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Consolidated Fuel Reprocessing Program

JOINING TELEOPERATION WITH ROBOTICS FOR ADVANCED MANIPULATION IN HOSTILE ENVIRONMENTS

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Abstract

~~Advanced servo~~manipulators have been used for many years to perform remote handling tasks in hazardous environments. The development history of teleoperators is reviewed, and applications around the world are summarized. The effect of computer supervisory control is discussed, and similarities between robots and teleoperator research activities are delineated. With improved control strategies and system designs, combination of positive attributes of robots with teleoperators will lead to advanced machines capable of autonomy in unstructured environments. This concept of a telerobot is introduced as a goal for future activities.

I. Introduction

Teleoperators have been used by the nuclear industry for nearly three decades to perform manipulative tasks within hostile environments.[1] This technology has been implemented and improved by applications in space, under water, and in laboratory development environments. Heightened interest in robotics is presently occurring in our society. It is therefore appropriate to review teleoperator applications as an important past and future foundation of robotic developments and research. Such a perspective will highlight the similar research goals but contrasting approaches in these two fields. Technology exchange between robotics and teleoperator developers should increase as these systems approach common goals.

The ultimate manipulation system might be described as being totally adaptable yet fully automated. Teleoperators offer adaptability due to their man-in-the-loop control schemes, whereas robots are normally operated in an autonomous mode to reduce labor costs. A middle-ground class of systems that function either autonomously or with real-time human interaction is envisioned for future systems. Developments in hardware and software for both robotic and teleoperated systems will make this goal a reality.

This paper presents the background of teleoperator development and principles. It is intended to emphasize the operational similarities and differences between teleoperators and industrial robots. Major milestones in the historical progression of teleoperator technology are given and compared to the history of robotic activity. A review of national and international applications of teleoperators is also provided. These activities range from outer space to undersea manipulators, and span projects from France to Japan. Research directions are reviewed, concentrating on the convergence of teleoperator and robot technology. Common goals pursued through different techniques are observed in present research. Improvements in mechanisms, modularity, kinematics, and man-machine interfacing techniques will have useful transfer from the teleoperator realm to the robotic domain. The expanse of research activity related to robotics will result in better motors, electronics, software, and sensors to improve the performance of both system types. We begin our review by discussing the fundamentals of teleoperation as background.

II. Fundamentals of teleoperation

A teleoperator system is a general-purpose, dexterous man-machine system that augments man by projecting his manipulation capabilities, often across distance and through physical barriers into hostile environments.[2] The most famous example of a teleoperator system is the space shuttle's remote manipulator system (RMS), used to deploy and retrieve satellites, but several other applications exist and are planned. For example, the handling of radioactive materials with teleoperators has been ongoing for 35 years, and undersea exploration and exploitation are being pursued by both the public and private sectors.

A teleoperator system is not a robot. Most teleoperator systems consist of a manipulator that is similar to a robot in many aspects, but what sets teleoperators apart is the man-machine interface which allows real-time interaction between the human operator and the mechanical manipulator. The most common form of teleoperator man-machine interface is the replica master arm. This interface allows the user to operate the slave throughout the workspace simply by moving the master manipulator arm, which is normally a kinematic replica of the slave. Many forms of master controllers exist:

1. Replica Master. Kinematically identical to the slave, this method of control usually provides force reflection to the operator. A high degree of proprioceptive feedback is present due to the similarities between master and slave. Normally the systems are 1:1 in geometric proportion, but scaling factors as great as 3:1 have been used by TeleOperator Systems (TOS).

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2. Switch Box Control. Similar to robotic pendant controllers, these control structures were used for the first teleoperator systems because of their ease of implementation. Operator efficiency and dexterity is lacking in this method due to the absence of force reflection and proprioception.

3. Joystick Control. This is superior to switch box control because coordinated motions can be made using computer guidance to accomplish movement. True force reflection through joystick control has not yet been accomplished commercially, and bilateral force-reflecting replica masters still hold certain advantages in efficiency.

Table 1 gives a comparison of the relative task efficiency using various controllers and manipulator systems. The emphasis on the man-machine interface is made to point out the major difference between teleoperators and robots. The primary operating mode for a teleoperator is with man as the decision maker in the control loop. This allows teleoperators to successfully accomplish tasks and conquer unexpected situations within unstructured environments. Man's ability to reason combined with the machine's attributes of strength and resistance to hostile environments produces a beneficial relationship. In contrast, the robot control system is designed to be autonomous. All but the most sophisticated robot applications are in structured surroundings with a limited set of operational requirements. The need for human intervention is limited to start-up programming with a pendant or by lead-through teaching. As sensor technology and artificial intelligence methods improve, the adaptability of robots will approach teleoperators, but at present these two systems find application in different environments.

Table 1. Task Efficiency for Various Teleoperator Control Methods and Manipulation Types

Manipulation/control	Task completion time (direct human 1:1)
Crane - Impact wrench with switch control	500 - 800:1
Unilateral (no force reflection) with switch control	500:1
Unilateral with joystick control	60—80:1
Force-reflecting servomanipulator with 1 arm	16:1
Force-reflecting manipulator with 2 arms	8:1
Suited human	8:1

The foundation of teleoperators is in the nuclear industry,[3] where the requirement to handle radioactively hazardous material led to the development of the first mechanical master-slave manipulator. These manipulators, as shown in Fig. 1, were able to perform dexterous tasks with force reflection through stainless steel tapes connecting master to slave (similar to a pantograph in concept).[4] Visual feedback was through shielded windows. Mechanical master-slave manipulators have one significant shortcoming: they have a small volumetric coverage limited by a fixed pivot point. To expand this coverage required elimination of the mechanical connection between master and slave. Two drive methods have been explored through the years: electromechanical and hydraulic. Hydraulics are most favorably applied in underwater or extremely heavy duty applications. Hydraulic systems offer a high power-to-weight ratio, if the sump tank is not considered, and they function well under the high static pressure environments of deep-sea applications. The electromechanical systems offer 1% force sensitivity through backdrivable gear trains. Most modern teleoperators are of the electromechanical manipulator type.

Early development efforts by General Mills (later Programmed and Remote Systems and now GCA) addressed unilateral concepts—that is, they provided no force reflection and were operated from a simple on/off switch box. Later implementations included force reflection through bilateral servo loops with low friction, high-efficiency torque transmission methods. The original force-reflecting servomanipulator development was performed by the Remote Control Division of the Argonne National Laboratory under the direction of Ray Goertz. Their research in mechanics and controls laid the foundation for development which continues today in both teleoperators and robotics. Table 2 gives a brief chronology of the major milestones of teleoperator developments.[5]

As implied thus far, teleoperators and robots share many common subsystems. An understanding of the fundamental control structure of a force-reflecting teleoperator is necessary to fully appreciate operational differences. Figure 2 shows the basic block diagram of a one-degree-of-freedom servo loop for a teleoperator. Motor types, encoders, amplifiers, and even digital control electronics are very similar between a teleoperator and a robot. It is the operational control of a teleoperator through real-time human interaction via a master controller that results in significant differences in control philosophy and methods. Force is reflected in a bilateral force-reflecting teleoperator by backdriving the motor to create a position offset (this can also be accomplished by direct force measurement, i.e., motor current or strain gages). A stiff position loop causes the slave to follow the master quickly until an obstacle is encountered, which usually causes deceleration of the slave. This in turn results in a force generated at the master due to the increased positional error. The velocity loops are for stabilization and inertia compensation. A typical robot control system will appear similar to the bottom half of Fig. 2 as the master motion is simulated by computer playback of commands previously taught. Robotic control loops will also include integral gain to eliminate steady state errors and some form of preprocessing to generate the desired path to follow.[6]

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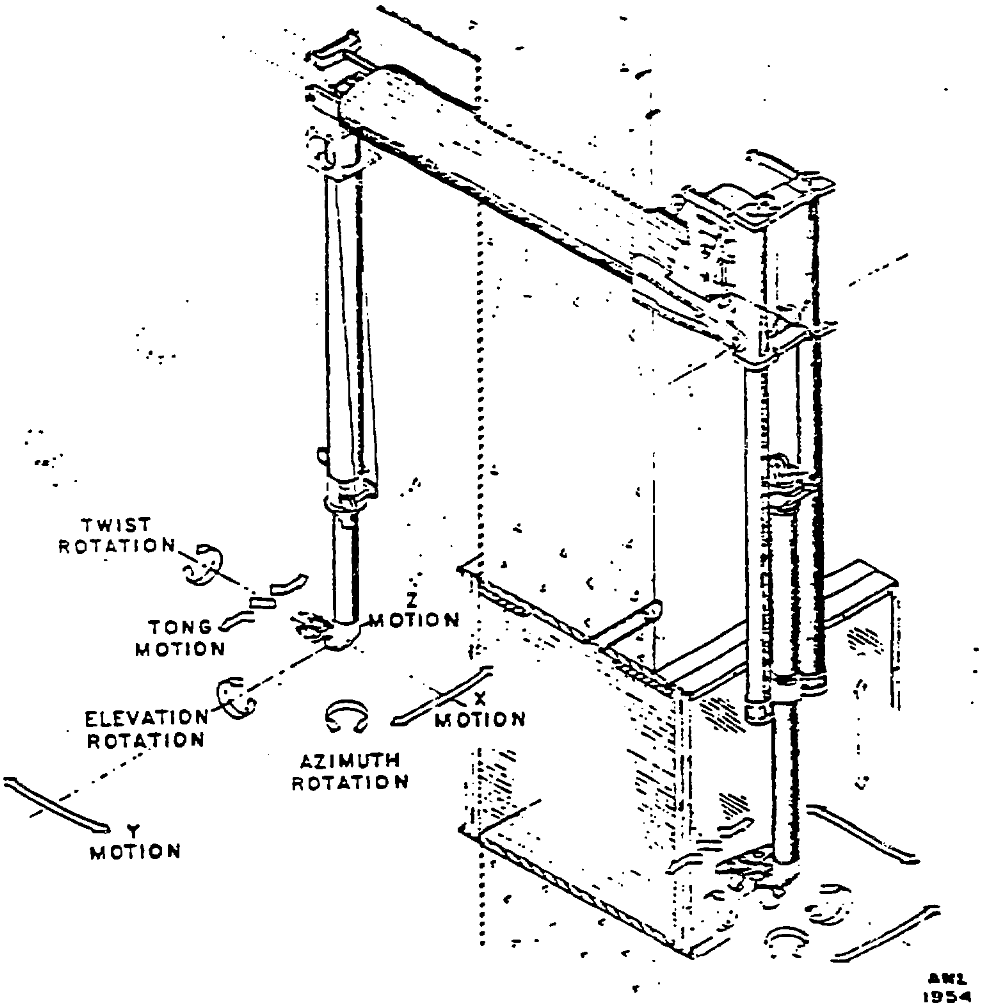

Fig. 1. Mechanical master/slave manipulation system.

75%

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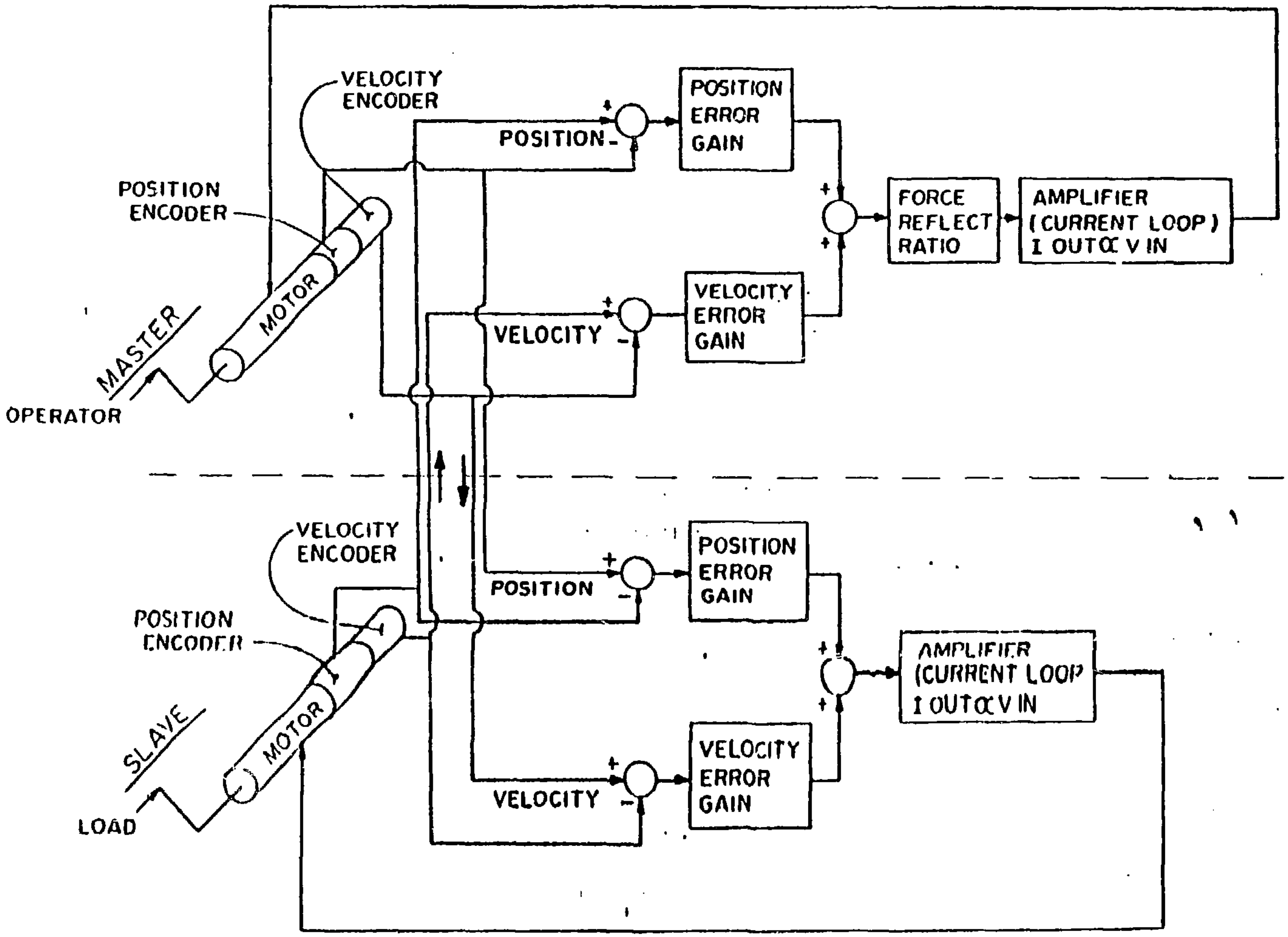

Fig. 2. Block diagram of bilateral servomechanism concept.

III. The evolution of robotics and teleoperated systems

To consider the potential future relationship between robotics and teleoperators, it is desirable to review the evolution of these two classes of manipulator applications. Robot and teleoperator manipulators, although quite similar in basic mechanical concepts, have followed very different evolutionary paths.

Teleoperator systems[4] were developed with the basic objective of accurately projecting a human operator's motor capabilities into a remote environment. In these systems, from the purely mechanical designs to the later servomanipulator designs, the fidelity accomplished in replicating human functions was the principle performance criterion.

Industrial robotics appears to have followed a different path, directed toward different objectives. The first industrial robots were, in essence, programmable parts-handling systems capable of fast operation, large load capacity, operation in harsh environments, and precise positioning. For the most part, the first robots were replacements for human production workers with the advantages of greater stamina, faster operation, and less cost. They were, however, limited to simple and relatively structured tasks.

Table 2. Teleoperator Development History

Year	Milestone
1948	Goertz and Argonne National Laboratory (ANL) developed first bilateral mechanical master-slave manipulator.
1948	General Mills produced a unilateral manipulator based on electric motors with switch control. Used for high capacity, large volume tasks.
1954	Goertz built an electric master-slave manipulator incorporating servos and force reflection. This was the first bilateral force-reflecting servomanipulator.
1958	General Electric built the Handyman electrohydraulic manipulator incorporating force feedback, articulated fingers, and an exoskeletal master control.
1961	The General Mills Model 150 manipulator was fitted for manned deep-sea operation.
1963	The U.S. Navy began deep-submergence projects which included developing underwater manipulators.
1965	ANL combined manipulation with head controlled TV camera and receiver.
1970's	NASA sent teleoperators into space: unmanned soil samplers went to the Moon and Mars.
1970's	NASA began development of a space shuttle manipulator in cooperation with SPAR, a Canadian firm.
1970's	The nuclear community rededicated efforts to develop improved teleoperators for facility maintenance.
1980	Supervisory control techniques were in hardware were demonstrated by Brooks at Massachusetts Institute of Technology.
1980	Universal controller techniques were developed and refined by the Jet Propulsion Laboratory and Stanford University.
1982	Oak Ridge National Laboratory and Central Research Laboratories designed and fabricated the first fully distributed, digitally controlled servomanipulator.
1983	ODETICS developed a tetherless electromechanical walking functionoid with a lift-to-weight ratio greater than one.

The differences in development objectives between the two classes manifests itself in the basic design parameters associated with the systems. Reviewing some of these parameters provides a good comparative framework for understanding the differences. Table 3 lists various design features (or objectives) and corresponding technical attributes (or implications) for manipulators in teleoperation and industrial robotics. In the case of human operation, it is critically important to provide the operator with a sense of feel and speed compatibility. This in turn requires that the manipulator be designed with minimum inertia and be operable in the human dynamic range. As depicated in Table 3, this form of low friction and inertia design involves the use of centralized actuators (located to reduce arm-link moments of inertia and to reduce motor size) and high efficiency power transmissions such as backdrivable gear trains and cable or metal-band pulley drives. Because these designs achieve low friction and are backdrivable, the forces generated by and/or against the manipulator mechanism are always apparent. In this class of manipulators, actuator drive torque (drive current in the case of dc servomotors) is an accurate indication of applied load (within 1% of maximum torque).

In contrast, industrial robots were developed at least initially to increase the ratio of production output to effective labor cost.[7] The effective labor cost of a robot is the complete operating and capital recovery cost of the system for its planned life. With emphasis on manufacturing productivity, industrial robots are designed to create economic advantage by trading off operating speed and precision against capital cost. Controlling capital cost translates into minimizing the purchase price of the robot, which in turn leads to design tradeoff decisions that reduce recurring manufacturing costs. The two design objectives of good position control and minimum production cost seem to have pushed most industrial robot designs (particularly electrical robots) in the direction of distributed actuator configurations with high-ratio gear drives (for torque amplification), utilizing adjustable gear centers to minimize backlash at the expense of meshing friction. In this class of manipulators production cost is comparatively low; they are capable of achieving relatively high accuracy and repeatibility by virtue of their high stiffness and low backlash, but they are non-backdrivable and have relatively large friction thresholds.

Table 3. Comparison of Manipulator Attributes

Attribute	Teleoperated Servomanipulators	Industrial Robot Manipulators
Principal function	Master/slave teleoperation	Autonomous, repititious operation
Environment	Complex, uncertain, often hazardous	Structured and generally fixed
Primary control parameter	Output force	Accurate position
Operating speed	Human range 0–40 in./s	As fast as possible, dependent on task and design
Load range	20–50 lbs	5–200 lbs
Kinematics	Rotary joints, 6 dof, general purpose tong	Rotary and prismatic joints, various dof, specialized end effectors
Compliance	Relatively flexible	Usually stiff
Actuators	Centralized	Usually local to joint
Torque transmission	Backdrivable, some backlash	Non-backdrivable, minimum backlash

Perhaps one would not be surprised by the fundamental differences between these two classes of manipulators since they were in essence addressing fundamentally different design objectives. The most fundamental factor relating these classes may be the issue of force modulation and reaction in the work task environment. In the material handling applications associated with industrial robots, force interactions are accommodated through position precision, jigging/fixture design, and special end-effector design. It has only been with the more sophisticated assembly applications that the issues of force interaction have become of interest. Assembly,[8] especially for high precision components, involves force interaction to facilitate part fit-up or insertion. In such applications the robot cannot rely completely upon position control but must also control applied forces to achieve the task.

The prevalent research approaches to achieving force control capability include augmenting the conventional designs with torque or force transducers. The installation of a 6-degree-of-freedom force transducer[9] at the robot wrist is a common approach. This type of transducer is used to resolve the three-dimensional forces and moments at the wrist. Appropriate transformations and algorithms are then used to close force control servo loops at the joint axes. This, of course, does not alleviate the problem of the large friction/non-backdrivability nonlinearities which are inherently present.

Manipulator development was initially dominated by applications in nuclear technology development.[3] In these systems a great deal of emphasis has been placed upon the engineering issues of force interaction in complex work environments. Microelectronics advances made the implication of George C. Devol's 1954 programmable automated robot patent realizable.[10] Since the first developments focused on pick-and-place parts handling, a class of industrial robot manipulators evolved emphasizing cost, speed, and position control. The number and type of industrial robotics applications have increased steadily. Today, many applications have lead developers into the realm of force control. It is believed that these types of applications will produce a continuing evolution which will decrease the fundamental differences we now see between industrial robotic manipulators and the electronic servomanipulators used in teleoperation.

IV. Overview of teleoperator systems application and development

Although many research efforts have been expended to develop teleoperators, only a few functioning systems exist. These systems invariably find application in hostile environments of one form or another. With the advent of low-cost digital controls, improved control techniques, and improved subsystems (motors, encoders, software, etc.) it is conceivable that cost reduction and improved versatility will justify increased use of teleoperator systems. A review of present application and development thrusts should give insight into the future direction od teleoperator technology.

Only two American companies currently market complete master-slave teleoperator systems commercially: Central Research Laboratories (Fig. 3) and TeleOperator Systems (Fig. 4). Both of these companies have been making master-slave teleoperators for some time and have units in operation around the country. Due to the small production volume, these systems remain labor intensive and are priced accordingly. Up to now these systems have been used primarily in hazardous radiation environments, but teleoperators are being developed for other areas. Four areas of application are reviewed here: nuclear, space, military, and industry. The first three are primarily government based, but private industry is also entering the field.

In the nuclear field the use of teleoperators is related to equipment maintenance and material handling in radioactive environments. Successful implementation of teleoperators has been ongoing in target maintenance for several years at particle accelerator facilities at Fermi Laboratory and Los Alamos National Laboratory.[11,12] In these applications, the teleoperator is required to replace target materials and fixtures between tests. Remote maintenance systems for nuclear fuel reprocessing facilities have used teleoperated systems, but only recently have research efforts been renewed to address large-volume dexterous coverage and remote maintainability of the remote slave manipulator system.[13] Other applications in the nuclear environment include systems to perform maintenance on radioactive heat exchangers in commercial reactors. Westinghouse has developed a modular manipulator which can be assembled quickly *in situ* and allows the

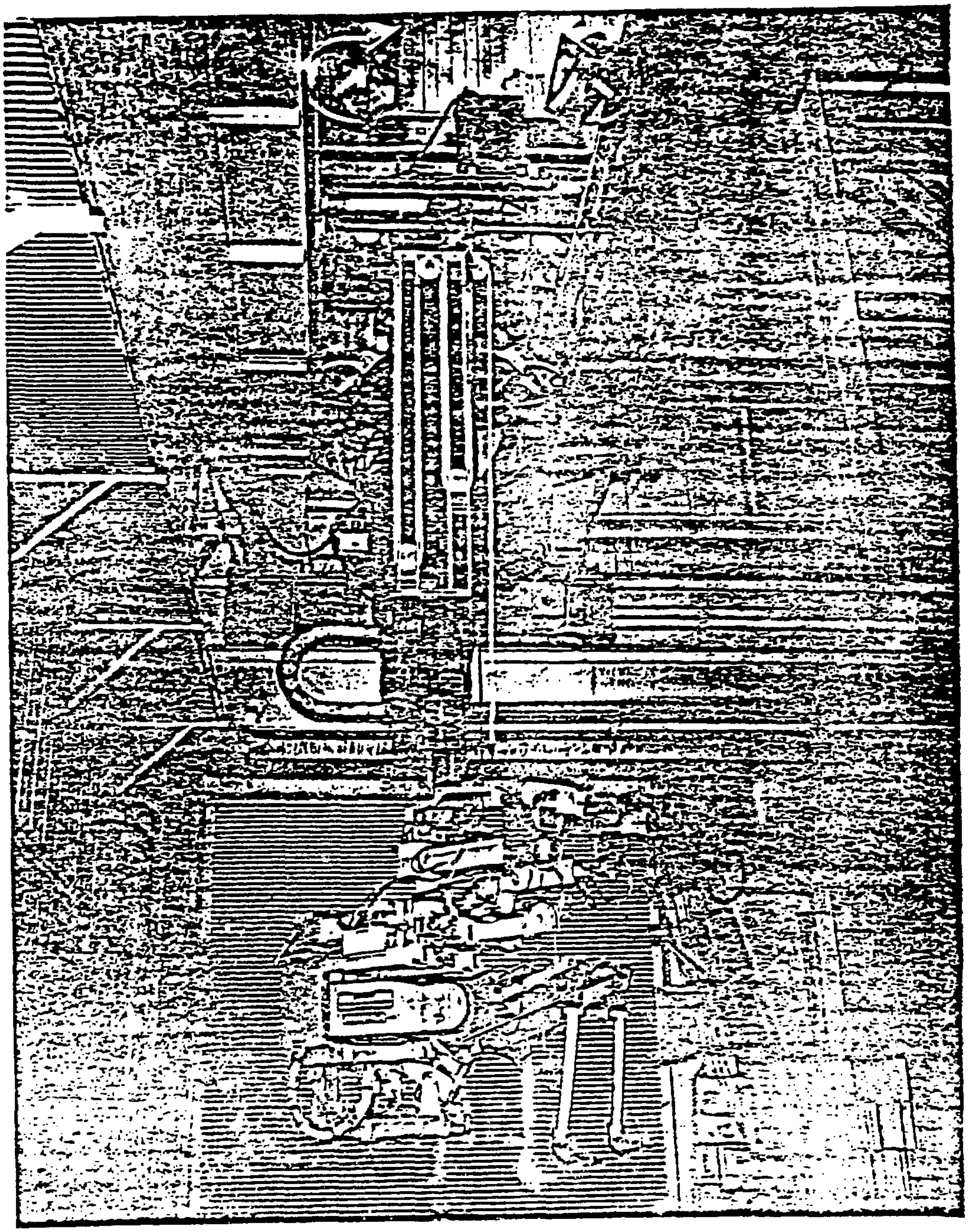

Fig. 3. Model M2 maintenance system by Central Research Laboratories.

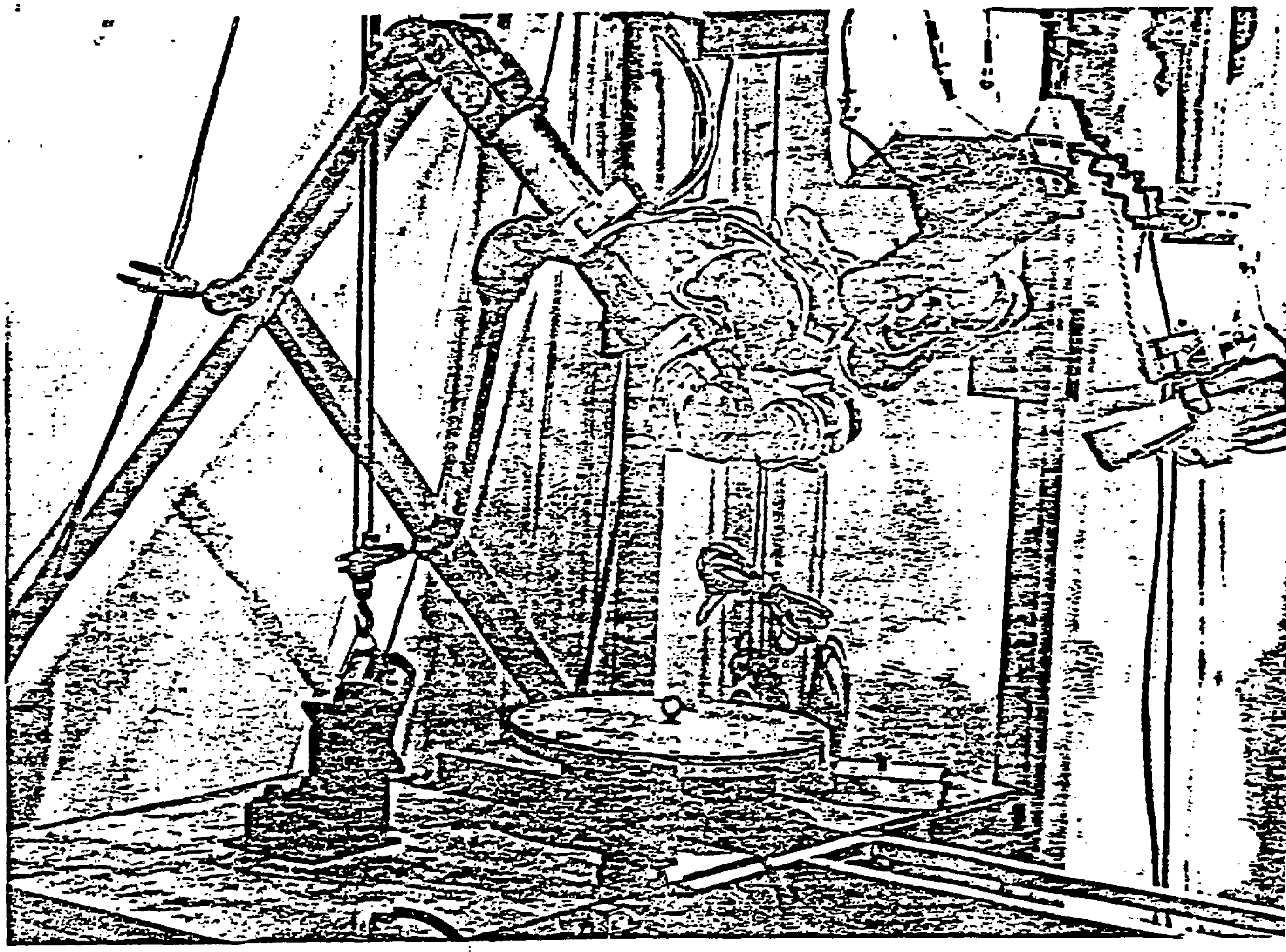

Fig. 4. SM-229 servomanipulators by TeleOperator Systems.

remote teleoperation of tooling to check and replace failed tubes in a steam generator.[14] General purpose teleoperators for inspection and maintenance in nuclear power reactors have been constructed, but their access is limited by facility geometry and tethered operation. Fusion research facilities plan to use teleoperators to maintain tiles and shields and to set up experiments within Tokamak reactors. Mobility is a problem in this application also, as it will be extremely difficult to develop transporter systems that can insert the manipulator system into and maneuver about the extremely complex internal structures of various fusion reactor concepts (e.g., Tokamak, Torus).[15]

Manipulator technology has been applied in the space arena in four instances. Manipulators were used to collect and analyze soil samples as part of the U.S. Lunar Surveyor Program and the USSR Lunar Exploration Program in the late 1960s. The Surveyor manipulator was used to dig a trench and perform other simple functions under remote control. The USSR manipulators acquired soil samples and deposited them in a return capsule. The third application was in the U.S. Mars Viking Program in 1976, when a computer-controlled manipulator helped to perform experiments on the Martian surface. In 1982 the U.S. space shuttle employed a Canadian-built 48-foot-long attached manipulator to unload payloads from its cargo bay and handle other objects in space.[16] Although only the space shuttle RMS is classified as a real-time teleoperator, all are examples of using machines to extend man's capabilities. Plans to develop sensory feedback on future space manipulators will make them more similar to earth-based teleoperator systems.

The U.S. Navy appears to be the leader in military teleoperator system development. The Navy's interest stems from the need to perform work tasks under water (especially in the hostile environment of extreme depths). The Navy has developed and operated a family of remotely operated vehicles (ROV) for nearly two decades. They usually have an umbilical cable for power and control and use a manipulator to retrieve submerged items.[17] Two non-routine recoveries have been performed by Navy ROVs: a nuclear weapon off Palomaries, Spain, in 1965 and the manned submersible Pisces III off Cork, Ireland, in 1975, just prior to the exhaustion of the pilot's air supply. The Navy continues significant efforts to develop tetherless vehicles and improved control techniques under the auspices of the Naval Ocean Systems Center. More recently the Army has shown interest in applying robotics in the battlefield to augment manpower requirements.[18] As this effort takes shape, it will be interesting to observe the tradeoffs made between the autonomous robot and the man-aided teleoperator.

A few industrial projects are worthy of special mention in the context of this paper. ODETICS recently announced a six-legged walking robot which combines teleoperator and robot control features. The outstanding features of this system include tetherless operation (self-contained power supply and radio wave control transmission), and a payload-to-weight ratio greater than one. Odex 1, shown in Fig. 5, is targeted for sentry duty applications with possible military uses.[19] Exxon Research and Production has developed a submersible petroleum production platform and a maintenance teleoperator system. The objective is to perform well-head operations on the ocean floor rather than build large, expensive platforms. The maintenance teleoperator is then used for upkeep of the submerged platform items. One tethered, teleoperated manipulator would service many submerged platforms. Shallow-water testing has already been performed successfully. A third commercial application which shows great promise is that of mining. Remoting the operator or eliminating him completely is the thrust of British efforts through the National Coal Board.[20] These examples represent the diversity of teleoperator activities within industry and U.S. government organizations, but many groups worldwide are also working to improve teleoperators.

Several foreign countries are involved in teleoperator development for hazardous material handling, primarily in nuclear applications. In West Germany, mobile platforms and force-reflecting manipulators for emergency situations have been developed.[21] The MF3 manipulator vehicle is a mobile platform supported by four independent crawler tracks (two per side). These tracks can be articulated automatically to maintain a level platform surface. The vehicle can climb a 45° incline or stairs, can climb over obstacles 3 feet in height, and can bridge gaps up to 3 feet. Several West German police forces have used the vehicle, which is produced by Blocher Motor Company, for bomb disarming and disposal. This vehicle has a 500-pound capacity and a control tether of 300 feet. Their servomanipulator system, the EMSM I, was the first to fully implement electronic counterbalancing. The 9-degree-of-freedom arm has a continuous capacity of 25 pounds, with somewhat compliant force reflection. This system also makes use of torque tubes for drive power transmission. The 9-degree-of-freedom kinematics allows the arm to take on many possible configurations for a given end-effector orientation and position. The redundant kinematics offers obstacle avoidance advantages, but it causes some operator interaction difficulties unless special control functions are implemented.

The French atomic energy agency, CEA, has supported an active manipulator development program for more than a decade. The MA-23 servomanipulator is the last major output of this program.[22] This system has been improved for remote glove box maintenance,[23] and similar systems have been outfitted for end-effector camera tracking, compliance correction, and insertion force control.[24] The French have two companies involved in manipulator manufacturing: (1) La Calhene, licensee for the MA-23 servomanipulator, and (2) Ateliers et Chantiers de Bretagne (ACB), manufacturer of power arms and overhead handling equipment. An MA-23 servomanipulator has been used with a large shielded cask and telescoping tube to produce a hot cell intervention system. The tube and manipulator fully retract into the cask, which is then set into position over a man-hole penetration for access to the cell.

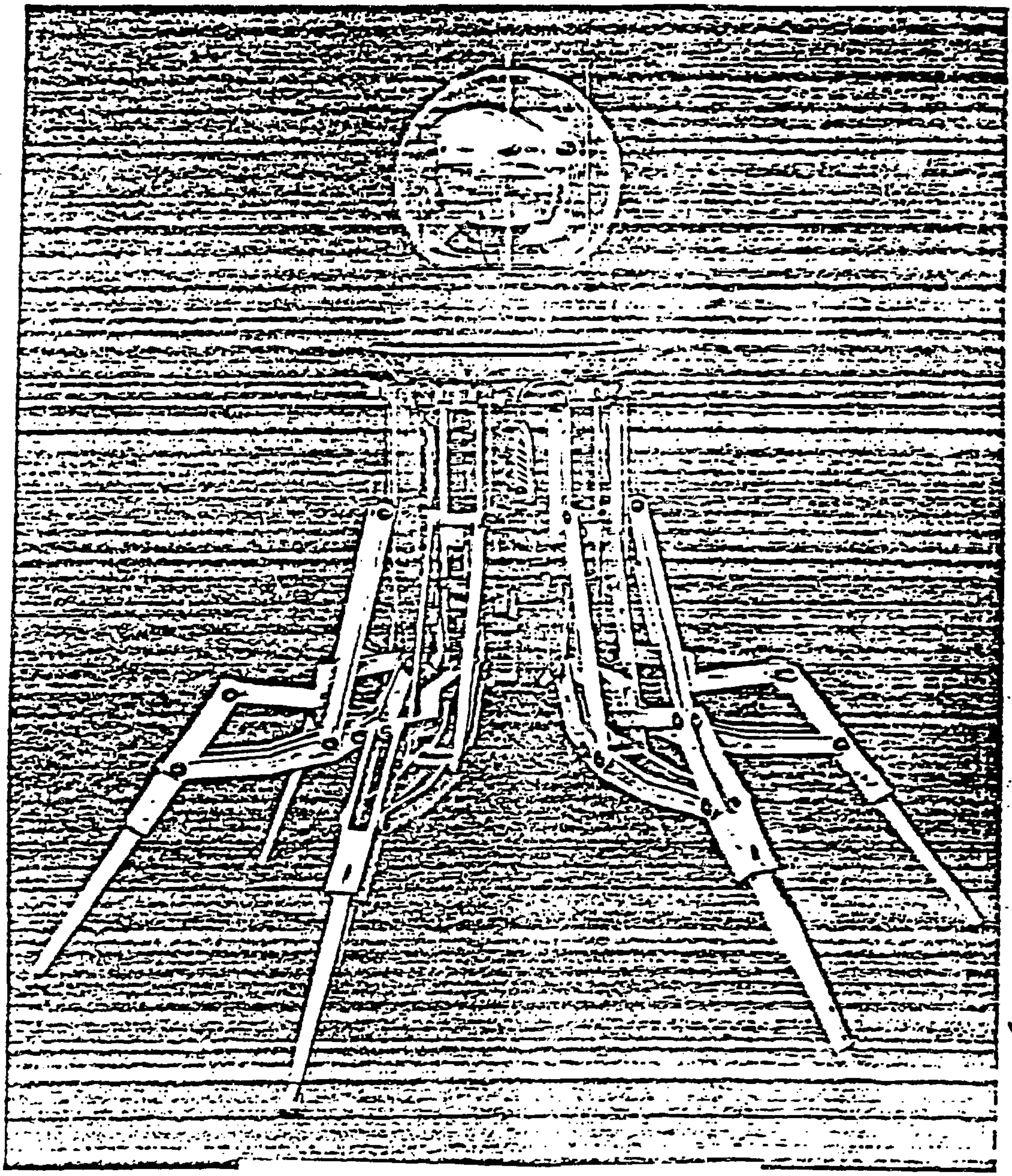

Fig. 5. Walking robot, Odex I by ODETICS.

Several other nuclear-related remote operations developments are being pursued in Europe. The Joint European Torus (JET) Fusion Program is incorporating remote maintenance for application using the Italian MASCOT servomanipulator designs. As an offshoot of this work, the Italian atomic energy agency is considering rejuvenation of its manipulator development to upgrade the MASCOT to today's electronics technology.[25]

The Japanese have been noted for their ability to develop, manufacture, and apply robotic technology. Their original development efforts in robotics and teleoperator systems, however, have been limited. We often forget that they got started in robotics by licensing (Kawasaki Heavy Industries) Unimation manipulator designs. Recently they have increased their efforts to develop teleoperator systems[26] for nuclear applications. The BILARM-83A is a cross between power manipulators and servomanipulators. High inertia resulting from large gear reductions requires that strain gages be used for force sensing. This particular force-reflection implementation results in slow system response and a lack of good operator control, even though an anthropomorphic master controller is used. Another Japanese teleoperator development uses distributed actuators, microprocessor-based controls, and electronic counterbalancing.[27] Crawling and walking vehicles are also being researched in Japan.[28,29] The major research centers are Meidensha Electric Manufacturing Co., Hitachi Energy Research Laboratory, and Toshiba. With such diversity of activity, the Japanese effort should be observed closely in the coming years.

The SPAR Corporation of Canada has developed and fabricated the teleoperator system for the U.S. space shuttle.[30] Its remote manipulator system has special considerations for operating in outer space, including: (1) distributed brushless actuators for operation in an oxygen-free environment, (2) joystick control to minimize operator station size, and (3) special docking sensors developed with the Jet Propulsion Laboratory.

Remote technology development has been a continuing effort in programs of the United Kingdom Atomic Energy Authority.[31] Because hot cell volumetric sizes have remained relatively small, and as a matter of philosophy, mechanical master/slave manipulators and unilateral power manipulators are the basic tools of remote maintenance. Development activities have focused on reliability refinements of basic manipulator designs. No major activity has been assigned to the development of servomanipulators.

V. Future research directions

The ultimate goal of robot and teleoperator systems is to provide unlimited flexibility and a high level of autonomy. The two system concepts are approaching this goal by different evolutionary pathways as discussed earlier. Today's industrial robot is perceived as quite autonomous, since once programmed further intervention is not nominally requried. Because of sensory limitations, these systems have limited flexibility in adapting to work environment changes, which is the motivation of computer vision research. The teleoperator is very adaptable, but it relies on human control to accomplish its work. Figure 6 graphically shows the relationship of these systems to the ultimate goal and gives insight into the focus of present research activities. Advanced robotic systems are striving for task adaptability through enhanced sensory feedback. Research areas concentrating on artificial intelligence, sensor integration, computer vision, and off-line CAD/CAM robot programming will make robots more universal and economical. Teleoperator systems are moving toward autonomous operation as an enhancement to human control. Research in supervisory control, man-machine interface methods to reduce operator burden, and computer data base management is intended to improve operator efficiency. Many research activities are common to both systems and are aimed toward reducing implementation cost and expanding the realm of application. These include improved communications methods, advanced digital control techniques, basic sensor development (force, tactile, vision, etc.), mobility, modularity, and subsystem components (actuators, amplifiers, materials, etc). A review of teleoperator research activities will show possible relationships to robotic developments.

The Jet Propulsion Laboratory has developed a universal manipulator controller.[5] The fundamental concept is to develop a master arm that can be used to operate any slave arm system by means of real-time transformation of the kinematic dissimilarities. Such a method could be applied in the future as a programming device for industrial robots. One would use a single controller and different transformation software to teach the desired motions to various commercial robot configurations. This concept would also facilitate single-operator supervision of several robots to provide remote recovery from fault conditions.

Distributed digital control techniques have recently been applied to teleoperator systems to improve their operational flexibility.[32] The advent of easily reprogrammable microprocessor control systems has led to improved diagnostic methods, control implementation, and reliability in teleoperator systems. Digital controls also allow sophisticated compensation algorithms for inertia, friction, counterbalancing, and other nonlinear effects which were difficult or impossible to accurately accomplish with analog circuitry. Servomanipulators tend to be mechanically compliant due to the emphasis on low inertia (small structure) and centralized actuators (long force transmission path). Current intelligent digital systems will allow such compliance to be corrected by control adjustments and will improve the positional accuracy of teleoperators.[33]

Mechanical modularity is another area in which both teleoperator and robot manipulators can be improved. A modularly constructed robot can be reconfigured for heavier loads, greater reach, or different kinematic constraints. American Robot Corporation describes its latest system as a Modular Expandable Robot Line

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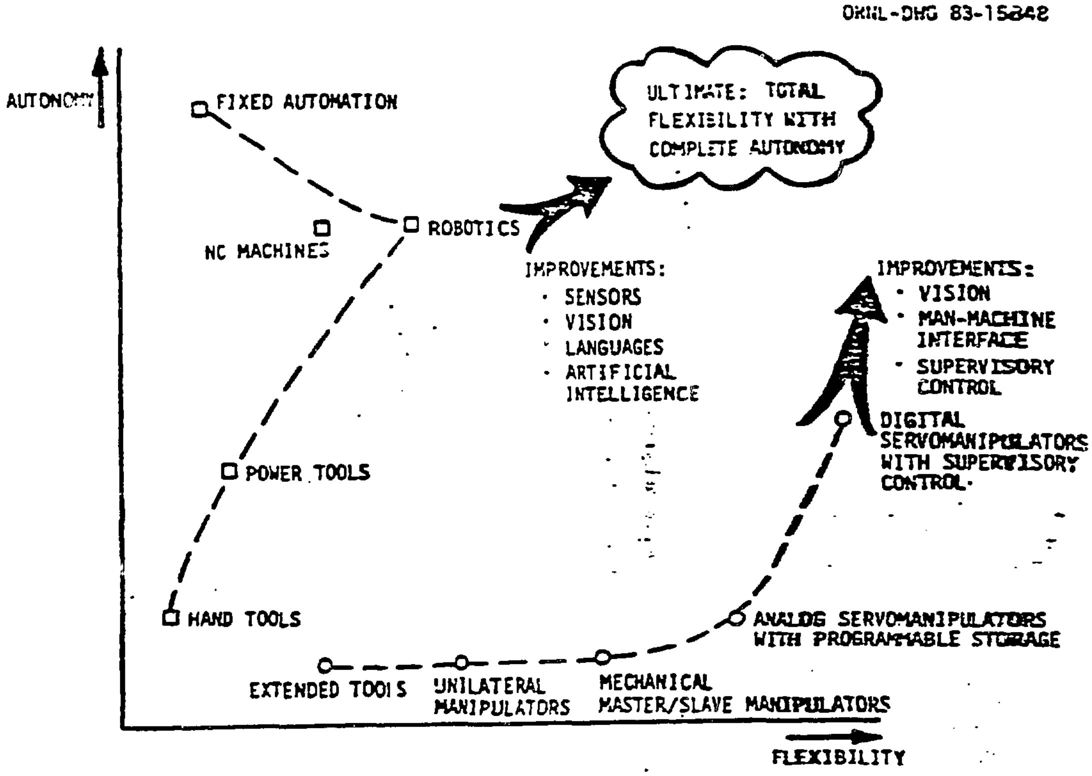

Fig. 6. Automation and versatility ~~for~~ of various manipulation methods.

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(Merlin).[34] Modular construction should also provide increased availability by facilitating faster *in situ* repair of failed systems. It is this aspect that is receiving emphasis in the latest teleoperator developments.* Modularity will also enhance mobility, in that the ability to reduce a manipulator to small, easily assembled parts should improve its transportability to various work sites.

Kinematic improvements in teleoperators have resulted from the development of manipulators which operate in the anthropomorphic (man-like) stance. This elbows-down configuration required development of unique wrist mechanisms to provide yaw, pitch, roll, and grip actuation while avoiding mechanical singularities. A joint effort between ORNL and TeleOperator Systems resulted in a mechanism similar to the Cincinnati Milacron three-roll wrist, but without mid-range singularities. The anthropomorphic stance reduces manipulator obstruction of viewing the work site, increases operator comfort at the master controller, and increases horizontal reach dexterity.

Improvements in man-machine implementation methods are aimed at increasing the operational efficiency of teleoperators. Graphic display techniques provide the operator with information concerning everything from system fault conditions to obstacle avoidance in a dynamic environment (See Fig. 7). The problem of acquiring data, decomposing it, and presenting it to an operator in a logical sequence is very similar to sensor integration for a computer system; artificial intelligence is required to condense available inputs into useful forms. Efforts in improved graphic presentation methods are common within the process control industry, whereas intelligent action based on input data is being extensively pursued by the defense community.

Underlying the operation of successful multifunctional systems is the ability to successfully partition actions into a series of defined acts. Such partitioning leads to a structured organization of programming tasks. The concept of hierarchical systems applies equally well to both teleoperator and robot systems.[35] Both systems can be decomposed into similar subsystems (servo control, sensor data acquisition, kinematic transformation determination, etc.) with congruent goals (manipulate, orient, enunciate, etc.). The efforts by the National Bureau of Standards[35] to develop interfacing criteria for robotic systems will also be beneficial to the teleoperator industry.

Vision research for teleoperators has emphasized the human aspects: multiple views, optimal perspective, stereo versus monocular, color versus black and white, and optimal lighting. The goal is to optimize the human perception of the work environment. As augmentative automation is pursued, the use of end-effector cameras and pattern image processing techniques and other carry-overs from robotic developments will be evident. Teleoperation research into environmental coloring to aid operator recognition and multiple viewing to improve depth perception may also find application in advanced computer vision.

Research activities in teleoperators and robotics are strongly complementary. The major motivation in robotic research is economics, but the different perspective offered by teleoperator development could open new areas useful to both. As the complexity of industrial robotics systems and applications increases, it is expected that these two related technologies will continue to converge.

VI. Summary

Teleoperator systems comprising man-controlled remote manipulators have undergone extensive development in nuclear applications over the past three decades. Today, teleoperator research has expanded and diffused into other fields such as space, military, and industrial applications. Modern teleoperator systems utilize the latest advances in materials, electronics, and microcomputer technology, all of which are very closely related to industrial robotics systems. Developmental similarities in kinematics, controls, mechanisms, modularization, mobilization and man-machine interfacing are expected to increase.

Future trends will lead to increased automation (robot operating modes) in teleoperation and autonomous intelligent operation in robotics. These trends will reduce the apparent distinction between the two classes of systems. It is expected that force-reflection techniques in teleoperated servomanipulators will contribute to robot force control applications in assembly. Research in robot sensors, especially computer vision, will surely lead to extensions in teleoperation.

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