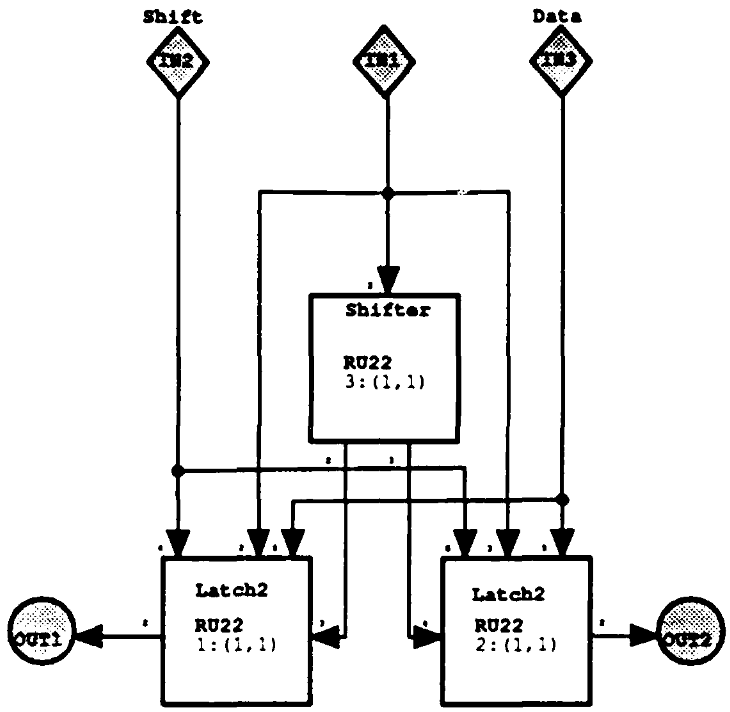
RECEIVER/5 LEAD RIBBON CONNECTOR



le:datapre/system.2.3 RECEIVER/Receiver-Display Module


Shift
IN2
IN1
Data
IN3
Shifter
RU22
3:(1,1)
Latch2
RU22
1:(1,1)
Latch2
RU22
2:(1,1)
OUT1
OUT2

Detailed Diagnostic Sequences

These list the testing sequences performed to isolate each failure, the symptom obtained at each test, and the time taken to perform each test.

```
******** New problem:  1(ru= 37 bb=  1 FIBER OPTIC CABLE) ********

Perform Test  39 (Byte 2 Observe)
XMIT             : ON        time= 13
REC              : ON        time= 13
Cogtime (prior to above T/R)   = 19
  Indic 39:1 (Abnorm)
           conditional time is  26, total man is   28


Perform Test  15 (Phase-Lock Check)
Cogtime (prior to above T/R)   = 12
  Indic 15:1 (Abnorm)
           conditional time is   0, total man is    3


Perform Test   8 (serial data)
SCOPE_COUPLE     : DC        time=  2
GROUND           : BOARD1    time= 10
SCOPE_SWEEP      : 10MS      time=  2
Cogtime (prior to above T/R)   = 23_
  Indic 8:0 (Norm)
           conditional time is  14, total man is   49


Perform Test  35 (Vcc5)
CALIBRATE        : YES       time=  7
Cogtime (prior to above T/R)   = 17
  Indic 35:0 (Norm)*critical*
           conditional time is   7, total man is   19

    •
    •
    •

Replace  ru  10 741 OP AMP                                   **REPLACEMENT**
REC              : OFF       time=  7
Cogtime (prior to above T/R)   = 23
           conditional time is   7, total man is   53

Perform Test  39 (Byte 2 Observe)
REC              : ON        time= 13
Cogtime (prior to above T/R)   = 16

           conditional time is  13, total man is   15


Replace  ru  37 FIBER OPTIC CABLE                            **REPLACEMENT**
Cogtime (prior to above T/R)   = 21
           conditional time is   0, total man is   40

End of problem. Man time= 342.00 Cog time= 551.00
```

Repair TimesBy Fault
(in ascending order of time - times include diagnosis)

This analysis lists the projected time to diagnose and repair each fault in the system. When PROFILE resorts to replacement to resolve an inability to determine the failure by testing, it randomly varies the order in which the possible failed components are replaced.

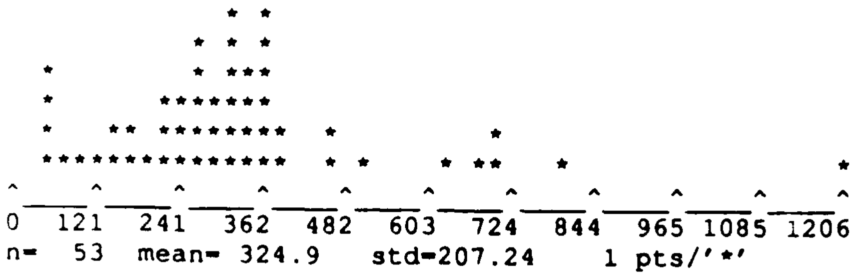
BB -	Basic block number
RU -	Replaceable Unit number
PROB -	Probability of failure
Mean -	Mean Diagnosis and repair time, per PROFILE
N	Number of samples
STD	Standard deviation in sample
MIN	Minimum repair time in sample
MAX	Maximum repair time in sample
EXP	Expected repair time for the fault

MANUAL SOLUTION TIME SUMMARY BY FAULT

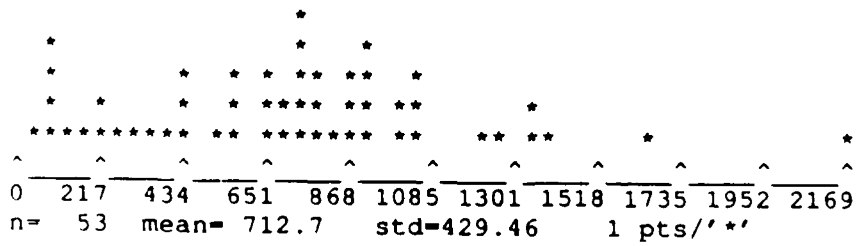
BB	RU	FAULT NAME	PROB.	MEAN	N	STD	MIN	MAX	EXP
24	17	10K Pot	0.029	41.0	1	0.00	41	41	1.17
50	36	Latch Wire	0.007	54.0	1	0.00	54	54	0.39
48	36	Data Wire	0.007	54.0	1	0.00	54	54	0.39
49	36	Shift Wire	0.007	54.0	1	0.00	54	54	0.39
23	15	4001 QUAD NOR	0.029	84.0	1	0.00	84	84	2.40
43	30	Man74 LED	0.029	86.0	1	0.00	86	86	2.46
51	36	Power Wire	0.007	113.0	1	0.00	113	113	0.81
44	31	Man74 LED	0.029	145.0	1	0.00	145	145	4.14
3	33	12 VOLT POWER SUPP	0.029	149.0	1	0.00	149	149	4.26
9	6	BCD Switch(b)	0.014	167.0	1	0.00	167	167	2.39
[illegible]	35	Power wire	0.014	170.0	1	0.00	170	170	2.43
10	2	4013A	0.014	184.0	1	0.00	184	184	2.63
16	34	power lead	0.014	209.0	1	0.00	209	209	2.99
5	6	BCD Switch(a)	0.014	214.0	1	0.00	214	214	3.06
35	25	4081AND(b)	0.010	227.0	1	0.00	227	227	2.16
42	21	4511 LATCH	0.029	239.0	1	0.00	239	239	6.83
34	26	4520 Div(b)	0.014	242.5	2	16.26	231	254	3.46
41	20	4511 LATCH	0.029	[illegible]3.0	1	0.00	243	243	6.94
26	14	Demodulator	0.010	258.0	1	0.00	258	258	2.46
47	22	Shifter	0.010	274.0	1	0.00	274	274	2.61
12	7	4046 PHASE-LOCK	0.029	277.0	1	0.00	277	277	7.91
[illegible]	11	741 OP AMP	0.029	277.0	1	0.00	277	277	7.91
21	12	741 OP AMP	0.029	277.0	1	0.00	277	277	7.91
11	2	4013B	0.014	289.0	1	0.00	289	289	4.13
25	14	Mixer	0.010	291.0	1	0.00	291	291	2.77
19	10	741 OP AMP	0.029	298.0	1	0.00	298	298	8.51
33	26	4520 DIV(a)	0.014	313.0	2	19.80	299	327	4.47
[illegible]	14	VCO	0.010	314.0	1	0.00	314	314	2.99
45	22	Latch2	0.010	317.0	1	0.00	317	317	3.02
36	25	4081 AND(a)	0.010	318.0	1	0.00	318	318	3.03
38	23	406[illegible](b)	0.010	318.0	[illegible]	[illegible].00	318	318	3.03
52	[illegible]	[illegible]ire	[illegible]	[illegible]	[illegible]	[illegible]	322	[illegible]	4.60

Distribution of Repair Times
(including diagnosis)

MEAN MANUAL SOLUTION TIME



MEAN MANUAL+COGNITIVE SOLUTION TIME



Analysis of Replacements

FREQ Number of times the replacement was made, in the sample
RAWTIME Time to perform the replacement
TOTAL Total time spent replacing the component, in the sample

ID	REPLACEMENT	FREQ	RAWTIME	TOTAL
5	CRYSTAL_32768HZ	3	420	1260
29	Crystal	3	420	1260
6	BCD Switch(a)	11	80	880
8	INFRA-RED LED	2	420	840
36	4 Lead Ribbon Conn	33	14	462
24	4081a	10	46	460
26	4520 DIV(a)	9	50	450
9	2N222 TRANSISTOR	1	420	420
16	Photo-Trans	1	420	420
25	4081AND(b)	8	46	368
23	4069a	6	46	276
28	4060 CLOCK	4	50	200
17	10K Pot	20	10	200
27	4013 D-FF	4	50	200
4	4060 CLOCK DRIVER	3	50	150
14	4046 PHASE-LOCK	3	50	150
3	4013 DUAL-D FLIP	3	50	150
1	4021 P/S SHIFTER	3	50	150
22	S/P Converter	3	46	138
2	4013 DUAL-D FLIP	2	50	100
10	741 OP AMP	2	46	92
13	4584 Schmitt	2	46	92
30	Man74 LED	2	46	92
31	Man74 LED	2	46	92
21	4511 LATCH	2	46	92
20	4511 LATCH	2	46	92
37	FIBER OPTIC CABLE	2	40	80
34	Ribbon Cable(2)	4	14	56
7	4046 PHASE-LOCK	1	50	50
11	741 OP AMP	1	46	46
12	741 OP AMP	1	46	46
15	4001 QUAD NOR	1	46	46
35	Ribbon Conn.	2	14	28
32	12 VOLT POWER SUPP	1	10	10
33	12 VOLT POWER SUPP	1	10	10

Analysis of Testing Frequency

FREQ	**Number of times the test was performed in the sample**
TIME	**Time to perform the test**
TOTAL	**Total time spent performing the test, in the sample**

ID	TEST	FREQ X	TIME=	TOTAL
8	serial data	19	35	665
31	TP42	23	23	529
6	Data out	13	35	455
24	TP49	18	23	414
10	Ampl. 40/50khz	18	23	414
25	TP46	16	23	368
39	Byte 2 Observe	155	2	310
22	Vcc3	11	23	253
36	TP420	10	23	230
11	40/50khz	9	23	207
41	tp417	4	48	192
15	Phase-Lock Check	64	3	192
5	70ns	5	33	165
32	TP41	7	23	161
40	tp418	3	48	144
37	TP422	4	35	140
9	Q1 to Dinp	4	35	140
20	TP32	6	23	138
17	TP37	6	23	138
23	TP414	5	23	115
30	TP47	5	23	115
35	Vcc5	8	12	96
18	TP36	4	23	92
14	TP33	4	23	92
28	TP48	4	23	92
2	8hz	4	23	92
42	Byte 1 Observe	40	2	80
12	Vcc	6	12	72
13	Data	2	35	70
21	TP31	3	23	69
33	A5b	3	23	69
16	TP38	3	23	69
7	Vcc1	4	12	48
19	TP35	2	23	46
29	TP415	2	23	46
27	TP413	2	23	46
26	Vcc4	3	12	36
38	TP421	1	23	23
34	A5a	1	23	23
1	B2	0	48	0
4	128Shift	0	23	0
3	B1	0	48	0

Analysis of Diagnostic Values of Indicator and Test Points

U-REDCT Uncertainty reduction when the indicator was used
U/TIME Uncertainty reduction per unit of time to read the indictor

ID	TEST NAME	U-REDCT	U/TIME
15	Phase-Lock Check	3044.92	1014.97
10	Ampl. 40/50khz	742.07	32.26
6	Data out	623.36	17.81
39	Byte 2 Observe	617.67	308.84
22	Vcc3	487.00	21.17
25	TP46	435.38	18.93
31	TP42	423.00	18.39
8	serial data	411.13	11.75
36	TP420	267.83	11.64
24	TP49	267.18	11.62
11	40/50khz	261.33	11.36
35	Vcc5	216.35	18.03
9	Q1 to Dinp	205.38	5.87
20	TP32	182.41	7.93
17	TP37	163.87	7.12
5	70ns	133.28	4.04
14	TP33	122.68	5.33
26	Vcc4	122.44	10.20
12	Vcc	112.29	9.36
2	8hz	103.64	4.51
32	TP41	96.53	4.20
18	TP36	96.17	4.18
21	TP31	93.37	4.06
13	Data	88.37	2.52
33	A5b	86.64	3.77
16	TP38	84.89	3.69
30	TP47	69.85	3.04
28	TP48	68.86	2.99
19	TP35	68.79	2.99
7	Vcc1	63.84	5.32
23	TP414	57.89	2.52
40	tp418	48.67	1.01
34	A5a	32.72	1.42
41	tp417	31.86	0.66
29	TP415	30.68	1.33
42	Byte 1 Observe	9.67	4.83
37	TP422	3.97	0.11
3	B1	0.00	0.00
1	B2	0.00	0.00
38	TP421	0.00	0.00
4	128Shift	0.00	0.00
27	TP413	-8.04	-0.35

Analysis of Diagnostic Impasses
(lists failures which could not be resolved via testing)

```
BB 6  (RU 4  "4060 CLOCK DRIVER") had multiple RU's suspect at problem end
In 2 trials this RU set was suspect:  3  4  5
Ave $cost=    1.00  ave timecost=  242.00

BB 9  (RU 5  "CRYSTAL_32768HZ") had multiple RU's suspect at problem end
In 1 trials this RU set was suspect:  4  5
Ave $cost=    1.00  ave timecost=   57.00

BB 17  (RU 16  "Photo-Trans") had multiple RU's suspect at problem end
In 1 trials this RU set was suspect:  8 16
Ave $cost=    1.00  ave timecost=  427.00

BB 29  (RU 27  "4013 D-FF") had multiple RU's suspect at problem end
In 1 trials this RU set was suspect: 24 27
Ave $cost=    1.00  ave timecost=   53.00

BB 31  (RU 24  "4081a") had multiple RU's suspect at problem end
In 1 trials this RU set was suspect: 24 26 27
Ave $cost=    1.00  ave timecost=   57.00

BB 32  (RU 28  "4060 CLOCK") had multiple RU's suspect at problem end
In 1 trials this RU set was suspect: 28 29
Ave $cost=    1.00  ave timecost=  427.00

BB 40  (RU 29  "Crystal") had multiple RU's suspect at problem end
In 2 trials this RU set was suspect: 28 29
Ave $cost=    1.00  ave timecost=   57.00

BB 45  (RU 22  "S/P Converter") had multiple RU's suspect at problem end
In 1 trials this RU set was suspect: 22 36
Ave $cost=    1.00  ave timecost=   21.00

BB 46  (RU 22  "S/P Converter") had multiple RU's suspect at problem end
In 1 trials this RU set was suspect: 22 23 25
Ave $cost=    1.00  ave timecost=   53.00
```

Analysis of False Replacements

Like an expert repair technician, PROFILE will sometimes replace a component which turns out to be operational. This occurs when either

a. the component is inexpensive, and easily replaced, and is easier to replace than to test.

or

b. the system design does not offer sufficient testing points to determine the true source of the failure.

FREQ	No. of times the component was falsely replaced, in the sample
TIME	Total time spent replacing the component when it was O.K.
$COST	Total spares cost consumed when component was O.K.

ID	FALSE REPLACEMENTS	FREQ	TIME	$COST(F X $)
6	BCD Switch(a)	9	783	9
36	4 Lead Ribbon Conn	29	609	29
29	Crystal	1	427	1
5	CRYSTAL_32768HZ	1	427	1
8	INFRA-RED LED	1	427	1
24	4081a	6	318	6
26	4520 DIV(a)	5	285	5
25	4081AND(b)	4	212	4
17	10K Pot	19	190	0
27	4013 D-FF	2	114	2
28	4060 CLOCK	2	114	2
23	4069a	2	106	2
4	4060 CLOCK DRIVER	1	57	1
1	4021 P/S SHIFTER	1	57	1
3	4013 DUAL-D FLIP	1	57	1
20	4511 LATCH	1	53	1
10	741 OP AMP	1	53	1
30	Man74 LED	1	53	1
31	Man74 LED	1	53	1
21	4511 LATCH	1	53	1
34	Ribbon Cable(2)	2	42	2
37	FIBER OPTIC CABLE	1	40	1

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