DOE/NE/37966--T3

Final Report

under Grant Number DE-FG02-86NE37966

for

U.S. Department of Energy Nuclear Energy University Program in Robotics for Advanced Reactors

by

Prof. D. Tesar
Dr. R. Hooper

Robotics Research Group
The University of Texas at Austin

12 April 1995

Mechanical Engineering
The University of Texas at Austin
Austin, Texas 78712
(512)-471-3039

MASTER

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I. INTRODUCTION

The U.S. Department of Energy has provided support to four universities and the Oak Ridge National Laboratory in order to pursue research leading to the development and deployment of advanced robotic systems capable of performing tasks that are hazardous to humans, that generate significant occupational radiation exposure, and/or whose execution times can be reduced if performed by an automated system. The goal was to develop a generation of advanced robotic systems capable of economically performing surveillance, maintenance, and repair tasks in nuclear facilities and other hazardous environments.

The approach to achieving the program objective was a transition from teleoperation to the capability of autonomous operation within three successive generations of robotic systems. The robotic system will always have the capability to request human assistance. The development of general purpose robots to perform skilled labor tasks in restricted environments was shown to have extensive payback in areas of energy systems (nuclear and fossil units), chemical plants, fire fighting, space operations, underwater activities, defense, and other hazardous activities.

The strategy that was used to achieve the program goals in an efficient and timely manner consisted in utilizing, and advancing where required, state-of-the-art robotics technology through close interaction between the universities and the manufacturers and operators of nuclear power plants. The research effort showed that a broad range of applications for the robotic systems existed for the improved operation of nuclear reactors and in other hazardous tasks. As a consequence, each institution was able to obtain additional support from other agencies, e.g., DoD and NASA. Areas of cooperation with other nations (e.g., Japan, France, Germany) were utilized.

This program featured a unique teaming arrangement among the Universities of Florida, Michigan, Tennessee, Texas, and the Oak Ridge National Laboratory, and their industrial partners, Combustion Engineering, Odetics, Gulf State Utilities, Florida Power and Light Company, Remotec, and Telerobotics International. Each of the universities and ORNL had ongoing activities and corresponding facilities in areas of R&D related to robotics. This program was designed to take full advantage of a balance of these existing resources at the participating institutions (see Figures 1, 2,).

DOE/NE ROBOTICS PROGRAM FOR ADVANCED REACTORS

Teamwork

The program tasks are executed in a unique teamwork arrangement among the four universities, their industrial partners, and ORNL. The assignment of tasks to the team members was developed by the team to take full advantage of the existing facilities and expertise at the participating institutions.

U of TN

- VISION & SENSING FOR MANIPULATION
- MULTISENSOR INTEGRATION
- TRAJECTORY PLANNING

U of TX

- MANIPULATOR DESIGN
- DYNAMICS, CONTROL
- FORCE FEEDBACK FOR KINESTHETIC CONTROL

ORNL

- RANGE-SENSOR-BASED WORLD MODELING
- SENSOR FUSION
- SYSTEMS INTEGRATION

U of FL

- LOCOMOTION AND NAVIGATION
- 3D PLANT MODELING
- SYSTEM HARDENING

U of MI

- RADIATION IMAGING
- VISION FOR NAVIGATION REASONING
- COMPUTER ARCHITECTURES

Figure 1.

UNIVERSITY CONSORTIUM ROBOTICS FOR ADVANCED NUCLEAR REACTORS

Nuclear Reactor Operations

- **USE ROBOTS TO PERFORM MAINTENANCE**

- **FOUR MAJOR UNIVERSITIES**
  - **Tennessee : Sensors, Machine Vision**
  - **Florida : Locomotion, World Model**
  - **Michigan : Navigation, Radiation Sensors**
  - **Texas : Manipulator Design & Control**

Partition Technical Activity

- **ALLOWS CONCENTRATION AT WORLD CLASS**
- **PARTNERS SUPPLY SUPPORTING CONCENTRATIONS**
- **IN-DEPTH HUMAN CAPITAL DEVELOPMENT**
- **BROADENS STUDENTS NETWORK**

Institutional Issues

- **LONG TERM LABORATORY DEVELOPMENT**
- **MAINTAINS COMMITMENT TO AGENCY**
- **ENHANCES INDUSTRIAL COOPERATION**
- **ORGANICALLY OBTAINS APPLICATION REQUIREMENTS**

Figure 2.

II. BACKGROUND TO PROGRAM

It was proposed to develop and demonstrate a modular robot technology based on a standard set of modules (actuators, actuator control, carbon fiber links, distributed system sensors, modular system controller, modular manual controller, etc.) which can dramatically improve the performance of manipulators in a multiple slave configuration from a stand-off supervisory manual controller (with force-feedback) by 4 orders of magnitude relative to industrial practice but to do so at significantly reduced cost. The architectural model for this development is similar to that embodied in the highly standardized, modular, and layered system now implemented in the personal computer. The technical and cost benefits relative to the cumbersome, expensive, and dedicated structures of one-off mainframe computers is obvious. The goal of this development task is to obtain the same architectural benefits for modular robot manipulators.

The subject of remote operations in nuclear facilities has been an active research and development interest of the principal, D. Tesar, since 1970. In 1980 he led a technical and economic assessment of the potential role of robotics in the maintenance, testing, and inspection of nuclear reactors:

> "Summary Report of the Nuclear Reactor Maintenance Technology Assessment," D. Tesar et al., Report to the DOE, University of Florida, Gainesville, FL, July 18, 1980.

The results of that assessment showed that, in 1980 dollars, the deployment of advanced level remote system technology by 1991 for 100 plants would yield the following benefits:

	Overall Plant Downtime		**Forced Plant Downtime**	
Annual Savings	Reduced Outage	Reduced ORE	Reduced Outage	Reduced ORE
Minimum	0.90B	0.28B	0.45B	0.10B
Expected	1.80B	0.42B	0.90B	0.18B

in billions of dollars annually. This shows that goals such as:

1. 40% reduction in overall outage time
2. 50% reduction in forced outage time
3. 75% reduction in overall ORE
4. 90% reduction in forced ORE

have major economic benefit. The expected overall annual savings due to advanced intelligent, remote systems technology by 1991 would approach $2.2 billion/year. The principal tasks associated with this effort are:

Service Task	Economic Ranking
1. Steam Generator Maintenance	1.0
2. Valve and Pipe Replacement	0.8
3. Component Replacement	0.7
4. Refueling Service	0.5
5. In-Service Inspection	0.3

6. Filter Changing	0.3
7. Surveillance	0.2
8. Underwater Operations	0.2
9. Waste Handling	0.2
10. General Plant Decontamination	0.2

This assessment did not include issues of major events (such as TMI, Chernobyl, plant decommissioning, or waste site clean-up). Lovett and Tesar up-dated this assessment in 1989:

> "Task Requirements for Robotic Maintenance Systems for Nuclear
> Power Plants," T. Lovett and D. Tesar, Report to the DOE,
> The University of Texas at Austin, August 1989

to show that the benefits over 100 plants today would be between \$1.15 and \$2.04 billion which matches very well the 1980 assessment.

Similar attention to the economic benefit for hazardous tasks associated with oil production on the ocean floor, coal production, fuel processing, and fusion reactors would add to the relevance of the technology.

The physical tasks associated with environmental restoration and waste minimization will range from simple inspection and transport to complex disassembly, cutting, welding, rigging, packaging, repair of failed equipment, etc. Some of the tasks will be underground (piping), in large volumes (tanks), in cluttered environments (reactors), etc., and will require a diverse class of manipulator systems. Some of these systems can be quite simple (3-DOF planar devices) to multiple arms of extra DOF (8 to 9 DOF) capable of precision tasks under varying forces in a cluttered environment, all operating remotely sometimes with human intervention through a manual controller or through supervisory software taught to perform repetitive tasks by human input. The work environment for the slave may contain high levels of moisture, corrosive chemicals, radiation, dust, etc. Hence, decontamination, maintenance, replacement of failed parts, etc., must be planned as part of the manipulator technology in its foundation architecture.

A broad range of unit processes are associated with these physical tasks:

- Operation of Simple Mechanisms
  - latches, cranks, slides, handles
- Disassembly Tasks
  - cutting, rigging, lifting, unbolting
- Packaging Tasks
  - size reduction, container welding, palletizing, etc.
- Site Analysis
  - inspection, subsurface sensing, radiation surveying, sample retrieval
- Excavation
  - digging, hauling, dust containment, concrete removal, tank removal, pipe removal

This spectrum of physical tasks suggests that a broad spectrum of robot systems will be necessary. The following is an abbreviated listing of these systems:

PROTOTYPE	**DESCRIPTION**	**RANKING**
1. Dual Arm Remotely	The most capable of all systems for	10

	Operated Vehicle (ROV)	maintenance on unstructured tasks, mobility may be provided by tracks.	
2.	Heavy Duty Transport ROV	Unit capable of transporting other maintenance systems or modules and supplies needed to perform remote operations--may be equivalent of a legged-climbing system.	7
3.	Medium Scale Maintenance Robot Arm	Versatile work horse robot for a wide range of precision operations (60"). Perhaps made of modules with up to 12-DOF.	6
4.	Cherry Picker Configuration	A combination in series of the large and medium scale robots (50 ft and 5 ft).	4
5.	Spidertype Robot	A small lightweight walking-climbing robot for surveillance, inspection, and supply of light material.	3
6.	Small Platform Maintenance Robot	A small manipulator (15") to work on delicate assembly operations transported by the spider robot.	2

This limited spectrum of required systems suggests a very demanding tech base development requirement:

1. Portability - The robot must be able to reach confined spaces (in canyons) and be able to move easily in a complex obstacle strewn environment. Hence, low weight and effective operational software for obstacle avoidance are essential.

2. Precision Under Disturbance - Many of the unit processes will involve forces making precision operation difficult because of large deflections. This means that a real-time dynamic model using high speed computation (HDW and SFW) will be essential to achieve feedforward deflection compensation and adaptive control.

3. Enhanced Technology - Today's industrial robots (the 2nd generation) are far removed from the technology required for waste site clean-up (the 4th generation) based on a high level of modularity, generalized geometry (serial, parallel, layered, and redundant) and high speed computational HDW and SFW. It requires a full balance of the electrical and mechanical disciplines with an increasing role for computer science.

The principal requirement that must be met for future implementation of robotics for waste site clean-up is the ability to create a large spectrum of robot systems from a limited collection of hardware and software modules. This full modular architecture would allow a rapid reconfiguration of a given system, reduce the cost of manufacture, allow tech mods (technical modifications) for rapid infusion of new technology, and reduce the real threat of obsolescence. This general architectural requirement is the primary thrust of this work.

The University of Texas contribution to the nuclear reactor robotics program dealt with all of the component and system technologies for the required manipulator (see Figured 3). This work became the core of a major program which is now recognized as the largest U.S. University Program for robotics in mechanical engineering. The program now has an annual funding of $1,800,000, involves 32 graduate students, $3,500,000 of research equipment in 16,000 ft.^{2} of space and increasingly has strong ties to industry. Over the duration of this program (1986-1993) a total of 43 major reports were written and submitted to DOE. These reports are listed in the later sections of this report. Each year during the program, the university team put on a demonstration of an integrated technology that was under development. UT-Austin produced 5 demo reports to support its activity in these demonstrations. Also, a total of 39 M.Sc. degrees and 16 Ph.D. degrees were awarded under this program (see Figure 4a,b). Figure 4 lists the names of each graduate and where they initially found employment.

DOE/NE ROBOTICS PROGRAM
UNIVERSITY OF TEXAS TASKS

1. MODULAR ROBOT DESIGN
   - Shoulder, elbow, wrist modules
   - 7-DOF manipulator configuration
   - Prototype construction funded by DARPA
2. ACTUATOR DESIGN
   - Compact, stiff structure
   - Duality promises fault tolerance
   - Increased precision
3. ROBO_CAD ROBOT SIMULATION PACKAGE
   - Interactive
   - Easy construction of serial and parallel robots
   - Interface capability to robots, controllers
4. ELECTRONIC CONTROLLER TECHNOLOGY
   - Actuator Controllers
   - Communications Technology
   - System Controller
5. CONTROL SOFTWARE
   - Adaptive controllers
   - Fault tolerance capabilities
   - Joint effort in experiments with ORNL and JSC
6. MANUAL CONTROLLER SYSTEM DESIGN
   - Force feedback capability
   - 2 of 3 prototypes used in Team Demos at ORNL
   - Universal interface
7. APPLICATIONS

   1992: ALMR RVACS Maintenance
   - Robot deployment system design
   - Plena area manipulator design

   1993: Reactor Vessel Inspection Robot (RVIR)
   - Sensor box design
   - Vortex tube for cooling from 375°F to 100°F

Figure 3.

GRADUATE ACTIVITY SINCE 1986

1. TOTAL GRADUATES

M.SC	39
PH.D.	16

2. EMPLOYMENT

DOE RELATED EMPLOYMENT IN ROBOTICS	9
OTHERS EMPLOYED IN ROBOTICS	24
THOSE TRANSFERRED TO NEW FIELDS	9
THOSE STILL IN GRADUATE SCHOOL	13
TOTAL	55

3. EMPLOYMENT OF GRADUATES

M.SC.

P. AGRONIN (M.SC.)	JPL
DIMITROULIS (M.SC.)	ENG. IN GREECE
R. LINDEMANN (M.SC.)	JPL
D. MARCO (M.SC.)	PRESIDIO OF MONTEREY
P. GRAVES (M.SC.)	LOCKHEED (JSC)
W. CRAVER (M.SC.)	LOCKHEED (JSC)
E. HERNANDEZ (M.SC.)	WORKING ON PH.D.
T. LOVETT (M.SC.)	CONSULT.-NUCLEAR ENG.
M. HEYDINGER (M.SC.)	HP-SAN FRANCISCO
P. BEVILL (M.SC.)	MACDAC (JSC)
K. LOLA (M.SC.)	G.D.-DALLAS
S. STANTON (M.SC.)	SANDIA-DOE
J. FENWICK (M.SC.)	REAL ESTATE-AUSTIN
R. HOOPER (M.SC.)	WORKING ON PH.D.
M. AALUND (M.SC.)	WORKING ON PH.D.
S. KIM (M.SC.)	WORKING ON PH.D.
R. SREEDHAR (M.SC.)	WORKING ON PH.D.
J. WELLMAN (M.SC.)	UNIV. OF TEXAS

Figure 4a.

R. MCANDREW (M.SC.)	ALPHA ENG.-AUSTIN
J. NETTLE (M.SC.)	COOPE-TOOL-HOUSTON
C. PENNINGTON (M.SC.)	APPLIED MATERIALS
T. AGER (M.SC.)	AUSTIN
M. BUTLER (M.SC.)	NAT'L. INSTRUMENTS
M. CHU (M.SC.)	WORKING ON PH.D.
R. GIDDINGS (M.SC.)	WORKING ON PH.D.
LING (M.SC.)	PROF.-TAIWAN
W. MACAULAY (M.SC.)	E-SYSTEMS-DALLAS
D. SREEVIJAYAN (M.SC.)	WORKING ON PH.D.
M. VAN DOREN (M.SC.)	WORKING ON PH.D.
J. GEISINGER (M.SC.)	WORKING ON PH.D.
C. HICKS (M.SC.)	INTERMEDICS
R. WALTER (M.SC.)	U.S. ARMY
M. RUBIN (M.SC.)	WORKING ON PH.D.
Y. TING (M.SC.)	UNIVERSITY IN TAIWAN
R. BRYNGELSON (M.SC.)	WORKING ON MBA.
R. SMITHSON (M.SC.)	WORKING ON PH.D.
C. PEUCIS (M.SC.)	POSITION FOR INDUSTRY.
B. MCNATT (M.SC.)	TEXAS INSTRUMENTS
B. HILL (M.SC.)	WORKING ON PH.D.

PH.D.

M. SKLAR (PH.D.)	MACDAC (KSC)
W. CHO (PH.D.)	PROF.-UNIV. OF KOREA
W. KIM (PH.D.)	PROF.-UNIV. OF KOREA
C. HAN (PH.D.)	PROF.-UNIV. OF KOREA
K. CLEARY (PH.D.)	STX (GODDARD)
S. LIN (PH.D.)	PROF.-TAIWAN UNIV.
R. AMBROSE (PH.D.)	MITRE (JSC)
KANG (PH.D.)	PROF.-UNIV. OF KOREA
J. WANDER (PH.D.)	UNIV. OF ALABAMA
B. YI (PH.D.)	PROF.-UNIV. OF KOREA
D. COX (PH.D.)	IBM
J. HUDGENS (PH.D.)	MITI-JAPAN
C. AMBROSE (PH.D.)	ASSOC. MITRE
D. SCHNEIDER (PH.D.)	U.S. AIR FORCE
Y. TING (PH.D)	UNIVERSITY IN TAIWAN
K. SHIN (PH.D)	UNIVERSITY IN KOREA
A. HERNANDEZ (PH.D)	ITESM,MEXICO
R. HOOPER (PH.D)	UNIVERSITY POSITION

Figure 4b.

III. MANIPULATOR MODULARITY

The basic premise of the work at UT-Austin is that a modular architecture can not only more rapidly move the technology forward, it can also reduce costs (in the same manner as has been achieved for the personal computer). Three major reports were written outlining this theme and developing requirements for the design activity tailored to nuclear reactor maintenance operations. Figures 5 through 8 graphically display the basic structural layout associated with this activity.

"*Task Requirements for Robotic Maintenance Systems for Nuclear Power Plants*", T. Lovett and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy under Grant DE-FG02-86NE37966, August 1989.

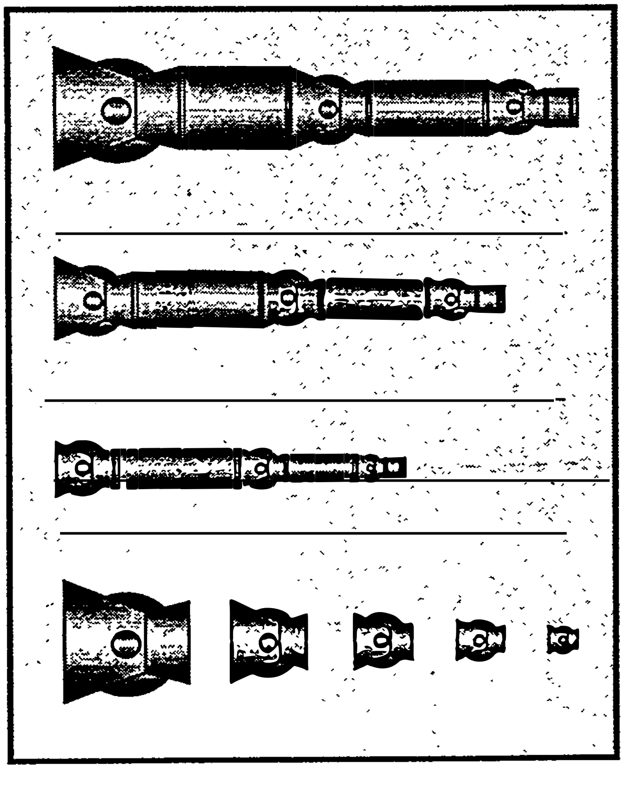
"*Computational Requirements for the Design and Control of the Fifth Generation Robot*", E. Hernandez, R. Sreedhar, R. A. Freeman, D. Tesar, Report to Cray Research Inc., U.S. Dept. of Energy under Grant DE-FG02-86NE37966, and NASA under Grants NAG9-320 and NAG9-360, September 1989.

"*An Applications-Based Assessment of Present and Future Robot Development*", M. S. Butler and D. Tesar, The University of Texas at Austin, Report to NASA under Grant No. NAG 9-411 and U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, May 1992.

MANIPULATOR DESIGN

Modular Robot Architecture

- A set of robotic modules developed:
  - 3 DOF Shoulder
  - 1 DOF Elbow
  - 3 DOF Wrist
  - 2 DOF Knuckle
  - 6 DOF Micromanipulator
- Graphical system simulation
- Reconfigurable technology
- Rules for design
- Obstacle avoidance procedures



Modularity allows quick assembly of a family of robots

Figure 5.

Module Design and Fabrication

- Design and construction of a multi-purpose modular robot testbed
- Structural design of shoulder, elbow, wrist, knuckle, micromanipulator modules
- Design, construction and testing of a frameless actuator module
- Fabrication and testing of a 3 DOF spherical shoulder module
- Design of the 7 DOF ALPHA modular manipulator

Modular Testbed

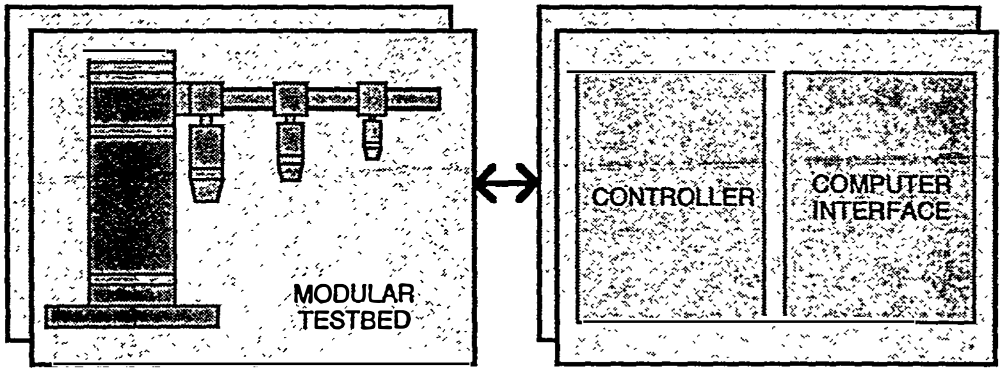
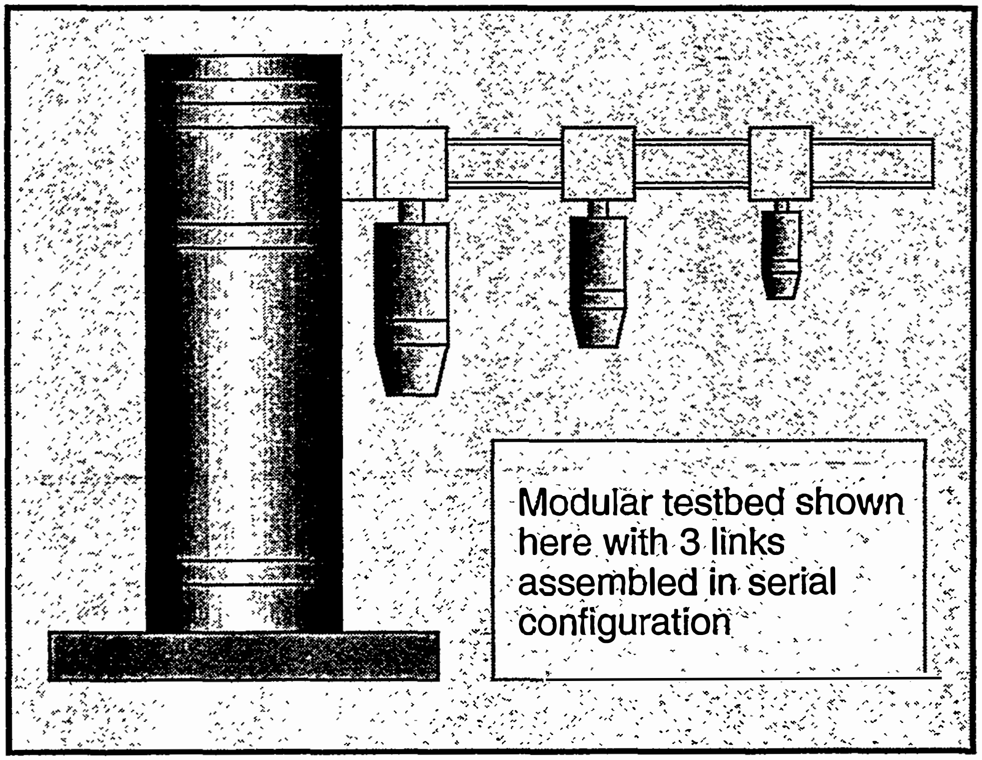


Figure 6

Modular Testbed

- General purpose testbed for component and system tests
- Three elbow joints
- Eight links
- Multi-purpose testbed stand
- IBM 486-based PC interface
- Component tests on actuators, gear drives, brakes, flexibility, backlash effects
- Tests on 1, 2 and 3-link serial arm configurations
- Tests on 4 and 5-bar parallel mechanism configurations

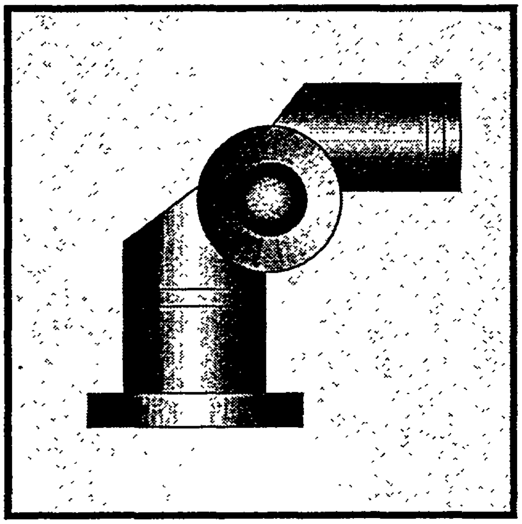


Modular testbed shown here with 3 links assembled in serial configuration

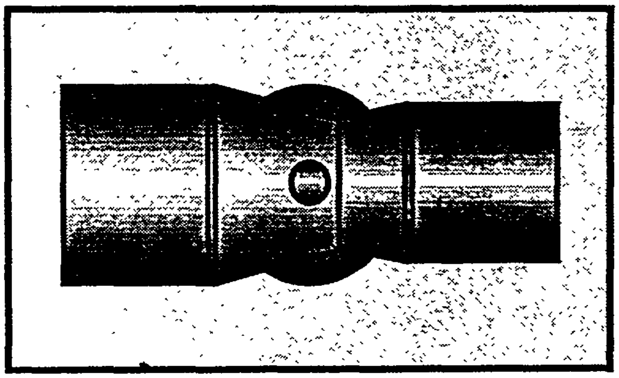
Figure 7

Robotic Modules

- 3 DOF parallel (spherical) shoulder
- 3 DOF serial shoulder
- 1 DOF elbow
- 3 DOF wrist
- 2 DOF knuckle
- 6 DOF micromanipulator



3 DOF serial shoulder module



1 DOF elbow module

Figure 8

IV. MANIPULATOR DESIGN

Manipulator design is the core to a successful structural development of robot systems. UT-Austin has 25 years of design activity associated with manipulators. The work in this program resulted in 12 major reports. Figures 9 through 12 illustrate some of this design activity.

Modeling of Modular Robots

- Investigate and establish a set of modular kinematic structures
- Kinematic analysis and animation
- Optimization of system parameters
- Develop CAD process to scale modules
- Establish criteria for evaluating best sizing
- Onboard operational software for each module
- Supervisory module communication software
- Kinematic analysis of certain dual modular arms
- 3D graphics of cooperating dual arms

Design of Link Dimensions

- Investigate dexterity of maintenance tasks
- Investigate complexity versus extra DOF
- Design classes of 1.2 and 3 DOF submodules
- Investigate complexity for dual arms
- Design manipulator geometry for up to 12 DOF

Structural Design

- Force analysis
- Material selection
- Bearing selection
- Wiring diagrams
- Hardware interfaces

"*Structural Analysis and Design of a Three Degree-of-Freedom Robotic Shoulder Module*", W. M. Craver and D. Tesar, The University of Texas at Austin, Report to DOE under Grant DE-FG02-86NE37966, January 1989.

"*Design of a Three Degree-of-Freedom Robust Robotic Shoulder Module*", J. Fenwick and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy, Grant DE-FG02-86NE37966, and NASA, Grant NAG 9-411, December 1990.

"*The Interactive Assembly and Computer Animation of Reconfigurable Robotic Systems*", R. Hooper and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy, Grant DE-FG02-86NE37966, December 1990.

"*Analysis and Design of the Kinematic Dimensions for Redundant Robot Manipulators*", S. Kim, R. A. Freeman, and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, August 1991.

"*Design, Construction and Demonstration of Modular, Reconfigurable Robots*", R. Ambrose and D. Tesar,

The University of Texas at Austin, Report to U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966 and NASA-JSC under Grant No. NAG 9-411, August 1991.

"*The Design of Epicycle Gear Trains for Modular Robot Structures*", C. Pennington and D. Tesar, The University of Texas, Report to U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, November 1991.

"*Design and Prototype Development of Robot Actuator Modules*", J. Iaconis, D. Tesar, J. Geisinger, K. Shin, T. Ager, C. Pennington, M. Chu, and P. Varatharajan, The University of Texas at Austin, Report to Navy Explosive Ordnance Demolition Test Center, U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, and NASA under Grant No. NAG 9-411, December 1991.

"*Design of a Family of Modular Roll Actuators for the ALPHA Project*," R. A. Smithson and D. Tesar, The University of Texas at Austin, Report to U.S. Office of Naval Research, Advanced Research Projects Agency under Grant No. N00014-92-J-4023 and to U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, December 1993.

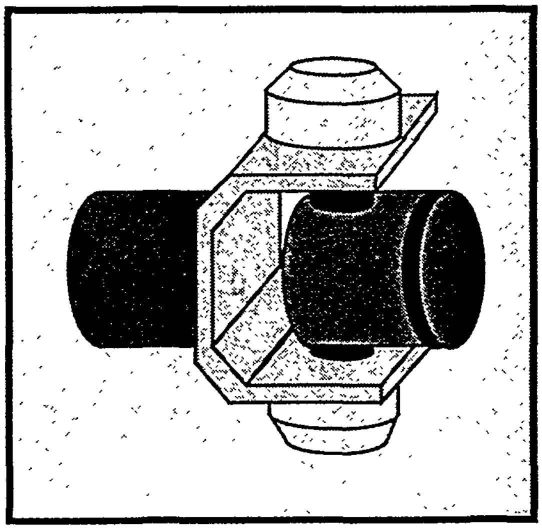
"*Design of a Serial Three Degree-of-Freedom Shoulder for Modular Robots*," B. M. Hill and D. Tesar, The University of Texas at Austin, Report to U.S. Office of Naval Research, Advanced Research Projects Agency under Grant No. N00014-92-J-4023 and to U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, December 1993.

"*Design of a Three Degree-of-Freedom Wrist for Modular Robots*," R. A. Bryngelson and D. Tesar, The University of Texas at Austin, Report to U.S. Office of Naval Research, Advanced Research Projects Agency under Grant No. N00014-92-J-4023 and to U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, December 1993.

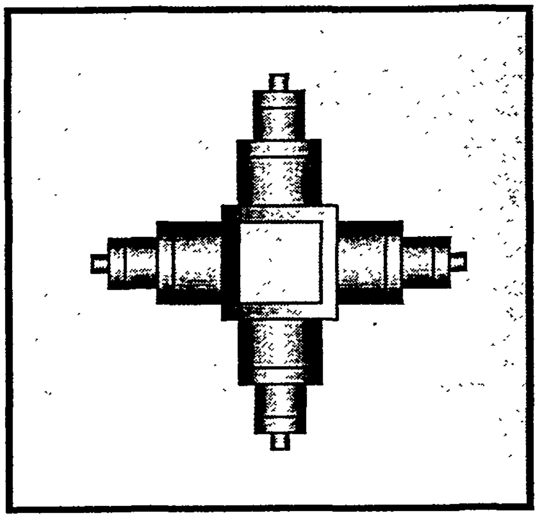
"*The Design of an Advanced Actuator Transmission for a Modular Robotic Manipulator*," B. S. McNatt and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966 and U.S. Office of Naval Research, Advanced Research Projects Agency under Grant No. N00014-92-J-4023, December 1993.

"*Structural Design of a One Degree-of-Freedom Elbow for Modular Robots*", M. Chu and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, May 1992.

"*Structural Design of a Two-Degree-of-Freedom Knuckle for Modular Robots*", T. Ager and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, May 1992.



3 DOF serial
wrist module

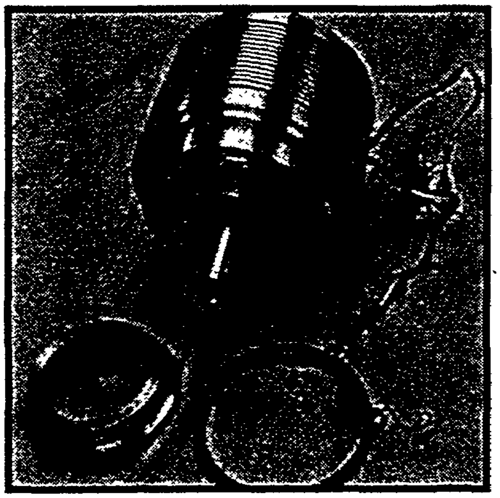


2 DOF knuckle
module

Figure 9

Actuator Module

- Dual components (motor, brake, gear, sensor, etc.)
- Compact packaging of components
- Frameless structure offers flexibility in applications
- Rugged design
- High output torque/weight quotient
- Actuator subassembly tests:
    - ◆ Structure subassembly
    - ◆ Motor subassembly
    - ◆ Gear subassembly
- Actuator system tests

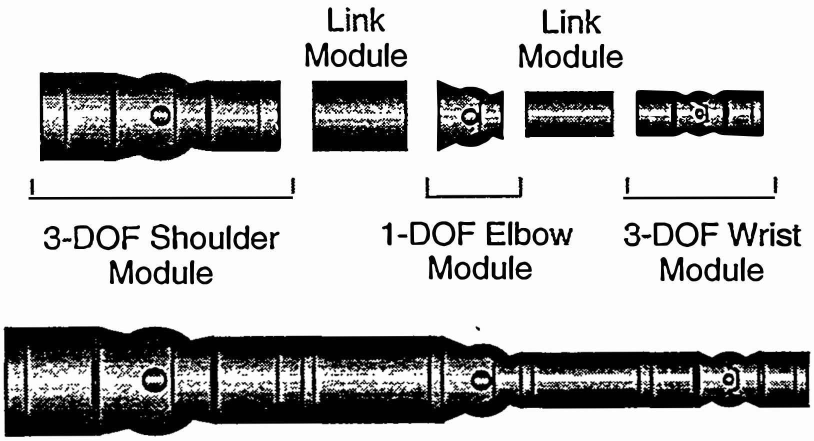


Actuator module
(one half is shown)

Figure 10

7 DOF Modular ALPHA Manipulator

- Serial, modular structure
- 3 DOF shoulder + 1 DOF elbow + 3 DOF wrist configuration
- Suitable for medium scale maintenance tasks (nuclear reactors, industry, general purpose maintenance, etc.)
- Target high value-added applications
- Broaden range of applications (10x)
- Increased speed of operation (10x)
- Enhanced performance (1,000x)

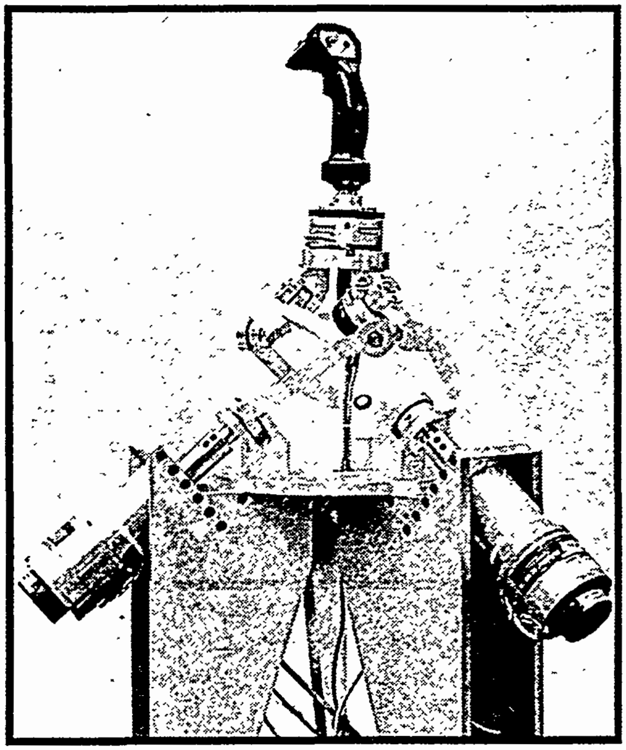


7 DOF ALPHA modular manipulator

Figure 11

Spherical Shoulder Module

- Three DOF, parallel, spherical structure
- Compact design
- Improved system rigidity
- Enhanced end-effector precision relative to serial structures
- High module payload capacity
- Optional force feedback capability



3 DOF spherical shoulder module implemented as a manual controller

The spherical shoulder module shown in the figure is built and interfaced with a MicroVAX workstation and a Cincinnati Milacron T3-726 industrial robot at the University of Texas.

It was subsequently used in two of the annual DOE/NE Robotics Team Demonstrations held at ORNL, Tennessee to control various platforms and manipulator arms.

Figure 12

V. MANIPULATOR DYNAMICS

Having obtained a structural design of a manipulator, it becomes necessary to study its dynamic model to obtain its controlling equations. Under this program, 8 major reports were written on dynamic modeling of manipulator systems. Figures 13, 14 illustrate some of the basic activity that was pursued

Kinematics of Motion Control

- Investigate the mathematical complexity of manipulators with 6 to 12 DOF
- Develop mathematical tools to operate a general manipulator among obstacles
- Develop mathematical tools for a manipulator with 1,2, and 3 DOF modules
- Develop mathematical tools to control dual arm systems

Development of Dynamic Models

- Dynamic model formulation for rigid-body assumption
- Dynamic model formulation with actuator flexure
- Dynamic model formulation with actuator and link flexure

Real-Time Operation of Dynamic Model Compensation

- Compensation for static loads
- Compensation for dynamic loads
- Compensate for dynamic and static loads and principal link deformations
- Investigate influence of system parameters to improve precision
- Develop operational software at the modular level
- Develop operational software at the system level

"*Efficient Algorithms and Real-Time Software for Quasi-Static Manipulator Deflection Modeling*", E. Hernandez and D. Tesar, The University of Texas at Austin, Report to NASA under Grant No. NAG 9-188, DOE under Grant No. DE-FG02-86NE37966, Cray Research, Inc., and University of Texas System Center for High Performance Computing, May 1989.

"*Development of a Dynamic Modeling Technique and its Application to the Analysis and Control of a High Precision Robotic Manipulator*", W. Cho and D. Tesar, The University of Texas at Austin, Report to DOE under Grant DE-FG02-86NE37966, August 1989.

"*Development of Robot Deflection Compensation for Improved Machining Accuracy*", J. Wander and D. Tesar, The University of Texas at Austin, Report to DOE under Grant No. DE-FG02-86NE37966 and Texas Higher Education Coordinating Board for Advanced Technology Program under Grant No. 4679, August 1991.

"*Dynamic Modeling and Optimal Joint Torque Coordination of Advanced Robotic Systems*", H. Kang and R. A. Freeman, The University of Texas at Austin, Report to NASA under Grant No. NAG 9-188 and U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, December 1991.

"*Analysis of Redundantly Actuated Mechanisms with Applications to Design and Control of Advanced Robotic Systems*", B. J. Yi, R. A. Freeman, and D. Tesar, The University of Texas at Austin, Report to NASA under Grant No. NAG 9-411 and U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, January 1992.

"*Static Robot Compliance and Metrology Procedures with Application to a Light Machining Robot*", J. Hudgens and D. Tesar, The University of Texas at Austin, Report to Texas Higher Education Coordinating Board for Advanced Technology Program under Project No. 003658-156 and U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, August 1992.

"*Development of Real Time Operational Software for a Fault-Tolerance Testbed*", M. D. Rubin and D. Tesar, The University of Texas at Austin, Report to NASA under Grant No. NAG 9-411 and U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, June 1993.

"*Dynamic Modeling, Property Investigation, and Adaptive Controller Design of Serial Robotic Manipulators Modeled with Structural Compliance*", S. Lin, S. Tosunoglu, and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy, Grant DE-FG-02-86NE37966, and Cray Research, Inc., Grant 0032188-00, December 1990.

SYSTEM MODELING

- Kinematic modeling of serial and parallel structured robots
- Forward and inverse kinematics solutions
- Efficient operational software with benchmark tests on
  - Cray X-MP, Y-MP
  - Alliant parallel processor
  - AP 500 array processor
  - Silicon Graphics workstations
  - VAX systems
  - 386 and 486 based PCs
- Criteria development and optimal solutions for redundant manipulators with more than 6 DOF
- Practical criteria implemented on ORNL's CESARM robot includes
  - Joint limit avoidance
  - Singularity avoidance
  - Self motion scaling for smooth arm operation
  - Minimum velocity norm (min. kinetic energy)
- Software package to construct and animate robots from a menu of modules

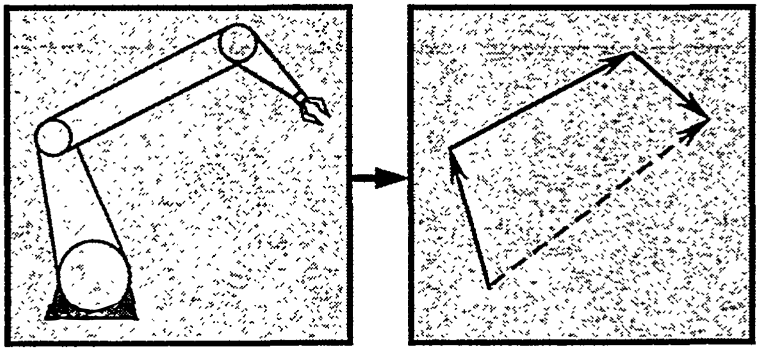
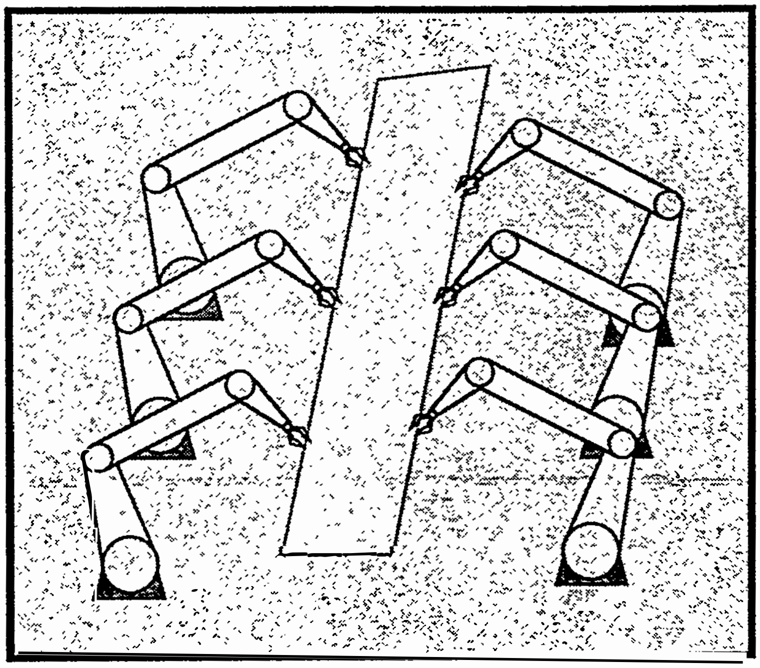


Figure 13

Dynamic Modeling

- Dynamic modeling of serial robots modeled with rigid links and joints
- Modeling of link and actuator flexibilities in serial manipulators
- Real-time operational software
- Dynamic system modeling for parallel robots
- Development of force control algorithms
- Benchmark tests
- System models for cooperating robots



Multiple cooperating robots

Figure 14

VI. MANIPULATOR CONTROL

Having the manipulator design and its dynamic model, it becomes necessary to develop the control technology and operational software to maintain the desired task performance of the system. This development effort resulted in the largest number of major reports to DOE (13). The UT program believes that it is the world's leader in this technology as illustrated by the following listing of topics that were considered. Figures 15 through 19 illustrate the control work pursued at UT.

Metrology of Robotic Systems

- Establish an advanced laboratory for robot metrology
- Implement precision end-effector global measurement
- Use modal analysis to establish reference models of industrial robots
- Develop tools to determine physical parameters in serial robots
- Implement tools to determine physical parameters in serial robots
- Transfer technology to ORNL facilities

Advanced Adaptive Control for Enhanced Task Performance

- Develop adaptive control schemes for global stability
- Develop simulation software to demonstrate stability
- Simulate software for industrial arms
- Include effects of actuator dynamics
- Identify suitable scheme for disturbance rejection
- Include actuator drive-train deflections
- Include finite number of link deformations
- Implement control scheme in real-time software
- Develop adaptive controllers for selected robot modules
- Demonstrate adaptive controller on a serial arm
- Develop real-time software for hybrid arm
- Investigate attributes of layered large/small control architectures

Control of Dual Arm Robotic Systems

- Evaluate operations that require dual arm systems and establish design criteria
- Establish geometric control algebra
- Demonstrate dual arm cooperation
- Establish dynamic modeling and internal force balancing
- Develop adaptive controllers for dual arm operations
- Design, build and test planar 3 DOF serial arms as testbed
- Develop real-time controller
- Develop operational software for real-time controller
- Demonstrate the operation of controller on planar 3 DOF system
- Design a dual-arm system for operation in hazardous environments

Development of Decision Making Software for Redundant Robots

- Evaluate level of obstacle avoidance for reactor maintenance operations
- Identify and formulate performance criteria relative to tasks
- Develop generalized kinematic inverse
- Software development and simulation to demonstrate generalized inverse

- Combine generalized inverse and obstacle avoidance
- Develop means to analytically predict singularities
- Develop software for computer graphics operator assist
- Develop analytical means to operate selected dual-arm systems

"*Control of Flexible Robotic Manipulators*", S. Lin, S. Tosunoglu, and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy under Grant DE-FG02-86NE37966, NASA-JSC under Grant NAG9-188, and Cray Research, Inc., July 1988.

"*Controller Development for CESARM and Hermies III: Shoulder Manual Controller Hardware and Software; Inverse Kinematics, Servo Control and Dynamic Model Based Control Software*", S. Tosunoglu, D. Tesar, et al., The University of Texas at Austin, for Dept. of Energy/ Nuclear Energy Robotics Program Demo '89, October 1989.

"*Decision Making Software for Redundant Manipulators*", K. Cleary and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy, Grant DE-FG02-86NE37966, and NASA, Grant NAG 9-360, March 1990.

"*Multicriteria Inverse Kinematics for General Serial Robots*", R. N. Hooper and D. Tesar, The University of Texas at Austin, Report to NASA under Grant No. NAG 9-411 and U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, May 1994.

"*Criteria Normalization to Support Decision Making in Intelligent Machines*", P. Bevill and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy, Grant DE-FG02-86NE37966, May 1990.

"*Real-Time Computational Modelling Software for Improved Control of Robotic Manipulators with Serial and In-Parallel Structures*", K. Lola and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy, Grant DE-FG02-86NE37966, May 1990.

"*A Technology Roadmap for an Electronic Actuator Control Module for Reconfigurable Robotic Manipulators*", S. Stanton and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy, Grant DE-FG02-86NE37966, July 1990.

"*Potential Function Based Obstacle Avoidance Algorithm for Manipulators with Extra Degrees of Freedom*", R. Sreedhar and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy, Grant DE-FG02-86NE37966, August 1990.

"*Design and Development of a Multi-Channel Robotic Controller*", M. Aalund and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966 and Texas Higher Education Coordinating Board for Advanced Technology Program under Grant No. 4679, May 1991.

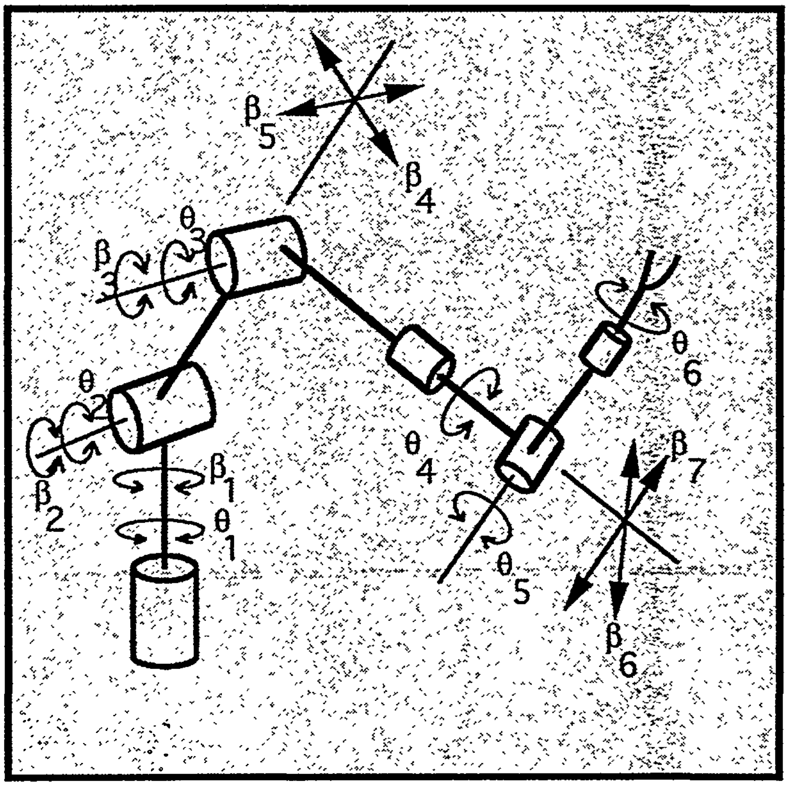
"*A Roadmap for Standardized Sensor Technology in Modular, Reconfigurable Robots*", J. P. Nettle and D. Tesar, The University of Texas at Austin, Report to NASA under Grant No. NAG 9-411, U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, and Texas Higher Education Coordinating Board for Advanced Technology Program under Project No. 003658-156, December 1991.

"*Criteria Development to Support Decision Making Software for Modular, Reconfigurable Robotic Manipulators*", M. J. Van Doren and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, March 1992.

CONTROLLER DEVELOPMENT

Parameter Identification

- System parameter identification methodology (metrology) for
  - Kinematic parameters
  - Mass parameters
  - Deformation parameters
- Experimental parameter identification of the Cincinnati Milacron T3-776 industrial robot



Kinematic representation of the 6 DOF Cincinnati Milacron T3-776 robot

Figure 15

Control of Redundant Robots

- Dynamic criteria development for the control of redundant robots
- Development of control algorithms
- 3-D graphic animation (CESARM, Robotics Research arms, etc.)
- Real-time implementation on the CESARM arm at ORNL

Link	Mass (kg)	Inertia (kgm^2)		
		I_x	I_y	I_z
Link 1	317.5	0	0	29.3
Link 2	680.4	5.9	52.7	43.9
Link 3	453.6	49.7	7.61	49.7
Link 4	68	0.59	0.59	0.35
Link 5	36.3	0.23	0.23	0.06
Link 6	27.1	0.12	0.12	0.06

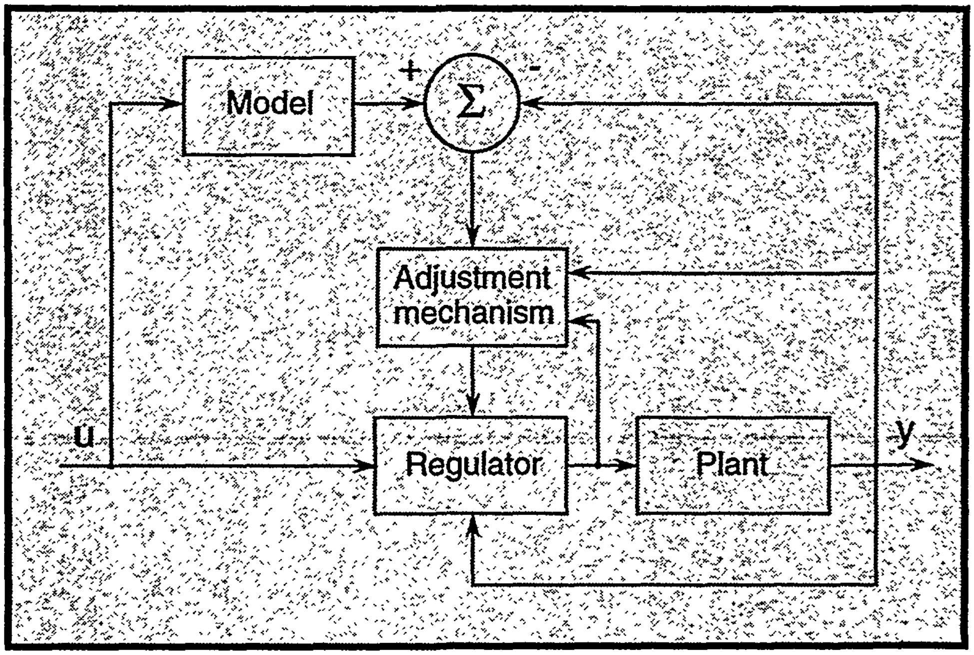
Cincinnati Milacron T3-776 mass parameters

- Control software for CESARM and HERMIES III
  - Joint servo control
  - Dynamic model based control:
    - Calculates full arm dynamics
    - Software optimized for CESARM
    - Integrates nonlinearity compensation and PID feedback components

Figure 16

Adaptive Controllers

- Developed advanced adaptive controllers for global stability while tracking reference trajectory
- Control methods include
    - Model reference adaptive control
    - Self tuning regulator
    - Sliding control
    - Computed torque with PID feedback
- Extensive development of simulation software to demonstrate stability
- Actuator dynamics included in the model

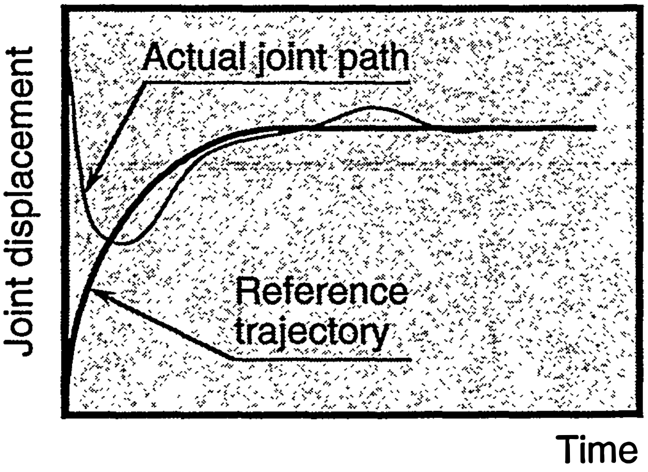


Block diagram representation of model reference adaptive control system

Figure 17

Control of Flexible Robots

- Controllers extended to flexible manipulators:
    - Structural link flexibility
    - Joint flexibility which includes deformations of the actuator shaft, gear train, and other drive components
- Simulations carried out on the model of a 6 DOF Cincinnati Milacron T3-776 arm with the following flexibilities:
    - 6 joint flexibilities (which yields a 12 DOF system)
    - 6 link flexibilities
    - 3 joint and 4 link flexibility components (represents a 13 DOF system)
- Controllability issues in flexible systems raised for the first time in literature

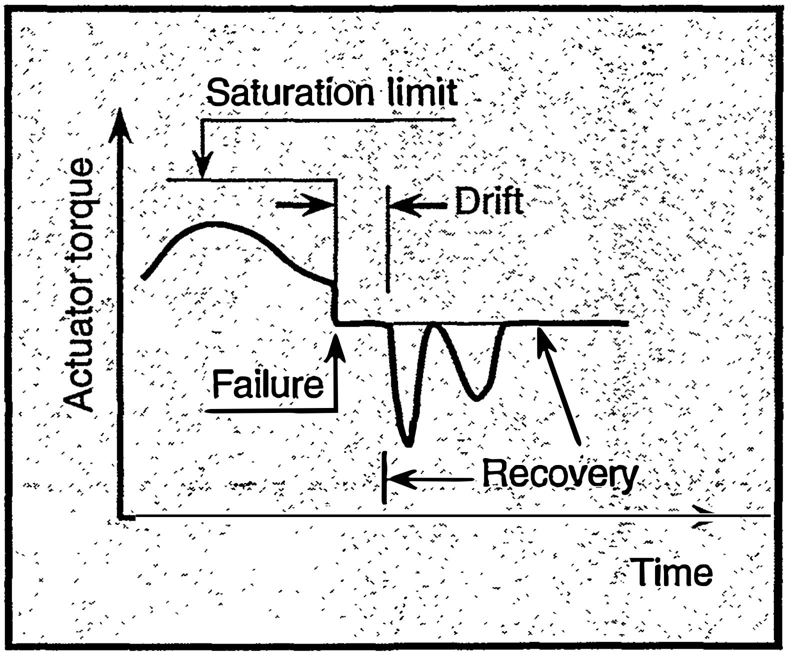


Tracking of a desired joint displacement

Figure 18

Fault Tolerant Robot Control

- Fault tolerant control of robots is addressed; robust controllers based on adaptive and sliding control methodologies are developed
- Two distinct methods for actuator saturation are proposed:
  - Torque redistribution
  - Time regulation
- Methods are developed for serial as well as parallel structured mechanisms



Actuator saturation avoidance using the torque redistribution algorithm

Figure 19

VII. FORCE FEEDBACK FOR KINESTHETIC CONTROL

The manual controller is the kinesthetic interface between the operator and the robot. The program has built a series of prototypes to test real time interface between man and machine. The resulting lessons learned are of real value in the operations of all systems (airplanes, manufacturing cells, etc.). A total of 7 major reports were written as a result of this work. Figures 20 through 23 illustrate the type of activity that was pursued.

Metrology of Robotic Systems

- Assess needs for manual controllers to satisfy reactor maintenance operations
- Construct a 9-string bilateral force feedback joystick
- Develop operational software to interface 9-string with industrial robot
- Design an 8 DOF force feedback joystick
- Construct 8 DOF force feedback joystick
- Develop real-time software for operation of generic manual controllers
- Develop cockpit design for stereo vision for manual controllers
- Test the manual controller in simulation with industrial robots
- Develop graphic display control for operator training among obstacles
- Test human factors and evaluate the system in terms of man-machine interaction

"*Installation and Operations Guide for The Three-Degree-of-Freedom Force Reflecting Manual Controller*" D. Tesar et al., The University of Texas at Austin, for Dept. of Energy/ Nuclear Energy Robotics Program Demo '88, August 1988.

"*Kinesthetic Feedback for Manual Control Using Intersecting Volumes*", J. Wellman and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy, Grant DE-FG02-86NE37966, August 1991.

"*Control Algorithms for Fault-Tolerant Robotic Manipulators*", Y. Ting, S. Tosunoglu, and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966 and NASA under Grant No. NAG 9-411, December 1993.

"*Decision Making for Intelligent Control of Dual-Arm Robotic Operations*", D. Cox and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, May 1992.

"*Development and Demonstration of General, Real-Time Control Software for Robotic Manipulators*", R. Giddings and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966 and NASA under Grant No. NAG 9-411, May 1992.

"*Actuator Controller Design and Implementation*", J. Geisinger and D. Tesar, The University of Texas at Austin, Report to Texas Higher Education Coordinating Board for Advanced Technology Program, Grant No. 4679, and U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, August 1992.

"*Architectural Study of the Design and Operation of Advanced Force Feedback Manual Controllers*", W. Kim and D. Tesar, The University of Texas at Austin, Report to U.S. Dept. of Energy, Grant DE-FG02-86NE37966, and NASA-JSC, Grant No. NAG 9-320, January 1990.

FORCE FEEDBACK FOR KINESTHETIC CONTROL

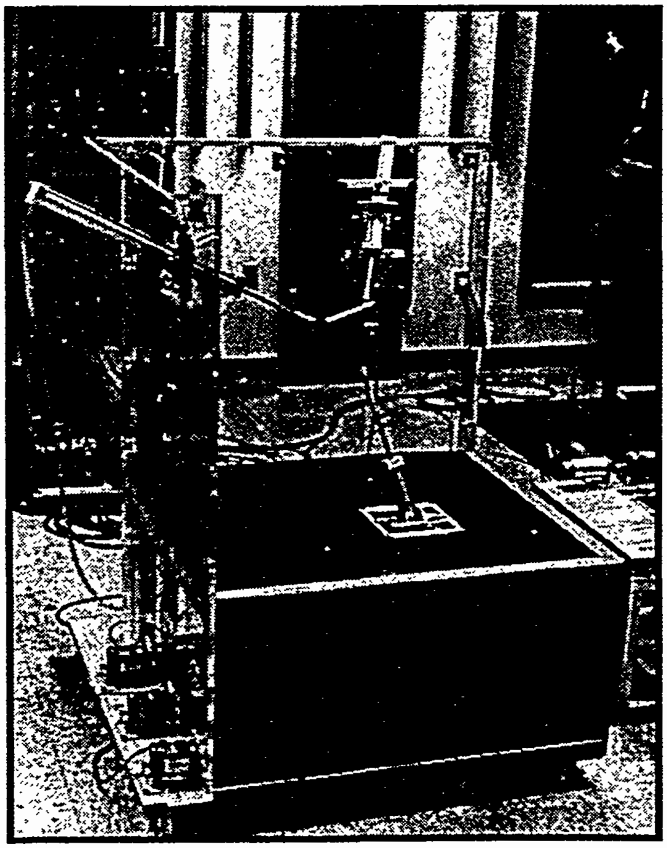
- Design and construction of a 6 DOF, 9-string force reflecting manual controller
- Integration of this controller to the MicroVAX workstation and Cincinnati Milacron T3-726 industrial robot
- Development of menu driven software to control
  - ◆ robot end-effector position
  - ◆ robot end-effector velocity
  - ◆ robot end-effector forces and torques which are fed back to the operator
  - ◆ Scaling of controlled parameters in real time by the operator
  - ◆ Easy re-referencing of the end-effector position
- Testing and demonstrations at the robotics lab
- Design and fabrication of a 3 DOF manual controller utilizing the spherical shoulder module
- Integration of the shoulder module to the MicroVAX and T3-726 robot
- Integration to the CESARM arm, HERMIES IIB and HERMIES III platforms for DOE/NE Team Demonstrations

Figure 20

9-String Manual Controller

- Six DOF, parallel structure
- Force feedback capability in addition to position control
- Uniform workspace
- Position or velocity control options
- Position / force scaling and re-referencing capabilities

The lengths of nine strings, connected to the joystick, specify the desired end-effector position and configuration of the controlled robot. This position is then mapped into the robot's work space. An inverse kinematics process determines the corresponding joint angles the robot needs to take. Servo controllers at the joint level accomplish this task.



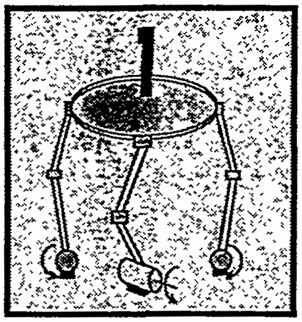
6 DOF force reflecting joystick developed at the University of Texas Robotics Research Lab

Figure 21

Shoulder Manual Controller

- Three DOF, parallel structure
- Optimized design for uniform workspace
- Compact design
- Minimum structural deflection
- Position control and force feedback features
- Position and velocity control options
- Position / force scaling and re-referencing capabilities
- Integrated and tested to control Cincinnati Milacron T3-726 robot, HERMIES IIB, HERMIES III platforms, and CESARM manipulator

Kinematic structure of the spherical shoulder (right); integration of the manual controller to a robot via computer interface (below)



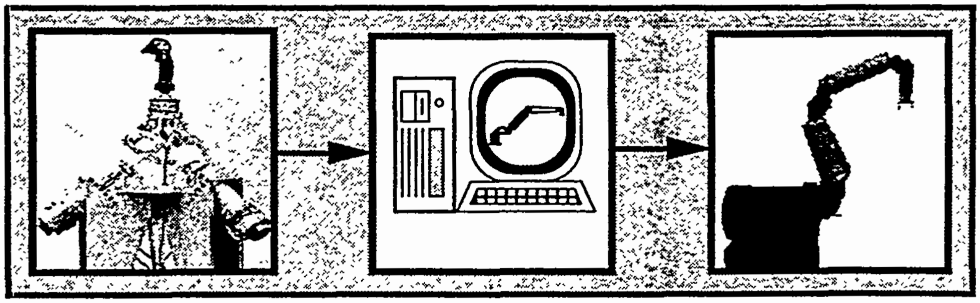


Figure 22

Shoulder manual controller pictured here during testing at the University of Texas Robotics Research Lab

Figure 23

VIII. UNIVERSITY TEAM DEMONSTRATIONS

All university team members participated in all of the yearly demonstrations of the evolving technology for robotics for advanced nuclear reactors. The UT-Austin contribution to each of these demos are illustrated in Figures 24 through 28.

1988: Design and Construction of a Force Reflecting Manual Controller

1989: Controller Development for CESARM and HERMIES III

1990: Autonomous Control of CESARM and HERMIES III

1992: Robotic Systems for ALMR RVACS Deployment and Manipulation

1993: Sensor Module Design for Inspection Tasks in the ALMR

Each Demo was accompanied by a major report to DOE.

Team DEMO 1988

Design and Construction of a Force Reflecting Manual Controller

A manual controller system was developed to control the HERMIES IIB 3 DOF platform at ORNL. A 3 DOF force reflecting controller was developed using the University of Texas spherical shoulder module. Software developed to interface to a MicroVAX was delivered to the demonstration team at ORNL.

The shoulder joystick was capable to control position of the platform as well as feeding back forces of a critical point measured by a force/torque sensor.

Team members: W. K. Kim, T. Ager, J. Wellman

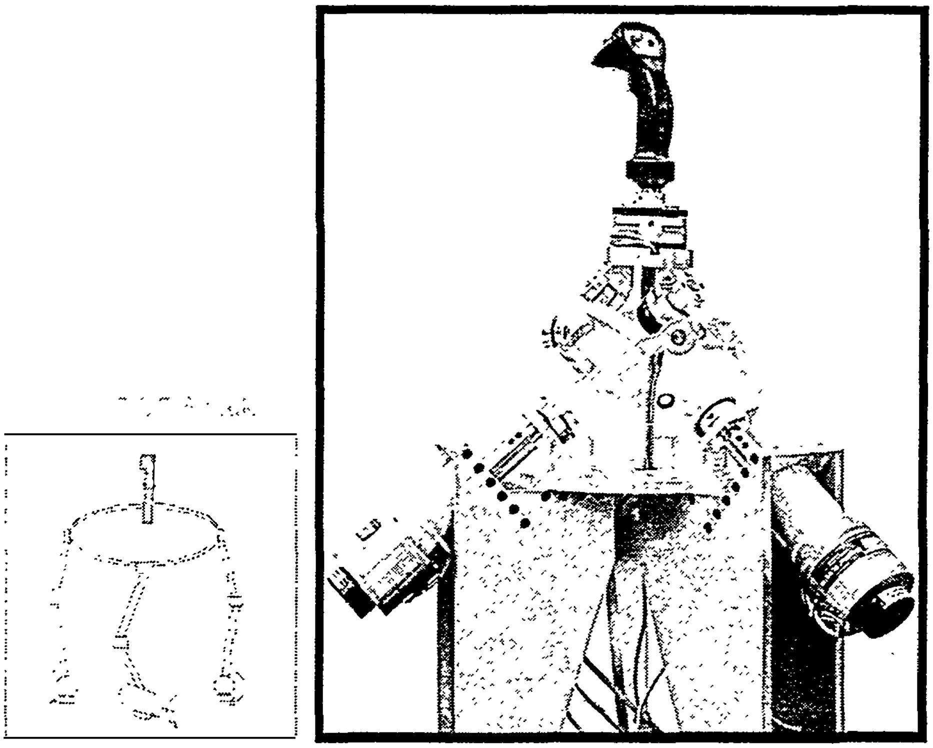
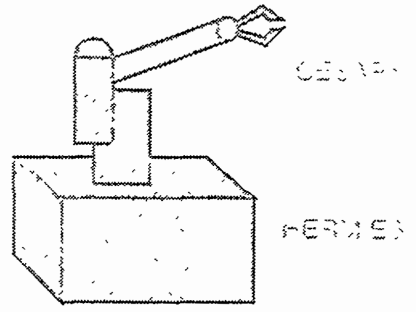


Figure 24



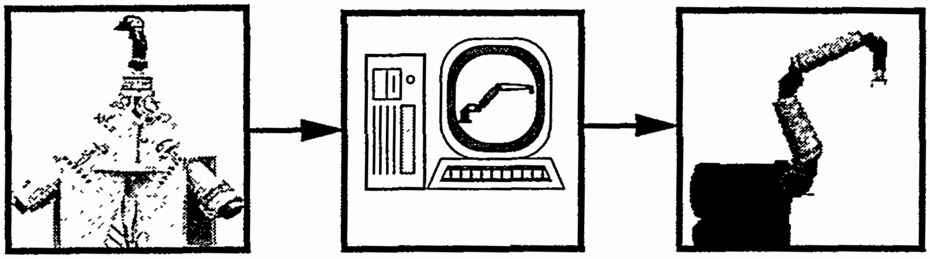
Team DEMO 1989

Controller Development for CESARM and HERMIES III

The team modified previously developed software to control a system consisting of the CESARM 7 DOF manipulator mounted on the larger HERMIES III platform.

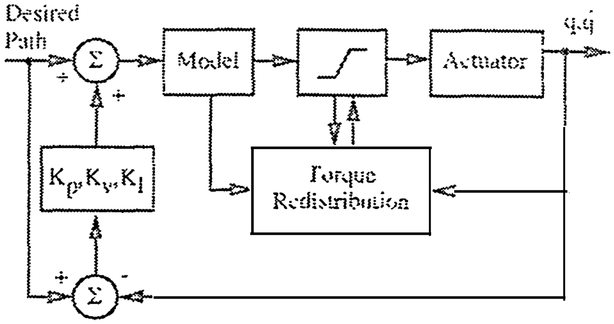
Software was developed for the CESARM manipulator to perform inverse kinematics, servo control, and dynamic model based control. A demonstration was performed that simulated spill clean-up in a nuclear reactor.

Team members: P. Bevill, K. Clearly, R. Ambrose, R. Giddings, B. Macaulay



3 DOF Shoulder Manual Controller

Figure 25



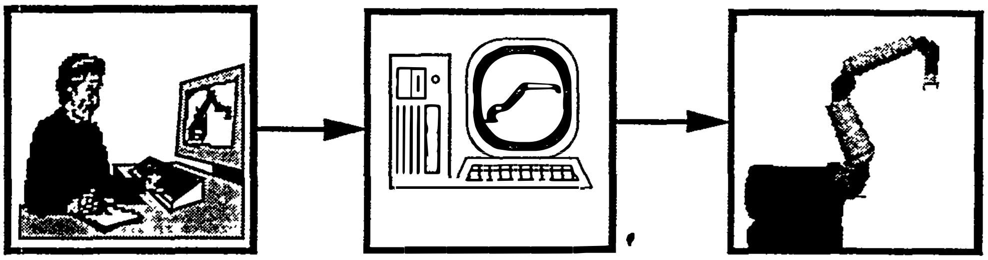
Team DEMO 1990

Autonomous Control of CESARM and HERMIES III

Controllers previously developed at the University of Texas were integrated with the controllers of 7 DOF CESARM manipulator and 3 DOF HERMIES III platform at ORNL.

Existing software was modified to comply with the event-driven structure developed by ORNL. Obstacle avoidance and joint limit avoidance were achieved through the redundancy of the CESARM. Radiation inspection on storage drums was demonstrated.

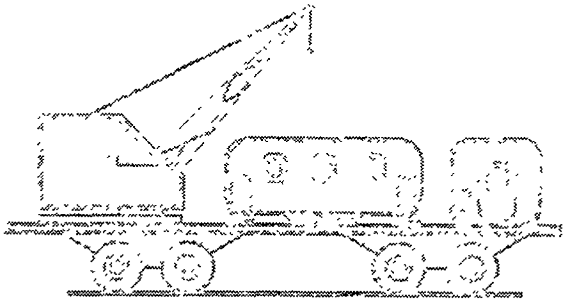
Team members: R. Giddings, B. Macaulay,
M. Chu, K. Shin



Autonomous Control of Multiple Robotic Systems

Figure 26

Team DEMO 1992



Robotic Systems for ALMR RVACS: Deployment & Manipulation

Routine maintenance of ALMR's Reactor Vessel Auxiliary Cooling System (RVACS) will be accomplished by a number of robotic systems. Deployment schemes for these robots via the entry ports and stacks were developed by the Texas team.

Design of a 7 degree-of-freedom (DOF) manipulator for plena area maintenance was also investigated. A field search for suitable existing robotics technology was conducted and subsequently a design was generated to modify existing industrial robots to withstand high temperature and radioactive environments.

Team members: R. Bryngelson, B. McNatt, Y. Ting, V. Menon, B. J. Yi

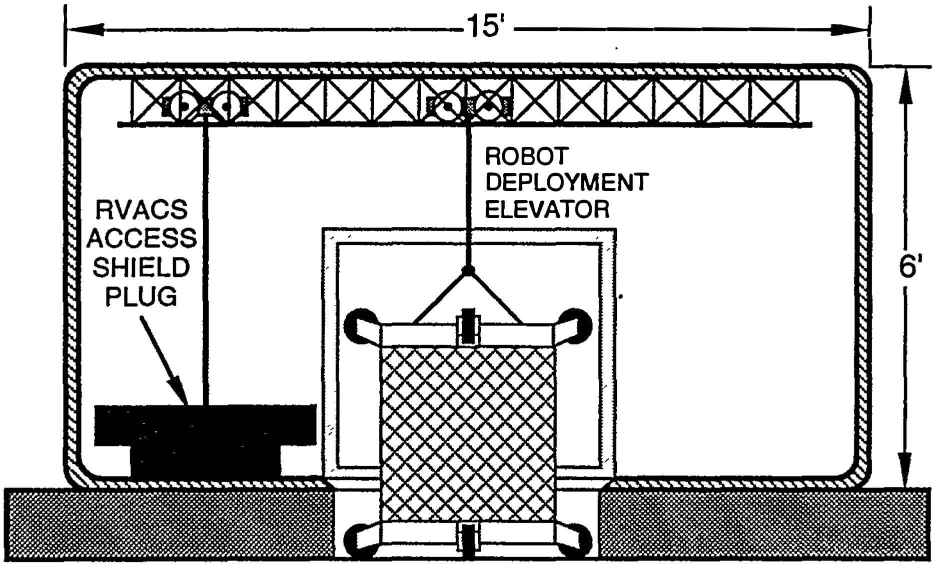
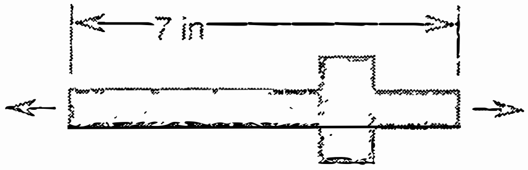


Figure 27



Team DEMO 1993

Sensor Module Design

In order to carry out remote inspection tasks in the ALMR (Advanced Liquid Metal Reactor), vortex tube technology was implemented to design a sensor module to keep sensitive equipment at acceptable temperatures.

Specifically, a sensor module was constructed and tested that demonstrated the effectiveness of the design by maintaining three CCD cameras at 60°F in an ambient temperature of 410°F.

Team members: K. Shin, B. Hill, M. Zung,
A. Hemandez, T. Lunifeld

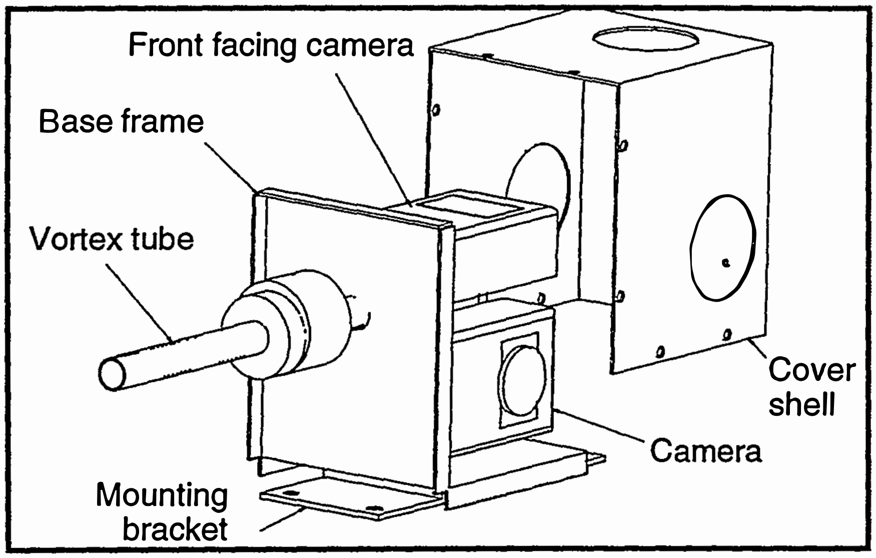


Figure 28