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MODULAR ROBOTICS
OVERVIEW OF THE "STATE OF THE ART"

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August 1996

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MODULAR ROBOTICS: OVERVIEW OF THE "STATE OF THE ART"*

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ABSTRACT

The design of a robotic arm possessing modular components and reconfigurable links is the general goal of a modular robotics development program. The impetus behind the pursuit of modular design is the remote engineering paradigm of improved reliability and availability provided by the ability to remotely maintain and repair a manipulator operating in a hazardous environment by removing and replacing worn or failed modules. Failed components can service off-line and away from hazardous conditions. The desire to reconfigure an arm to perform different tasks is also an important driver for the development of a modular robotic manipulator.

In order to bring to fruition a truly modular manipulator, an array of technical challenges must be overcome. These range from basic mechanical and electrical design considerations such as desired kinematics, actuator types, and signal and transmission types and routings, through controls issues such as the need for control algorithms capable of stable free space and contact control, to computer and sensor design issues like consideration of the use of embedded processors and redundant sensors. This report presents a brief overview of the state of the art of the technical issues relevant to modular robotic arm design. The focus is on breadth of coverage, rather than depth, in order to provide a reference frame for future development.

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1. INTRODUCTION

Many of the robotic activities found in a nuclear environment, and specifically the nuclear environmental management (EM) environment, have special requirements to ensure reliable robot operation for extended periods of time under adverse conditions. Because of the hazardous conditions generally encountered in nuclear applications, robot reliability is of utmost importance. In anticipation of failure, or in the event of failure, maintenance and repair with minimal human contact, respectively, become paramount. Reliability, maintainability, and repairability are therefore the major attributes driving the development of a modular robotic manipulator for the nuclear environment.

In many cases the adverse conditions and special requirements of nuclear environments are likely to lead to manipulators designed for unusual workspaces and performing tasks not typically intended for commercial industrial robots. Because of uncertainties in the workspace and uniqueness of tasks, these robotic systems will need to be adaptable and reconfigurable so that (1) one design may serve in a number of different roles, (2) spare parts inventory is significantly reduced, (3) repair is fast and may be done remotely, (4) the manipulators may be reconfigured and adapted for different tasks in the same work cell, (5) the cost of robot design is distributed over many units, and (6) training time and operation time are reduced because of the common interface. This type of manipulator design is referred to as modular design.

The technical drivers and the technical developments needed to respond to those drivers are summarized in Table 1. Each of these is addressed (to some extent) in this report.

Modular robotics efforts should focus on kinematic concepts; redundancy; actuator technology; module definition; interfaces between modules (including mechanical, electrical, hydraulic, optical, etc.); controls such as stiffness/force control and bilateral force reflecting; and state-of-the-art hardware issues such as drive train packaging, drive train optimization, and distributed electronics including power amplifiers and power electronics. In the following sections some of these issues will be addressed, and suggestions for possible directions that the modular robotics activities should take will be mentioned.

Table 1. Modular Robotics Drivers/Response Chart

	Technical Response Areas				
Technical Drivers	**Mechanical Design**	**Electrical Design**	**Control Systems**	**Computer Systems**	**Sensor Systems**
Maintainability	1. Modular drive train 2. Ability for remote driving of joints 3. Remotely operated fasteners	1. Modular electrical components 2. Fiber optics	1. Adequate documenting of design 2. Modular software	Rack-mounted hardware	Replaceable, modular sensors
Reliability	1. Quality hardware. Design for reduced complexity 3. Design safety factor	1. Quality components 2. Design for reduced complexity	1. Control system designed for robustness 2. Sensor fusion	1. Quality boards 2. Distributed processing 3. Minimum system design	1. Quality sensors 2. Redundant sensors 3. Advanced sensor designs
Reconfigurability	1. Mechanical connectors 2. Modular link design	1. Electrical connectors 2. Rotary transformers	1. Automatic generation of kinematics and inverse kinematics	1. Open hardware architecture	1. Link processors for preprocessing raw sensor data 2. Auto ID scheme
Obstacle Avoidance and Collision Avoidance	1. Compact design 2. Internally routed cabling 3. Redundancy 4. Design for impact	1. Compact design 2. Internally routed cabling 3. Fiber optics 4. Design for impact	1. Path planning 2. Graphical preview 3. World model tied with real-time control 4. Reflex control tied with whole-arm sensors 5. Control of redundant manipulators	1. High speed for preplanning without huge delay 2. High speed for real-time path alterations, especially for teleoperation	1. Obstacle detection sensors (e.g., ultrasonic, vision) 2. Whole Arm detection
Tool/End-Effector Design and Application	1. Quick-change tool interface 2. Stiff structure 3. High payload 4. Multifingered hands	1. Electrical interface for tool 2. Embedded electronics in tool	1. Arm controller robust to end load and to impulse loads 2. Control of multifingered hands	1. Rack-mounted hardware to add processors for tools 2. Auto tool changing 3. Auto tool ID	1. Wrist/Tool force/torque 2. Joint torque 3. Actuator velocity 4. Joint position and velocity
Object Contact	1. Low in inertia 2. Compliance as needed 3. Invariant inertia sensor	1. High bandwidth electrical components	1. Force control 2. Impedance control 3. Combined pos/force control	1. High MIPS 2. DSP technology	1. Wrist/Tool force/torque 2. Joint torque 3. Actuator velocity 4. Joint position and velocity

Table 1. Modular Robotics Drivers/Response Chart (continued)

	Technical Response Areas				
Technical Drivers	**Mechanical Design**	**Electrical Design**	**Control Systems**	**Computer Systems**	**Sensor Systems**
Without Contact (i.e., free space)	1. Low inertia 2. Low friction 3. Invariant inertia sensor	1. High bandwidth electrical components 2. New electric motors	1. Gravity compensation 2. High bandwidth controls	1. High speed for real-time computation 2. High MIPS 3. DSP technology	1. Joint position 2. End-point position
Payload Capacity	1. High payload-to-weight ratio 2. Hydraulic actuators vs electric actuators 3. New electric actuators	1. Light-weight embedded electronics	1. Control schemes able to use full operating range of actuators 2. Arm controller robust to end load and to inertia variations 3. Stiff controllers for continued accuracy at high payloads	1. Light-weight embedded processors if applicable	1. Light-weight sensor designs 2. End-point position
Low Cost	1. Simple design 2. Avoid costly materials	1. Simple design 2. Avoid costly electronics	N/A	1. Commercial hardware	1. Simple design 2. Avoid costly sensors
Accuracy, Repeatability, Resolution	1. Stiff structure 2. Stiff drive train	1. Analog where needed	1. High bandwidth	1. High-speed	1. High-resolution position sensors 2. End-point position 3. Vision
Communications	1. Cable passages provided	1. Communications interface 2. Fiber optics	1. Separate communications processor	1. Separate communications processor	1. Connection integrity sensors
Radiation Resistance	1. Shielding 2. Avoiding plastics	1. Radiation-tolerant electronics (e.g., CMOS) 2. Critical electronics located remotely	N/A	1. Remote location 2. Rad-hardened boards only in extreme cases	1. Radiation-tolerant sensors (e.g., avoid glass encoders or sensors with embedded electronics

2. RELIABILITY, MAINTAINABILITY, AND RECONFIGURABILITY

The impetus behind the pursuit of modular design is the remote engineering paradigm of improved reliability and availability provided by the ability to remotely maintain and repair a manipulator operating in a hazardous environment by removing and replacing worn or failed modules. Failed components can be serviced off-line and away form hazardous conditions. Delbert Tesar confirms this fact in stating that one of the three main benefits of modularity is to make quick repairs[1]. In addition, the desire to reconfigure an arm to perform different tasks is also an important driver for the development of a modular robotic manipulator. These topics are developed in the following sections.

2.1 RELIABILITY ISSUES IN MECHANICAL DESIGN

Design for reliability is essential for any robot or teleoperator. Fault tolerance has been previously considered for modular arm design, for example in Au[2]. The question of how to design a manipulator to detect failures (or impending failures) and then to shut down (degrade) in a graceful manner is important for manipulators intended for hazardous, inaccessible environments. The manipulator might be able to finish a task with fewer degrees of freedom (DF) or less payload capacity or just operate enough to remove itself from the hazardous environment for repair. Particular kinematic arrangements could provide increased reliability resulting from decreased loading on critical components and improved manipulability. Redundant kinematics may also be used to improve reliability.

Cabling and hose connection issues affect reliability. Do rotary transformers, inductive coupling, or fiber optics reduce manipulator reliability? If so, can their reliability be improved? Can connectors be made to mate automatically in a reliable manner?

State-of-the-art design generally requires a Failure Mode, Effects, and Criticality Analysis[3] and a fault tree analysis[4]. Fault trees can be used in two ways. (1) They can be used dynamically to provide on-line information concerning fault sources and potential ways to recover from faults. (2) They can be used as an off-line design tool to improve the reliability of manipulator designs[5]. The ability to dynamically reconfigure a controller to accommodate faults is also a possibility and should be considered for modular robotic applications[6].

2.2 RELIABILITY ISSUES IN CONTROL SYSTEMS DESIGN

Position sensors should be absolute and not relative devices so that recovery from a loss-of-power condition is possible. Resolvers are more resistant to gamma radiation than optical encoders and are therefore preferred. Resolvers have a significantly higher mean time between failures (MTBF) value than optical encoders. Resolutions of resolvers are comparable

(MTBF) value than optical encoders. Resolutions of resolvers are comparable with optical encoders (16 bits of resolution is readily attainable), but resolvers are somewhat more expensive. The cost of resolvers is not, however, excessive. If velocity sensing is required, a resolver-to-digital converter with a velocity output can be used; however, velocities from these are only accurate for type 2 and lower servo loops, and tachometers should be used for accuracy in all situations.

The development of a small Inertial Measurement Unit (IMU) that would provide end-effector linear and angular accelerations, velocities, and positions could provide data not usually employed for manipulator control. This signal could be used to improve the reliability of the modular arm by developing a redundant feedback control loop.

Redundant sensors can improve reliability and should be considered in the design of a modular robotic arm. The new ODETICS Inc. arm, for example, employs both a resolver and a potentiometer for joint position measurements. This provides single-fault tolerance. Again, the issue of sensor fusion for improved reliability becomes important in the case of redundant sensors.

Can drive train-mounted force/torque sensors and wrist-mounted sensors be used in reliability-enhancing algorithms? Theoretically, they are providing redundant information but many practical problems preclude substituting one mathematically transformed signal for the other (e.g., drive train compliance, noncollocation of sensor and actuator for wrist-mounted force/torque sensors, and inexact knowledge of link and joint parameters).

The use of parallel processors to improve reliability may be of benefit for a modular robotic arm design. This may be especially true if embedded processors are designed.

2.3 GUIDELINES FOR REMOTE FAULT RECOVERY AND MAINTENANCE

The general guidelines for designing for remote maintenance are to design equipment with individually replaceable modules, group together (to the extent possible) items of similar radiation resistance in these modules, provide diagnostic capabilities sufficient to identify the cause of failure, and locate (if possible) the diagnostic equipment out of the high-radiation environment. For details the reader should consult the references cited in the section discussing radiation resistance; however, a few specifics are discussed as follows:

1. Replacing discrete modules and repairing or servicing old modules away from hazardous conditions are central to the remote engineering paradigm. The ability to remotely service these modules even after removal from the primary hazardous environment may be necessary depending upon particular operating conditions. The design for module replacement and off-line servicing will increase system availability and should be a primary objective of modular manipulator consideration and design.

2. It is frequently useful to provide a method of remotely driving a manipulator joint with manipulator tools in case of a joint failure condition. This may be accomplished by specifying a double-ended motor shaft with a hexagonal end. This is useful to diagnose failure and/or to drive the unit into a more favorable position for maintenance.

3. The concept of modularity is essential for a maintainable robotic system. As an example, in replacing the motor/gear box, a positional sensor should be designed as a module. Furthermore, all replaceable modules or subassemblies that require lifting for transport, installation, and replacement should have lifting bails or an equivalent if practical. Avoid porous materials and designs that may trap material (this creates a decontamination problem). Polished metal surfaces (electropolishing is a common finishing technique used in the nuclear industry) for decontamination of parts is preferred.

2.4 RECONFIGURABILITY

Maintainability and reliability are important drivers for a modular robotic arm design, but an arm that can be reconfigured for different tasks is also an important driver. Reconfigurability can be approached from two disparate viewpoints: (1) an operational view where redundant degrees of freedom of the arm are used to provide reconfigurability either for optimizing some criterion (which could be task-specific) or for recovery from a failure and (2) a mechanical "tool box" view where an arm is physically reconfigured to optimize its performance for a specific task or set of tasks.

The ability to reconfigure an arm generates a unique set of problems. When and how should the arm be reconfigured? Is the objective to maximize a manipulability measure[7], possibly even a task-based design[8]? Once the arm is reconfigured, the automatic generation of kinematics and inverse kinematics (discussed in another section) becomes important. Also important is the ability to tune controllers automatically for different loads depending upon their position in the arm. Techniques such as those developed by Chen for robots[9, 10] and by Kress[11] for teleoperators might be applicable. Methods to calibrate a reconfigurable arm automatically and remotely would also be useful in order to improve the overall accuracy, repeatability, and resolution achievable by the various configurations. Development of automatic calibration techniques including precision calibration jigs and fixtures could be important for a modular robotics arm[12]. Insitu calibration would be burdensome because of the size and complexity of calibration jigs and fixtures; consequently, developing a modular robotic arm that does not require insitu calibration is important.

The development of a modular interface connector (termed the m^2 concept) that would provide the ability to change the amount and type of available connections (e.g., electrical power, hydraulic power, sensor, etc.) on each module is also an important development issue. The idea is to provide additional interfaces as needed such that if additional links are included whose connections exceed those available, then additional interface modules are included to meet those needs. Acceptable designs for these interface modules need to be developed.

3. MECHANICAL DESIGN

Mechanical design of any robot must accommodate advances in hardware; otherwise, the robot quickly becomes obsolete. This is especially acute in the computer controls hardware where developments are constantly occurring to greatly improve the available computing power and speed. Modular design allows for the rapid inclusion of new technology. This helps avert the threat of obsolescence or the alternate problem of high cost for completely new one-of-a-kind designs[13]. In addition, a modular design will allow for optimization to occur in smaller, more manageable portions. Optimized or improved actuators, sensors, electronics, software, and other modules could be integrated into the robot. The design problem would, therefore, contain far fewer design parameters and would be much more tractable to the designer[13].

3.1 MODULAR ROBOTICS MECHANICAL DESIGN

Some applications of modular robotics involve poorly defined tasks (i.e., tasks not suited for preplanned, assembly-line-type robotics) and are likely to involve unexpected events. Problems will need to be addressed on-line, possibly even to the extent of redefinition of the manipulator configuration required. In addition, equipment availability will significantly affect cost, making rapid repair valuable. The advanced servomanipulator (ASM)[14] developed for nuclear fuel reprocessing applications, the Laboratory Telerobotic Manipulator (LTM),[15,16] and the Micro-Gravity Manipulator (MGM)[17] developed for space applications demonstrate a history of work toward manipulator modularity. The ASM has modular arm sections and modular actuators. The LTM and the MGM have modular links and drive trains. These manipulators each have limitations for general applications: the ASM, designed principally for remote maintainability, is limited by gear backlash allowed in order to reduce friction and to improve force reflection sensitivity (which, by design, cannot be adjusted without significant arm disassembly); the LTM is limited by friction[18] by the weight of the modules (which would not be an issue in the zero gravity environment for which it was designed). At present, a modular arm is being designed at the Robotics Institute of Carnegie Mellon University (CMU)[19]. This arm, named the Reconfigurable Modular Manipulator System, employs a stock of assumable joint and link modules of different size and performance specifications. The general idea is to have a "tool box" of modules to configure the arm as desired. Another modular arm designed by ODETICS for the Jet Propulsion Laboratory has common joint interfaces (there are two different interface sizes) and could be reconfigured[20].

3.2 MECHANICAL COMPONENTS

The development of discrete mechanical modules is extremely important to the development of a modular robotic arm. Modular motors, modular drive trains (including gear reducers and sensors), modular electronics, as well as modular links, contribute directly to improved reliability through the ability to perform maintenance remotely and relatively quickly and also reduces the mean time to repair for failed arms. Certain mechanical parts of a modular arm may need to be specially designed. For example, the LTM had specially designed traction-drive differentials[21] in an attempt to reconcile the classic telerobotic dichotomy of needing low friction and low inertia for teleoperation and needing no backlash and high stiffness for robotic operation. The development of light-weight transmission systems and speed reducers such as the cable system of DiPietro[22] is another example. Specially designed links such as composite material links may also become a design issue (though not likely).

Gear reducers are an especially important design area for modular robotic arms. Of considerable interest, because of the need for drive train torque feedback, is the possibility of integral reducer/torque sensor design. These designs use strain gauge instrumented harmonic drives and are being investigated by a number of researchers[23,24,25,26]. Pacific Northwest Laboratories is also looking at a very small sensor based on pressure transit technology.

3.3 KINEMATICS

Typical industrial manipulators have kinematics that can range from the classical PUMA-type (six revolute joints) all the way to a Cartesian-type (three prismatic and three revolute joints) of kinematic structure. There are also redundant industrial manipulators such as the Robotics Research Corporation arm. Combining any kinematic solution with very stiff mechanical structures typically eliminates most designs. A 6-DF revolute manipulator is optimal in the sense of maximal work volume subject to a constraint on its length and its ability to reach all positions in its workspace in each configuration if, and only if, the manipulator or its kinematic inverse is an elbow manipulator (i.e., a manipulator with an elbow joint separating a 2-DF base and a 3-DF wrist)[27]. Designing redundant manipulators, if that is decided to be the direction modular robotics should go, is where many significant kinematic design problems will be encountered.

The consideration for which kinematic designs are most appropriate for nuclear (especially EM) applications, becomes an issue in the design of a modular robotic arm. More importantly, however, is the consideration of which basic kinematic concepts best lend themselves to reconfigurability. In other words, is a pitch/yaw, pitch/yaw, etc., arrangement like the LTM best or can a single revolute joint module set and a single prismatic joint set be combined together to form any arbitrary kinematic arrangement conceived? Certainly, intersecting joint axis have computational advantages but have more difficult and complicated mechanical designs. Methods for mapping task specifications into manipulator design are available for modular arm design and reconfiguration[28,29].

An important problem with a reconfigurable manipulator is the generation of the kinematic and inverse kinematic software for a manipulator. Both symbolic methods and numeric solutions exist for solving the kinematic problem[30,31] of a serial-link manipulator. Solving the inverse kinematic problem in symbolic form for a nonredundant manipulator is difficult; however, numerical methods such as Newton-Rapson appear to be workable and generally converge quickly[32]. For a redundant serial-link manipulator, the kinematic problem can still be handled either numerically or symbolically. The inverse kinematic problem is more difficult and is related to the redundant control problem (discussed in the next subsection).

3.4 REDUNDANCY

Closely related to the kinematic problem is the one associated with designing manipulators with extra degree-of-freedoms. Examples of commercially available redundant arms include the Robotics Research Corporation arms and ODETICS dexterous manipulator. The advantage of such a manipulator is the increased ability it provides. Fault recovery (i.e., failure of an actuator or joint sensor), collision avoidance, and a more intelligent allocation of actuators (e.g., optimizing the velocity or force ratio, etc.) are all possible with a redundant manipulator. The disadvantage of using redundancy is that the payload-to-weight ratio of the manipulator becomes worse. Further, redundant control is still an unsolved problem in that most real-time control schemes do not guarantee a path that is conservative, which is a problem for repetitive operations (i.e., closure of the Cartesian trajectories does not necessarily imply closure of the joint space trajectories).

Noticeable advances have been made in the redundant control problem. For example, a fast singular value decomposition routine based on Given's rotation was implemented in the late 1980s by Maciejewski[33] that allowed, for the first time, real-time implementation of redundancy algorithms like the damped least-squares scheme. Local task measures such as manipulator mechanical advantage,[34,35] manipulator velocity ratio,[36] and manipulability measure[7] can now be readily calculated. The major problem continues to be the unpredictability of the trajectory generated based on local optimization schemes. If a redundant manipulator is required, it might be advantageous to lock certain joints most of the time to make it a nonredundant manipulator.

3.5 ACTUATOR TECHNOLOGY

The ASM is a modular manipulator. Its actuators are located on the shoulder to minimize torque requirements for the lower joints and to minimize off-diagonal terms in the inertia matrix. This approach significantly complicates mechanical power transmission. The LTM design employs distributed actuators but is designed for space applications in which actuator weight only affects inertia, not manipulator payload capacity. The performance of a distributed actuator, modular manipulator would be greatly enhanced by significant improvements in the power to weight and size ratios of electromechanical actuators. New actuator designs including Shape Memory Alloy and piezoelectric actuators and the consideration of hybrid systems with some joints hydraulically actuated and some joints electrically actuated should be part of a modular robot conceptual design.

Most industrial robotic manipulators using electric motors have a payload-to-overall manipulator weight ratio from 3 to 5%. To achieve a fraction of a millimeter positional repeatability since the joint sensors are accurate to 16 bits (i.e., 20 arc seconds of orientation accuracy), the links of the beam have to be made extremely rigid. To improve upon the payload-to-overall manipulator weight ratio, web-like structures based on careful finite element studies need to be designed. Manipulators built by the Schilling Corporation are based on such a design. In addition, Schilling uses materials such as titanium, which has higher material strength and stiffness. For 5- to 10-kg payloads and with tip speeds around 1 to 2 m/s, base motors are typically around the 755-W (1-hp) range.

New types of electric motors based on revolutionary new magnetic materials are presently being examined. The rare earth magnetic materials have a flux density around 0.75 Tesla. Since motor torque is proportional to the product of flux density and armature current, the larger the flux density, the larger the motor torque. In the laboratory, flux densities have been reported to around 10 Teslas, which is an order-of-magnitude improvement over present electric motors. Unfortunately, the material used to achieve these densities is brittle and cannot be used in present electric motors. At present, the research community is attempting to make this new magnetic material less brittle, and availability is anticipated to be 1 to 3 years from now. For redundant-type manipulators these types of motors could possibly improve the payload-to-weight ratios significantly.

Hydraulic actuators are important in applications requiring large payload-to-weight ratios. SARCOS Inc.[37, 38], Kraft, Schilling, International Submarine Engineering, and others manufacture and sell hydraulically actuated manipulators. Specific torque and specific power for hydraulic actuators are typically an order of magnitude greater than for electric actuators. Hydraulic technology will be important for modular robotic arm design.

The question of which joints are candidates for which type of actuators depends upon all of the task requirements (e.g., capacity, accuracy, speed, etc.); however, certain actuator types may be better suited for particular joints than others. These should be identified for modular arm design. Also, the design of sensor or diagnostic systems that allow actuators to be run at or above their rated performance levels without fear of failure would improve performance of any robotic manipulator design.

3.6 END-EFFECTOR DEVELOPMENT

End-effector development is critical to the success of any robotic or telerobotic manipulator system. Most industrial manipulators rely on specially designed tools that are changed depending upon the task. General-purpose end effectors (e.g., the Stanford-JPL hand and the Utah-MIT hand) have been developed[39]; however, these devices are far too bulky and unwieldy for practical consideration and remain only research tools. The SARCOS Dextrous Teleoperation System has a three-fingered hand[38], and ODETICS also has developed a three-fingered reconfigurable hand[40]. The development of either a practical quick-change end effector or a general-purpose end effector will be necessary for the success of a modular robotic arm. Central to the development of a general purpose end effector will be the answer to the questions of what is the minimum and what is the optimal number of degree of freedoms required for a robotic end effector. In contrast to these questions is the possibility that several existing special-purpose tools may be adequate. These issues are not specific to modular arm design but are important in the broad context of robotic arm development.

3.7 CONNECTORS—POWER AND SIGNAL

Cable and wire routing are a major issue in manipulator design. Manipulators containing well-instrumented joints require many electrical connections between the joints and control computers. A possible alternative is to use processors embedded in the manipulator links to preprocess the raw sensor signals in order to send reduced data sets resulting in much fewer electrical connections. Embedded data acquisition processors were used in the LTM design in conjunction with fiber-optic data links[41]. The number of conductors was dramatically reduced, making it possible to design the arm with all internal cabling. This idea is limited by the radiation requirements of the application, the radiation tolerance of the embedded electronics and fiber requirements of the application, the radiation tolerance of the embedded electronics and fiber optics, and reliability and maintainability issues. The LTM concept of embedding data acquisition electronics should be extended to include embedded power amplifiers, which would further reduce the cabling problem. Embedding joint data acquisition and power amplification electronics must be considered in the conceptual design phase for the manipulator. Even with embedded electronics (and certainly without them) the issue of cable, wire, and hose routing must be addressed in the context of modular design.

Cable routing is a major issue in manipulator design for cluttered environments. Cable handling/routing is recognized as one of the most dominant constraints in manipulator design. Industrial experience has repeatedly shown that cable routing is a key factor in reliability also.

Because generally low power levels are involved, power can be transferred across joint boundaries through either cables or by means of rotary transformers **[Esser,91]**. Rotary transformers are relatively new to robotics; power losses are around 8%. Modular robotics design will need to consider what type of interface connectors are acceptable for the different power and signal transmission needs. In addition, the need for all electric, hydraulic, or hybrid electric/hydraulic will need to be considered. Will the mixture of hydraulic and electric connectors in the same interface create additional problems and constraints?

3.8 RADIATION AND HAZARDOUS ENVIRONMENT CONSIDERATIONS

Detailed discussions on design guidelines for mechanical manipulators in radiation environments have been published **[Burgess,88; Harrel,83; Vandergriff,90]**. Specific radiation ratings of typical materials and components are cited in these references. Some of the salient features of these references and ORNL's experiences are summarized as follows:

1. To reduce damage resulting from high-radiation environments, mount standard high-temperature-resistant motors with a silicon-free Class H insulation as far as possible from high-level radiation sources. AC servo motors are preferred over brush-type motors because of longer MTBF rating, which is attributed to lack of brush wear. If radiation levels are too high, supplemental shielding can be placed around motors with subsequent penalties of weight, space, and cooling. Use of high-radiation-resistant, nuclear-qualified motors are typically expensive and require long lead times to purchase. Unless the cost and time are justifiable, these types of motors should be avoided.

2. Seals and lubricants for the motor and gear box need to be examined. Seals and lubricants should be able to withstand radiation levels of over 10^8 rads. Radiation-resistant seals and lubricants are available and should be used. Cable insulation is another area that needs to be examined, and again levels in excess of 10^8 rads are easily obtainable. Again the reader should consult the previous references for a very detailed listing of proven materials.

3. Electronic components are typically considered to be one of the weakest elements in a radiation environment. Standard practice has been to move all electronic components as far as possible from the radiation sources. However, if some electronic components cannot be placed out of the radiation environment, the previously cited reference[45] should be consulted.

4. If particle contaminants are a concern, then boots around the joints of the manipulators should be added by the manufacturer or some other type of protective covering should be applied. This could be a major problem for a modular arm design. Design for high-pressure and high-temperature wash down for decontamination is important in radiation environments. This implies that properly sealed connectors, drive shafts, and cover plates are an important consideration.

5. Initial work is being done on investigating the failure modes of electronic components. Preliminary work at the University of Florida indicates that the primary mechanism for failure is the inability of integrated circuits to switch at the required clock speed[46]. Integrated Circuits (ICs) which fail at a particular clock speed can be made operational at a reduced clock speed. This may provide a mechanism for recovery from faults to allow the manipulator to remove itself from the radiation environment. In addition, the ability to predict failure may be possible by periodically operating the ICs at higher clock speeds and observing their behavior.

3.9 FLEXIBLE LINK PROBLEMS

Typically, past robot arm designs emphasized stiff mechanical structure over payload capacity. Because of the demands for higher capacity, longer reach, and greater number of degree of freedoms, structural (link) flexibility becomes an important issue. The scope of this paper is far too limited to address the problems associated with flexible structures in robot design and control; however, a few questions are highlighted relative to modular design. (1) Will link flexibility be significant relative to joint compliance? (2) If link flexibility is important, what approaches are applicable for reduction of flexibility or control of flexible modes (e.g., active and passive damping, trusses, end-of-arm manipulators or activated inertias)?

3.10 DESIGN METHODOLOGY

A methodology for modular manipulator design is illustrated in Fig. 1. A similar figure describing a design methodology for a general robot arm has been published[47].

Clearly the design of any manipulator is an iterative process involving many different design loops. Critical to the modular robotics manipulator design is focusing initial efforts on the development of modular subcomponents, actuators, drive train, control electronics, and sensors. Control algorithm development should also receive attention initially so that control system requirements may influence system design. The development of a set of modular robotic-specific computer-aided design tools or an optimization technique/routine used for optimizing the various system designs would also improve the final concept.

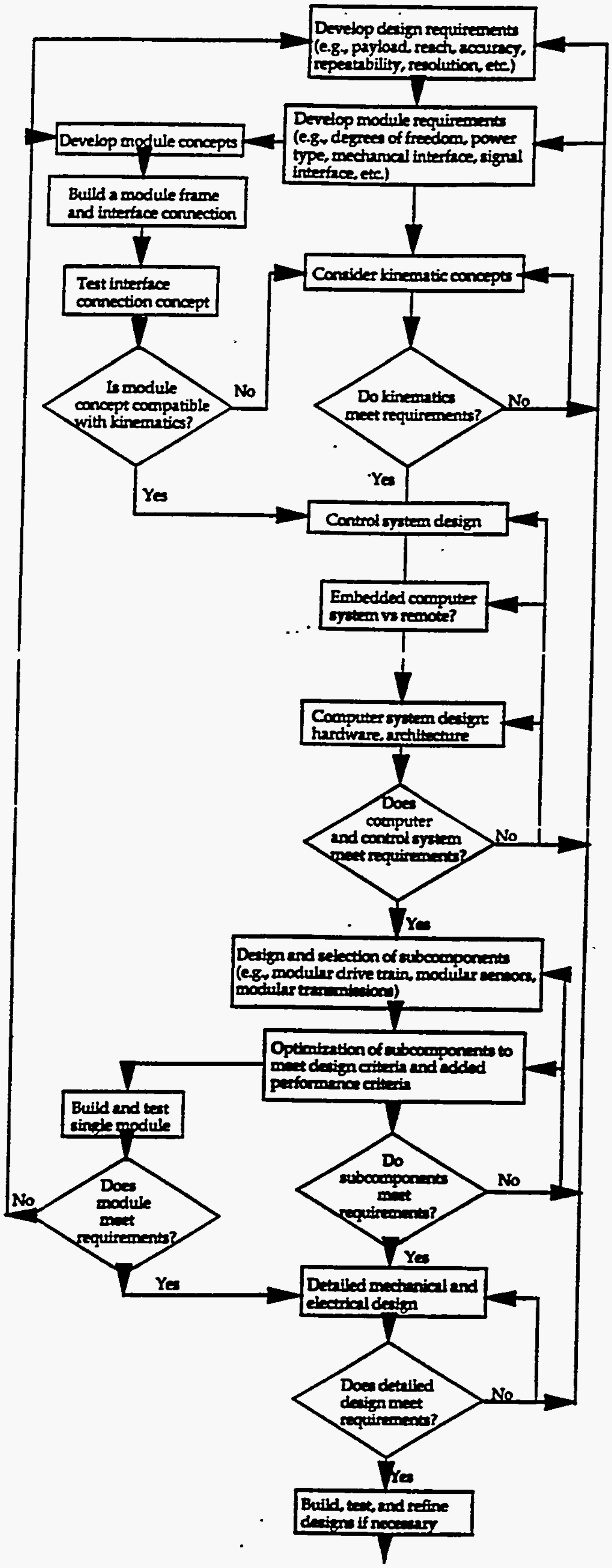

Fig. 1. Design methodology for modular robot.

4. CONTROLS TECHNOLOGY

Control architectures for modular robots need to be modular (just as the hardware design) in order to accommodate new developments in software as well as hardware. Software requires maintenance, and modularity also benefits here. A high-priority need is to create an architecture for the modular robot that accommodates as rapid an evolution in hardware as is possible in the marketplace[48]. A modular architecture that has a layered, nearly standardized interface and that takes local priorities, scaling issues, subsystem integration, etc., into consideration makes technical modification easily possible. This helps to alleviate obsolescence[48].

4.1 CONTROL ARCHITECTURE AND SOFTWARE

Robotic systems need to be adaptable and require a marriage of teleoperation, supervisory man-in-the-loop operation, and repetitive robotic operation, owing to the uncertainties in the workspace and uniqueness of tasks. Control architectures should allow for implementation of each of these scenarios. A telerobotic system is one that is capable of performing either as a teleoperator system or as a system in which the slave manipulator functions as a robotic manipulator where its trajectory and force or impedance are being determined by a computer. The advantage of having a merger of these two capabilities is that repetitive tasks have the potential of being automated, which reduces the demands placed on the human operator.

The major design difference between classical teleoperated manipulators and robotic manipulators is in the compliance and backlash in their design. Teleoperators are designed with minimum physical cross section and inertia in order to provide the most sensitive force reflection. Low inertia design results in light-weight drive trains with significant compliance. This is not detrimental to the positional performance of a teleoperator because an operator is able to visually compensate for the positional error created by the compliance. In contrast, typical industrial manipulators are designed with large cross sections for high stiffness to achieve high positional accuracy. Classical teleoperator design calls for a compromise between acceptable levels of friction and backlash. Backlash is accepted to reduce joint friction for good force reflection. It is again assumed that the operator can compensate for positional error resulting from the increased backlash. In contrast, typical industrial manipulators pre-load drive train gears to reduce backlash, achieve high positional accuracy, and accept the losses associated with additional friction. Because of the large joint friction, industrial robots perform poorly as slaves in achieving force reflection. Historically, to convert an industrial robot to a force-reflecting slave manipulator, a force torque sensor is added to its end effector. The problem associated with such a design has been typically lower performance than a classically-designed teleoperator. Typically, the force/torque signal is extremely band limited because of the noncollocation problem associated with the sensor and the drives[49]. Further, a classically designed teleoperator is force reflecting at every link, while the other is force reflecting only at the end effector. A simple way of overcoming the backdrivability problem in tight positional servodevices like an industrial manipulator is by means of joint torque loops. The idea is not new and was first tried by Arzabaecher[50] in the early 1960s, by Flatau[51] in the 1960s, by Luh et al.[52] in the early 1980s, and by ORNL[18] in the LTM in the late 1980s. By using high-gain torque feedback, most of the joint friction can be effectively reduced. Torque ripples caused by harmonic gear reducers and the rotational inertia of the actuator can be shown to also be effectively reduced. Achieving high-gain torque loops is critical in the design of a good telerobotic system. Further, it could be argued that it is critical for the design of a good robotic system, too, since interaction with different environments is a critical limitation of present industrial manipulators.

Control systems for modular arms are typically distributed, hierarchical designs that are modular themselves. The software must be made modular to accommodate future changes and to facilitate portability. The LTM control system[53] is of this type. The result is independent controllers for each joint[54] that communicate to higher-level processors. The question of partitioning the responsibility between distributed and central processors becomes important for modular arm design. Should embedded processors perform some of the control tasks or should they merely collect and communicate data?

The LTM control system is programmed in the C language; however, C++ will most likely be the choice for the next generation. The LTM software is modular in design and operates with control functions written in a table for execution at loop rate. The functions and their order can change from loop to loop. In the LTM, the hierarchical architecture is realized through arm processors that are connected to joint processors at each joint. One arm processor communicates with and controls a number of joint processors. The number of joint processors that a particular arm processor communicates with depends upon the arm configuration (i.e., the number of links and joints).

One noteworthy real-time operating system that has been developed specifically for robotic applications is the CHIMERA, used by CMU's reconfigurable manipulator[56, 57, 58]. CHIMERA provides a UNIX-like environment and allows hierarchical models for robot control, such as NASREM, to be easily implemented. MICA[59] and RIPE[60] provide programming environments that allow rapid software development of robotic systems.

4.2 MANIPULATOR CONTROL ALGORITHMS

Impedance-type control schemes should be pursued for modular robotic activities because of the need for active compliance. Passive remote compliance center (RCC) devices on the end effector of industrial manipulators were designed to overcome a serious limitation of industrial manipulators[61]. When performing a peg-in-the-hole task with chamfer-type holes, the compliance and the compliance center of the end effector must have a certain relationship in order to avoid a jamming and wedging phenomenon. While typically RCC devices are passive devices, significant work has been done in active compliance devices such as impedance-type control schemes[62,63,64]. Even a grinding-type task can significantly benefit from impedance-type control schemes[65]. For a chamferless insertion task, admittance-type control, which could be reformulated as an impedance-type control scheme[66], can overcome uncertainty in the orientation and displacement in the peg insertion problem.

4.3 TELEOPERATION

For the EM applications envisioned, a modular robot needs to perform well, not only as a robotic manipulator but also in a teleoperated system. Typical control schemes tying together a master manipulator with a slave manipulator (in our case the slave will be the previously discussed modular robotic manipulator) fall generally into two categories: position/position (classical) and position/force (see Fig. 2). The classical architecture is widely used in industrial teleoperator systems such as the Schilling and Kraft systems. Further, the M2, ASM, and LTM manipulators at Oak Ridge National Laboratory (ORNL) are all based on the position/position design. The position/force architecture[67] was examined by Goertz[68] in the early 1960s, and an actual system was built by Flatau[51] in the late 1960s. Poor performance has historically been the reason the position/position design has been picked over the position/force architecture; however, this could change. The position/position teleoperator architecture has good stability margins and whole body force reflection. Position/force architecture has poorer stability margins because of the problem of noncollocation of sensor and actuator, and does not give whole body force reflection. Typically, hydraulic systems are position/force.

Teleoperation will require the development of a universal master because the ability to reconfigure will make joint-to-joint-type controllers like those found on classical teleoperated systems[68] unworkable (unless the master is made modular and reconfigurable as well). Universal master systems such as the JPL controller[69] have been developed, and control algorithms for dissimilar systems are achievable with present-day processing power[70].

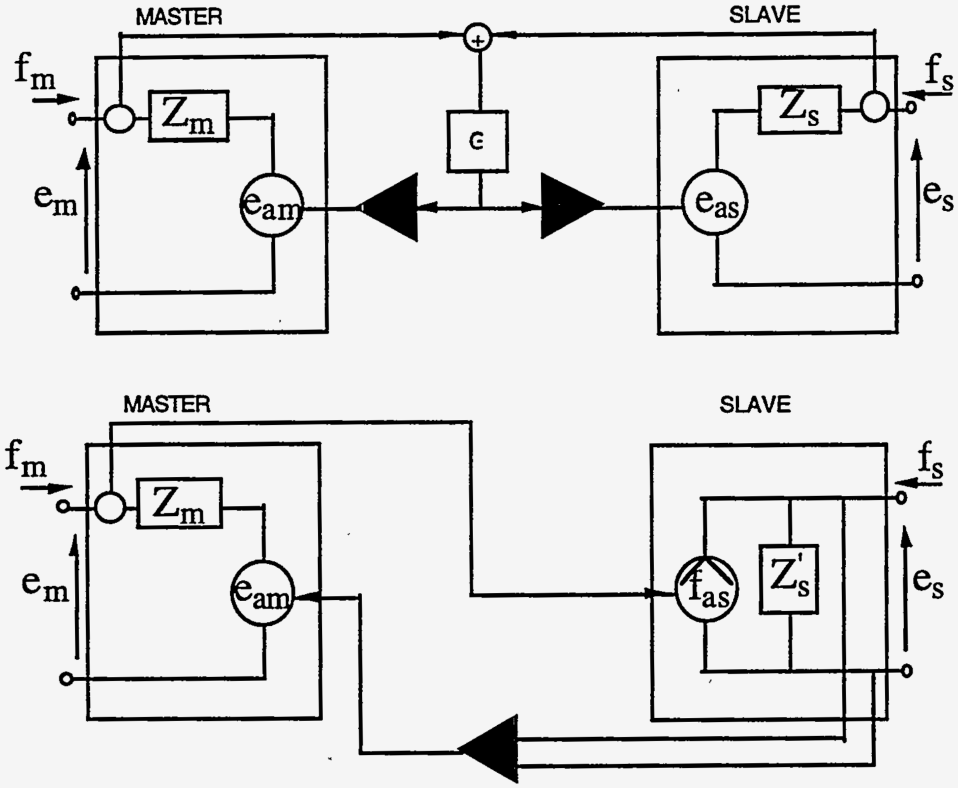

Fig. 2. Teleoperator architectures (a) classical and (b) position/force.
(Spice Equivalent: e_i = torque, f_i = velocity, i= m,s)

4.4 SENSORS

At the minimum an industrial manipulator has joint positional sensors. To make its joints more backdrivable, local torque sensors around each joint should be provided. These torque loops also reduce the effect of local torque ripple moments created by harmonic gear reducers. The LTM, the Schilling ATLAS manipulators, and the Robotics Research manipulators all employ joint torque sensors. The sensor designs used in these manipulators do not allow for compensation of all of the joint friction, and new sensor designs with different placement and higher signal-to-noise ratio would be useful. Depending on the type of architecture being used, a force-torque sensor on the end effector would be needed to control contact forces or to implement impedance-type controllers.

The development of a small IMU that would provide end effector linear and angular accelerations, velocities, and positions could provide data not usually employed for manipulator control. The applicability of these signals in an advanced control algorithm should be studied along with the development of the sensors.

Visual servoing of robotic manipulators could have some merit. Mounting of a camera (or cameras) either on or off the manipulator have been examined. Such schemes could be used for object tracking or compensating for deflection of the manipulator itself. If end effector tracking is used, then manipulators using light-weight materials are a possibility. However, light-weight manipulators are very flexible and do present additional control challenges[71].

4.5 COLLISION AVOIDANCE SENSORS

Design of sensors for detection and avoidance of impending collision is important for any manipulator system designed for use in hazardous environments. The arm must protect not only against damage to itself but also the external equipment. Sensor systems such as the whole arm sensor systems being developed by Wintenberg et al.,[72] Merritt Systems[73], and Novak[74] are good examples of collision detection systems. A modular arm requires updating the knowledge of the location of the collision detection sensors resulting from configuration changes, which should not be a problem for sensor systems permanently fixed to the modular links.

4.6 WORLD MODELING

Development of a world model transcends many of the technical issues related to modular robotics. A world model could be used for determination of potential configurations and improvements gained by such changes, for graphical preview of moves, and for obstacle avoidance. Development using, interpreting, and updating an adequate world model is an unsolved problem for the complicated time-dependent environments usually found in typical robotics applications and are topics for future research.

4.7 HUMAN-MACHINE INTERFACING

Complementary with the development of a world model is the development of a human-machine interface. Many industrial robots utilize simple teach pendants or teach/playback modes where the manipulator is moved manually. For the modular robot these methods of input are possible (depending on the application), but a more advanced system employing a graphical user interface should be developed for EM applications.

Display and interpretation of data is pertinent to human-machine interface development. Data acquisition, data display, data fusion, and development of an operator console for supervisory control are all areas important to the development of an effective human-machine interface for a modular robotic arm.

5. CONCLUSION

The development of a modular robotic arm is the next logical step in the evolution of robotic manipulators. As stated in previous sections, the present impetus behind pursuit of modular design is the remote engineering paradigm of improved reliability and availability provided by the ability to remotely maintain and repair a manipulator operating in a hazardous environment by removing and replacing worn or failed modules. Servicing of failed components can take place off-line and away from hazardous conditions. In addition, the desire to reconfigure an arm to perform different tasks is also an important driver for the future development of a complete modular robotic manipulator.

A truly modular robot is a technologically advanced system requiring more development. Modular concepts, however, are applicable and have value for robotic designs. Future efforts should focus on the general areas of sensor development, distributed electronics, control system development, and modular-robotics-specific topics such as design of modular drive trains, power and communication interfaces for connecting modules, automatic generation of kinematics and inverse kinematics, methods for determining arm configurations, and controls. The development of arbitrarily interchangeable modules, however conceptually pleasing, should be forestalled in favor of first developing a pseudo-modular design having modular drive train elements, modular sensor packages, and modular electronics. This design could emphasize the advantages of easy maintenance and improved reliability.

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APPENDIX

OUTLINE OF TOPICS SPECIFICALLY FOR MODULAR ROBOTICS DESIGNED FOR EM APPLICATIONS

I. Design Issues
  A. Mechanical design
    1. Kinematics
      a) What kinematic designs are most appropriate for EM applications?
      b) What kinematic designs are most appropriate for reconfigurability?

    2. Discrete modules
      a) What discrete modules are desirable? (e.g., 2-DF modules, discrete drive trains, or discrete motors)

    3. Interface connections—mechanical, hydraulic, sensors, pneumatics, tendons, and hybrids of any of the different modules
      a) What are acceptable interface connectors for the different transmission needs?
      b) What combinations are required (i.e., are some all electric and some all hydraulic interfaces acceptable, or will there always be a need for electric/hydraulic?)?

    4. Modular interface (m^2 concept)
      a) Can the interface connectors be made modular (i.e., can additional interfaces be added as needed such that if additional links are included whose connections exceed those available, then an additional interface module is included, etc.?)?
      b) What would be acceptable designs for the interface modules?

    5. Packaging—hydraulic vs electric interchanging
      a) Which technology is best suited for the modular robotics concept?

    6. Cabling and hose routing vs module size
      a) How can cables, hoses, etc., be routed in the best manner with respect to modularity?

7. Structural flexibility and joint compliance
    a) Will link flexibility be significant relative to joint compliance?
    b) If link flexibility is significant, what approaches (i.e., active and passive damping and nontraditional kinematics such as trusses) are applicable?
    c) Is the use of end-of-arm manipulators, controlled inertias or gyros for active damping viable?

B. Actuator technology
  1. Payload-to-weight ratio improvement for electric actuators
    a) For what joints are electric actuators viable at present?
    b) Are there future near-term developments in actuator technology that will improve the availability of electric actuators?
    c) Can sensor systems be designed so that actuators can be run above their rated values without fear of failure?

  2. All hydraulic arm
    a) Can hydraulic actuators be made clean enough (i.e., do not leak) for EM applications, especially in light of minimization of secondary wastes?

  3. Combination of electric and hydraulic actuators
    a) Is hydraulic actuator technology compatible with electric within the same arm?
    b) What are the problems with module-to-module interface design for a hybrid hydraulic/electric arm?

C. End-effector development
  1. New hands/grippers
    a) What are the minimum number of degrees of freedom that would improve performance relative to EM activities?
    b) What type of hands, grippers, or special-purpose end-effectors exist that are applicable to typical EM applications and could be made compatible with a modular system?

II. Controls-Related Technologies
  A. Control systems hardware
    1. Embedded electronics
      a) What are the requirements for an embedded electronics system (i.e., should it simply collect and communicate data or should it perform joint-level controls?)?

    2. Distributed processors—DSP technology
      a) Are new DSP processors applicable as joint-level distributed controllers?

3. Supervisory controller hardware
    - *a)* What are the requirements for a high-level controller (e.g., good as an human-machine interface, good for graphical display of arm motion, control loop rates, communication requirements, etc.)?

4. Redundancy
    - *a)* What type and levels of redundancy are best suited for EM applications?
    - *b)* Would redundancy be an asset for a broad number of jobs?
    - *c)* Is programming and control of redundant arms too costly with respect to the advantages gained?
    - *d)* How can redundant arms best be controlled?

B. Expended control architecture for telerobotic systems—controls for robotic and teleoperation

1. Sensors for control
    - *a)* Encoders vs resolvers: which are best?
    - *b)* Joint vs actuator sensors: are both needed?
    - *c)* What new developments are needed to support drive-train torque measurements?
    - *d)* What new developments are needed to support wrist-mounted force/torque measurements?

2. End-point tracking
    - *a)* Can an inertial measurement system be designed and effectively used?
    - *b)* Is a vision-based end-point tracking system viable?
    - *c)* Is the ODETICS concept of laser beamed down the link viable?

3. Collision avoidance
    - *a)* What sensors are available to help monitor obstacles and avoid collisions?
    - *b)* What control techniques are effective in obstacle avoidance?
    - *c)* Is whole-arm obstacle avoidance desirable, and if so, how can the present whole-arm systems be integrated into a modular design?
    - *d)* What issues, with respect to sensor fusion, are important for collision avoidance?

4. Position/force control loops for telerobotic arms
    - *a)* Is a position/force controlled system superior to a classical position/position controlled system?
    - *b)* What are the sensitivities of a position/force controlled system?
    - *c)* What are the issues with respect to stability of a position/force controlled system?
    - *d)* What are the sensor requirements for a position/force controlled system?

C. Human interface

1. Dissimilar master-slave teleoperation issues
    - *a)* Are dissimilar master-slave systems necessary, or should a modular replica master concept be pursued?
    - *b)* If dissimilar systems are deemed viable, what mathematics are important for dissimilar master-slave systems (e.g., quaternions, singular value decomposition)?
    - *c)* If dissimilar systems are deemed viable, what control algorithms are suitable for dissimilar master-slave systems (e.g., Cartesian stiffness/impedance)?

2. Display fidelity and modality
    - *a)* Is a real-time graphic interface needed?
    - *b)* If dissimilar systems are deemed viable, how is information displayed in a dissimilar master-slave system?

III. Reliability, Maintainability, and Reconfigurability

A. System reliability

1. Fault detection and graceful degradation
    - *a)* How can a manipulator be made to detect failures (or impending failures) and then to shut down (degrade) in a graceful fashion (i.e., reduced capability, obviously, but still able to move out of an area, etc.)?

2. Sensor fusion issues
    - *a)* How can one make use of (and sense out of) data from different and multiple sensors to improve reliability?

3. Kinematics design
    - *a)* What kinematic designs are best from a reliability standpoint?

4. Redundant sensors—positional and force/torque (torque loops and force/torque sensor at end effector)
    a) What sensor types and locations improve reliability?
    b) How can drive-train torque sensors and wrist-mounted force/torque sensors be used to provide redundancy for improved reliability
    c) Should redundant sensors be employed to improve reliability?
    d) Can redundant measurements be used to improve reliability (e.g., inertial measurement system employed for arm motion if joint sensors fail)?

5. Parallel controllers
    a) How can parallel controllers improve system reliability?
    b) How are decisions arbitrated between parallel controllers?
    c) How many parallel paths are needed for reliability?
    d) How can control code be "parallelized" to improve reliability?

6. Manipulator cabling
    a) What types of manipulator cabling can be used to create a reliable system (e.g., Transformer rotary joints for power transfer)?
    b) What are the flexing limits of typical cables?
    c) Could inductive coupling be used reliably?
    d) Could fiber optic coupling be used reliably?
    e) What types of wireless transmission are available?

7. Connectors
    a) What type of connectors produce reliable coupling?
    b) Can blind mate connectors be made reliable?

B. System maintainability
1. Serviceability issues
    a) Can a manipulator be designed to make it easily serviced? How?
    b) What are the relevant issues with respect to remote servicing?
    c) Can modularity improve maintainability? How?

2. Modular drive train
    a) Can a modular drive train improve maintainability?
    b) If modules are replaced as a matter of routine maintenance, can these modules in turn be maintained in an area remote from the arm?

3. Diagnostic electronics
    - *a)* Can sensor systems that monitor actuator temperature, hydraulic pressure, etc., be designed so that diagnostic routines can be run to predict failure or to help fix problems when failures occur?

C. Reconfigurability

1. Task specific-manipulability index, etc.
    - *a)* Can the arm be reconfigured to improve task specific-manipulability index?
    - *b)* What manipulability measures are useful and what routines are applicable to quickly determine the various manipulability measures?

2. Reliability issues like fault tolerance
    - *a)* Can reconfigurability be used to improve fault tolerance?

3. Autogeneration of kinematics and inverse kinematics and the associated code
    - *a)* What routines are applicable to the automatic generation of inverse kinematics and forward kinematics?

4. Autotuning and calibration
    - *a)* Will autotuning be necessary for a reconfigurable arm, and if so, what routines are applicable to the autotuning problem for a reconfigurable arm?
    - *b)* How can a reconfigurable arm be calibrated to provide desired positional accuracy, etc.?

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