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Version 1: for the interested party & professional

ROBOTICS HANDBOOK

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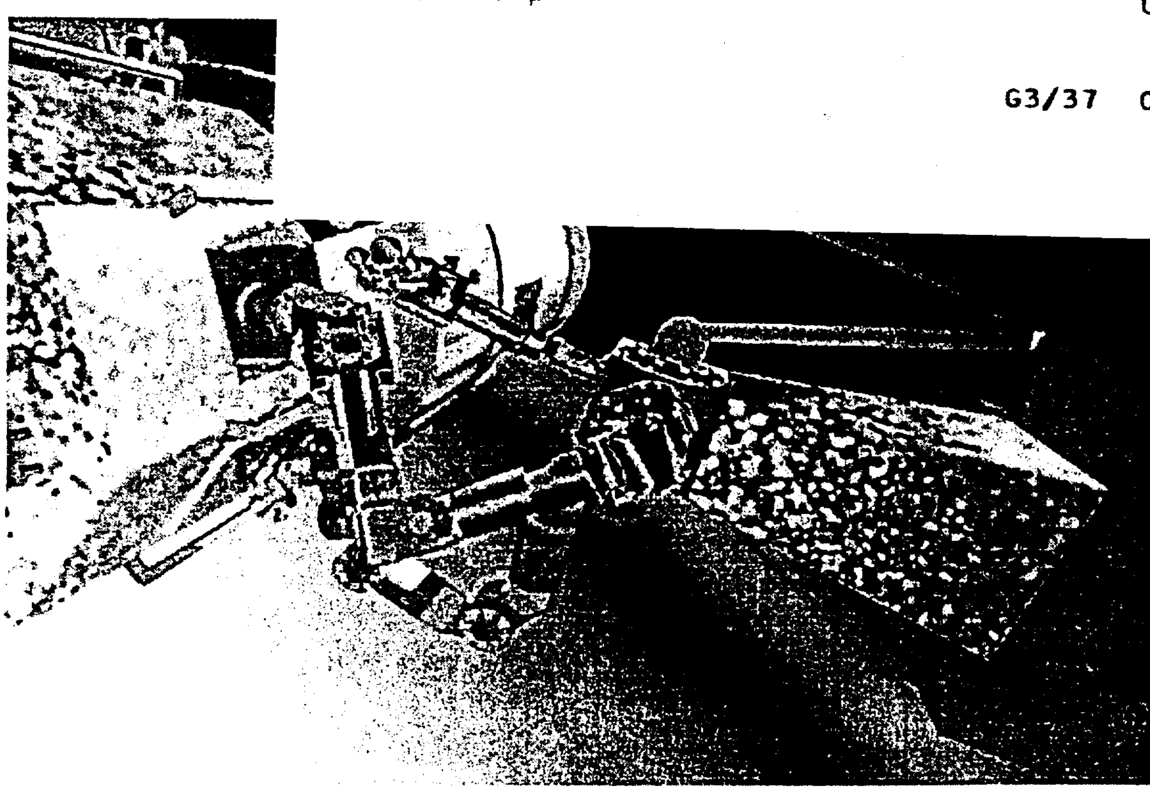

Depiction of the Ranger orbital testbed robot

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Editor's Note:

This publication was produced in Washington, DC in December 1993 by NASA's Office of Advanced Concepts and Technology, one of the NASA Headquarters Program Offices.

Portions of its contents were obtained from a variety of sources on the Internet, other portions were solicited directly from organizations and companies. The NASA portion was provided by the Spacecraft and Sensor Division, NASA OACT.

The editor wishes to thank all the individuals, organizations and companies who contributed to this version and to the editorial and production assistance provided by IDEA and PRC and various different NASA offices.

A subsequent version, expected early in 1994, will feature material of interest to individuals pursuing university-related research or who wish to pursue academic interests in the field of artificial intelligence, telepresence or robotics. That version will also feature a friendly, user's guide to the Internet.

Watch for elements of both versions to be published on a variety of Internet-connected servers. -- Stay Tuned!

-Chas. Redmond

Purpose of this publication:

This publication is intended to provide a compendium of information on the field of "robotics" to a non-exclusionary set of audiences. This is Version 1 and is a special edition for attendees to the NASA Tech Briefs–NASA-sponsored Tech 2003 Conference in Anaheim, Calif.

The publication covers several categories of information about robotics:

The first section provides a brief overview of the field of Robotics;

The next section provides a reasonably detailed look at the NASA Robotics program. NASA's Automation and Robotics programs are components of the Spacecraft and Sensor Design Division, Office of Advanced Concepts and Technology, NASA Headquarters. The Telerobotics Program Manager is:

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The third section features a listing of companies and organizations engaging in robotics or robotic-related activities; followed by a listing of associations involved in the field; followed by a listing of publications and periodicals which cover elements of robotics or related fields.

The final section in this version is an abbreviated abstract of refereed journal material and other reference material relevant to the technology and science of robotics, including such allied fields as vision perception; three-space axis orientation and measurement systems and associated inertial reference technology and algorithms; and physical and mechanical science and technology related to robotics.

This abstract was produced using the key words "robot" and/or "ai" and/or artificial intelligence and running those key words through the NASA Library System RECON technology database. The reference materials found were then reviewed and only those items which appeared to be the first publication instance of the technology or science were retained. The original search results produced an ASCII text file spanning the years 1969 through 1993 and exceeding 16 megabytes of data.

From that search base it is evident the field is rich with reference material. There appear to be two rather dramatic episodes in the short history of robotics. The first extended from the mid-1970's through the early 1980's and produced a spate of items in refereed journals and as papers at symposia covering mechanical, adroitness and adeptness issues of manipulator systems. The second apparent episodic event occurred in the late 1980's and has extended through the present time. This phase has produced a tremendous jump in the number and variety of paper or presentations expressing a new understanding of the application of intelligence to the use of mechanical robotic devices, and in the further exploration of the mechanical elements particularly related to issues of dexterity.

One inferred result from this suggests that in the short three-decade history of robotics, the first phase–the early genesis period–produced the basic set of mechanical levers and applicators which were then explored for their physical and mechanical properties during the next decade. This discovery and physical analytical path has evolved in the third decade to the use of smart sensor systems, onboard intelligence and logic systems and is aimed at preserving the safety and physical options of a robot.

The student, researcher, or industrial designer seeking insight or reference material in these different elements of robotics can limit the amount of required reading by keeping these historic realities in mind.

Finally, this collection has some obvious weaknesses which could not be averted in the first several editions. There are significant robotic programs underway at laboratories of the National Institutes of Standards and Technology (Dept. of Commerce), the U.S. Army, the U.S. Navy, the Dept. of Energy, and the Dept. of Defense Advanced Research Projects Agency. Reference material covering those additional programs has not yet been obtained for inclusion. Additionally, there are the inevitable omissions in the listing of publications, firms, organizations, and associations. As these omissions are recognized, changes will be made in the baseline document.

Changes, suggestions, additions and/or deletions should be sent in written or electronic format to:

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What is Robotics?

This article originally appeared as an *FAQ* (Frequently Asked Questions) on the News Group "comp.robotics" on the Internet. The original material was compiled and written by Kevin Dowling, a member of the Carnegie Mellon University Robotics Institute, with numerous contributions by other readers of comp.robotics .

Kevin Dowling has given permission to NASA Office of Advanced Concepts and Technology to reproduce this material both in printed form on paper and to distribute this through additional electronic channels. /changes, additions, comments, suggestions and questions to this section uniquely should be directed to:

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What is Robotics?
There is a lengthy, committee-written definition from one of the robotics organizations that defines robotics as preprogrammable, electro-mechanical devices which perform a variety of functions. That definition is rather dry and, in the end, uninspiring.

Better ones might include:
- *Force through intelligence.*
- *Where AI meets the real world.*
- *I know it when I see it.*

Webster says:
- *An automatic device that performs functions normally ascribed to humans or a machine in the form of a human.*

The word 'robot' was coined by the Czechloslovakian playwright Karel Capek (pronounced "chop'ek") from the Czech word for worker or serf. Capek was reportedly several times a candidate for the Nobel prize for his works and very influential and prolific as a writer and playwright. Mercifully, he died before the Gestapo got to him for his anti-Nazi sympathies in 1938.

The use of the word Robot was introduced into his play R.U.R. (Rossum's Universal Robots) which opened in Prague in Jan of 1921. The play was an enormous success and productions soon opened throughout Europe and the US. R.U.R's theme, in part, was the dehumanization of man in a technological civilization.

There is some evidence that the word robot was actually coined by Karl's brother Josef, a writer in his own right.

The NASA Robotics Program

Early Beginnings of Robotics Program
In 1985 NASA instituted a research program in telerobotics to develop and provide the technology for applications of telerobotics to the United States space program. Over the eight-year life of the program, the program has evolved significantly in terms of its content, goals and approach. The lessons learned in that time comprise the organizing framework of the current program. The Telerobotics Program has important contributions to make to each of the NASA thrust areas including science, transportation, platforms, exploration and operations. These contributions are intended to most effectively utilize limited astronaut time by facilitating tasks such as inspection, assembly, repair, and servicing, as well as providing extended capability for remotely conducting planetary surface operations.

The Telerobotics Program is an element of NASA's ongoing research program, under the responsibility of the Office of Advanced Concepts and Technology (OACT). OACT's charter is to develop new technology for the United States aerospace program. A major Automation and Robotics (A&R) line item was defined under OACT in 1986; it incorporated elements of previous OACT-sponsored research in automation, robotics and human factors, and added a new series of demonstrations.

Teleoperators
During its history, NASA has undertaken a number of research programs aimed at developing remote manipulation capabilities for use in space.

There were three Teleoperations research programs at NASA which predated the current one. In 1961, early grants from NASA to Dr. Thomas Sheridan at Massachusetts Institute of Technology (MIT) funded work on the effects of time delay in remote manipulation with and without force feedback. In 1968, this lead to the establishment of the first remote manipulation research program, and was sponsored by the Office of Aeronautics and Research Technology, which is now OACT. The second program was sponsored by the Office of Space Flight. It lasted through the 1970s and was carried out primarily at Marshall Space Flight Center (MSFC), and focussed on researching free-flying teleoperators.

The third program was sponsored by the Office of Space Science, ending in 1982. Conducted primarily at the Jet Propulsion Laboratory (JPL), it researched the use of master-slave teleoperation. Interesting work was also initiated at Johnson Space Center (JSC) in the control of a large remote manipulator, and at Ames Research Center (ARC) which researched the use of an arm from a hard shell space suit to control a remote slave arm. The Telerobotics Program described in this document is the fourth research program in this area.

The Office of Aeronautics and Space Technology (OAST) sponsored a Machine Intelligence Study Group in 1978, headed by Carl Sagan, to analyze the opportunities and needs for automation and robotics and the potential benefits of those technologies. That group published a seminal report of its finding in 1980. In that same year, OAST initiated a small research and development effort in artificial intelligence with a focus on planetary operations and followed up the Sagan report with a summer study on A&R for future NASA missions. In 1982 OAST initiated a research and development program in computer science which encompassed and enhanced the machine vision and artificial intelligence research mentioned above. Also in 1982, the House of Representatives held hearings on robotics technology in the United States. This was the beginning of Congressional interest in A&R which later played a large role in augmenting and shaping the automation and robotics research and development efforts at NASA.

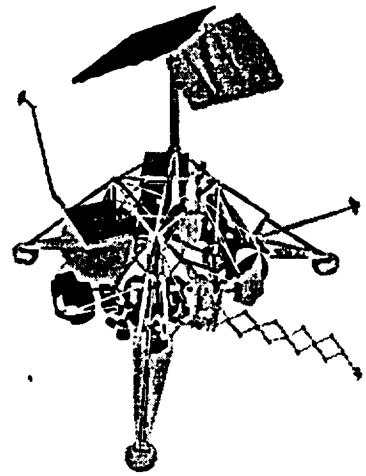
Space Human Factors

In 1983 OAST initiated a Space Human Factors program which included significant research and development on teleoperation and on human interface with artificial intelligence. This was both complimentary and supplementary to the Computer Science Program. In 1984 Congress passed legislation authorizing the development of Space Station Freedom and mandated that NASA implement a program to advance and use A&R technologies, especially with regard to Space Station. In response OAST began planning to integrate all of its research and development in A&R related technologies into a single, more focussed program. In 1985 OAST integrated the relevant aspects of its computer science and human factors programs, which totaled about $4M in fiscal year 1984, and initiated the Automation and Robotics Program with funding of over $8M in fiscal year 1985.

In 1987 OAST initiated the Civil Space Technology Initiative which incorporated the existing automation and robotics efforts, and greatly expanded the program. By fiscal year 1987 the Automation and Robotics Program funding was almost $18M, and under CSTI it grew to over $29M by fiscal year 1989. In fiscal year 1992 the A&R program was split into three distinct programs: Artificial Intelligence, Planetary Rovers and Telerobotics. That same year the Telerobotics Program received a one-time augmentation of $10M, which was an offshoot of the cancellation of the Flight Telerobotic Servicer (FTS) program by Congressional action. This augmentation was accompanied by legislation directing that it be invested in the development of "competitive robotics." At the end of that year, NASA underwent a reorganization which merged the space technology divisions of OAST with the former Office of Commercial Programs into the current Office of Advanced Concepts and Technology.

Previous Program Milestones

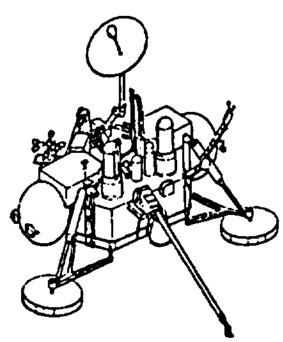
During this entire time NASA and the world-wide aerospace community gained very little experience in the operational use of robotic manipulation systems in extra-terrestrial environments. To date, there have been only four examples of a remotely manipulated



device being used as an operational component of a spacecraft mission in an extra-terrestrial environment. This set is limited to:

•The Surveyor 3, 5, 6, and 7 missions, which soft-landed on the Lunar surface in 1967 and 1968. The Surveyors used a three-degree-of-freedom (DOF) soil scoop used to dig small trenches in the Lunar regolith in the immediate vicinity of the landing site. Samples from the trenches were then collected by the manipulator and placed onboard the spacecraft for analysis.

•The Viking 1 and Viking 2 missions which landed on Mars in July and September of 1976. The Viking landers included a four-DOF soil scoop used to collect Mars soil samples in the immediate vicinity of the spacecraft. Samples from the trenches were then collected by the manipulator and placed onboard for analysis.



•The Soviet Lunakhod missions, which sent two unmanned mobile wheeled rover vehicles to the Lunar surface. Each of these vehicles was operated by remote teleoperation without time-delay compensation. Navigation of the vehicles was performed via a observe-plan-transmit-move-wait strategy. Lunakhod 1 operated for approximately eleven Lunar days, traveling a total of 10 kilometers. Lunakhod 2, with twice the speed of Lunakhod 1 and more experienced controllers, traveled 35 kilometers in about five Lunar days. In addition to the teleoperated navigation capability, each Lunakhod also utilized a teleoperated point penetrometer which measured regolith densities.

•The current Space Shuttle Remote Manipulator System (RMS), which was first flown aboard STS-2 in 1981. This six-DOF manipulator is a 50-foot long, three-segment teleoperator with a snare-before-contact end-effector, and is designed for the deployment, capture and recovery of large Space Transportation System (STS) payloads. The RMS has been used to perform several tasks on-orbit, including the deployment of the Hubble Space Telescope (HST), use as an EVA astronaut foot restraint during the repair of Westar and Palapa-B, knocking ice from water dump nozzles on STS-41-D, and retrieval of the 21,300 pound Long Duration Exposure Facility (LDEF).

Characteristics

In all cases these devices are, by terrestrial standards, fairly primitive teleoperators with very limited capabilities. For example, terrestrial robots inherently have many capabilities which allow them to outperform humans on some tasks. They can be more precise and more repeatable and do not become tired or bored. Robots are chosen to accomplish tasks which are highly repetitive, which are very well defined, which exist in stable, unchanging environments, and do not require significant oversight or human intervention. Current terrestrial robotics can be characterized as:

- ***limited to industrial manufacturing***
- ***preprogrammed control***
- ***precisely structured environments***
- ***single, highly repetitive tasks***
- ***heavy, rigid devices***

Teleoperators, with human controllers, have an advantage over robots in some other situations because of the difficulty of preprogramming reactions to all of the contingencies that may occur during a task. Current terrestrial teleoperation can be characterized as:

- ***limited to undersea and nuclear applications***
- ***limited to real-time manual control***
- ***used in semi-structured environments that are hostile to humans***
- ***non-repetitive tasks***
- ***limited maintainability and considerable backlash***

Terrestrially, teleoperators are currently the choice for tasks which are not done sufficiently often to amortize the cost of programming a robot, tasks in which the environment cannot be sufficiently controlled to permit robot operation, tasks in which sufficient manual dexterity, sensing, and artificial intelligence is not yet available in robots, and tasks in which a human operator is warranted because of the cost of a possible failure of a robot is too high.

By comparison, space telerobotics technology requirements can be characterized by:

- ***need for both manual and automated control***
- ***semi- to unstructured environments***
- ***non-repetitive tasks***
- ***variable time delay between operator and manipulator***
- ***dexterous, lightweight and flexible manipulators***
- ***complex kinematics and dynamics***
- ***novel locomotion mechanisms***
- ***minimal and simple servicing of the device***
- ***hostile environment of thermal gradients, radiation, vacuum, variable lighting***
- ***ability to recover from unplanned events, including system faults and errors***

In short, the next generation of space telerobotics must be far more flexible than the current generations of terrestrial robots and teleoperators.

Advancing the State of Robotic Art

To advance the state of the art of space telerobotics to be equivalent to, and even surpass, terrestrial teleoperations and robotics is not trivial. The concept of telerobotics encompasses both the concept of robotics and of teleoperation, and seeks to unify the technologies for robotics with those for teleoperation in such a way that the advantages of both are magnified and the limitations of both are minimized. Thus a telerobot would be more capable than either a robot or a teleoperator, and able to perform a larger class of tasks than can be accomplished by either robotics or teleoperation.

This added power and flexibility is needed to free scarce human time from a myriad of space operations tasks that are dangerous, repetitive, or simply non-interesting. It is important to note that the emphasis of this program, however, is not on eliminating or minimizing the need for humans in space exploration, but rather to find the right cooperative mix of human and automated agents for any given set of mission goals. For example, it has been demonstrated that some tasks, such as the repair of the Solar Max satellite and replacement of battery boxes on the Hubble Space Telescope, can be accomplished by astronauts conducting extravehicular activity (EVA), by free-flying remote teleoperators, and with a cooperative mix of telerobots and EVA astronauts. Each of these approaches has advantages and limitations which vary based on the task to be performed.

Recognizing that space operations outside of life supporting environments such as the Space Station are relatively dangerous, the capability to augment the capabilities of space-suited astronauts with mobile, manipulative machines is very attractive. Space operations require the ability to work in an environment which is not well defined and which is not controllable, unlike a factory environment. Therefore, telerobotic systems with local and remote teleoperation capabilities are attractive approaches to providing remote manipulation and mobility.

On the other hand, remote space operations often involve some communications time delay so that terrestrial teleoperation techniques are inadequate. For example, operating a remote satellite servicer from the ground will require compensation for a few seconds delay due to the communications relay through satellite and ground systems. In addition, the scarcity of human resources in orbit, such as on the Space Station, makes the full automation of routine manipulative tasks attractive. Also, robotic control of some aspects of tasks (such as keeping a sensor an exact distance from a surface being inspected) is far superior to human control capabilities with teleoperation. Thus, telerobotic systems with robotic capabilities present advantages to certain applications.

The degree to which teleoperated or robotic capabilities are used depends on the application. For example, a Space Station astronaut may perform a one-time repair task on a complex mechanism outside the station almost completely in a teleoperated mode (assuming no time delays). At the other extreme, physical teleoperation is impractical to control a rover on the surface of Mars with a communications delay of tens of minutes; therefore, automation is required.

Space Telerobotics Applications

Applications of space telerobotics technology which have been identified as opportunities for the program include satellite servicing, space system construction and servicing, and remote operations on planetary surfaces. The program has examined tasks for these types of applications and has selected sets of capabilities to be targeted for demonstration to prove the utility of telerobotics in performing these tasks.

The space operations tasks for which telerobots could play an increasingly larger role include inspection, assembly, servicing and repair. In ground operations robots will see increasing use in the manufacture of Space Shuttle and Space Station components, in the refurbishment of the Space Shuttle Orbiter between flights, in the test of satellites in thermal–vacuum chambers, and in emergency responses to hazardous materials incidents.

Telerobotics can and will make important contributions to both ground and space operations in space science, space transportation, platforms and planetary exploration. In space, telerobotics will allow operations to occur in places where astronauts are not present, and will increase the capability, effectiveness, efficiency, and probability of success, of operations where astronauts are present or only a short distance away.

Lessons Learned

During the history of this program, different strategies to support the development of telerobotics technology have been utilized. Of particular note was the evolutionary approach utilized during the first half of the program. Under this approach, the program was divided into two areas: basic component development (or "core research"), and the applications testbed. The component development portion of the program was directed toward the creation of new mechanisms, algorithms, and individual piece components which would solve a single problem in the area of operator interface, control execution, planning and reasoning, or sensing and perception.

The applications testbed was to be a single facility of modular design which could support the testing and demonstration of any of the developed component technologies. By utilizing common subsystems, it was thought that the developed component technologies could easily be ported to the testbed for integration and demonstration, thereby reducing overall costs to the project by avoiding the creation of multiple testing facilities for each new component. At the same time, the use of the modular architecture would allow the continuous upgrading of the capabilities and functionality of the testbed itself, which could incorporate applicable new technologies as they were developed.

However, several problems have been found with this approach. By not establishing a specific set of tasks and capabilities which would define "the testbed" and reviewing and reevaluating future expansion in regard to meeting the design goals, it was impossible to determine when the testbed was "completed." Thus, the testbed attempted to provide an ever–expanding capability under increasingly complex constraints. The focus for achievement of goals was placed on the telerobot design, with less consideration given to the host vehicle and supporting infrastructure. While the results in some cases led to impressive technological achievement, the system itself led to unnecessary complexity with regard to achievement of any single task. At the same time, the attention devoted toward component technology development suffered, due to resources constraints imposed by the ongoing maintenance and development of the testbed. The lessons learned during this phase can be characterized as:

- ***evolution without an explicit stopping criteria leads ultimately to infinite complexity***
- ***the rapid pace of computer development would necessitate costly update and revision for complex integrated testbed software/hardware***
- ***reference task capability must be explicitly determined and used as a measure so that progress can be assessed***
- ***a tight coupling of new component technology development with robust task performance evaluation introduces formidable problems***
- ***overall system performance should be used to prioritize focused technology development***
- ***the robot-friendly design of the host vehicle is as important as the design of the robot itself.***

After four years, the Telerobotics Program took a new direction. A number of smaller projects, with specific task sets and success requirements, were defined. The goal was to determine existing capability as early as possible by rapidly prototyping a telerobot and assessing its capabilities and limitations, and thus identifying empirically the "tall poles" in achieving a more capable device. These "tall poles" include assessing which components would yield the greatest systems level improvement by being upgraded, and the explicit consideration of ways in which the host vehicle could be designed or redesigned to improve overall system capability. Further, implications of the support personnel infrastructure are examined.

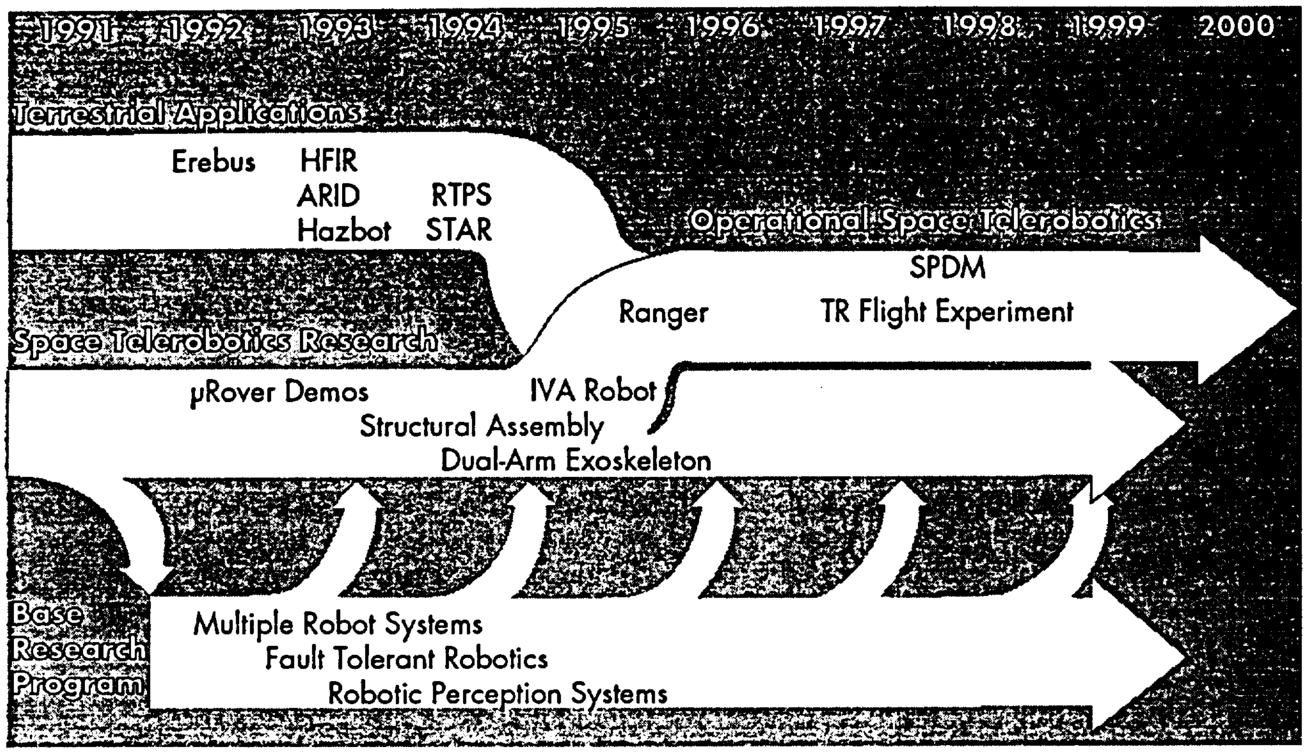
At the same time, it was fully recognized that component technology development alone, without a complimentary balance of complete application development, would not be sufficient to convince potential users of the utility of telerobotics. The development focus of the program would have to be expanded to cover the spectrum from fundamental, basic research to complete, near-operational systems which accomplished real tasks in user environments.

Program focus on user missions

Since its inception, the Telerobotics Program conducted by the Office of Advanced Concepts and Technology (OACT) has been closely coordinated with the NASA organizations which are the intended recipients of the developed telerobotics technology. This coordination takes place at multiple levels, with the potential user community technology needs expressed both formally and informally to OACT.

At the highest strategic level, OACT works with the user offices to develop an annual Integrated Technology Plan (ITP) in support of the civil space program. The purpose of the ITP is to serve as a strategic plan for the OACT space research and technology programs, and as a strategic planning framework for other NASA and national participants in advocating and conducting technology developments that support future U.S. civil space missions. The integration of strategic

NASA Telerobotics Program milestones and development interplay



requirements, directions and goals for the Space Telerobotics Program is incorporated within the ITP process.

The ITP is revised annually to reflect changes in mission planning, approval of new focused and research base efforts, and progress in ongoing technology development efforts. Moreover, both the ITP and derived OACT space technology element plans are subjected to annual external and internal review to ensure continuing quality and relevance. In the case of the Telerobotics Program, that includes full involvement of the user communities (industry, university, and NASA) with the program as advocates, advisors, and requirements providers.

In addition to the formal submission of requirements from the user program offices to OACT via the ITP process, each user organization works informally with the Telerobotics Program at a more detailed level to transmit requirements to, and receive technology products from the program. This interchange typically takes place as part of the activities of the Telerobotics Intercenter Working Group (TRIWG), which actively guides the direction and strategy of the Telerobotics Program. The TRIWG consists of representatives from each organization participating in the Telerobotics Program, and meets quarterly to provide direction on the content and focus of the program. The TRIWG performs detailed technical reviews of the ongoing technology and application tasks, and coordinates the transfer of this technology to the user organizations. At each meeting, representatives of the user organizations are present to update the formal technology requirements and assess how the Telerobotics Program is responding to these requirements.

As these updated technology requirements are passed to the Telerobotics Program each year, the program is reassessed to determine the correlation between the requirements and the planned developments of the program. If appropriate, new tasks are initiated in the program to address new technology needs, or existing tasks may be re-targeted. At any given time, approximately 70% of the tasks within the program are targeted to address specific user requirements aligned with a specific planned mission (this is the "technology pull" portion of the program). The remaining 30% of the program is composed of tasks which address new innovative technologies. These technologies have been identified by the program as having a potential to significantly advance the state of the art, and worth investigating without a pre-identified user requirement (this is the "technology push" portion of the program).

Current space robotics user requirements
The Telerobotics Program has been structured into three specific mission or application areas: on-orbit assembly and servicing, science payload tending, and planetary surface robotics. Within each of these areas, the program supports the development of robotic component technologies, development of complete robots, and implementation of complete robotic systems focused on the specific mission needs. These three segments align with the application of space telerobotics to the class of missions identified by the potential space robotics user community.

The On-orbit Assembly and Servicing segment of the program focuses on the development of space robotics for on-orbit satellite construction, servicing and maintenance, and includes target applications such as assembly of tetrahedral space truss structures, robotic enhancement of Space Transportation System (STS) Payload Bay operations, and ground-based robotic servicing of external Space Station Freedom payloads. The user community includes Space Station Freedom, the Space Transportation System, and possibly other attached-payload user communities.

The Science Payload Robotics segment of the program matures technologies for robotics which will be used inside astronaut-occupied environments (i.e. inside pressurized living space) to maintain and service science payloads. This capability will off-load the requirements of intensive astronaut maintenance of these payloads, and permit operation of the payloads during periods when astronauts may not be present. The specific application areas include IVA robotics for Space Station Freedom and laboratory tending robotics for SpaceLab and SpaceHab.

The Exploration Robotics segment of the program develops robotics for eventual exploration of the surfaces of the Moon and Mars. These projects are developing mobility systems, control execution, navigation planning, autonomous exploration, sample acquisition and other technologies to enable high levels of local autonomy. Specific missions which are supported include the Mars Environmental Survey (MESUR) Pathfinder project, and other programs planned by the Office of Space Science user community.

It is important to note that the tasks selected for the three focused segments of the program address requirements of the class of missions planned by the user organizations, and not necessarily one specific mission. For example, the tasks in the Exploration Robotics section of the program are selected to address the full suite of technologies required for autonomous Mars and Lunar surface robotic exploration, and not just the earliest planned mission from the associated user plan. This accomplishes two things: requirements from individual user missions are well leveraged with those of other missions, and developing technologies which target requirements common to multiple missions are less likely to need revision in the event that a particular user mission should be modified or canceled.

Two additional program segments have been defined to support the three focus areas. The Robotics Technology segment develops component technologies which have been determined to be of potential benefit in addressing multiple needs of the known robotics requirements. These elements of the program are typically long lead-time items, which may take many years to fully develop and bring to an appropriate level of readiness. This portion of the current program includes such elements as fundamentally new robotic joint designs, exoskeleton systems, fundamental robotic control theory development, and widely-applicable proximity sensor technology. The Terrestrial Robotics element of the program provides a mechanism for the application of developed technologies into terrestrial task environments. These tasks move the technologies developed in the other elements of the program from the laboratory setting into operational use, and take advantage of the relatively easy terrestrial access, well understood environments, and myriad problems to be solved to demonstrate the applicability of space telerobotics.

Selected Technologies NASA Is Funding

Multiple autonomous robots

The Aerospace Robotics Laboratory (ARL) at Stanford University is developing new concepts for the precise manipulation of objects in free space. The ARL is pursuing three fields of robotic manipulation: system control of multiple manipulator systems, control of free–flying vehicle systems, and high–performance control of flexible manipulators.

In the area of cooperative manipulation, Stanford researchers have demonstrated a system of two cooperating manipulators able to autonomously track, capture, manipulate, and assemble free–flying objects under the direction of an intuitive "point-and–click" graphical user interface. It has been extended to include obstacle–avoidance motion planning, operation from a vibrating base, and adaptive control. A 3-D cooperative system is nearly operational.

The ARL is also actively researching combined control of free–flying vehicle and manipulator systems. Accomplishments in this area include autonomous tracking, pursuit and capture of a free–flying, rotating object from a free–flying base, thrusterless robot locomotion using manipulators for push off and catch, and team cooperation between multiple two–arm free–flying robots.

The ARL's on–going research in high–performance control of flexible structures has been extended to include adaptive control, joint flexibility, multilink flexibility, and the control of dynamic payloads from a flexible arm.

Advanced robot joint / trip roller clutch

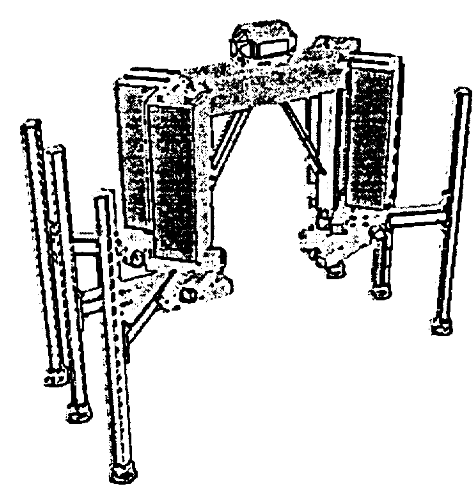
This task will develop an advanced electromechanical joint with a goal of producing at least a four-fold improvement in size (volume/mass) and power/torque output. At the same time, it will advance the state-of-the-art in controllability, safety and reliability. The Advanced Robot Joint will be fundamental to all electromechanical devices including robots and scientific instruments and, as such, will upgrade all manner of NASA satellites, robots, platforms and scientific instruments. During the first year, a trip roller clutch will be developed; the second year, a dual roll joint test bed will built and cableless power will be demonstrated; the third year, new motors and transmissions will be introduced and the fourth year, an advanced joint will be assembled Quantifiable technology improvements goals for the project include: (1) a four to six times improvement in torque/weight and in torque/volume ratios, (2) 25-50% improvement in power/efficiency.

Telepresence

JPL is investigating the augmentation of telemanipulation capabilities through the development of human–equivalent dexterity with remotely operated hands in two development phases, with emphasis on minimal training and use of human–rated tools. Ultimately, a force reflecting master slave arm/hand system in exoskeleton form with 7–DOF arm and 16-DOF four–fingered hand will be prototyped, integrated with a quasi-exoskeleton visual telepresence system.

Safety system for use near flight hardware

This project will develop a robotic sensor system that



utilizes non- contact sensors and other safety mechanisms to provide robust collision prevention. This will enable a robot to be used near flight hardware with confidence that no inadvertent contact will occur. The major component of this research will be the development of proximity sensor based control of the manipulator. This will require an extensive overview and analysis of proximity sensing techniques, mechanisms, and characteristics. Also, the use of multiple sensors with varying characteristics will require the development and use of advanced sensor integration, fusion, and control methods.

Redundant robot systems

The objectives of this program element are to perform research in advanced robotics regarding fault tolerant manipulator systems. For space operations, extraordinary reliability will be needed to protect space assets, and to ensure that robots are capable of physical task performance over long duration missions. The goal of the failure tolerance in manipulator design task is to develop a major testbed to treat failure tolerance in mechanical structures associated with robotics and computer controlled machines. Three levels of failure tolerance in the mechanical structure and similar controlling software will be developed based on criteria-based decision making in a finite fault tree to operate the system to avoid faults in real time. This work is being conducted at the University of Texas at Austin (UT), under the sponsorship of the Johnson Space Center.

This work seeks to develop approaches for the design of space manipulators that remain operational in the event of failures. This fault tolerance approach must be multi-level to accommodate failures within the manipulator hardware and software system.

The facilities currently utilized by the Telerobotics Program include:

- ***CMU Field Robotics Center***
- ***GSFC DITFAC Gantry Laboratory***
- ***GSFC Intelligent Robotics Laboratory***
- ***JSC Manipulator Development Facility***
- ***KSC Robotics Development Laboratory***
- ***LaRC Automated Structural Assembly Laboratory***
- ***LaRC Intelligent Systems Research laboratory***
- ***Stanford University Aerospace Automation Laboratory***
- ***UMd Neutral Buoyancy Research Facility***
- ***UMd Space Systems Laboratory***
- ***MIT Mobile Robotics Laboratory***
- ***JPL Surface Inspection Robotics Laboratory***
- ***JPL Mobile Robotics Laboratory***
- ***JPL Robot Systems Laboratory***

Links to Other Government Programs

Throughout the life of the NASA Telerobotics Program, NASA has worked to build and maintain coordination with other government robotics programs, including those of the National Science Foundation (NSF) and the National Institute of Standards and Technology (NIST). These efforts include cooperative activities, collaborative research, and external transfer of NASA-developed robotics technology. These efforts have three purposes: to develop industrial applications of telerobotics technology, to apply telerobotics technology to terrestrial science and research efforts,and to strengthen intra-government coordination. Several of the activities are summarized below, beginning with the efforts targeting development of industrial applications of telerobotics technology:

•The Automated Manufacturing Research Program, conducted by NIST is investigating automation in factory-floor settings, and the relative advantages of improved work cells against more capable manipulation systems. NASA participates in the annual program review conducted by NIST, and coordinates with NIST to transfer NASA-developed robotics workcell technology into this effort.

•In previous years, NIST and the NASA telerobotics efforts have cooperatively developed several new technologies and architectures for the control of robotic systems. For example, the NASREM robot control architecture was jointly developed by NASA and NIST as a precursor to the NASA Flight Telerobotic Servicer program. The architecture is now used as a standard architecture definition methodology by many NASA, NIST and industry projects. NASA has directly supported NIST in several of these cooperative activities, with annual funding for robotics research reaching up to $1 million per year. NASA and NIST are currently negotiating further cooperative research efforts in this area.

•The NASA and NSF robotics research programs have jointly co-sponsored the "Bilateral Exchanges on the Approaches to Robotics in the United States and Japan" conference, which conducted investigations into the methods, techniques and technologies used by government and industry to research and develop fundamental new robotics technologies. The outcome of this activity was publication of a manuscript which contrasted the approaches used in the United States and Japan, and which offered NASA and NSF insights into the content of the robotics development programs supported by MITI, NASDA, and several Japanese industries.

•The Advanced Research Projects Agency (ARPA) has selected the Langley Research Center robotics program as one of their technical agents in the area of robotics. Under this agreement, LaRC and DARPA cooperatively issue university research grants to sponsor the development of innovative new robotics technologies, as well as increase robotics educational expertise in the United States.

•The program has maintained close ties with the U. S. space robotics industrial community, and monitored industrial developments of potential applicability to the NASA space robotics and planetary rover research efforts. Representatives of the U. S. space robotics industrial community participate in the Telerobotics Intercenter Working Group, and in technical program reviews and assessments such as the Space Systems Technology Advisory Council. This coordination facilitates the transfer of NASA-developed technologies to the space robotics industry, and aids in the rapid application of these technologies to terrestrial manufacturing and automation problems.

•The program coordinates with several robotics industry advisory and technology interchange groups, to facilitate the transfer of NASA-developed technology to the industrial community and receive comments on the overall direction and focus of the program. One such group is the Space Automation and Robotics Technical Committee (SARTC) of the American Institute of Aeronautics and Astronautics which meets three or four times annually with the charter of disseminating information about space automation and robotics and promoting the technology to industry, academia, and government. The SARTC is composed of industry representatives from the aerospace community, as well as government and academia.

Two of the joint efforts which target application of telerobotics technology to terrestrial science and research efforts are listed below:

•Several programs sponsored by NSF both sponsor and utilize telerobotics and robotics technology research and development. In 1992 NASA and NSF cooperated in conducting the Mt. Erebus Explorer project, a project to deploy a robot into the interior of a volcano crater in the Antarctic. This project, conducted as part of the Telerobotics Program and the Antarctic Space Analog Program, demonstrated innovative new robotics technologies developed by NASA. It is anticipated that this project will spawn several new activities which may revolutionize volcanic sample collection and lead to significant new applications of robotics in terrestrial field science operations.

•In addition to the involvement with the NSF Polar Programs Division (which cooperated with the Mt. Erebus Explorer project), NASA is currently negotiating with the NSF Oceans Division to investigate the potential for application of NASA-developed robotics technology to underwater science sampling operations. Of particular interest is the underwater Remotely Operated Vehicle (ROV) technology which NASA developed and demonstrated under the Antarctic sea ice with the cooperation of NSF in 1992. Additional negotiations are underway with the NSF Information, Robotics and Intelligent Systems Division to jointly sponsor robotics research and investigate opportunities for transfer of NASA-developed robotics technologies to NSF grantees and research programs.

Examples of coordinated activites to strengthen intragovernment cooperation are shown below:

•The Adaptive Suspension Vehicle Program, funded by ARPA and conducted at the Ohio State University (OSU), is researching mechanisms and algorithms for human-directed walking machines. This activity coordinates closely with the walking machines research project sponsored by NASA at Carnegie-Mellon University (CMU). The NASA developments have based several new technologies and project architectures on the early ARPA efforts. The relationship continues with OSU participating in ongoing CMU technology assessments, including a recent February 1993 review of the Mt. Erebus Explorer project.

•OACT has developed a Memorandum of Understanding (MOU) with JPL and the U. S. Army Tank Automotive Command (TACOM) which agrees to the cooperative development of unmanned vehicle research and capabilities. One of the benefits of this MOU is the cooperative utilization of the TACOM unmanned vehicle control station, which permits

NASA and JPL to utilize a common control architecture to reduce the effort and expense of developing duplicate vehicle control systems. To date, this agreement has resulting in a savings of over $5 million to the NASA planetary rover technology development projects.

•ARPA has worked closely with elements of the NASA Telerobotics Program for several years. Several products of the Telerobotics Program have been successfully transferred to ARPA, and incorporated in their systems. For example, the Task Control Architecture (TCA) developed under the NASA program has recently been selected by ARPA as the baseline architecture for their autonomous mobile robotics program (the TCA has also been selected by Tindle Air Force Base as the fundamental architecture for their Rapid Runway Repair robotics program). The ARPA programs have also produced elements incorporated into the NASA Telerobotics Program, including the Autonomous Land Vehicle system which was utilized as a component of the Mt. Erebus Explorers task.

•NASA and the U. S. Air Force jointly chair the Robotics and Telepresence Subcommittee of the Space Technology Interdependency Group (STIG), which meets twice each year to provide an interface between the NASA, Department of Defense, and Department of Energy operations technology thrusts and information transfer organizations. This activity also includes conducting the annual Space Operations, Automation and Robotics (SOAR) Conference, which included over 30 technical sessions, publication of 135 technical papers, and attendance by over 600 registrants from NASA, the U.S. Air Force, U. S. Navy, U. S. Army, ARPA, Department of Energy and the industrial community.

This list is not exhaustive, but is a representative cross-section of the type of activities conducted by the NASA Telerobotics Program and other government organizations.

Telerobotics flight experiments

Since its' inception, the overall purpose of the Telerobotics Program has been to develop new telerobotics technologies and have those technologies incorporated into operational flight systems. However, mission managers have been hesitant to incorporate these technologies into mission profiles when the technologies are new and unproven in flight environments. To overcome this hesitation, the program has historically planned to conduct a series of flight experiments and demonstrations which would validate the technologies. To limit cost, the program has planned to utilize telerobotic flight systems developed by other NASA offices as the demonstration platforms, including systems such as the Flight Telerobotic Servicer (FTS), the Satellite Servicing System (SSS), the Demonstration Test Flight-1 (DTF-1), and the Orbital Maneuvering Vehicle (OMV). However, each of these platforms has been canceled before completion, resulting in the loss of the planned demonstration opportunity. The result is that the program has yet to validate any of the developed technologies in an actual flight experiment or on-orbit operational application.

To alleviate this shortcoming, the program has defined a strategic goal of developing and deploying an internally-developed series of flight experiments which will be capable of demonstrating that the developed technologies are robust and capable enough to be utilized in flight environments, and that they are mature technologies which potential users should be considering for operational applications in space. This program has been assigned appropriate resources to begin the planning and development of a flight experiment package which could serve as the first step in addressing this challenge. During Fiscal Year 1992), the program has started to address this objective in earnest, with the recruitment of a set of flight experiment concepts, and the initiation of a Phase A-level flight experiment definition task which could lead to a full flight experiment project by Fiscal Year 1996.

In June 1992 the program conducted a Telerobotics Flight Experiment Workshop with the goal of identifying a telerobotics flight experiment concept which would demonstrate the capabilities and technologies developed by the program in an orbital environment. The experiment would have to contend with several constraints: unlike previous robotics flight experiments (such as the FTS DTF-1 or SSS), it was unlikely that any additional funding would be identified by the agency to support this activity and the cost of the experiment would have to be extracted from the existing baseline funding of the program; therefore the cost of the experiment would have to be relatively low (i.e. up to a few million dollars, instead of tens or hundreds of millions of dollars). The need to demonstrate telerobotics capabilities on-orbit is believed to be fairly urgent, so the experiment should be developed and conducted within the next four years. The experiment must be representative of the capabilities developed by the entire program, so it must demonstrate multiple technologies incorporated in a complete application system and not just a single component or subsystem. While it is unlikely that a second flight opportunity would immediately follow the experiment, the possibility can not be precluded; therefore the experiment should include options for follow-on flights which would augment (but not be required by) the initial flight experiment.

The experiment under consideration, known as "Ranger", is being lead by the University of Maryland and includes collaborative participation from the Jet Propulsion Laboratory, the Goddard Space Flight Center, and the Space Automation and Robotics Center (SpARC) at the Environmental Reseach Insitute of Michigan (SpARC is one of the OACT Centers for the Commercial Development of Space). Ranger will be controlled from a ground station at the University of Maryland, and will provide valuable data in correlation of neutral buoyancy simulations, advanced telerobotics control and design, remote maneuvering, human factors of ground-based control for space telerobots, and advanced small spacecraft technology. The system represents a class of operational servicing vehicles which would be of use today, and will be of increasing utility as more complex systems, such as Space Station Freedom, the Earth Probes, and the Great Observatories, are completed. In addition, this class of vehicle offers significant opprtunities for the commercial development of space, and the creation of a commercial servicing industry infrastructure for on-orbit operations.

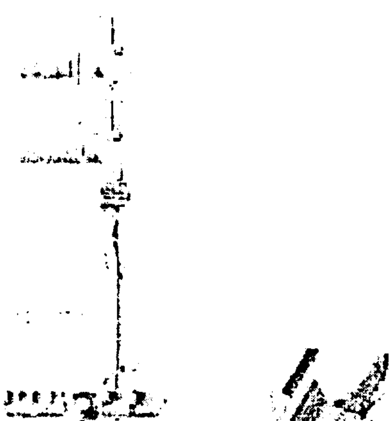
RANGER space operations research vehicle
The overall goal for this experiment is to obtain data on telerobotic operations in space with a low-cost, rapid development program. The specific objectives of the Ranger project include:

• Correlating neutral buoyancy telerobotic simulations by developing nearly identical underwater and space flight units, and performing identical tasks in both environments;

• Compressing the hardware development cycle by using neutral buoyancy hardware to validate flight hardware and software;

• Reducing the costs to flight by making selective use of Class-S and Mil-Spec components, minimizing paperwork not essential to flight performance, and maximizing in-house operations on the flight hardware;

To minimize the cost of the experiment, two factors were considered: man-rating equipment to qualify for use in the Space Shuttle is an expensive and time-consuming (albeit necessary) process, and obtaining a dedicated flight opportunity is similarly an expensive option. Therefore, the experiment should be designed to be flown on an expendable launch vehicle, and opportunities to fly as a secondary or co-primary payload on an existing manifested flight are being pursued.

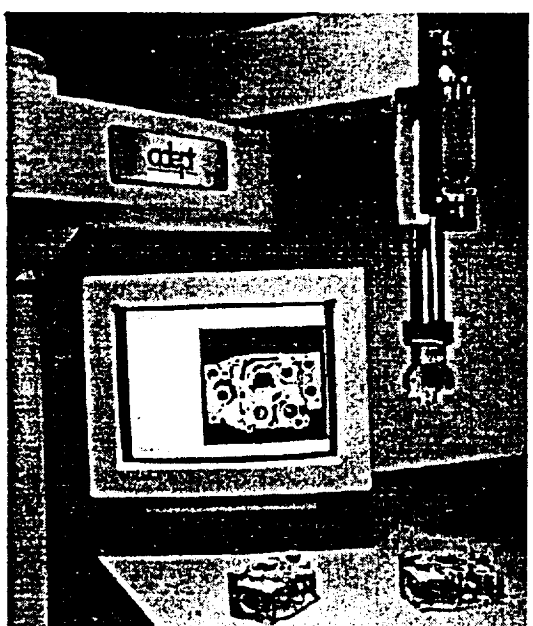


Telerobotics and telepresence will play major roles in the remote exploration of other worlds and the human habitation of space!

Organizations & Companies Involved in Robotic Activities

FIRMS ENGAGED IN ROBOTICS-RELATED WORK
There are a small number of companies targeting the research community for the mobile robot market. TRC, RWI, Cybermotion and Denning have all sold and are selling mobile devices for research and real applications. A number of Automatic Guided Vehicle companies sell their machines but their primary applications are factory operations.

Adept Technology, Inc.
Adept Technology, Inc.
150 Rose Orchard Way
San Jose, CA 95134
tel: 408-432-0888
fax: 408-432-8707
Adept Technology, Inc. is a global leader in the design, manufacture, and marketing of robotics and

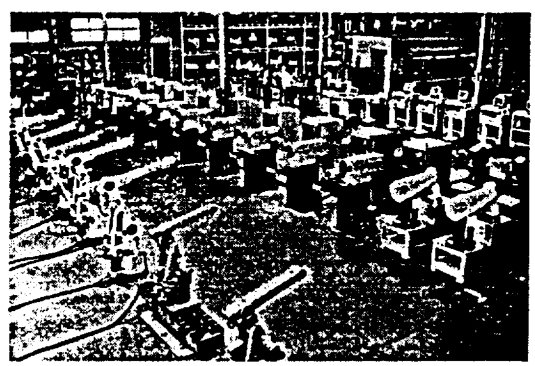


motion control products for small parts assembly and automated material handling. High speed direct-drive and harmonic-drive SCARA style arms. 0.001" (.025mm) repeatabiliy. Payloads from 4-25kg Can be used in clean room and food applications as well. Adept sells vision systems and controllers also. Adept was founded in 1983 by Brian Carlisle and Bruce Shimano.

AdeptVision AGS-GV is a high-resolution, grayscale vision system used for measurement, inspection and guidance.

AIM MotionWare is a powerful application software package that greatly simplifies the set-up and operation for automated workcells.

Antenen Research
P.O. Box 95
Hamilton, OH 45012
Antenen Research specializes in new and used robots for manufacturing, research and training. Our tremendous inventory entails a single, affordable source of equipment for a wide variety of automation projects. Antenen Research maintains the largest selection of new and used robots in



North America, offering current technology at a savings of 40% to 70%.

Asea Brown Boveri (ABB), Vesteraas, Sweden
ABB Robotics
2487 South Commerce Drive
New Berlin, WI 53151
tel: 414-789-9235
Now own Cinncinatti Milacron robotics group, Graco and Trallfa.

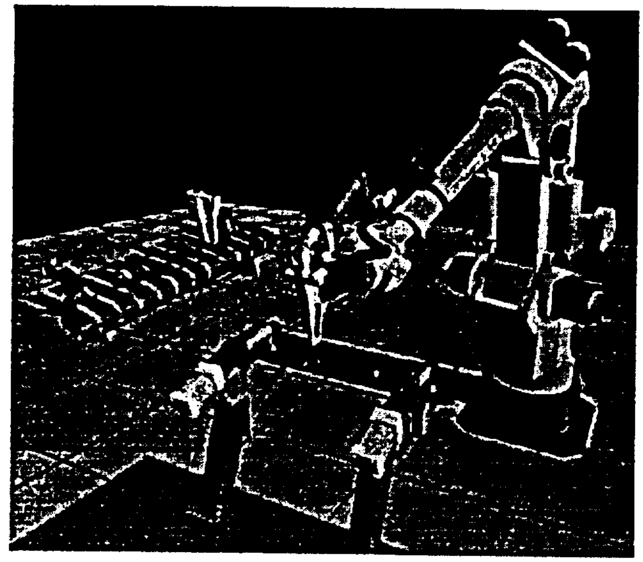
Bell and Howell
Mailmobile Company

81 Hartwell Avenue
Lexington, MA 02173-3127
tel: 617-674-1110
Mailmobiles were developed by Lear-Siegler in the mid-70's for the industrial cleaning market. They left this market and Bell & Howell, the audio-visual company, was refocusing on office automation products and picked up this product from Lear-Siegler. There are three models of Mailmobile, the Packmobile, the Sprint and the Trailmobile. About 3000 systems sold and about 2000 probably in operation. They use a chemical trail that floureseces under UV light. Payloads up to a couple of hundred kg. Some systems have been operating for over 15 years.

CRS Plus
PO Box 163, Station A
830 Harrington Court
Burlington, Ontario
Canada L7R 3Y2
tel: 416-639-0086
fax 416-639-4248
Sells several manipulators. 5-DOF around $25K, 6DOF around $33K. Sell end-effectors as well (electric, vacuum and penumatic). Wrist can be bought separately. Controllers use RAPL, a VAL-like language. Fairly open architecture. 3Kg payloads +/- 0.05mm repeatability.

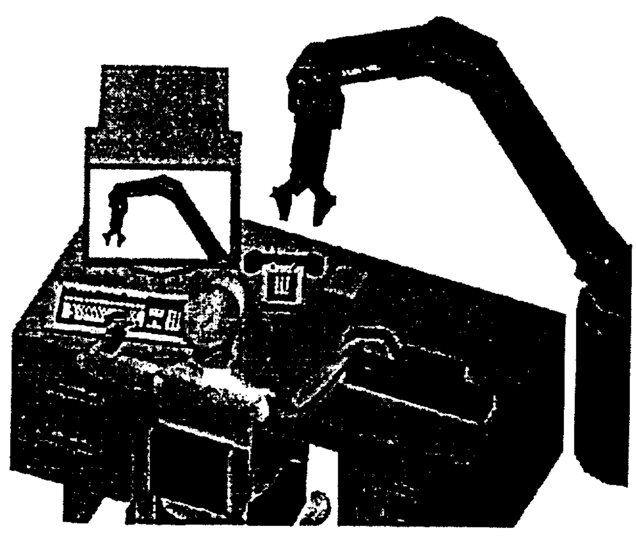
Cybermotion
5457 Jae Valley Road
Roanoke, VA 24014
tel: 703-982-2641
John Holland's company. Mobile K2 bases making use of ingenious torque-tube synchronous drive system. Security markets and research platforms, manipulators for base as well. Map building software too.

Deneb Robotics Incorporated
Deneb Robotics Inc.
P.O. Box 214687
Auburn Hills, MI 48321-4687
tel: (313) 377-6900
Deneb's UltraSpot and UltraArc are 3D graphics-based interactive engineering tools for designing, programming, and optimizing spot welding applications through simulation and analysis. UltraPaint provides process engineers with a powerful tool for the comprehensive and efficient analysis of paint guns, fixtures and production systems to assure the optimal process plan before robot programs are



created. UltraSpot's built-in functions automatically provide: normal-to-surface spot weld orientation; optimal robot placement to avoid collisions and minimize cycle time.; optimized collision-free paths; and stationary tool center point welding

Deneb's UltraArc, the stimulation and programming

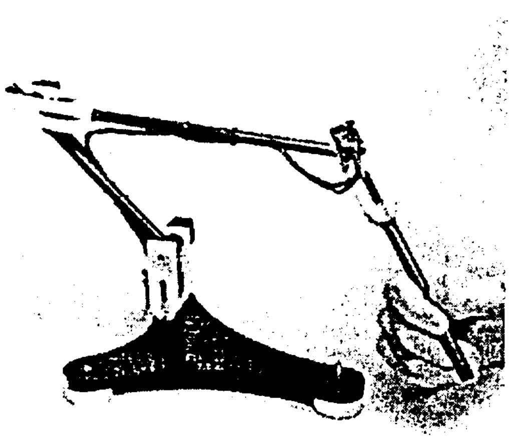


tool for Arc welding, is an interactive 3D graphics-based engineering tool specifically for designing, programming, and optimizing robotic arc welding applications through simulation and analysis. The QUeueing Event Simulation Tool, QUEST, from DENEB is a modeling and analysis of manufacturing systems tool. Detailed physical system properties combined with interactive 3D graphics and visual analysis deliver a new level of ease, power and accuracy. Deneb's Tele-interactive Graphics Robot Instruction Program, Telegrip, is a 3D simulation-based interactive programming and control tools for robots and other computer-controlled devices. TELEGRIP provides a bilateral, real-time operator interface to robot and device controllers enabling operators to work safely, quickly, and efficiently in complex environments. TELEGRIP provides a dynamic, single point of control.

Denning Mobile Robotics Inc.
21 Concord Street
Wilmington, MA 01887
tel: 508-658-7800
Mobile robots - synchronous drive bases for research platforms. Building automated camera platforms for newsrooms, working on floor cleaning machines with an industrial partner. Denning also has a number of products including a position scanner, and IR beacons. A Denning floor scrubber is working in a post office in Pittsburgh, Denver and Washington, and at a UPS site.

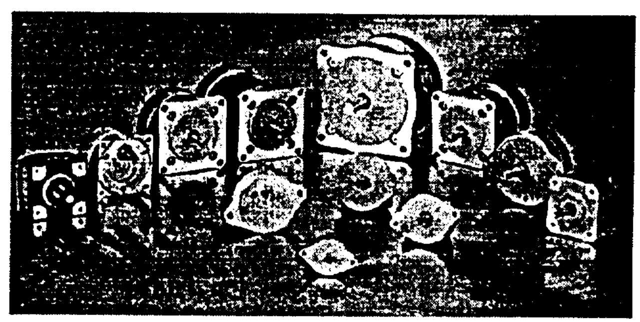
Honeybee Robotics
204 Elizabeth Street
New York, NY 10012
tel.: 212-966-0661
fax: 212-925-0835

Immersion Human Interface Corporation
P.O. Box 8669
Palo Alto, CA 94309
tel: 415-599-5819
email: immersion@starconn.com
Immersion Human Interface Corporation is proud to introduce the Immersion Probe, a unique new human interface tool for natural manual interaction with three-dimensional computer environments.



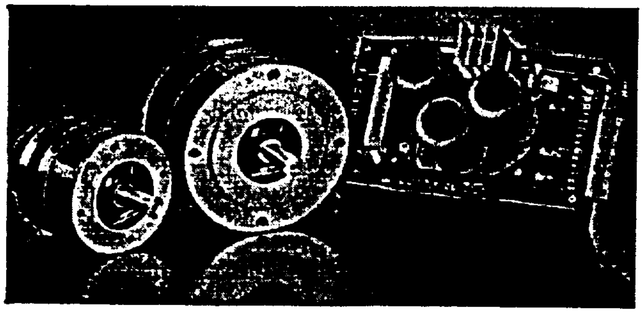
IS Robotics
4353 Park Terrace Drive
Westlake Village, CA 91361 USA
tel: 818-597-1900
email: robots@isx.com
Associated with ISX Robotics of Cambridge. T-1: tracked robot approx 50cm x 36cm. $5k. R-2: Wheeled machine. Gripper with 7.5cm opening, 18cm lift, 1kg lift force. $7K. Ghengis II: Six-legged machine with whisker bump sensors and force detection on legs. About $2k. Uses the ubiquitous MC68HC11E2 microcontrollers. Robots include IR and bump sensing for obstacle detection. Pyro sensors and color camera with pan-tilt are optional.

Kollmorgen: Motion Technologies Group
Kollmorgen
Motion Technologies Group
201 Rock Road
Radford, VA 24141
tel: 703-633-4124
fax:703-731-0847
Kollmorgen Motion Technologies Group is a company taking bold new strides to ward the future. Kollmorgen can provide the following: high production rates in factory automation; precise control in rugged applications; reliable transportation on land



or under the sea; and economical motion control for office and commercial machines.

Kollmorgen brushless servo systems represent the leading edge of today's high performance motion control technology. Thanks to recent advances in rare earth magnetics and digital power electronics, Kollmorgen brushless system deliver efficiency, dynamic response and reliability at a price unimaginable just a few years ago.



Kraft TeleRobotics, Inc.
Kraft TeleRobotics, Inc.
11667 West 90th Street
Overland Park, KS 66214
tel: 913-894-9022
fax: 913-894-1363
Kraft TeleRobotics, Inc. is a developer and manufacturer of teleoperated systems and components. Their standard product list includes, hydraulically powered force feedback manipulator arms (GRIPS), remotely operated vehicles (M5-A SCOUT), remotely operated force feedback excavators (HAZ-TRAK), force reflecting Hand Controllers, RF Video & Audio systems and RF Control Systems.

Grips: designed to provide advanced manipulative capabilities for both manned and remotely operated vehicles, GRIPS finds application in a wide variety of work assignments.

mecos Robotics AG
Gutstrasse 38
8400 Winterthur
Switzerland
tel: int 0-52-29-58-28
fax: int 0-52-29-96-53
email: mecos@ifr.ethz.ch
Company formed as a spin off of the Institute of Robotics, ETH (Swiss Federal Institute of Technology). "mecos Robotics" specialises in modular and adaptive robot manipulators and robot vehicles (mobile robots). All "mecos Robotics" systems uses the same type of controller, a VME based computer. This system comes with high level development tools, and for research institutions the systems have the advantage of being open. The overall goals of all "mecos Robotics" systems are flexility and modularity. The manipulator's mechanical configuration can be changed at will (number and type of joints, length of links, etc.) Manipulators use linear aluminum extrusions with integral motions for joints. The controller accounts for configuration changes. With this principle of modularity and flexibilty hybrid force / position controllers have been realised on "mecos Robotics" arms. Price depending on configuration (50.000,- Swiss Franks and upwards).

The mobile robot program from "mecos Robotics" follows this principle. The physical size and the mechanical configuration can be altered. The standard configuration has three wheels with air tyres and independant suspension. One wheel is used for steering and propulsion (imagine a kids tricycle). The overall size is 0.7 m (W) • 1.0 m (L) • 0.5 m (H). The price depends on configuration and starts around the 70.000,- Swiss Franks mark.

Micro Dexterity
6401 Poplar Avenue, Suite 190
Memphis, TN 38119
fax: 901-761-0727

MITRE Corporation
1120 NASA Road One
Houston, TX 77058

Mitre is primarily a systems engineering, systems integration, and systems planning organization specializing in the fields of command, control, communications, intelligence, and information systems and their related technologies.

Motoman [Hobart/Yaskawa]
3160 MacArthur Boulevard
Northbrook, IL 60062-1917
tel: 708-291-2340
fax 708-498-2430
Large industrial manipulators for welding, painting, palletizing, dispensing, etc. Can be floor, ceiling or wall mount units. Payloads for the 8 robots in the K-series range from 3kg to 100kg and repeatability of 0.1 to 0.5 mm over that same range. They are vertical jointed-arm type manipulators. (i.e. 4 bar linkage to reduce arm intertias). 3 S-series robots are SCARA-type manipulators with payloads of 50-60kg and varying workspace sizes.

Yaskawa also has bought the rights to RobotWorld, Vic Schienman's unique gantry design robot system. This system allow a number of mobile modules in the same workspace to zip around at speeds up 80"/sec (3G accel). RAIL and C can be used in a multi-level programming environment. 0.002" Accuracy, 0.0005" repeatability.

Nomadic Technologies, Inc.
Nomadic technologies, Inc.
1060-B Terra Bella Avenue
Mountain View, CA 94043
tel: 415-988-7200
fax: 415-988-7201
Nomadic Technologies is a company that designs and manufactures integrated mobile robotic systems for Robotics and Artificial Intelligence research. Mobile base and sensors (IR, Laser ranging, touch, GUI software development) $10K range.

The Nomad 200 is an integrated mobile robot system with four sensing modules: tactile, infrared, ultrasonic, and 2D laser. The Nomad 200 is an ideal mobile platform for teaching and research in Robotics and Artificial Intelligence. Prices for the system run: Mobile Base $10,000; Control System $6,000; Tactile Sensing System $1,500; Fixed Sonar System $2,500; Infrared System $2,500; Structured Light Vision System $7,000; RF Modem Kit $2,000; Digital Compass $1,500; Speech Synthesis $450; Additional Battery Pack and Recharging System $400

Oceaneering Space Systems
8260 Greensboro Drive, Suite 650
McLean, VA 22102
tel.: 703-442-6604
fax: 703-442-9489

Odetics
Anaheim, CA
Six-legged, (pantograph) Walking machine.

ProcessVision
Comdale Technologies (Canada) Inc.
833 The Queensway, Suite 202
Toronto, Ontario, Canada M8Z 5Z1
tel: 416-252-2424
fax: 416-252-9794

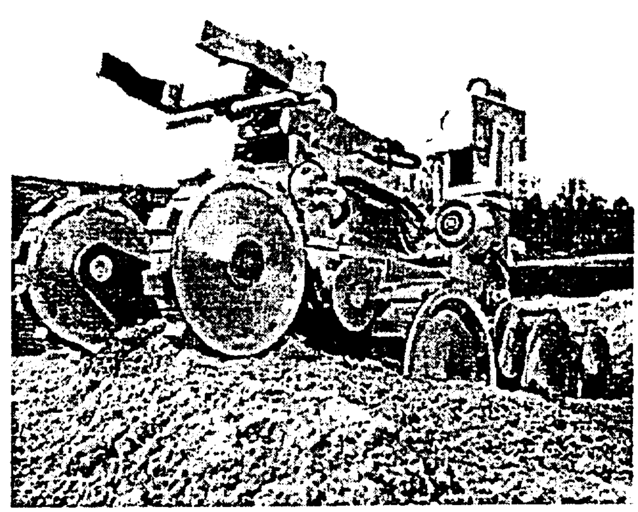
RealFlex
BJ Software Systems
1560 W. Bay Area Blvd., Suite 220
Friendswood, Texas 77546
tel: 713-488-3007
fax: 713-488-0203

Real World Interface (RWI)
P.O. Box 270
Dublin, NH 03444
tel: 603-563-8871
Small synchronous drive bases, primarily for research purposes. Approx $6K

RedZone Robotics
David W. White
2425 Liberty Avenue
Pittsburgh, PA 15222-4639
tel.: 412-765-3064

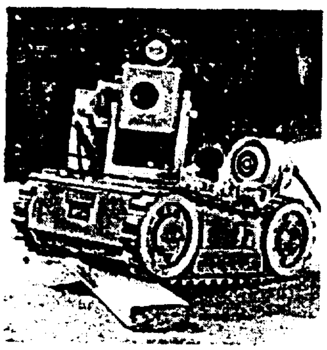
Remotec
114 Union Valley Road
Oak Ridge, TN 37830
tel: 615-483-0228
fax: 615-483-1426
The ANDROS line of teleoperated mobile robots. These were designed to be useful in the nuclear industry and in other hazardous applications, and are very rugged. You can hose them down. Available in a range of sizes, with a variety of optional attachments, such as video cameras, arms, etc.

Hazardous Duty Mobile Robots: The Andros Mark V-A is the largest and strongest of the Remotec Robots. It is environmentally sealed to operate in any weather conditions or surfaces. It also is equipped with two television cameras for remote viewing and a dexterous manipulator for hazardous tasks. Cost is $66,250(+shipping and training). The Andros Mark VI-A is a smaller version of the Andros Mark V-A. The Andros Mark VI-A also features the unique articulated track chassis which allow it to operate over rough terrain, cross obstacles and ditches, climb stairs, and operate in sand, gravel,



mud and grass. The Mark VI-A is 19 inches wide, this allows for operation in very constrained areas without sacrificing the all terrain capabilities. Cost is $55,600 (+shipping and training).

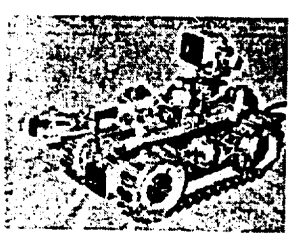
The Mini-Inspection Surveillance Robot is a mobile inspection robot designed to perform remote visual, audio, radiation, and other environmental surveillance functions within hazardous areas. MISR's compact size enables it to easily maneuver in the most confines space, including piping, while the rugged track design provides excellent obstacle climbing capabilities. Cost is $22,500 (+shipping and training).



The MISR II is less then ten inches wide and is ideal for applications in restricted areas such as duct work and piping. Cost is $22,500 (+shipping and training).

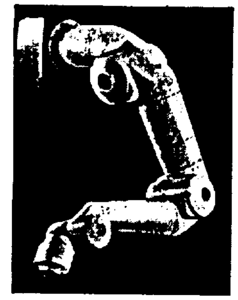
Robotics Research Corp.
P.O. Box 206
Amelia, OH 45102
tel: 513-831-9570
fax: 513-381-5802

RRC offers a variety of dexterous manipulators which can be operated individually or in dual-arm mode. Their second generation, denoted the "i-Series", is lighter and provides great dexterity. They are currently building "spaceflight-qualified" manipulators for NASA (GSFC) using this new generation of their product.



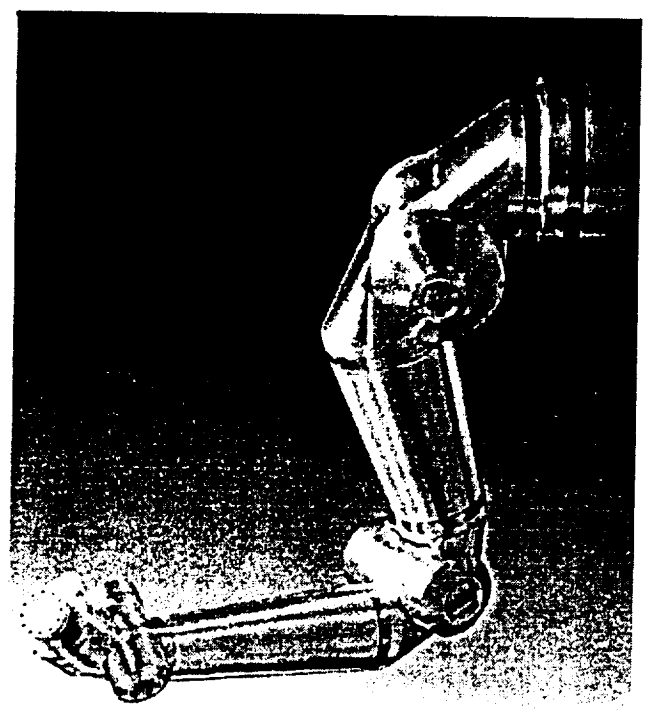
They have also been doing some work developing sensor-based automatic obstacle detection and avoidance technology which uses a patented algorithm with arm-mounted sensors. They have also built two massively-redundant 17-DOF Anthropomorphic systems for Grumman and JPL to serve as testbeds for researching "man-equivalent" robots for space applications.

Robotics Research Corporation is a leading supplier of advanced technology robotic manipulator and control products. The company manufacturers a line of highly dexterous, force-controlled, electric manipulators that are in wide use by government agencies, industrial corporations and universities working on man-equivalent robotic and telerobotic applications.



The K/B-1207 Dexterous Manipulator is an exceptionally light-weight kinematically-redundant manipulator designed for industrial and scientific applications that demand precision, speed and human-arm-like tool-handling dexterity.

Salisbury Robotics, Inc.
3fingered Salisbury hand and force sensing fingertips.
20 Pemberton St.
Cambridge, MA 02140
tel: 617-661-8847
email: <jks@ai.mit.edu>



Sarcos Research Corporation
261 East 300 South Suite 150
Salt Lake City, Utah 84111
Manufacturing is done by:
Animate Systems Inc.
1780 West 2300 South
Salt Lake City, Utah 84119

Spinoff of University of Utah's Center for Engineering Design (CED). Teleoperated systems, manipulators. Audio-animatronic work as well. Beautiful force reflecting work and systems. High performance and small hydraulic valves and actuators.

Sony Corporation of America
Factory Automation Division
542 Route 303
Orangeburg, NY 10962
tel: 914-365-6000
fax: 914-365-6087
Several SCARA type manipulators including a double armed manipulator. This model is used for the assembly of 8mm camcorders!

TRC
15 Great Pasture Road
Danbury, CT 06810
tel: 203-798-8988
Labmate research platform - $7500, plus additional optional sensors etc. Other prodcuts for hospital markets and floor cleaning machines. (Helpmate and RoboKent respectively)

Upstart Robots
567 Belvedere Street
San Francisco, CA 94117
tel: 415-550-0588
BugEyes: Integrated object recognition Vision System.

BugEyes is a single board computer system with an integrated CCD camera that can see and recognize an object in full or partial rotation and undernormal ambient lighting conditions.

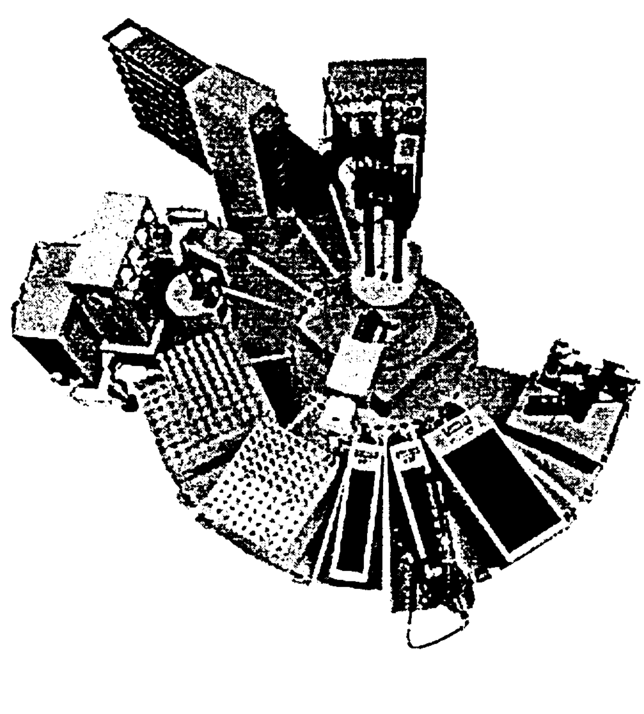
USA Robot
PO Box 4018
Portland, ME 04101
tel: 207-774-3822
Maxym production robots for business. Simple accurate 3D linear motions coupled with power tooling. Workspaces up to 2x4x.5 feet. IBMPC software for designing parts and production paths. 2 mil/foot accuracy. Units come with 3.25HP Porter-Cable router and vacuum foot. This is not a machine like the giant production turning and routing machines used by large furniture makers but is a nice small machine for small production shops.

Yamazaki Construction Company, Tokyo
Intelligent Robot Lab
Kaika Building
2-7-1 Sotokanda
Chiyoda-ku 101 Tokyo, Japan
tel: 81-3-5256-0715
LR1 robot - small research robot, basically a VME cage on wheels with some ultrasonic sensors and a nice constant force suspension. Has shown up at IEEE R&A conferences $30K.

Zebra Robotics
Jeff Kerr
Menlo Park
tel: 415-328-8884
Small manipulators with integral force control.

Zymark Corporation
Zymark Center
Hopkinton, MA 01748
tel: 508-435-9500
fax: 508-435-3439
Founded in 1981 Zymark has multiple technology solution to automating the environmental lab. Zymark has installed over 2000 ZYMATE® Custom Automations Systems. Zymark is dedicated to meeting the automation needs of environmental laboratories.

Zymark provides powerful tools for laboratory managers to improve and assure data quality, while providing more timely results and motivating valuable people.



ASSOCIATIONS RELATED TO THE ROBOTICS FIELD

Advanced Robot Technology Research Association (Japan)
Kikai-shinko Bldg
3-5-8 Shiba-Kohen, Minato-ku, Tokyo
tel: 03-434-0532
fax: 03-434-0217
Has joint research programs with member companies. Members are 20 or so Japanese companies including:
•Ishikawajima-Harima, Oki Electric, Kawasaki Heavy Industry, Kobe
•Steel, Komatsu, Sumitomo Electric Industries, Toshiba, JGC, NEC,
•Hitachi, Fanuc, Fujitsu, Fuji, Matshushita Research Institute, Mitsui,
•Mitsubishi Heavy Industries, Mitsubishi Electric, Yaskawa

AIAA
American Insitute of Aeronautics and Astronautics
370 L'Enfant Promenade, SW
Washington, DC 20024
tel: 202-646-7400
Technical Infonnation Service tel: 212-247-6500
Conferences and publications, several cover automation technologies for servicing on the ground and in space as well as exploration.

American Society of Mechanical Engineers (ASME)
345 E. 47th Street
New York, NY 10017
Mechanical Engineering magazine, like the IEEE's Spectrum, is an excellent general publication on aspects of mechanical engineering. There are often publications on robotics and the ASME sponsors a number of other publications and conferences that are relevant to robotics.

Association for Unmanned Vehicle Systems (AUVS)
Washington, D.C.
tel: 202-371-1170

Center for Autonomous & Man-controlled Robotic & Sensing Systems
Charles Jacobus, CAMRSS director
ERIM
PO Box 8618
Ann Arbor, MI 48107
tel: 313-994-1200 x2457
Member companies include: Ball Aerospace, Coulter Electronics, ERIM, Fairchild, Ford Aerospace, Geospectra, Grumman, Industrial Technology Institute, KMS Fusion, Michigan State, UofM.

IEEE
Institute of Electrical and Electronics Engineers
Service Center
445 Hoes Lane
Piscataway, NJ 08854-4150
tel: 201-981-0060
A large organization with hundreds of publications including journals, transactions, Spectrum, sponsoring conferences, workshops and meetings.

Kenneth Simons & Peter Poole
global models software - mailing list
Box 1234
Banff, Alberta TOL-OCO Canada

National Service Robots Association (NSRA)
900 Victors Way
PO Box 3724
Ann Arbor, MI 48106
tel: 313-994-6088
An organization devoted to robots other than on the factory floor.

Robotics Industry Association (RIA)
(same address as NSRA)

Rodney Brooks/Alife IV
MIT Artificial Ingelligence Lab
545 Technology Square
Cambridge, MA 02139, USA

Society of Manufacturing Engineers (SME)
One SME Drive
PO Box 930
Dearborn, MI 48121
tel: 313-271-1500

SPIE (The International Society for Optical Engineering)
P.O.Box 10
Bellingham, Washington 98227-0010
SPIE has publications, meetings and conferences in

the field of intelligent robots, mobile robots, teleoperation, machine vision, etc.

The San Francisco Robotics Society of America
933 Treat Avenue
San Francisco, CA 94110
tel: 415-550-0411
fax: 415-648-6427
The San Francisco Robotics Society of America is dedicated to the exchange of information about robotics in order to stimulate education in the sciences, create new businesses, and to enjoy robotics as a hobby.

Utility/Manufacturer Robot Users group (UMRUG)
Harry T. Roman, Principal Engineer - Research
MC: 16-H
Public Service Electric and Gas Company
80 Park Plaza
PO Box 570
Newark, NJ 07101
tel: 201-430-6646

Books for the Student

Laboratory for Interactive Learning
Beyond the Limits software
Hood House
University of New Hampshire
Durham, NH 03824
tel: 603-862-2186
fax: 603-862-1488

Industrial Dynamics
Jay W. Forrester
This complete presentation of the system dynamics approach to the study of industrial systems explains Forrester's objectives, classification of models, and advice to managers. This book includes chapters on characteristics of a customer-producer-employment system, the managerial use of industrial dynamics and the principles for modeling dynamic systems.

Principles of Systems
Jay W. Forrester
Principles of systems introduces the concepts of system structure, then shows by example how structure determines behavior. Discusses rate and level equations for inventory and delivery delay relationships, and production flow cycles. This book is suitable for use in studying the dynamics of urban, ecological, corporate and other complex systems also.

STELLA® for Business
Barry Richmond, Steven Peterson
Stella is a Macintosh software computer program for simulation of real world problems. Stella makes it possible for anyone in business to lay out a diagram of how something works. It might be the flow of product through a manufacturing system, or the current strategic plan.

Introduction to System Dynamics Modeling with DYNAMO
George P. Richardson and Alexander L. Pugh III

DYNAMO User's Manual Sixth Edition
Alexander L. Pugh III
The software computer program DYNAMO interprets system dynamics models as used to represent business, social, economic, biological, psychological, engineering, and other systems. DYNAMO facilitates simulations of real-world problems on IBM compatible computers. Designed for working managers and analysts.

Robot Activities for Students & Hobbyists' Firms

Angelus Research
6344 Sugar Pine Circle
Angelus Oaks, CA
tel: 714-794-8325
A small differentially-steered mechanism (no casters!) utilizing a 68HC11 controller w/ 32K RAM and RS-232 interface. Four visible collision sensors (range 3-12 inches depending on ambient light) and two whiskers. On-board battery (Pb- acid and built in charger) monitors current as well for stall current. Software included with easy-to-use command set. A lot of features for a very affordable device. $395, controller board available separately and basic kit available for $325

B.G. Micro
P.O. Box 280298
Dallas, TX 75228
B.G. Micro has been in the Electronics Industry for

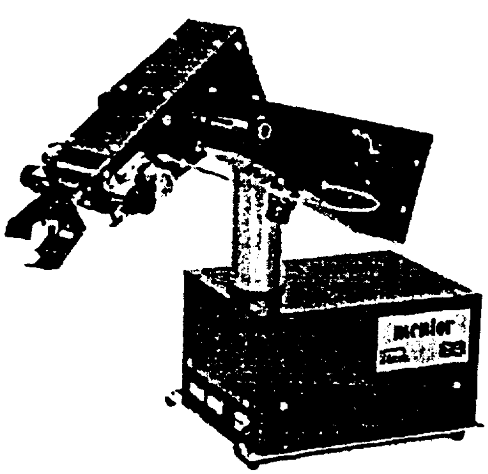
12 years. Although B.G. Micro primarily offers mail services to hobbyists, B.G. also provide large companies around the world with Integrated Circuits, motors and various electronic components.

Feedback Incorporated
Feedback Inc.
437 Dimmocks Mill Road
P.O. Box 400
Hillsborough, NC 27278
tel: 919-644-6466
or 800-526-8783
fax: 919-644 6470
Feedback Inc. is a company specializing in service to engineering and technology education. The products are designed, built and supported with education in mind. Computer software and text material appropriate to the level of program involved is supplied with each item.

Educational Satellite Receiver
The educational satellite receiver acts as a real operating satellite ground station. The system functions as a component of engineering telecommunications programs, as an operational component of a weather station or as a module in technology education for satellites and space exploration.

"Neptune" Electrohydraulic Robot
The NEPTUNEs are powerful robots using hydraulics as their power source enabling heavy loads to be handled at a long reach. Advanced features and powerful software ensure value as an educational instrument.

"Mentor" Revolute Robot
The MENTOR provides an excellent introduction to the use of robotics. Control of the MENTOR is by personal computer which treats it as a memory mapped peripheral and virtually any personal computer or micro-processor system can be used to control the mentor.



Lego Dacta
555 Taylor Road
PO Box 1600
Enfield, CT 06083-1600
tel: 800-527-8339
fax: 203-763-2466

The educational division of LEGO Systems, Inc. The products can be used for educational purposes in a variety of study areas:

SCIENCE
With LEGO DACTA products, students can develop science process and inquiry skills such as predicting, hypothesizing, experimenting, inferring, collecting data and building and using models.

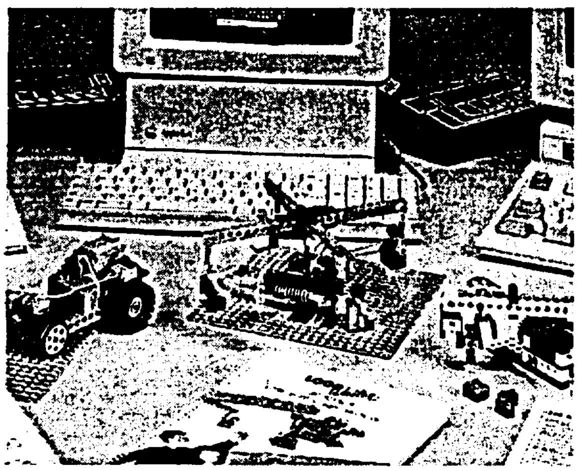
TECHNOLOGY
LEGO DACTA products stimulate the study of communication, transportation, manufacturing, and construction by providing a wide variety of problem solving challenges. Simple machines, motorized machines, pneumatic devices, and computer controlled models are contribute to the range of possible activities.

SOCIETY

Cooperative learning with LEGO DACTA products gives students practice preparing for the challenges which must be faced by tomorrow's society.

The **TECHNIC Mini-Series** are small, versatile building sets which provide an economical hands-on introduction to the simple machine concepts of gears, levers, and pulleys. Elementary school students actually see gears, levers, and pulleys at work as they build and investigate simple machines.

Dacta sells the LEGO Technic product line. These



are the geared and motorized versions of the LEGO system. Kits recommended for robotics include:

•1038 Technical Universal Buggy - dual drive vehicle. $60
•1032 Technic II w/ motorized transmission - $76
•9605 Technic Resource Set - general parts kits - $200

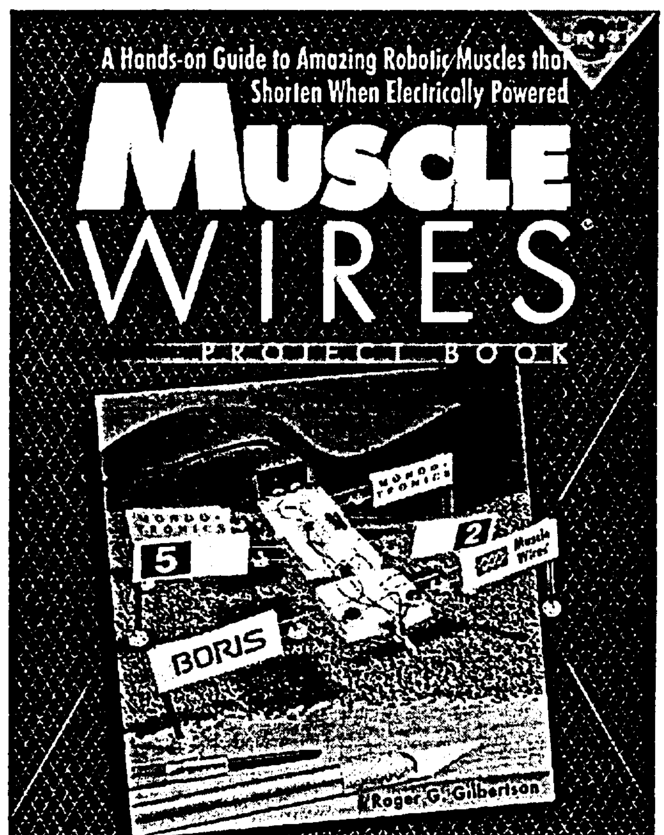
Other places for Lego-to-Mac software:
Paradigm Software tel: 617-576-7675
Bots tel: 415-949-2126

MIT has papers on LEGO projects available via Internet FTP from: kame.media.mit.edu. Look in pub/el-memos for a number of files. Memo8.* is "LEGO/LOGO: Learning Through and About Design"

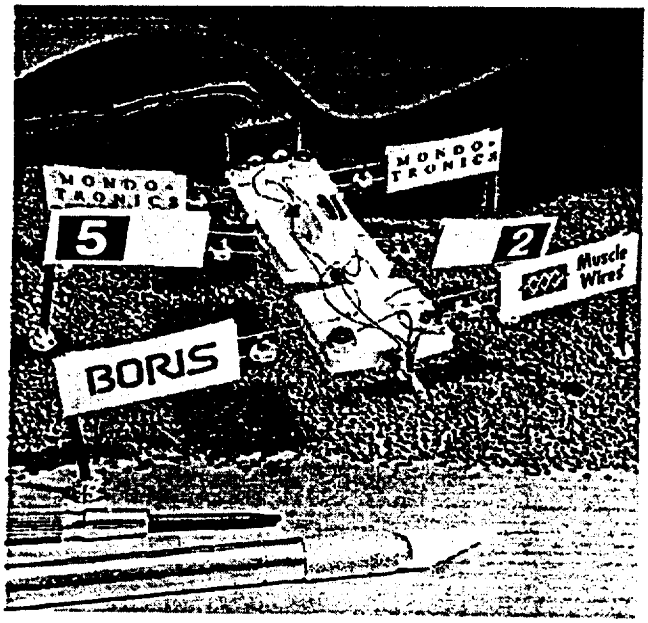
Stiquito
A small nitinol-based mobile robot is available from Indiana Univeristy in a technical report and as a kit. Send your request for the report with payment to: *Computer Science Department, 215 Lindley Hall, Indiana University, Bloomington, IN 47405*

To receive the technical report only send $5.00 PRE-PAID and add ATTN: TR363A to the address. To receive the technical report and a kit containing all materials needed to construct Stiquito and its manual controller send US$15.00 PRE-PAID and add ATTN: TR 363a Stiquito Kit

Mondotronics
524 San Anselmo Ave., #107
San Anselmo, CA 94960
tel: 415-455-9330
or 800-374-5764
fax: 415-455-9333
email: <mondo@holonet.net>
A number of muscle wire (nitinol) projects including a small walking machine. Book and sample kit with 1m each of 50,100 and 150 um wire - enough to build all 14 projects in book. The firm also sells extensive manner and variety of the titanium-nickel wire (memory wire) which can be stretched from 3 to 10 percent of the length of the wire and when

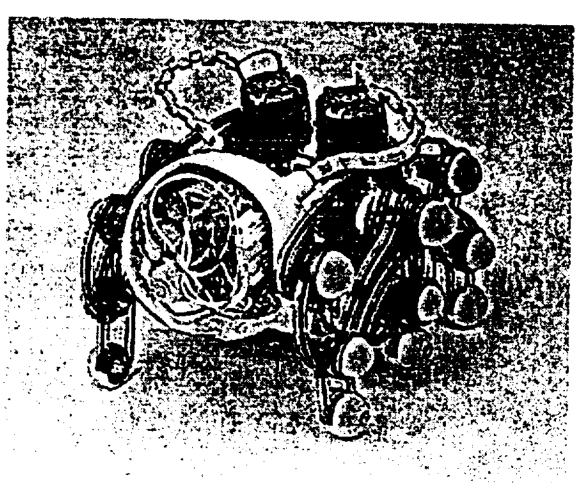


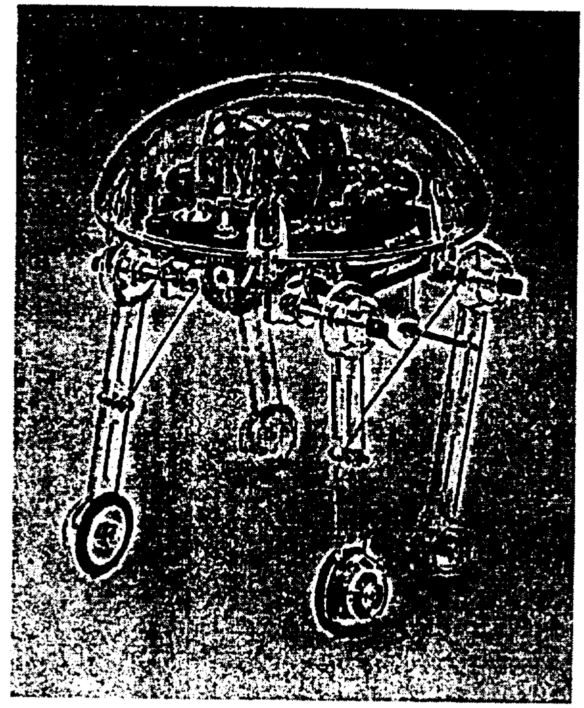
heated by running a current through the wire will return to its original length. The firm offers the wire in pre-wound compression and expansion spring forms in a variety of length and diameter. Used in a simple robot, the wire offers the possibilities of non-mechanical application of force. Several



of the projects in the muscle wire project book use the wire as a form of electrical muscle to power multi-legged robots. The wire is offered in a range of diameters and spool lengths as well as pre-cut lengths for the project book. Purchased in spools, the wire becomes much more economical and lends itself to class-related projects.

OWI Incorporated
1160 Mahalo Place
Compton, CA 90220
tel: 310-638-4732
fax: 310-638-8347
MOVIT kits are popular in grade school through post-graduate studies as an introduction to robotic





science. MOVIT robot kits are also used in technology workshops at many museums, and have become popular educational tools for engineers and executives at major corporations. These are small toy-like robots that reflexively respond to obstacles, sounds or light depending on the model. They're cute and show what can be done with a relatively small amount of hardware.

The kits are available from:
•*Kelvin Electronics (800) 645-9212*
•*Pitsco (800) 835-0686*
•*Edmund Scientific*

OTHER ORGANIZATIONS ENGAGED IN ROBOTICS

Most large aerospace companies have groups working in or looking into robotics. McDonnell Douglas Aerospace (Huntington Beach Calif., Houston, Huntsville, and Cape Canaveral); Martin Marietta (Denver), Rockwell International (Downey, Calif.), Boeing (Seattle) to name a few. Mitre Corporation of McLean, Virginia, and Houston, is also doing quite a bit in robotics.

Advanced Robotics Research Centre
Salford, UK
The Advanced Robotics Research Ltd (incorporating the National Advanced Robotics Research Centre, UK) is a joint UK Government and UK Industries funded research organisation involved in the research of enabling technologies for the advanced robotics systems.

Idaho National Engineering Laboratory (INEL)
D. Lance Murri
EG&G Idaho, Inc.
P.O. Box 1625
Idaho Falls, Idaho 83415-2090
tel: 208-525-547
fax: 208-525-5996

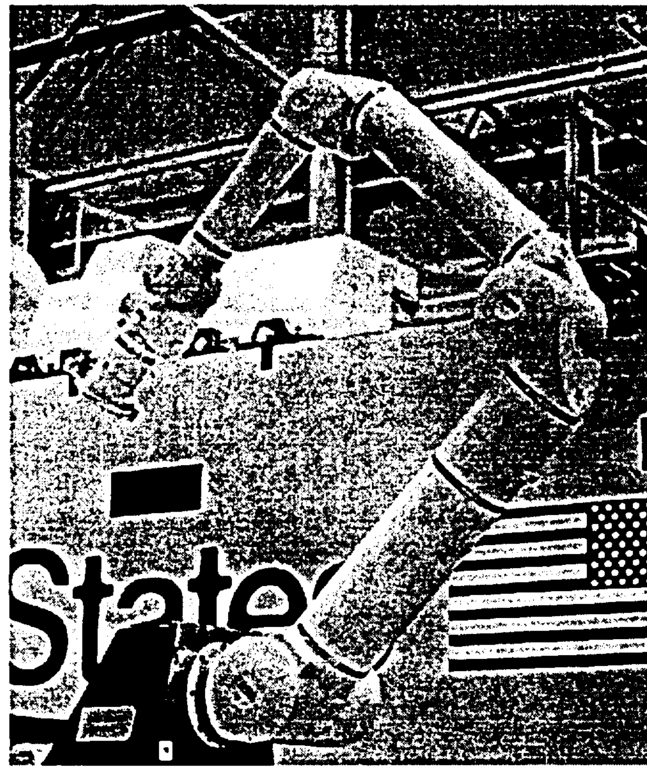
Mechanical Engineering Lab (MEL)
Tsukuba City
Kazuo Tanie: Robotics and cybernetics

NASA Ames Research Center
Moffett Field, CA
Butler Hine email: hine@ptolemy.arc.nasa.gov
Terry Fong email: doctor@tardis.arc.nasa.gov
Telepresence and virtual user interfaces, vision (optical and parallel processing), free-flyers, task planning, agents.

NASA Goddard Space Flight Center
Greenbelt, MD 20771
Stepehn Leake email:
<nbssal@robots.gfsc.nasa.gov>
Since the cancellation of the Flight Telerobotic Servicer (FTS), the Robotics Lab has been concentrating on work in the area of automated space craft servicing. The goal is to replace or supplement Extra Vehicular Activity (EVA) with teleoperated or semiautonomous robotic systems for external vehicle maintenance. Current project includes a robot to assist in second Hubble servicing mission.

NASA Jet Propulsion Labs
Pasadena, CA
Tony Bejczy, Chuck Weisbin, Brian Wilcox, Larry Mathies, Henry Stone, David Miller
Hazardous-environment robots, teloperation, control, space and planetary missions.

NASA Johnson Space Center (JSC)
Houston, TX
Charles Price
More of an operations house but lots of shuttle RMS work. Becoming central site for Artemis (lunar explorer) work.



NASA Kennedy Space Center (KSC)
Robotics Group
Bill Jones
Like JSC, KSC is an operations house with responsibility to keep shuttles flying and integrate payloads. There is a small but growing robotics group that is emplacing ground support robotics applications. Recent work includes filter inspector for launch pad payload areas, shuttle radiator inspector and a mobile system for thermal protection system tasks.

NASA Langley Research Center, (LaRC) VA
Jack Pennington
Vision, inspection, 3-D sensors

Oak Ridge National Lab
ORNL/CESAR
PO Box 2008, MS-6364
Oak Ridge, TN 37831-6364
tel: 615-574-6126
Alex L. Bangs email: BangsAL@ornl.gov

Center for Engineering Systems Advanced Research (CESAR)
Research in mobile and manipulator robotics, including redundant and multiple manipulators, cooperating mobile robots, parallel vision systems, sensor fusion, real-time quantitative reasoning and behavior based control, and machine learning. Current applications include robots for nuclear power stations, environmental restoration and waste management, material handling, and space exploration. Researchers: Alex Bangs, Marty Beckerman, Judd Jones, Reinhold Mann, Ed Oblow, Francois Pin, Michael Unseren.

Redzone Robotics
2425 Liberty Avenue
Pittsburgh, PA 15222-4639
tel: 412-765-3064
A spin-off of CMU, Redzone has focused on hazwaste and nuke manipulator applications but is branching out into mobile applications. Primarily protoypes and not multiple unit manufacturing.

Southwest Research Institute
San Antonio, TX
Robotics and Automation Department
Some large systems for servicing aircraft (painting, spraying, deriveting etc)

Vision Applications
New York, NY
Small, low cost fovial camera systems. Development stages. Unique integrated, super small camera/pan/tilt device. Miniature active vision systems, video telephones.

Publications & Magazines

Robotics Publications:
There are a number of academic journals and trade magazines devoted to robotics. There are no magazines currently devoted to the hobbyist or designer of robotic mechanisms. In the 1980's Robotics Engineering (nee Robotics Age) lasted for 7-8 years but folded.

This list of periodical covers the academic journals, the trade magazines devoted to both robotics and relevant sub-areas, and the lone newsletter for hobbyists.

The IEEE has a formidable array of journals, transactions and magazines. Here are a few that are relevant to robotics work:

IEEE Transactions on Robotics and Automation
IEEE Transactions on Systems, Man and Cybernetics
IEEE Control Systems Magazine
IEEE Computer Magazine
IEEN Transactions on Pattern Analysis and Machine Intelligence
IEEE Transactions on Industrial Electronics
Cost: One has to join the IEEE and then subscribe. Student rates are much less expensive than non-student rates.

International Journal of Robotics & Automation
Published by: ACTA Press, P.O. Box 2481, Anaheim, CA 92814, Editor-in-chief: Professor T. C. Hsia, Dept. of Electrical Engineering and Computer Science, University of California, Davis, CA 95616

International Journal of Robotics Research
MIT Press, 28 Carleton Street, Cambridge, MA 02142, Cost: $50/year to individuals

Journal of Intelligent & Robotic Systems
Three issues per volume, $58.50 per volume (individual)
Kluwer Academic Publishers Group, PO Box 322,, 3300 AH Dordrecht,, The Netherlands —in the US: PO Box 358, Accord Station,, Hingham, MA 02018-0358

Journal of Robotic Systems
G. Beni and S. Hackwood, editors, College of

Engineering, University of California, Riverside, Riverside, CA 92521-0425, Publisher:, Interscience Division, Professional, Reference, and Trade Group, John Wiley and Sons, Inc., 605 Third Ave., New York, NY 10158

Robotics Today
Published by the Society of Manufacturing Engineers, One SME Drive, PO Box 930, Dearborn, MI 48121, tel.: 313-271-1500

Robotics World
Published quarterly
Communication Channels, 6255 Barfield Road, Atlanta, GA 30328, (404) 256-9800
They also publish the Robotics World Directory $49.95

Robot (Japanese)
Industrial Robots and Application Systems, published bimonthly by Japan Industrial Robot Association (JIRA), Kikai-Shinko Building, 3-5-8, Shiba-Kohen, Mina To-ku, Tokyo, Japan, Tokyo tel.: 03-3434-2919, fax: 03-3578-1404

Robotica
International Journal of Information, Education and Research in Robotics and Artificial Intelligence; this is a quarterly publication, US $179 per year, Cambridge University Press, The Edinburgh Building, Shaftesbury Road,, Cambridge CB2 2RU (UK)
—in the US: Cambridge University Press, Journals Department, 40 West 20th Street, New York, NY 10011-4211

Industrial Robot
Quarterly, $145/year, MCB University Press Ltd., 62 Toller Lane, Bradford, West Yorkshire, England, BD8 9BY, tel.: 44-274-499821, fax: 44-274-547143
—in the US: MCB University Press Ltd., PO Box 10812, Birmingham, AL 35201-0812, (800) 633-4931 (toll free US and Canada)

Automation in Construction
Publisher: Elsevier Science Publisher B. V., Amsterdam, Desk Editor: Erik de Vries, Editor: Dr. T. Michael Knasel, 10324 Lake Avenue, Cleveland, OH 441102-1239., fax: 216-651-5136.

Useful and relevant trade magazines: (Usually free, mostly ads or industry news. Many articles written by advertisers. Great sources of product information.)

Sensors
Helmers Publishing, 174 Concord Street, PO Box 874, Peterborough, NH 03458-0874, tel.: 603-924-9631. This is a trade magazine devoted to sensing devices. Publishes annual directory.. Cost: Free to qualified subscribers, $55/yr otherwise

Advanced Imaging
445 Broad Hollow Rd., Melville, NY 11747, tel.: 516-845-2700 voice, fax: 516-845-2797
Subscription free to qualified professionals, $50/yr otherwise.

Other publications include:

Machine Design
Design News
Motion Control
GPS World
RF Design
Sea Technology
Laser Focus
POB (surveying profession)
Broadcast Engineering (TV and radio engineering)
Embedded Systems
EE Times (news of the electronics industry)

Other extremely useful resources that every laboratory or company should have are the

Thomas Register and the EEM. The Thomas Register is $250 for a complete set and they issue new ones every year. A cheap investment for finding companies and parts.

Conferences & Symposia

Conferences

There are a wide variety and number of conferences related to robotics and automation. Some are focused on industrial applications, many are "researchy" in nature and most are a mixture of both. Proceedings should be available in most good libraries or by inter-library loan.

•Annual Conference of IEEE International Conference on Robotics and Automation (ICARA);

•International BEAM Robot Olympics Competition: Ontario Science Center, Toronto, Ontario, Canada.

"The BEAM Robot Olympics is not so much a series of technological competitions as a chance for robot enthusiasts to present their designs to each other, the press, and the public. It is also a open forum for anyone who wants to get started in the field to compete and compare. Any and every robot will be considered so long as it does not come from a kit or store. Robots of similar ability will be pitted against each other in simple competitions, but generally robots will be judged on sophistication of behavior, novelty of design, efficiency of power source, and quality of hardware."

Details soon will be posted on the Internet. On-line rules also will soon be available. email: mwtilden@watmath.uwaterloo.ca

Here are other annual conferences relevant to robotics or AI:

•Annual Conference on Intelligent Robots and Systems;
•Annual Symposium on Industrial Robots;
•Biannual Symposium International Symposium of Robotics Research;
•Biannual Autonomous Intelligent Systems;
•International Conference on Computer Vision;
•British Machine Vision Conference;
•IEEE Intelligent Vehicles Conference;
•IMAC/SICE International Symposium on Robotics, Mechatronics and Manufacturing Systems;
•American Association for Artificial Intellignece (AAAI) Probably the largest and most prestigious conference on AI. Is now sponsoring a robot competition at the annual AAAI conference.

There are also specific conferences in these application areas:
•Mining;
•Int. Symposium on Mine Mechanization and Automation (organized by the Colorado School of Mines);
•Canadian Symposium on Mining Automation;
•Canadian Conference on Computer Applications in the Mineral Industry.

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Listed in chronological order and then alphabetically...

An abbreviated abstract of refereed and reference material

Assembly of Computers to Command and Control A Robot. W. L. Kilmer and L. L. Sutro Montvale, N.J., Afips Press, 1969 25 p. American Federation of Information Processing Societies, Spring Joint Computer Conference, Boston, Mass., May 14-16, 1969, Proceedings. Volume 34. p. 113-137.

Biomechanics, Proceedings of the First Rock Island Arsenal Biomechanics Symposium, Augustana College, Rock Island, Ill., April 5, 6, 1967 D. Bootzin and H. C. Muffley New York, Plenum Press, 1969 190 p.

Introduction to Control theory for Engineers. A. Sensicle New York, Hart Publishing Co., Inc., 1969 252 p.

Roving Vehicle Navigation Subsystem Feasibility Study. R. A. Lewis North Hollywood, Calif., Western Periodicals Co., 1970 4 p. in U. of Hawaii, Hawaii International Conference on System Sciences, 2nd, U. of Hawaii, Honolulu, Hawaii, Jan. 22-24, 1969, *Proceedings.* Part I. p. 316-319.

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