TELEPRESENCE AND TELEROBOTICS

John Garin,
Joseph Matteo,
and
Von Ayre Jennings, Ph.D.

Martin Marietta Aero & Naval Systems
103 Chesapeake Park Plaza
Baltimore, MD 21220

ABSTRACT

Martin Marietta is developing the capability for a single operator to simultaneously control complex remote multi degree of freedom robotic arms and associated dextrous end effectors. An optimal solution within the realm of current technology, can be achieved by recognizing that (1) machines/computer systems are more effective than humans when the task is routine and specified, and (2) humans process complex data sets and deal with the unpredictable better than machines. These observations lead naturally to a philosophy in which the human's role becomes a higher level function associated with planning, teaching, initiating, monitoring, and intervening when the machine gets into trouble, while the machine performs the codifiable tasks with deliberate efficiency.

This concept forms the basis for the integration of man and telerobotics, i.e., robotics with the operator in the control loop. The concept of integration of the human in the loop and maximizing the feed-forward and feed-back data flow is referred to as telepresence.

Telepresence at Martin Marietta consists of an exoskeleton master commanding an anthropomorphic slave robot. The slave will serve as a human surrogate, replacing man in hostile environments. The exoskeleton master controller will provide a feeling of transparency (operator believes he is in the robot's surroundings) through advanced controls. This approach will address integration of the human into the control loop.

INTRODUCTION

The new, high technology battlefield has become an extremely lethal environment where survival will depend on human surrogate devices. These hazardous environments are such that with the human protected by armor and/or environmental suits (i.e., space suit, diving equipment), performance is greatly degraded and the human life is under unacceptable risk. In some cases human access may be impossible.

Hazardous environments such as Nuclear-Biological-Chemical (NBC) environment, subsea or outer space, will require robotic systems that can perform human-like tasks. The performance of these tasks will require robotic arms that have redundant kinematics, bandwidth, and weight-to-power ratios of the human.

Modern robotic arms that resemble humans have seven or more degrees of freedom (DOF) to allow arbitrary positioning and orientation of the end effector. Manipulators with more than six DOF can have control problems as the manipulator configuration often becomes degenerate (two or more DOF produce the same motion of the end effector). We are addressing robotic arm requirements of 7 DOF. This type of kinematic arrangement is required to perform human-like tasks and provide telepresence functions.

Redundant kinematics significantly affects telerobotics control, and requires special man-machine interfaces. To avoid degeneracies, a special controller must be used, one type of which (an exoskeleton controller) Martin Marietta is now developing.

PRECEDING PAGE BLANK NOT FILMED

There are basically three (3) types of kinematic stances used in telerobotics. The nuclear industry typically uses the "elbow up" stance. The upper arm extends horizontally outward, lower arm dropping vertically downward, and the end effector extending horizontally.

The Japanese have implemented a design that has the "elbow sideways" or the actuators causing motion in a horizontal plane. This kinematic arrangement is referred to as a Selective Compliance Articulated Robotic Arm (SCARA). It is very useful for industrial applications because motion is independent of gravity, but has limited use in telerobotics.

The third configuration is the anthropomorphic stance which resembles that of the human arm. The upper arm drops vertically, and the lower arm and end effector axes are aligned, extending forward horizontally. Martin Marietta will be concentrating on the anthropomorphic stance of the human as their model. The choice affects control issues greatly and is based on the rationale in the following paragraph (Figure 1).
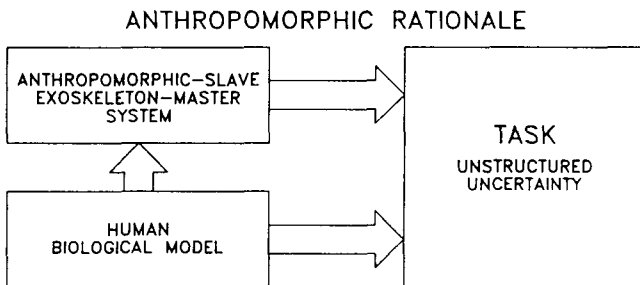
ANTHROPOMORPHIC RATIONALE

Figure 1. Teleoperator System Modelled After Human Operators will be More Intuitive, Easier to Use, Reliably Controlled

A telerobotic system that is modelled after the human operator will be more intuitive, and thus easier to use (less cognitive input) and more reliably controlled (less fatigue to the operator). This reduces learning time, and creates a more natural control environment.

TELEPRESENCE AND TELEROBOTICS

Martin Marietta Aero and Naval Systems started the development of telepresence systems in 1986.

The objective of the Aero & Naval Systems Exo-skeleton Master and Anthropomorphic Slave (EMAS) arms system is to provide dextrous manipulation. This system will utilize and develop the man-machine interface and be used in a tele-operational control mode to provide maximum telepresence effect: sensory information back to the operator.

The term telepresence refers to the information required by the operator to "feel" a sense of "presence" in the working environment. The issues dealing with telepresence relate to three major human factor issues:

- Perception
- Cognition
- Psychomotor Control

To complete any task, whether teleoperated or not, the task must first be understood (perception), a decision must be made about what action to take (cognition), and then that action must be carried out (psychomotor control). This same thought process is paralleled in the robot controller.

The ultimate goal of this system is to provide human-like manipulation capabilities. In some cases, physical capabilities will exceed those of humans.

The measure of these capabilities can be summed into dexterity which refers to the ability of the manipulator to perform tasks that require human-like manipulative capabilities. The robotic arms will provide that type of manipulation. The degree of dexterity will be characterized by comparing the time to perform this task by a human with his/her bare hands to that of the robotic arms. The measured parameters will be:

- rate of task completion
- accuracy/quality of task performance
- impact of system on remote environment
- impact on operator, i.e. workload/fatigue

The overall relationship between the major components of the exoskeleton master and anthropomorphic slave are shown in Figure 2.

ANTHROPOMORPHIC SLAVE

The anthropomorphic slave arm will approximate human performance and be scaled in both size and strength. Specifically, a single manipulator can handle an object up to 50 pounds in weight and
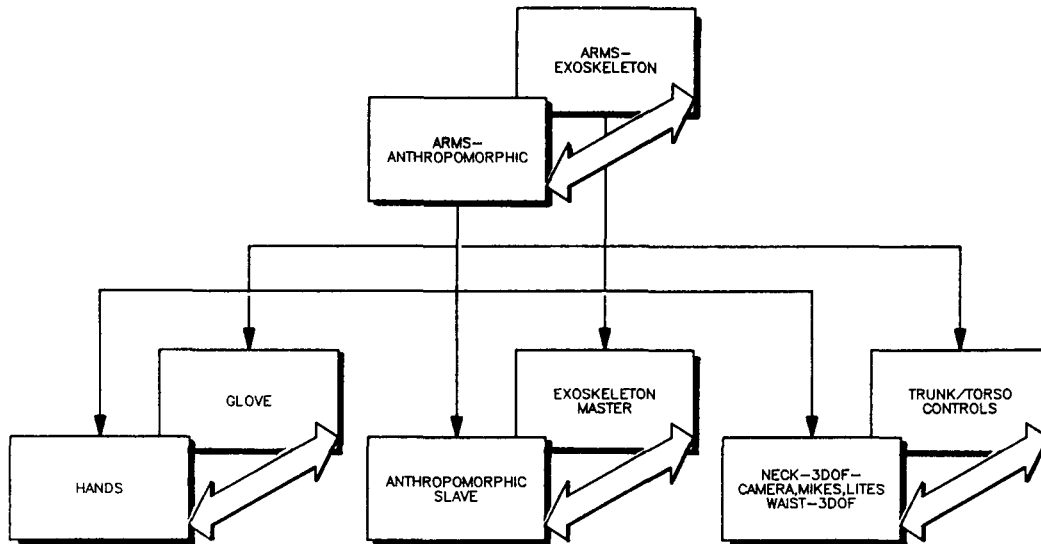
Figure 2. Telepresence System Exoskeleton Master and Anthropomorphic Slave

move it throughout most of a hemisphere with a radius of approximately 4 feet. The total weight of 1.5x scaled up slave arm should be no more than approximately 160 pounds. For portability, it can be quickly disassembled into modules weighing no more than 40 pounds each. The most demanding sequence of operations involving motion of a heavy (approaching capacity) object, grasping the object, and reorienting and moving the object across the manipulator range of motion to a new location can be accomplished in less than 5 seconds with great accuracy. At lesser load, the arm can reach speeds of 160 ft/sec² and 360 ft/sec² tip speed carrying 25 lb. and 0 lb. payloads, respectively. The single arm manipulator system is able to meet the performance specifications while mounted on a platform, a ROV submersible, or on the back of a light truck and while subjected to an adverse field environment.

EXOSKELETON MASTER

The exoskeleton master goals include being used by 5–95th percentile operators. This is achieved by providing adjustments in the major anthropometric ranges. These ranges of adjustments are still being determined.

The following information and sensory feedback shall be provided back to the operator (Figure 3).

Hand Controller (Master)

1. Force Reflection
2. Somesthetic Feedback
   - Tactile
   - Pressure (below skin surface, deep muscular pressure)
   - Temperature
3. Joint Angle Sensing
4. Haptic Display

Arm Controller (Exoskeleton Master)

1. Force Reflection
2. Joint Angle Sensing
3. Stiffness Sensing (Kinesthesia)
   - EMG
   - Muscle Sorno
   - Co-Contraction

SERVO CONTROL REQUIREMENTS

Innovation in servo–control system design has been under development. This architecture is as shown in Figure 4. Control of both force and position are required. The system must adapt to payload, be achievable on a flexible or moving platform, and driven by sensors of position and force. Control algorithms are arranged for rapid computation on distributed processing computers. The following (4) control modes are provided.
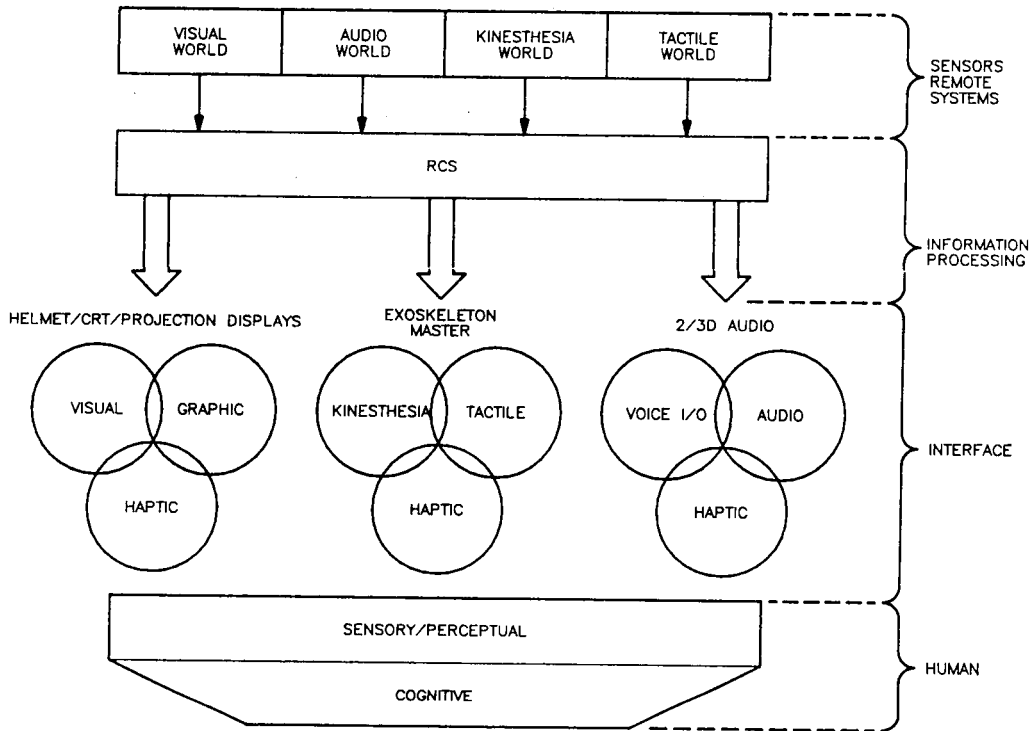
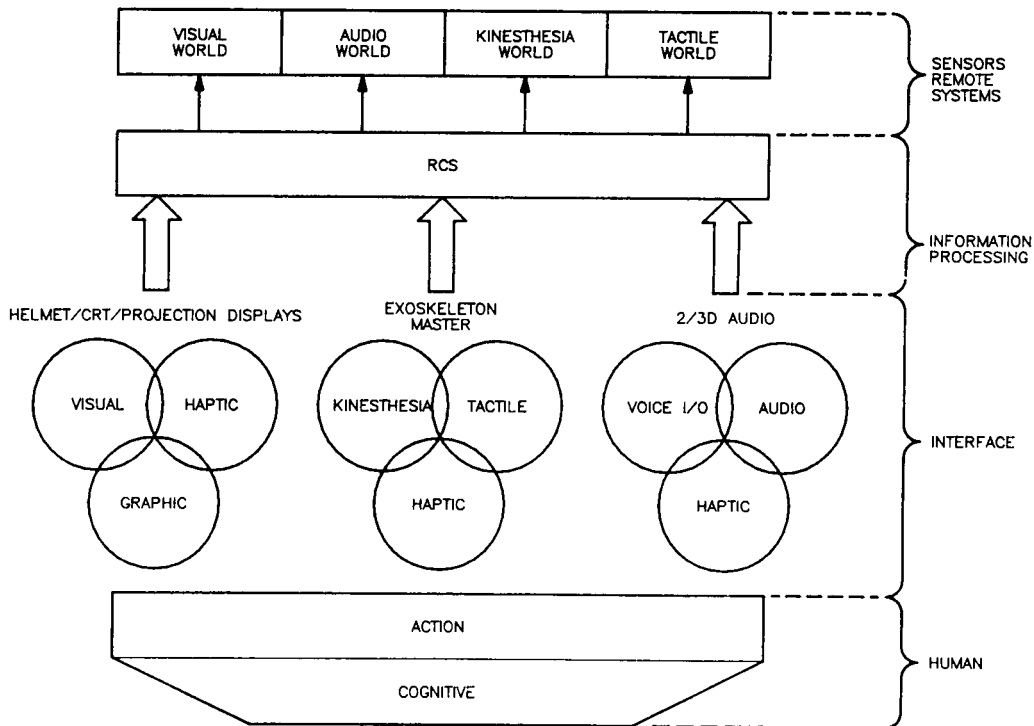Figure 3. Telepresence Control Station Feed Back

Figure 4. Telepresence Control Station Feed Forward

- Computer Supervisory Control – The slave arms shall be able to perform preprogrammed functions such as:
  - manipulator arm storage
  - tool extraction and storage
  - repetitive tasks that have been previously taught
  - collision avoidance (arm to arm)
  - end of arm camera tracking

- Control Adaptive to Accuracy – Speed of motion is faster when less accuracy of position or force control is required.

- Cooperation Control – Two arms are able to cooperate on the handling of a long and heavy object and on the application of opposing forces to one or two objects.

- Collision Survival – The arm will stop motion without damage to itself upon contacting an obstruction to the motion of any link of the arm, when the speed of motion is one quarter of the highest speed.

INTEGRATED WORK STATION

For telerobotics to be a cohesive system or provide telepresence, four key perceptual functions, visual, audio, kinesthesia and tactile world (Figures 3 and 4), must be integrated.
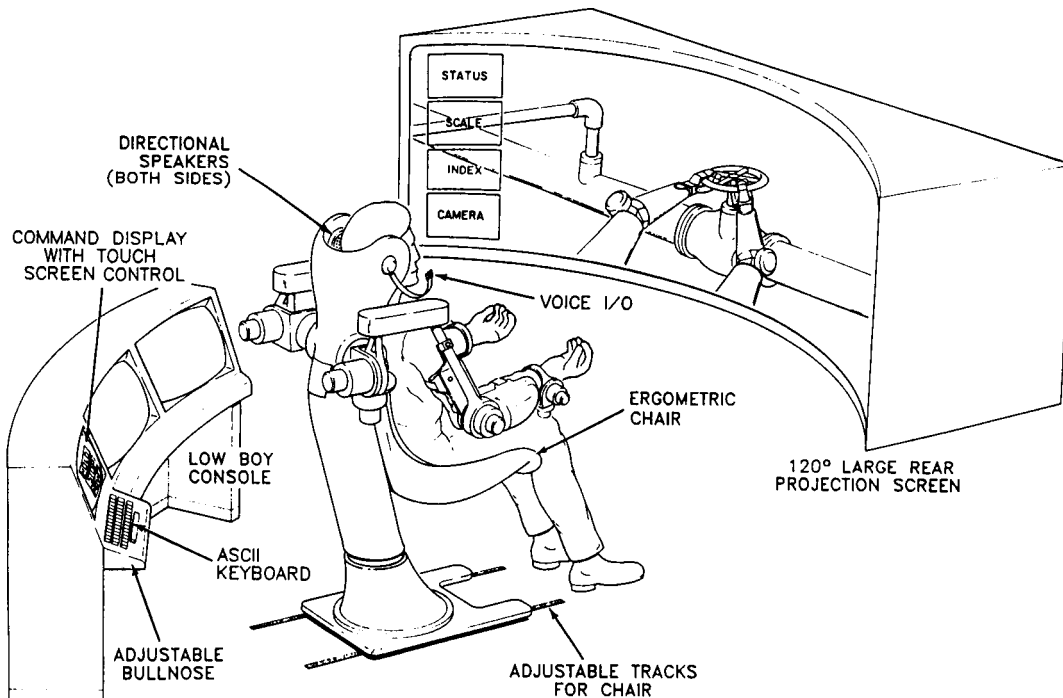
The visual feedback will be achieved through a video system with enough resolution to match operator acuity. The audio system will provide real-time auditory information with 3D cues. The kinesthesia information is provided through the exoskeletal controller in the form of forces and torques. The tactile world is addressed through touch sensors on the surfaces of the arms and fingers.

a) Development of a comprehensive concept for an anthropomorphic manipulator system (Figure 5). The overall concept for this system consists of the slave manipulator, an exoskeleton master controller, telepresence sensory displays and a computer control system. The underlying approach to the concept is to integrate the human operator into the system in a way that

takes advantage of the human's tremendous perceptual, cognitive and psychomotor capabilities. For example, the manipulator arm has 7 degrees of freedom that are identical to the arrangement of joints on the human arm. Similarly, forces and torques acting on the manipulator will be fed back to the human's arm in a way that will cause operators to feel as if they were doing the manipulator task themselves. In this way, the anthropomorphic approach will allow the operator to concentrate on the task to be done instead of what motors to turn on or off.

Figure 5. Telepresence Control Concept

b) Definition of Functional Requirements for Anthropomorphic Performance. Several psych-omotor and perceptual characteristics of the human operator were considered in defining the system functional requirements. For example, the movement characteristics of single joints in humans were evaluated to help define the limiting conditions for the corresponding manipulator joint (Figure 6). Other parameters examined included range of motion, accuracy, repeatability, static and dynamic torque for joint movements and a variety of psychophysical characteristics such as position and force sensitivity.

c) Technology assessment and trade-off studies for actuators, sensors and power transmission. Using the functional requirements derived from anthropomorphic considerations, various manipulator parameters were defined and analyzed. These include the joint ranges of motion, static and dynamic torques (Figure 7), and actuator optimization (Figure 8).

d) Completion of Final Mechanical Design. The final design of the anthropomorphic manipulator, based on the design requirements described above, consists of a series of inter-changeable modules that can be configured not only as an anthropomorphic design but in a variety of other configurations (Figure 9). This manipulator will serve as a unique test bed that represents a critical first step towards teleoperated control of highly maneuverable robot systems.
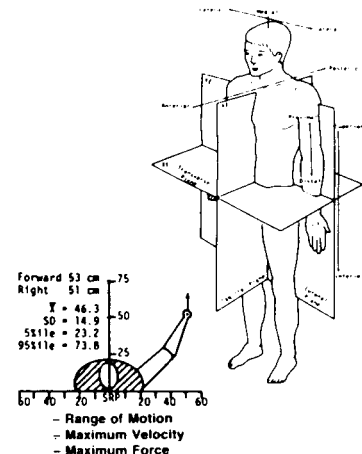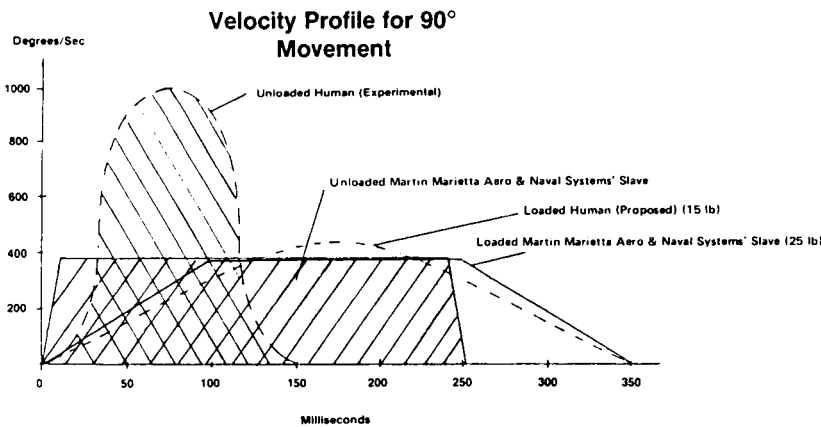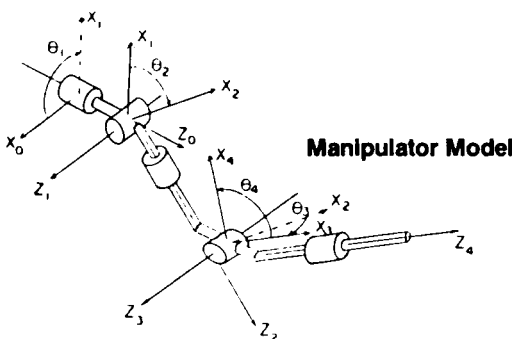

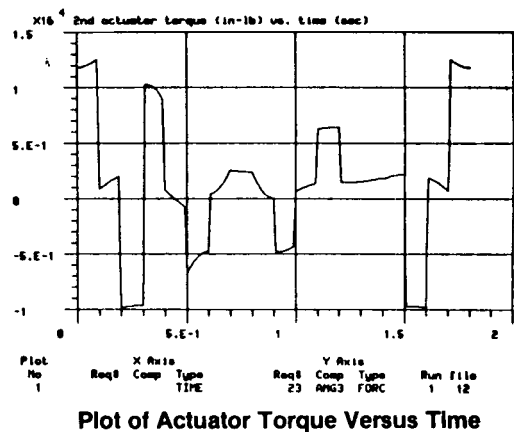Figure 6. Human Performance Characteristics

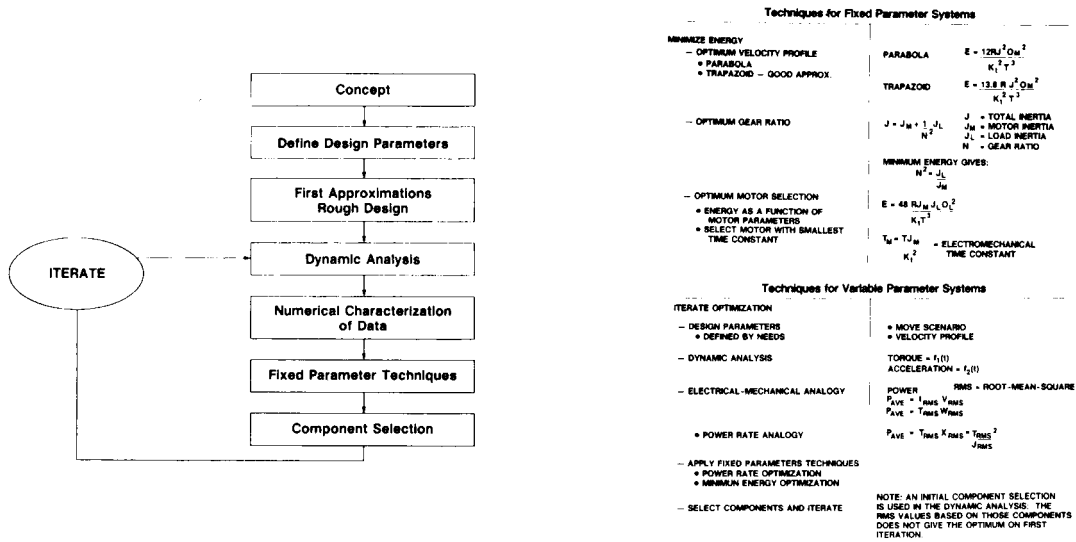
Figure 7. Analysis of Manipulator Dynamics
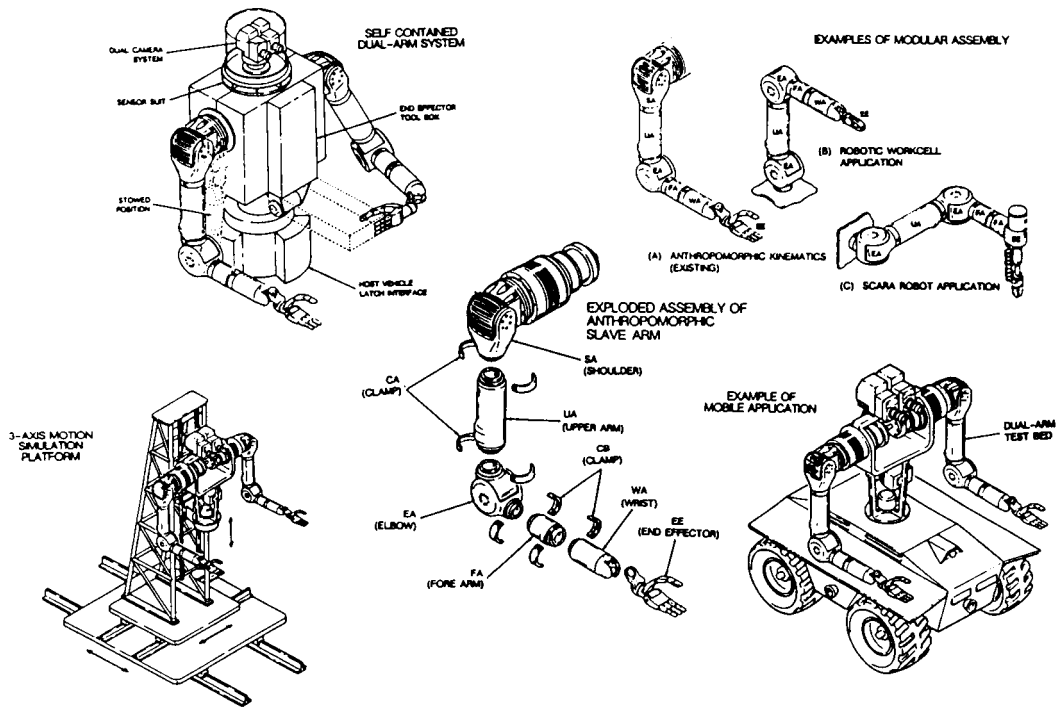
Figure 8. Actuator Optimization

Figure 9. Anthropomorphic Manipulator

1) Conceptual design of the exoskeleton master controller is shown in Figure 5. The exoskeleton controller will be a unique method for controlling the anthropomorphic manipulator by using movements of a human operator's arm. This form of teleoperator control will also allow the forces and torques acting on the manipulator to be directly applied to the operator's arm, resulting in an intuitive and easy to understand presentation of complex sensory data.

2) A test bed for teleoperator control of the anthropomorphic manipulator is being developed initially using a single degree of freedom

417

master-slave arrangement (Figure 10). This will consist of the elbow joint from the manipulator with its associated sensors and servo control and the elbow joint of the exoskeleton master device (described in the previous section). This test bed will be used to develop force reflection algorithms and algorithms for position or force control of the manipulator. These algorithms will allow a unique and powerful form of robot control to be tested, where human operators command robot movements by performing the movement themselves. This will provide initial information of kinesthesia.
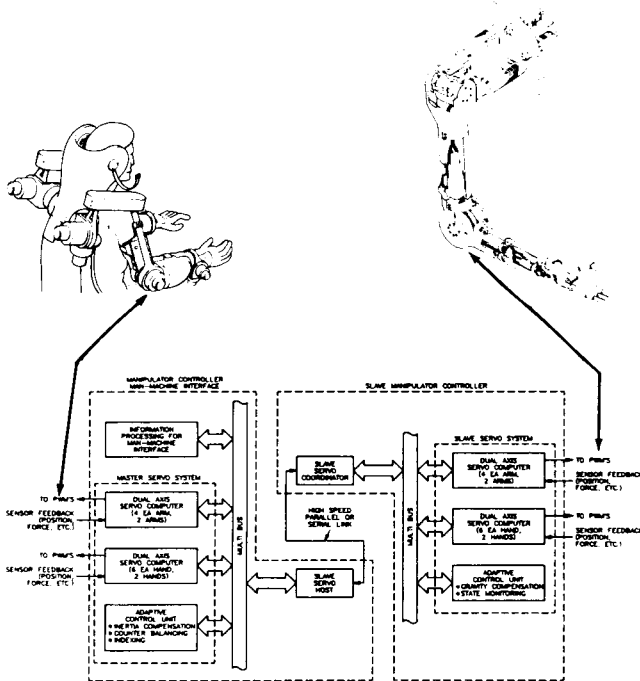
The tactile information will be provided through a glove like device to feed information back to the operator's hands (see Figure 5).

We have proceeded to develop the manipulator system and the control station as described below.

Significant progress was made in two areas:

1) Design of anthropomorphic manipulator system:

The design of a unique 7 degree-of-freedom manipulator was completed. This manipulator, when constructed this year, will be one of the most advanced robot arms available in terms of speed, dexterity, accuracy and load-to-weight ratio. Progress was made in several key areas that contributed to the overall design.

2) Control approach

The control development has also progressed. The Advanced Servo Computer (ASC),

Figure 11, developed in 1986 was enhanced to address the needs of teleoperation.

The ASC board is an extremely powerful data acquisition and processing system that will allow a variety of high-speed and sophisticated low-level servo control algorithms to be implemented.

The ASC board will be used as shown in Figure 11 as part of the low level control for the master/slave system. The RCS (Real-time Control) approach is being implemented as shown in Figure 12. The functionality is also shown in Figures 13 and 14.

The basic concept is to utilize a powerful servo board which can handle sensory inputs and communications. As the cycle time to complete these tasks increases, the system stability increases and allows the use of more simple models.
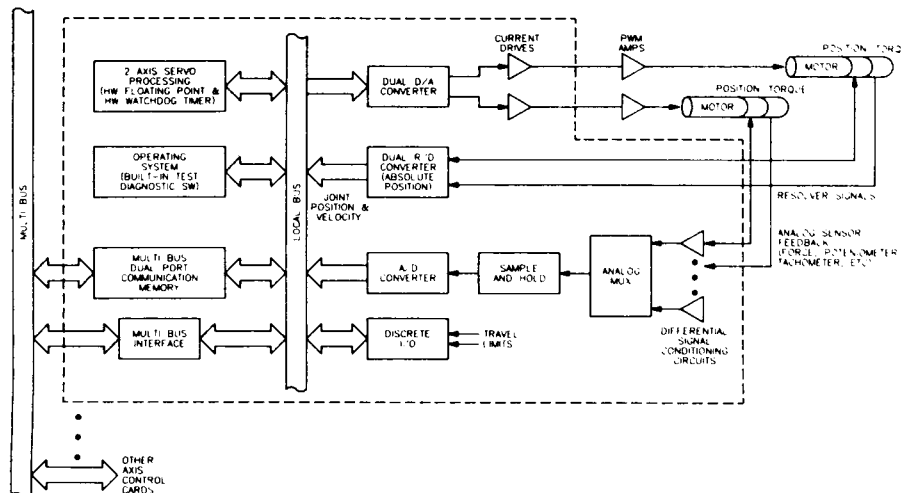

Figure 10. Telepresence Anthropomorphic Master/Slave Test Bed

Figure 11. Dual Axis Servo Control Card
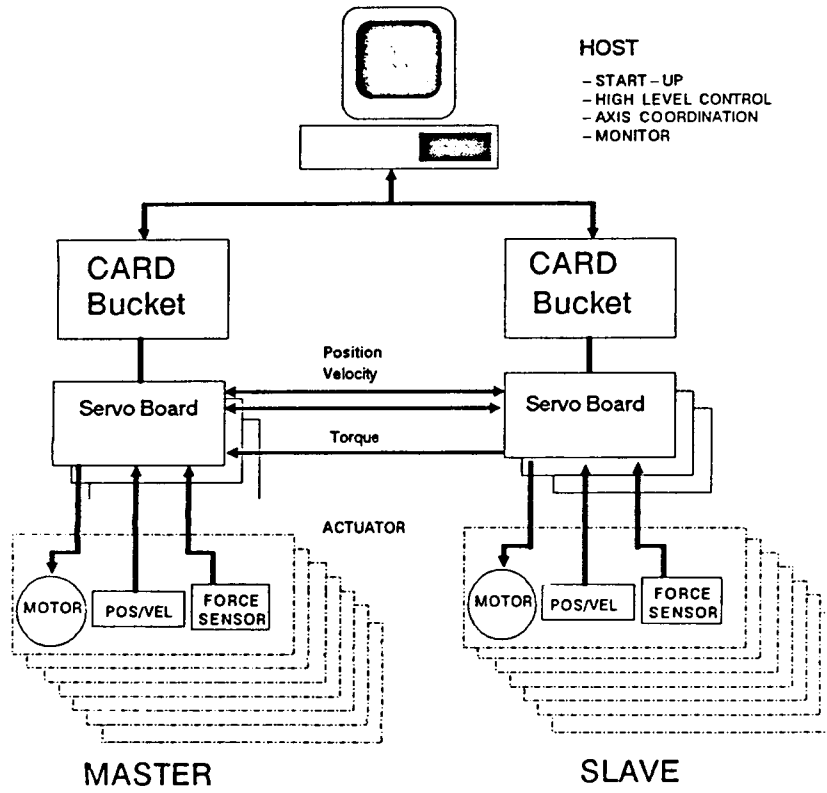
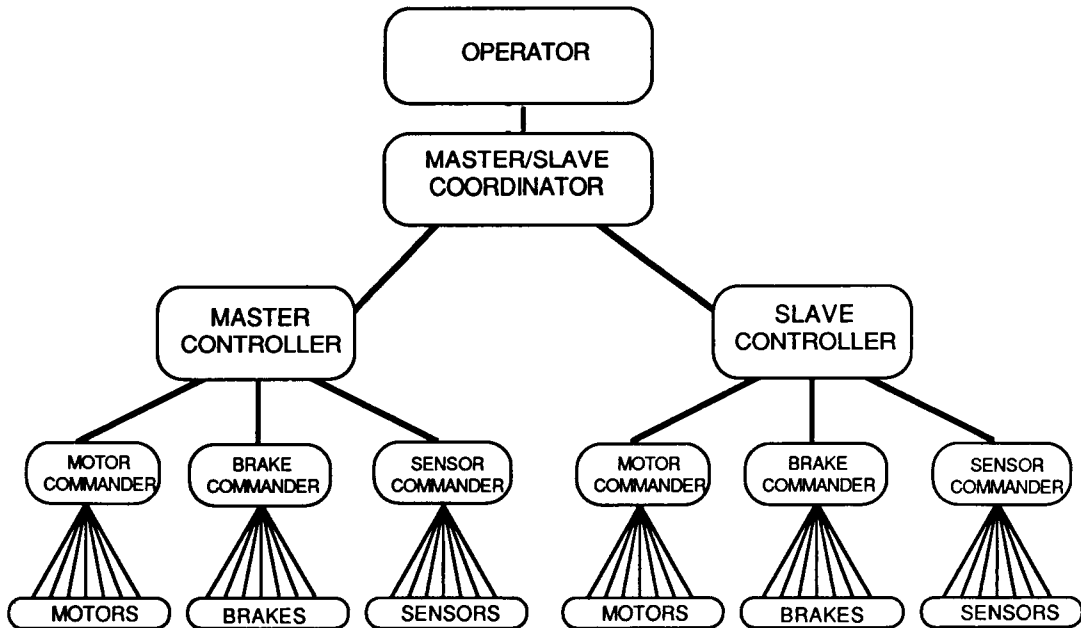**Figure 12. DOF Control Architecture**

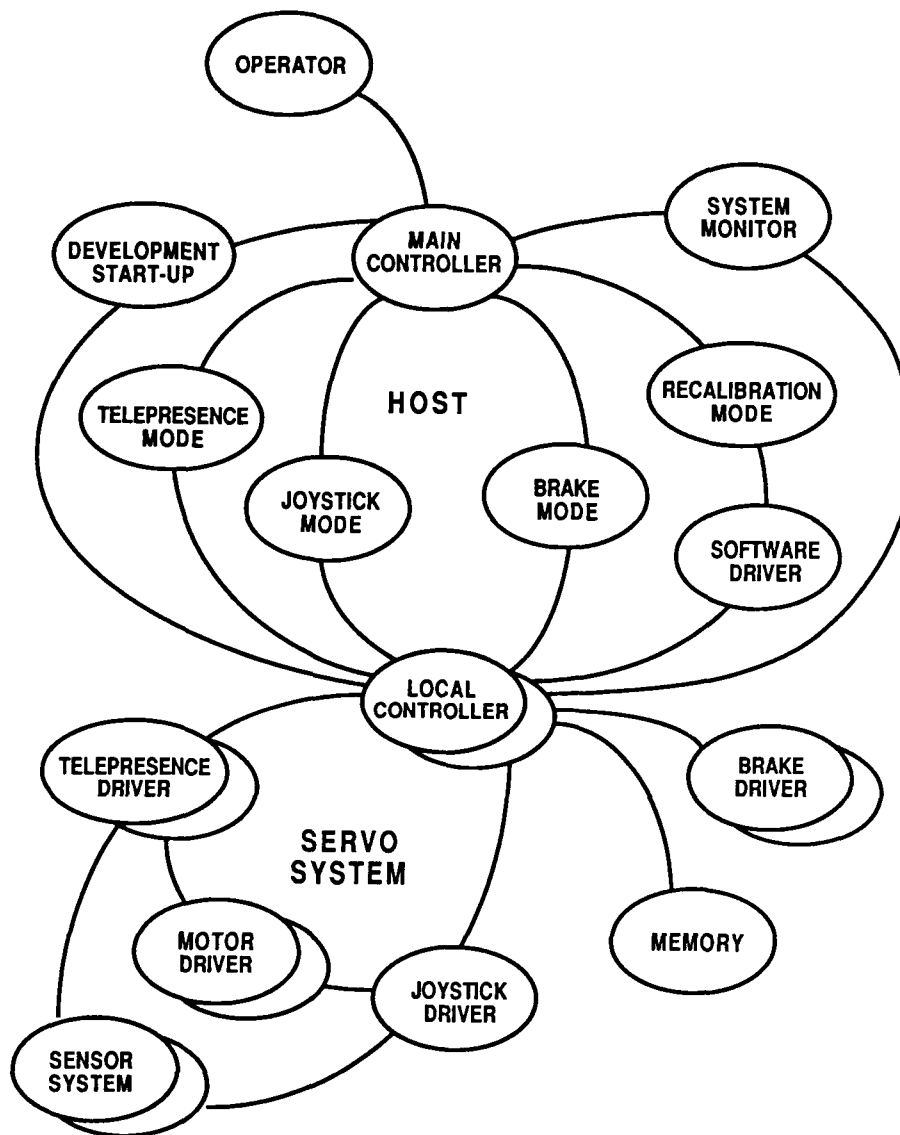**Figure 13. RCS Task Decomposition – Master/Slave**

Figure 14. Data Flow

CONCLUSION

In conclusion, Martin Marietta is developing a significant capability to develop and test new concepts for man–machine interface and telerobotic systems. Through these test beds, the 1 DOF and 7 DOF systems, we will be developing the solutions for telepresence and optimizing methods of control and performance of teleoperations. The intention is to provide systems that will truly be functional human surrogates in hazardous environments.

The mechanical design uses state–of–the–art actuation components in an extremely compact design (patent pending). Special techniques were developed to optimize system components, and often custom–made parts are used.

The control system is designed to allow investigation into many types of tele–operation control. The system is based around a powerful and flexible servo controller uniquely designed for teleoperation. The online system's approach addresses the basic premise of teleoperation (man is best for the unstructured thinking, the robot is best for repetition) by keeping the algorithms simple, improving the sensory feed back to the human, and allowing him to make natural high level and high speed inputs to the controller.