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This report provides a detailed account of equipment purchases made under a DoD University Research Instrumentation Grant (AFOSR-89-0135). The equipment includes a Silicon Graphics IRIS 4D/120GTX workstation and a variety of hardware components which have been selected as components of a real-time server network designed to support a graphical interface to experiments in the control of mechanical systems. A brief description is provided of the resulting hardware implementation and its use in controlling three different experimental systems—a flexible beam, a rotating kinematic chain, and a six axis industrial robot. A detailed breakdown of expenditures is provided.

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DoD/URIP Grant No. AFOSR-89-0135

Program Entitled

SENSOR BASED CONTROL OF ROBOTIC MECHANISMS

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FINAL REPORT
(8/15/90)

ABSTRACT

This report provides a detailed account of equipment purchases made under a DoD University Research Instrumentation Grant (AFOSR-89-0135). The equipment includes a Silicon Graphics IRIS 4D/120GTX workstation and a variety of hardware components which have been selected as components of a real-time server network designed to support a graphical interface to experiments in the control of mechanical systems. A brief description is provided of the resulting hardware implementation and its use in controlling three different experimental systems—a flexible beam, a rotating kinematic chain, and a six axis industrial robot. A detailed breakdown of expenditures is provided.

1. SUMMARY OF PURCHASES

In accordance with a revised budget dated February 22, 1989, the subject grant has been used to purchase instrumentation as itemized below. These components have been assembled to provide a real-time control server with graphical interface for the Boston University Robotics Laboratory. The control server consists of a network of INMOS T-800 Transputers™ (32 microprocessors designed to be interconnected for parallel computing applications) with appropriate I/O circuitry for data acquisition and output to actuator amplifiers. The user's interface to the network is by means of a Silicon Graphics IRIS™ 4D/120GTX workstation. A technical summary of the operation of this system is provided in an appendix to this report. Below is a brief account of the current status of equipment installation as well as a detailed breakdowm of purchases.

Installation activities: An IMS BO14-1 VMEboard has been installed in one of the VME slots in the IRIS. This supports bus level communication between the IRIS and a Transputer module on the board, which is in turn connected via Transputer links (20Mbits/sec serial channels) to the other Transputers in the network. At this writing, INMOS has released software development systems only for SUN 3 and IBM/PC compatible computers. Hence it has been necessary to modify the IMS D505A software development system to run on the IRIS. Moreover, to achieve bus communication rates high enough to enable the IRIS to provide real-time graphical rendering of laboratory data, it has been necessary to write a device driver (which has been completed using a model previously developed for a different application by INMOS). Successful installation of the software development system and the device driver has provided our Lab with a convenient environment for writing, testing, and debugging OCCAM™ * programs for the Transputer network and has allowed us to expreiment with high speed data transfers from the Transputers to the IRIS.

Additional equipment which has been purchased under the subject grant includes an IMS BO11-2 VMEboard with T800 Transputer and 2MBytes dual ported RAM, to be linked to the real-time server network and act as host computer for our six axis MERLIN robot. We have also purchased a VME-VME bus connector with 1MByte of dual ported RAM. This can be used to link either our IRIS or a SUN workstation directly to the MERLIN robot, and it provides an alternative to using the IMS BO11-2 (with T800 Transputer) as host controller. This provides a desirable redundancy in the system and at the same time simplifies certain implementations while allowing greater flexibility in component testing for implementations in which the BO11-2 is designated as the robot's host computer. We have bought a servo motor to be used in a new set of rotating kinematic chain experiments; we have bought strain gages to rebuild our flexible beam experiment (which was partly destroyed in the initial testing of the Transputer controllers); and we have bought a slip-ring assembly so that our rotating beam apparatus can be used to study the dynamics of beams undergoing continuous rotations. Also to support the flexible beam experiment, we have purchased chip level instrumentation amplifiers (to provide conditioning for strain gage circuits). Finally, to support analytical

* OCCAM is the parallel processing language which INMOS has developed for Transputers.

work on the rotating systems under study, we have purchased a Macintosh SE/30 to run Mathematica™.

Technical remarks regarding the instrumentation: The equipment under discussion was selected to provide relatively powerful low-level controllers for running laboratory experiments while at the same time providing ample capacity for real-time data acquisition and a sophisticated graphics oriented user interface. The IRIS 4D/120 GTX, in particular, was chosen for its powerful 3-dimensional graphics rendering capability (400,000 3-d vectors/second, 100,000 3-d polygons/second), its CPU speed of 20 MIPS, and the availability of a VME-bus interface through which to connect the real-time control server. Various other pieces of equipment were acquired to support the following activities:

1. Rotating kinematic chain experiments: Beginning wih our early papers on the dynamics of rotating kinematic chains ("Parametric Dependence in the Equilibrium Dynamics of Rotating Structures," ASME Winter Annual Meeting, Boston, December 1987, and "Equilibrium Mechanics of Rotating Systems," 26-th IEEE Conf. on Decision and Control, Los Angeles, pp. 1429-34.), we have become increasingly interested in performing experiments both to verify theoretical predictions and to uncover subtle phenomena which would not otherwise be emphasized in the theory. Recently, for instance, we have discovered that certain unstable dynamic (or relative) equilibrium rotations (so called supercritical rotations) of some driven kinematic chain mechanisms can be stabilized by superimposing a small amplitude, high frequency periodic term over the (constant velocity) forcing. The theory of such stabilization is not yet completely understood, but the analysis seems to involve averaging theory in an essential way. The physical phenomenon itself, however, appears to be fairly robust. Some of the equipment whose purchase is described below will support further experiments with rotating kinematic chains. In particular, a new chain mechanism will be built using the E.G. & G. MT-3528-117CF servo-motor.

2. Rotating elastic beam experiments: The recent control literature describes a number of experiments in the control of rotating elastic beams. The control server network which we have described will be connected to the flexible beam experiment depicted in Figure 1. An encoder and tachometer on the driving motor provide direct measurement of the position and velocity of the hub. Strain gages along the beam have also been used to provide shape data in several control experiments. An optical sensor for tip position is under development. One novel feature with this apparatus is the possibility of not aligning the beam's resting neutral configuration along a radial axis. This provides the opportunity to study the rotating beam in a regime where the dynamics are highly nonlinear. (See Baillieul and Levi, "Constrained Relative Motions in Rotational Mechanics," to appear in Arch. Rat. Mech. and Analysis for details.) Also, a new slip-ring assembly will support study of long-term beam dynamics when the beam is undergoing rotations with constant rate baseline motions present.

To enhance our rotating beam apparatus, we have purchased additional strain gage kits, instrumentation amplifiers (10 IC's from Analog Devices, Inc.) and two special purpose boards to control the beam, acquire data from the strain gages, and provide a real-time interface with the control server network.

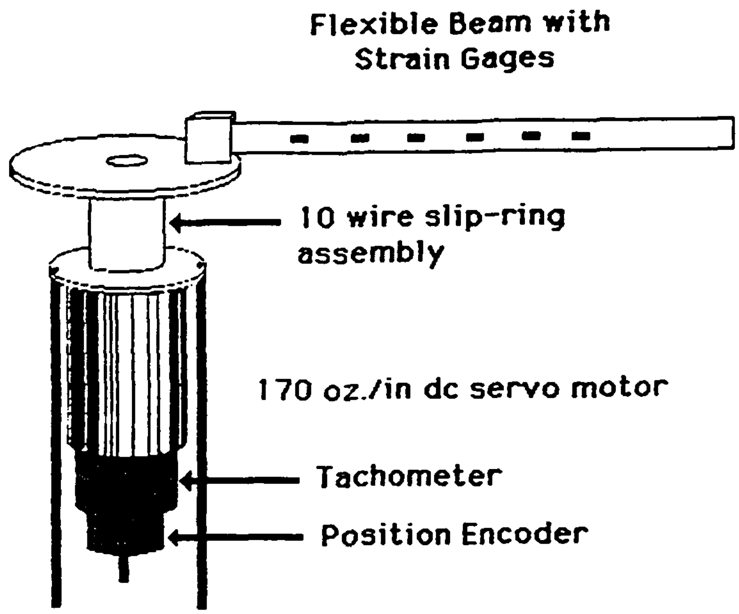


Figure 1 A rotating beam experiment

3. Sensor based robot control experiments: The Boston University Robotics Laboratory operates several industrial robots including a six axis MERLIN (maufactured by American CIMFLEX Corp.). The Laboratory has developed a high speed host interface which allows the manipulator to be controlled by means of a memory mapped interface to a host computer. The host comp uter currently in use is a single board Motorola MVME133 (with Motorola 68020 CPU) whose dual ported RAM may be addressed from either the resident CPU or via a Versabus-to-VMEbus connection from the robot's 68000 based contoller. Students in the Laboratory have written a cross compiler for a SUN 3 workstation which allows users to write motion control programs in C which can be compiled on the SUN and downloaded and executed on the MVME133.

One goal of the equipment purchases in this report has been to provide greater sensor I/O capacity for the host interface to the MERLIN robot. For this reason, we have designated an INMOS BO11 board with T800 Transputer and dual ported RAM to replace the MVME133 as host computer. Like the MVME133, the BO11 has a VME connector, but it also has much greater I/O capacity. Indeed, using Transputer links to connect the BO11 to our server network, there is almost no limit to the number of sensors which can be used in real-time control of the robot. To support experimentation, we have also acquired a VME-VME Adaptor with MByte dual ported RAM to directly link a VME-based workstation (such as the IRIS or SUN) to the MERLIN's bus.

2. SPECIAL PROBLEMS AND FUTURE RESEARCH GOALS

While the choice of Transputers to handle real-time control implementations has proven satisfactory in so far as they have met technical requirements for speed and interupt handling, these processors and their native language OCCAM^{TM} have provided a challenge to those would-be users who have not had previous Transputer experience. We are eagerly awaiting the release of the Transputer C compiler which is due from INMOS within the next month. Although any native C will have features in common with all parallel computer languages, it is hoped that this environment will be sufficiently comfortable for C programmers that students who know C will be able to master the Transputers in less than a semester.

We also aim, in the coming months, to build a library of routines which support the motion control experiments described above. Not only will such a library provide utilities which can be used by anyone wishing to design an experiment, they will also provide a body of examples for novice OCCAM programmers.

EQUIPMENT PURCHASES

Grant AFOSR-89-0135 Detail

ITEM	Budgeted	Actual Cost	Delivery Date (Approximate)
1. IRIS 4D/120 GTX B Engineering Workstation (inlc. 3 yr. service agr.)	$80,907.00	81,173.80	6/27/89
2. INMOS Transputer Components for a real-time distributed processor system for control implementations:			
(a) Four (4) XP/DCS CPU Motherboards	$8,000.00	7,400.00	5/25/89
(b) Two (2) IMS B404-4 Transputer Modules	$5692.00	4475.83	8/10/89
(c) IMS D505b Transputer Software Development system	$750.00	1008.24	9/12/89
(d) IMS BO14-1 Transputer Motherboard	$2040.00	2044.96	9/12/89
(e) Misc. Components for Distributed Processor System: incl. Four (4) IO/MOD boards, One (1) COM/MOD communications module, Cables, and One Lab Rack with Power Supply	$8500.00	5755.00	12/31/89
(f) IMS BO11-2 Transputer Motherboard	$4900.00	4908.69	1/16/90
3. One (1) VME-VME Adaptor Model 412 from BIT3 Computer Co. incl. 25' cable and 1 MByte dual ported RAM	$2895.00	4093.61	1/12/90
4. Custom design motor control card, strain gage card, and two (2) pc-boards from Evergreen Design	*	2770.00	1/16/90
5. Miscellaneous Hardware	$5000.00		
(a) Servomotor with Tachometer and position encoder from Inductive Components, Inc.	**	763.02	7/10/90
(b) Two (2) Strain gage and Epoxy Kits (FAB-12s-35sx & EPY-150 resp.) from BLH Elctronics	**	239.63	6/27/90

(c) Ten (10) AD 624 Instrumentation Amplifiers from Analog Devices, Inc.	**	180.13	6/15/90
(d) Instrumentation Slip Rings from Maurey Instrument Corp. (SR 2066-10-.50)	**	1569.67	7/10/90
(e) Macintosh SE30 w/ 5MByte RAM &40M disk	**	2656.20	7/5/90
10. Development Cost (device driver to integrate Transputer network and IRIS Workstation)	$5315.00	3800.00	9/15/89
TOTALS	123,999	122,838.78	

* Included in Rev. B of XP/DCS board set.

** Items refered to original budget heading "Miscellaneous hardware"

VENDOR ADDRESSES
by Item

Item 1 from:

Silicon Graphics, Inc.
128 Technology Center
125 Technology Dr., 4-th Floor, Suite 4
Waltham, MA 02154

Attention: John Coukos
Sales Representative
(617) 891-8100

Items 2,4 from:

Evergreen Design
8 Buttermilk Lane
Branford, CT 06405

Attention: F. Levin
Designer
(203) 483-1584

Item 3 from:

BIT-3 Computer Corp.
8120 Penn Avenue South
Minneapolis, MN 55431-1393

Attention: Larry Larsen
Sales Representative
(612) 881-6955

Item 5(a) from:

Inductive Components, Inc.
53 Stiles Road
Salem, NH 03079

Attention: Tom Moran

Item 5(b) from:

BLH Elctronics
75 Shawmut Road
Canton, MA 02021

Attention: Mike Morrell
(617) 821-2000

Item 5(c) from:

Analog Devices, Inc.
Two Technology Way
P.O. Box 280
Norwood, MA 02062

Attention: Natalie McPhee
(617) 329-4700

Item 5(d) from:

Maurey Instrument Corp.
4555 West 60-th Street
Chicago, IL 60629

Item 5(e) from:

University Computers, Inc.
660 Commonwealth Ave.
Boston, MA 02215

Item 6 from:

Steven P. Weibel
Boston University Robotics Lab
College of Engineering
Boston University
Boston, MA 02215

Draft 8/15/90

APPENDIX

Introduction to THE BOSTON UNIVERSITY ROBOTICS LABORATORY REAL-TIME CONTROL SERVER

The Boston University Robotics Laboratory Server Network for Real-Time Control is a custom designed research facility providing a high resolution graphical interface to a parallel network of microprocessors which can be programmed to control a wide variety of mechanical systems. All low level functions involving data acquisition, closing of servo loops, and so forth are implemented using INMOS T800 Transputers—32 bit microprocessors which are designed to work as nodes in parallel processing networks. Because Transputers support both internal and external interrupts, and because they are designed for parallel execution of communicating sequential processes, they provide a real-time environment which is ideal for implementing MIMO designs for controlling systems having many degrees of freedom. The graphical host and principal user interface to the Transputer network is a Silicon Graphics 4D/120 GTX IRIS workstation. The various functions of the IRIS, the Transputer nodes, and other Server Network components are detailed in the remainder of this report. A complementary report, now in preparation, discusses programming of the B.U. Robotics Laboratory Real-Time Server Network.

The IRIS Host and Bus-level Interface: The Silicon Graphics 4D/120 GTX IRIS workstation, which serves as host and principal user interface to the Real-Time Server Network, is equipped with two MIPS Inc. CPU's for a combined performance of 20 M.I.P.S. Moreover, special purpose graphics hardware (the pipelined "Geometry Engine™" processors) provides the IRIS with excellent 3-D graphics rendering capability. (Frequently cited benchmarks include 400,000 3-D vectors/sec and 100,000 3-D polygons/sec.) The workstation performs several functions within the Network. It is a powerful tool for simulations of mechanical system dynamics, and since it has a bus-level connection (described below) to the rest of the Server Network, it allows real-time graphical rendering of data streams from working experiments. The workstation also serves as host for software development for all nodes in the Control Server Network.

The interface between the IRIS and the Transputers in the Server Network is by means of an INMOS BO14-1 board installed in the VMEcage of the IRIS. This board is configured with two IMS B404-4 Transputer modules (TRAMs), each of which is a complete microcomputer consisting of a T800 Transputer running at 17 Mhz together with 128Kbytes of SRAM and 2MBytes of DRAM. The BO14-1 board is compatible with VMEbus Specification Rev. C.1 and operates as a VMEbus slave. Each of the T800 Transputers has four 20Mbits/sec serial ports called Transputer links or simply links. These links are designed to provide run-time communication between sequential processes on different Transputers. Each link consists of a serial output and a serial input, both of which can carry data and link control information. The links on the BO14-1 can be configured using two COO4 crossbar link switches, and by means of these switches and the COM/MOD communications module described below, link connections can also be established with other Transputers in the Network.

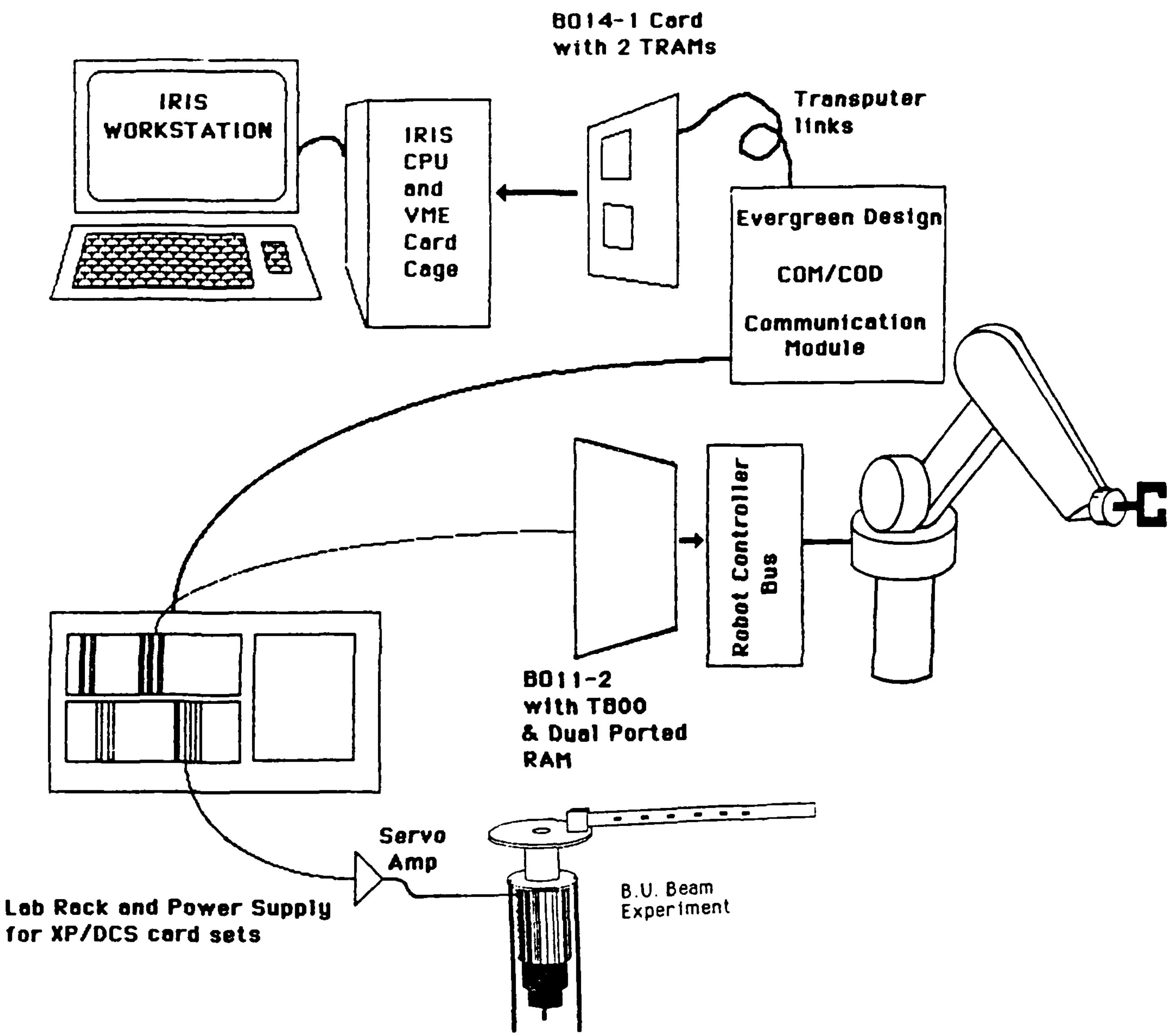


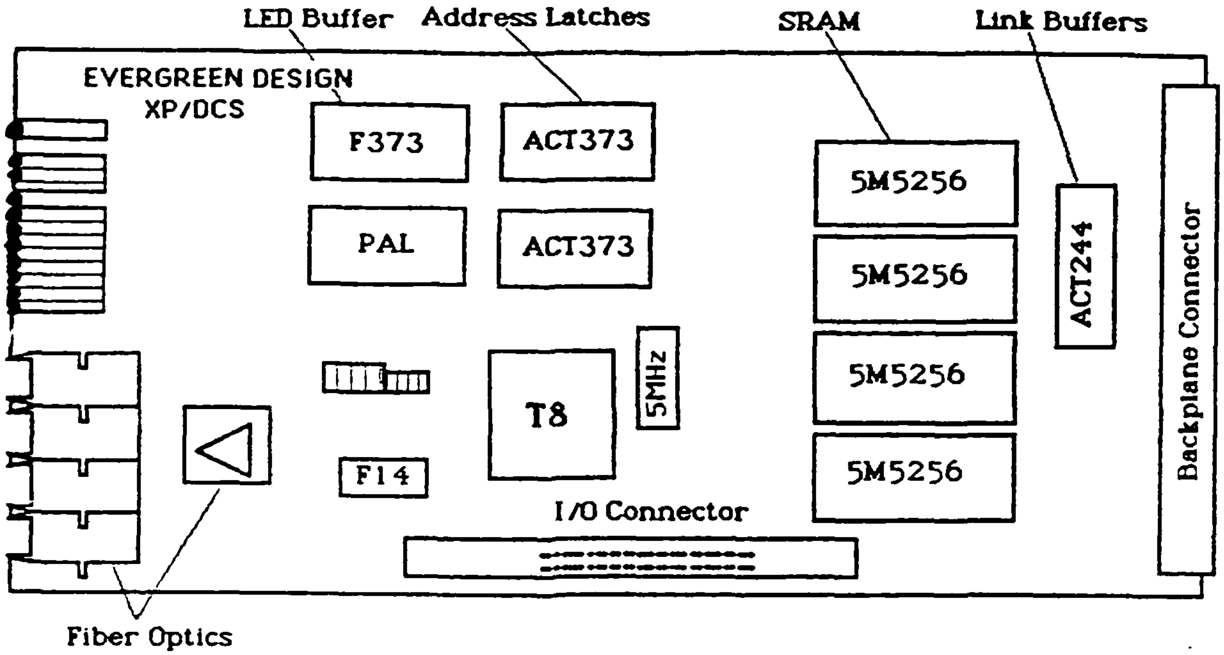
Figure 1: The Boston University Robotics Laboratory Real-Time Control Server

The natural language for real-time graphics programming on the IRIS is C. Although C would also be the natural choice in many computer environments for real-time control implementations, the language currently used for the B.U. Server Network is OCCAM™. OCCAM bears a special relationship with the Transputer since they have been developed essentially in parallel since 1982 by INMOS. The fact that OCCAM is the best documented and best supported language for the Transputer must be weighed against the time-cost many programmers face in learning to use features not present in more common languages such as C. Since the INMOS C compiler for Transputers is still in beta test, and since we have not wanted to commit to developing Server software in a 'third party' version of C, we continue to develop parallel application programs in which the IRIS based functions are written in C and the Transputer based functions are written in OCCAM.

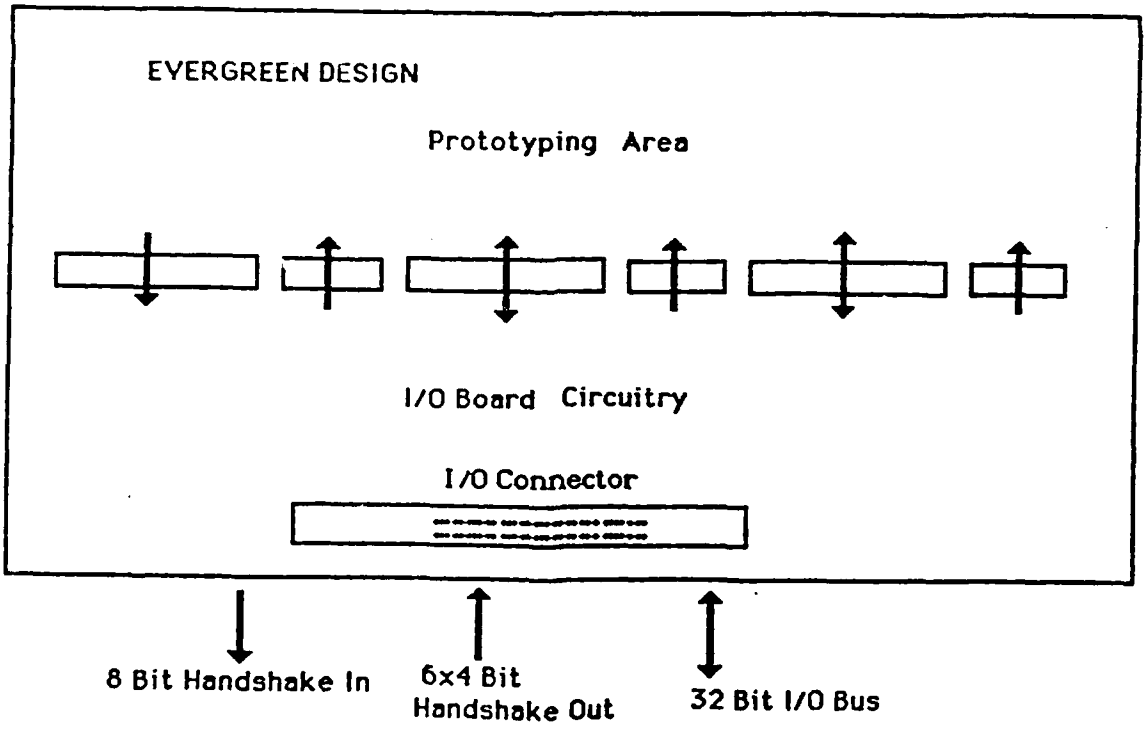
To support high bandwidth, bus-level communication and to allow the IRIS to be used for Transputer software development, a UNIX device driver for the BO14-1 board has been written. A functionally equivalent device driver is available from INMOS as part of the OCCAM 2 Toolset™ (IMS D505A). This is designed for SUN 3 systems, however, and no similar product is currently available for the IRIS. For SUN users, the OCCAM 2 Toolset provides a fairly complete software development system, and although the modules in the package cannot be run on the IRIS CPU's, the device driver provides transparent access to most development tools (OCCAM compiler, debugger, etc.) since these can be run on the designated root T800 Transputer on the BO14-1 board. Moreover, because software may be loaded into Transputer memory via the links, the entire Server Network may be programmed via the Transputers installed in the IRIS. Figure 1 provides a sketch of the Boston University Robotics Laboratory Real-Time Control Server.

The Transputer Network: In principle, all Transputers in the Server Network may be interconnected by INMOS's twisted pair link cables. To insure that 20Mbits/sec link speeds are maintained, however, these cables are restricted to approximately three feet in length. Since for many laboratory applications, the distances between communicating processors should exceed this restriction, a communications module (COM/MOD in Figure 1) has been developed by Evergreen Design, Inc. to provide signal conditioning allowing link communication over cable lengths of up to 10 meters.

To be used in real-time control implementations, the Transputers must be interfaced with various other pieces of hardware (A/D, D/A, etc.). In the B.U. Server Network, such interfaces are accomplished using XP/DCS board sets from Evergreen Design. Originally developed for use at Yale University, these boards can be used as computational nodes in a wide variety of laboratory applications. As shown in Figure 2, each board set distributes computation and I/O functions across two (or possibly more) boards. The XP/DCS CPU board includes a 17 MHz T800 Transputer processor, 128KByte (zero wait state) SRAM, and fiber optic interface capability (for operation in EMI hostile environments such as encountered in home-made robot designs). Both the CPU motherboard and I/O daughterboard are standardized to the Eurocard form factor, using a board size of 100mm $\times$ 220mm. The backplane connector is compatible with INMOS' ITEM Rack standard, although our Server Network uses a custom design lab rack/power supply module. The I/O daughter board derives its power from the



(a) XP/DCS CPU Board



(b) XP/DCS I/O board

Figure 2: XP/DCS board designs

XP/DCS motherboard. I/O communication is supported by a latched 32 bit bidirectional I/O bus together with six individually addressable sets of four latched handshaking output lines and eight handshaking input lines. This I/O bus configuration can accommodate interfaces to a wide variety of actuators, sensors, and other devices. The rotating beam experiment depicted in Figure 1, for example, includes I/O from a position encoder-decoder circuit as well as several A/D channels for velocity and strain gage readings.

To further exploit the flexibility of the Transputer network approach to real-time control, we have developed a board level interface to the controller of a six-axis MERLIN™ robot. As shown in Figure 1, this involves an INMOS BO11-2 VMEcard with 2 MBytes of dual ported DRAM. Transputer link cables connect the BO11-2 with an XP/DCS board in the Server Network. The VME connector on the BO11-2 is plugged into a VME-to-Versabus adaptor in the robot controller, and commands to the robot actuators are issued over a memory mapped interface between the T800 Transputer on the BO11-2 and the robot's control processor. Although this arrangement involves an inherent overhead of 4 msecs between commands, low bandwidth closed loop robot control can be achieved. More demanding applications would require complete redesign of the robot controller, and such an undertaking is not contemplated at this time.

Research Objectives: Research in the Boston University Robotics Laboratory is aimed at understanding the dynamics and control of complex mechanical systems such as kinematic chains and mixed structures in which the number of degrees of freedom exceeds (perhaps greatly exceeds) the number of actuators. Work is currently under way to connect new experiments in the rotational mechanics of kinematic chains and other structures to the network. As described above, the B.U. Real-Time Control Server will obviously provide a powerful tool for research on the mechanics and control of such systems. Although at present the Server requires a high degree of sophistication on the part of users (knowledge of much of the laboratory apparatus used in real-time control as well as C and OCCAM programming), our goal is to simplify the use of the facility as much as possible. As more experiments are brought on-line and standard solutions to implementation problems are developed, we aim to create a refined graphical interface and a well documented set of routine approaches to the design of mechanical experiments.

Acknowledgement: Support from INMOS and the Air Force Office of Scientific Research (Grant AFOSR-89-0135) for the B.U. Real-Time Control Server is gratefully acknowledged.

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Professor of Aerospace and
Mechanical Engineering