AD-A190 238 ADVANCED PROGRAMMING AND CONTROL TECHNIQUES FOR COMPLEX MECHANICAL SYSTEMS(U) BOSTON UNIV MA COLL OF ENGINEERING J BAILLIEUL 30 OCT 87 AFOSR-TR-87-1796 1/1

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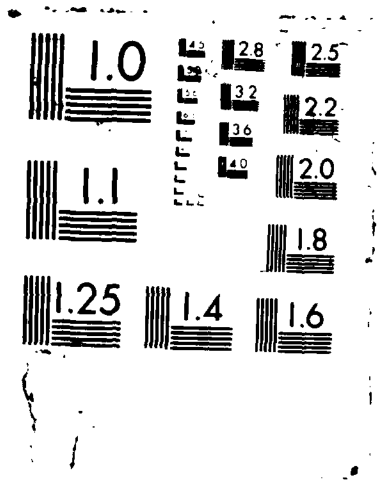
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REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S): AFOSR-TR- 87-1796
6a. NAME OF PERFORMING ORGANIZATION: College of Engineering Boston University; 6b. OFFICE SYMBOL (If applicable): AE/ME	7a. NAME OF MONITORING ORGANIZATION: Air Force Office of Scientific Research
6c. ADDRESS (City, State and ZIP Code)	7b. ADDRESS (City, State and ZIP Code): Directorate of Mathematical & Information Sciences, Bolling AFB DC 20332-6448 Bldg 410
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: AFOSR; 8b. OFFICE SYMBOL (If applicable): NM	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: AFOSR-86-0273
8c. ADDRESS (City, State and ZIP Code): Bolling AFB DC 20332-6448 Bldg 410	10. SOURCE OF FUNDING NOS.: PROGRAM ELEMENT NO. 61102F; PROJECT NO. 2917; TASK NO. A5; WORK UNIT NO.

11. TITLE (Include Security Classification): Advanced Programming And Control Techniques for Complex Mechanical Systems

12. PERSONAL AUTHOR(S): Professor John Baillieul

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Final	FROM 7/30/86 TO 7/29/87	87-10-30	14

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	robot manipulator, force/torque sensing wrist, high speed interface

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report provides a detailed account of equipment purchases made under a DoD University Research Instrumentation Grant (AFOSR-86-0273). The equipment includes computers, a robot manipulator, and a force/torque sensing robot wrist, all of which are being integrated into an experimental robot control system. A brief description of several research activities supported by this instrumentation focuses on topics in experimental mechanics, sensor driven control of robots, and advanced programming techniques for complex mechanical systems. An appendix provides details of the original project budget.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL: Major James Crowley, Dir. Math & Inf. Sciences	22b. TELEPHONE NUMBER (Include Area Code): (202) 767-5025; 22c. OFFICE SYMBOL: NM

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE.

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

DoD/URIP Grant No. AFOSR-86-0273

AFOSR-TR- 87-1796

Program Entitled

ADVANCED PROGRAMMING AND CONTROL TECHNIQUES FOR COMPLEX MECHANICAL SYSTEMS

Principal Investigator

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FINAL REPORT

(10/29/87)

ABSTRACT

This report provides a detailed account of equipment purchases made under a DoD University Research Instrumentation Grant (AFOSR-86-0273). The equipment includes computers, a robot manipulator, and a force/torque sensing robot wrist, all of which are being integrated into an experimental robot control system. A brief description of several research activities supported by this instrumentation focuses on topics in experimental mechanics, sensor driven control of robots, and advanced programming techniques for complex mechanical systems. An appendix provides details of the original project budget.

1. SUMMARY OF PURCHASES

In accordance with our September 1986 budget submission, we have purchased an American CIMFLEX Merlin robot and controller with software, high speed host interface software and hardware, a Motorola MVME133 host computer, a force/torque sensing robot wrist, and a SUN 3/110C engineering workstation. The history of these purchases is briefly encapsulated in Table 1. Having completed the designated purchases, the focus of our research project has shifted to integrating the components to create a useful laboratory facility for research into advanced programming and control techniques for complex mechanical systems. The integrated system is depicted in Figure 1. A narrative summary of instllation activities is as follows:

1. The MERLIN robot and AR-BASIC control software were delivered to temporary quarters of the Boston University Robotics Laboratory in early November, 1986. It was shipped with the wrong transformer and did not become operational until January, 1987. Between January and August 1987, this robot was used in a variety of tests and experiments using the manufacturer's controller and AR-BASIC software. It was found that the robot could read and respond to analog data from a force/torque sensing wrist, but the complete cycle of reading, computing, and initiating a response typically has taken about 0.5 seconds. This is a clear indication that high bandwidth force-feedback control algorithms cannot be implemented using the manufacturer's hardware and software. Having anticipated this problem, we have begun testing a host control computer which we expect will provide a much more effective real-time operating environment. (See below.)

The robot ceased to be operational on August 14 as it had to be packed for moving to its permanent location in our newly designed Robotics Laboratory. Because of construction delays, the robot has not yet been completely reinstalled. It is anticipated that the robot will once again be fully operational by December, 1987, and will be functioning under the control of the MVME133 host computer by January, 1988.

2. The MERLIN High Speed Host Interface hardware (consisting of six EPROMs) was delivered in December, 1986 It was installed in June, 1987, after deleivery of the MVME133 host computer.

3. The HAL-Versa Engineering Synergist I Versabus-to-VMEbus interface card and the Motorola MVME133 68020 real-time computer were delivered to Boston University in June 1987. These pieces of equipment were selected for purchase after a careful review of candidate host computers for our robot. In the original project proposal, we had designated a Matrox MBC-86/12B (8086/8087) to serve as host computer. This computer had previously been interfaced to a MERLIN robot at the National Bureau of Standards. It was decided not to duplicate the NBS system in favor of developing a totally new system in which the central microprocessors were all manufactured by Motorola. The motivation for this decision is the hope that we shall obtain maximally straightforward communication between our software development computer (a SUN 3/110c with Motorola 68020 MPU), our real time host computer (a Motorola MVME133 with Motorola 68020 MPU), and the robot controller (which has a

Motorola 68000 MPU).

The most complex interface among the designated system elements is between the MVME133 host computer and the robot controller. The high speed communication necessary to implement real-time control can be achieved by having the computer communicate with the robot controller MPU over a bus interface. Unfortunately, the buses don't match. All suitable 68020 host computer candidates which we evaluated had VME buses, while the MERLIN controller has a Versabus. The HAL-Versa Engineering Synergist I Versabus-to-VMEbus interface card solves this problem and allows us to allocate a one (1) Kbyte block of the host computer's dual-ported RAM, accessible via the bus interface to the robot's controller. It is through this shared memory that commands and actuator status information are passed between the robot and the MVME133 host computer.

4. The SUN 3/110C engineering workstation was delivered to Boston University in February, 1987. It's arrival was delayed due to the large number of orders the manufacturer, SUN Microsystems Inc., had to fill at that time. After its arrival, this computer has proven to be the most satisfactory piece of equipment to be purchased. To date a large amount of software has been written by our laboratory personnel. An object code translation utility (UNIX a.out format to Motorola s-record format) has been developed so that programs written on the SUN can be down loaded and executed on the MVME133. An RS232 link between the SUN and the MVME133 has been installed and seems to be working satisfactorily. The main problem which we now forsee for the SUN system is that the initial disk capacity (71Mbytes) will not be adequate. For this reason, we have recently placed an order for an expansion disk which *will triple our capacity.*

5. The 6-axis force/torque sensing robot wrist from Barry-Wright Inc. was delivered in March, 1987. The operation of this sensor is illustrated in Figure 2. Six independent degrees of freedom of forces and torques are measured by a system of strain gauges. These measurements are processed by circuitry within the wrist and reported in either of two forms to the robot's computer. When the wrist operates in digital output mode, strings of six numeric values punctuated by the ASCII equivalent of 'line-feed-carriage-return's are reported continuously. This form of readout is ideal for real-time displays on a computer terminal. Unfortunately, due to a timing problem, the AR-BASIC control software on the MERLIN is unable to parse these data strings. Analog output from the wrist sensor is also possible. A host system to which the wrist is connected can poll each of the six force/torque axes and receive a voltage in reply. The magnitude of this returned voltage indicates the force or torque measured along the axis in question. This mode of operation with the wrist has been succesful, and a number of simple demonstration programs with the wrist connected to the MERLIN's controller have been written. Because the AR-BASIC software has proven so slow to read and respond to output from the wrist, however, it is clear that practical use of force/torque feedback will have to involve the sensor communicating directly with the host computer.

EQUIPMENT PURCHASES*

Under Grant AFOSR-86-0273

ITEM	Budgeted	Actual Cost	Delivery Date (Approximate)
1. MERLIN 6-Axis 40" Robot Arm and Robot Controller	$56.000	56.000	11/5/86
2. AR-BASIC robot control software	$11.500	11.500	11/5/86
3. MERLIN High Speed Host Interface (HSHI) Option: Six (6) HSHI servo EPROMS; HSHI software; HSHI documentation	$7.500	7.500	12/1/86
4. Additional Interface Hardware: Motorola MVME133 68020 real-time computer; HAL-Versa Engineering Synergist I Versabus-to-VMEbus interface card	$2.500	2.003	6/19/87
5. SUN 3/110C Engineering Workstation	$18.130	18.558	2/6/87
6. Six degree of freedom force/torque sensing robot wrist	$4.275	4.479	3/25/87
TOTALS	$99.905**	100.040***	

* Funding sources: Grant AFOSR-86-0273 for the amount $85.600 and Boston University Cost Sharing in the amount $14.335.

** Other related expenditures: $995.00 robot delivery charge + $495.00 HAL Versabus-to VMEbus interface card.

*** All amounts in excess of original budget figures have been absorbed by Boston University.

TABLE 1

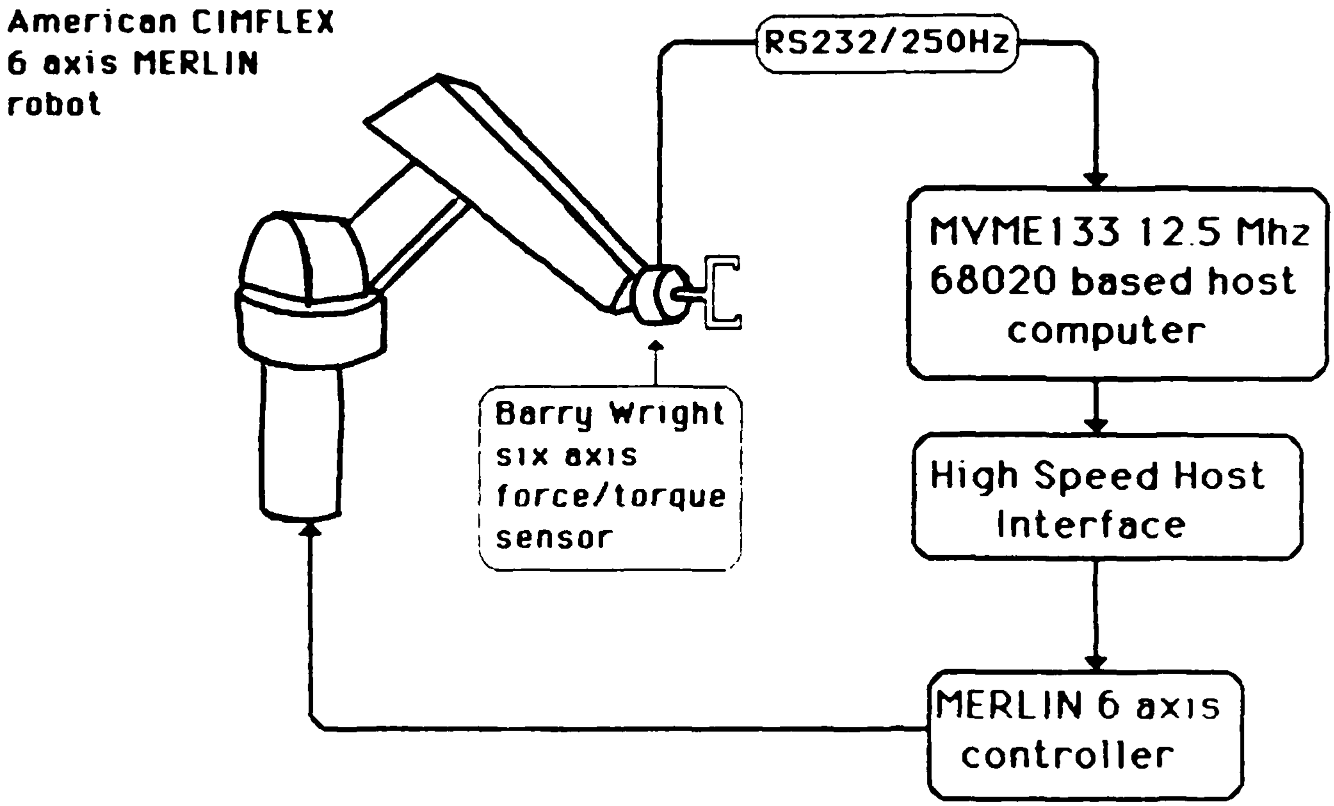

Figure 1: *Advanced robotic programming and control architecture*

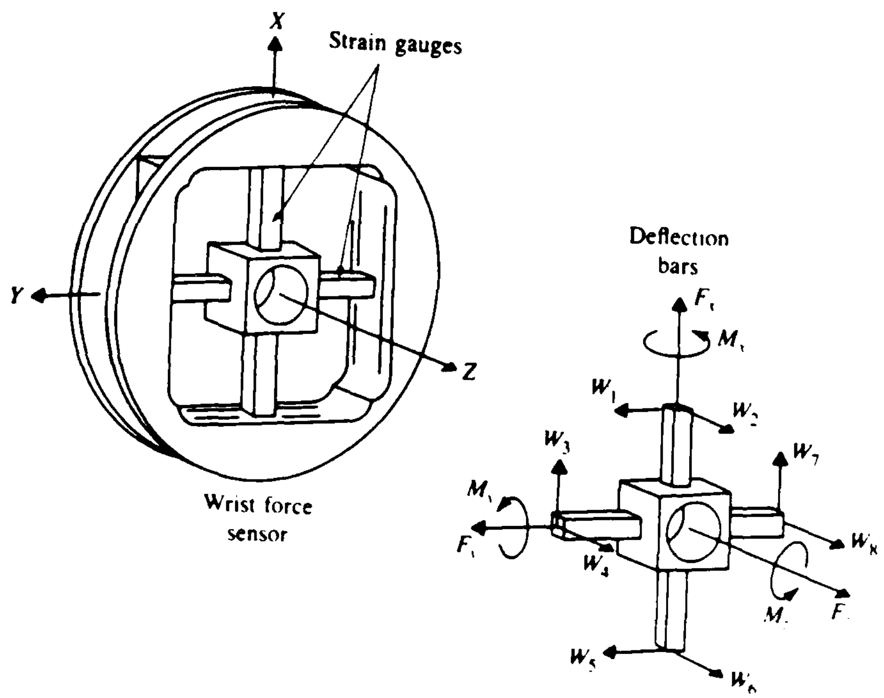

Figure 2: *Force/torque sensing robot wrist*

2. RESEARCH SUMMARY AND FORECAST

The robotic and computer equipment described above is supporting a variety of research activities at Boston University including: (i) the analysis and control of complex elastic and articulated mechanisms. (ii) sensor driven control of robotic systems. and (iii) advanced programming techniques for complex mechanisms and systems.

The analysis and control of complex elastic and articulated mechanisms: The Principal Investigator is currently involved in an Air Force sponsored research program on the nonlinear control theory of complex mechanical systems. Recently published work describes a new class of dynamical models for rotating structures and certain aspects of a theory of qualitative dynamics of these models. A nonlinear stability theory of equilibrium rotations for several types of articulated and elastic mechanisms has been developed with its main focus on the dependence of dynamic stability of equilibrium states on physical parameters such as angular momentum. As parameters are varied. the models undergo various bifurcations. the understanding of which will be crucial for the planning and execution of fast large angle slewing manuevers of flexible spacecraft and other mechanisms having complex nonlinear dynamics. While we believe recent reports in the literature augur well for significant advances in the dynamical theory of rotating structures. it is nevertheless useful to complement theoretical investigations with empirical work to validate predictions and obtain a more exact understanding of the way in which phenomena such as buckling due to inertial loading depend on parameters. Moreover. because our models and the underlying physical dynamics are exceedingly complex. experiments are essential in suggesting important new avenues for future research. It will probably only be possible to develop very accurate models of transient effects from empirical observations.

The MERLIN system described in the previous section will be a central element in experiments involving three degree of freedom slewing of elastic rods. plates. kinematic chains. etc. Using the force/torque sensing wrist and the capability of our system to support novel control implementations. we aim to develop techniques to sense and control the buckling of flexible and articulated workpieces being handled by the robot. Such techniques are of practical interest for automated parts handling robotic applications where the parts in question may include sheets of metal. plastic. or even cloth or may have free joints. The active control of buckling should also be important in the control of flexible spacecraft and highly maneuverable aircraft.

Sensor driven control of robotic systems: Future generations of robotic technologies will involve lighter weight manipulators in which flexible links undergo elastic deformations when loaded. In such a manipulator. there is no simple analytic relationship between positions. forces. and torques measured at the joints and the same variables measured at the end effector. Sensory input from tactile. force. vision. and other sensors thus becomes critically important for advanced robotic technologies.

Even for today's industrial robots engaged in rather routine assembly operations. it is important to incorporate more sensory feedback into control systems. Applications involving multiple cooperating robots working in a shared workspace. for example. may benefit from proximity sensing. and as mentioned above. the handling of flexible materials can be facilitated by force feedback. We have recently begun a research project sponsored by the Digital Equipment Corporation for developi.g a two-robot workcell system. The two robots which will be used are the MERLIN and an old IBM7535 which had previously been acquired by our lab. Since it would not be cost effective to redesign the controller for the IBM robot. we shall depend on the advanced sensory capabilities which can be given to the MERLIN. In addition to the force/torque control (which will be essential for any activity in which the two robots simultaneously grasp a single workpiece) we hope to begin experiments with sonar proximity sensors. Simultaneous operation of force/torque and sonar sensors will provide an opportunity to investigate the practical issues in sensor "fusion" and the design of control laws using multisensory feedback. This type of control requires adaptation algorithms which govern the transition from focus on one sensory modality to another as dictated by real-time changes in the operating conditions.

Advanced programming techniques for complex mechanisms and systems: The experimental robotic system which we have described provides considerable flexibility for implementations of real-time control algorithms featuring novel uses of sensory feedback. To realize the full potential of this system. we are in the process of creating a modular software development environment in which the principal user interface is a SUN 3/110C engineering workstation. This workstation is connected by an RS232 link to a Motorola MVME133 68020 real-time computer which in turn communicates directly with the MERLIN's 68000 control computer by means of shared memory (on the MVME133 board) and the Versabus-to-VMEbus interface described above. We have written a translator which converts C programs written on the SUN to Motorola s-record format. In this form. the programs may be downloaded from the SUN to the MVME133. Before real-time control experiments can be started. it has been necessary to configure one (1) Kbyte of the shared dual-ported RAM in the MVME133 for use in passing commands and actuator status data at servo rates between the MVME133 and the robot controller.

To aid in program development for control experiments. we have developed a package of motion display software for the SUN system. Exploiting the graphics capability of the SUN. this package allows the programmer to view various aspects of a given robot motion simultaneously in different windows. Currently the display is configured so that the time history of each of six joint trajectories is displayed together with a 3-dimensional graphical representation of the entire manipulator. Input to this graphical display is currently an input file containing a previously stored motion. recorded from a simulation. Future versions of the software will allow the input file to be recorded from actual robot motions. and if timing permits. real-time display of robot motions.

This graphical simulation software forms the nucleus of a CAE facility for robotics which we aim to expand in several ways. First. we plan to develop the capability to create robot control programs graphically The first step is to allow simulated robot motions to be controlled by the mouse or specially designated set of control keys on the SUN. These simulations will be designed to capture enough detail to permit actual trajectories to be recorded and automatically compiled into appropriate robot control programs for execution on the MVME133. A second goal is to augment our existing motion display software to include displays of dynamic effects and readings from sensors. Our goal is to have the system provide real-time read-outs of the values of all significant parameters describing the robot's operating conditions. An immediate challenge in this connection is the definition of graphical primitives to depict the values of sensed quantities such as forces and torques (measured with respect to any specified coordinate frame). Real-time display of sensory data will allow the user to modify applications programs to improve performance. This type of display is also essential to support such long range objectives as graphical programming of contact forces.

APPENDIX

Budget Revision - 9/12/86

DoD/URIP Grant No. AFOSR-86-0273

Program Entitled

ADVANCED PROGRAMMING AND CONTROL TECHNIQUES FOR COMPLEX MECHANICAL SYSTEMS

Principal Investigator

Prof. John Baillieul
Aerospace and Mechanical Engineering
Boston University
110 Cummington Street
Boston, MA 02215

(617) 353-9348, 353-2814

REVISED BUDGET

(Revised 9/12/86)

A less expensive engineering workstation is proposed. The savings will allow the purchase of a force/torque sensing robot wrist, which will greatly enhance the proposed research project.

REVISED BUDGET

Equipment available from:

American CIMFLEX Corporation*
121 Industry Drive
Pittsburgh, PA 15275

Attention: Michael E. Elchik
Robotics Program Coordinator
(412) 787-3000

One (1) Standard MERLIN 6-Axis 40" Robot Arm and Robot Controller

Robot includes:

- High-precision 6–axis modular robot arm.
- Wrist boot and 30" base

MUC-II Controller includes:

- Motorola 68000 CPU
- 640KB RAM memory
- Digital I/O
- Teach pendant with joystick
- Isolation transformer
- Two (2) 512 KB floppy disk drives
- Real-time operating system
- Motion control software, AR-SMART teaching language
- One set user manuals
- Motors and drive amplifier cards
- ISC Color Video Terminal

SYSTEM LIST PRICE	$70,000
LESS EDUC. DISCOUNT	-14,000
TOTAL NET PRICE	$56,000

(continued on next page)

AR-BASIC robot control software	$14,400
LESS EDUC. DISCOUNT	-2,900
TOTAL NET PRICE AR-BASIC Software	$11,500

MERLIN High Speed Host Interface (HSHI) Option:

Six (6) HSHI servo EPROMS
HSHI software (floppy disk and backup copy)
HSHI documentation

TOTAL NET PRICE of HSHI $7,500

TOTAL COST (Robot System, High Speed Host Interface, and AR-BASIC Software) $75,000

Additional Host Interface Hardware:

Matrox Model MBC-86/12B 128k 10MHz 8086/8087 CPU board
HAL-Versa Engineering Synergist I Versabus-to-VMEbus interface card

ADDITIONAL HARDWARE COST $2,500

(continued on next page)

Equipment available from:

SUN Microsystems, Inc.
1 Cranberry Hill
Lexington, MA 02173

Attention: Roger Appell
Sales Representative
(617) 863-8870

One (1) SUN 3/110C Engineering Workstation

Workstation includes:

MC68020 based microcomputer with 4 MByte memory
High resolution color monitor, mouse, and keyboard
3 slot card cage with VME bus
71 MByte disk and tape drive
Berkeley 4.2 UNIX operating system
PASCAL, C, FORTRAN, ASSEMBLER

SYSTEM LIST PRICE	$25,900
LESS B.U. DISCOUNT	-7,770
TOTAL NET PRICE	$18,130

Equipment available from:

Products for Automation Division
Barry Wright Corporation
700 Pleasant St.
Watertown, MA 02172

Attention: Mr. Les Germaise
(617) 923-1150

One (1) Six degree of freedom force/torque sensing robot wrist

Features

200 Newtons peak lifting capacity
0.1 Newton resolution

LIST PRICE	$4,750
LESS EDUC. DISCOUNT	-$475
TOTAL NET PRICE	$4,275

TOTAL COST (of all equipment and software)	$99,905
BOSTON UNIVERSITY CONTRIBUTION	-14,335
AMOUNT FROM DoD/URIP	$85,600

(Surplus over prev. budget $35)

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