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"EXOSKELETON MASTER CONTROLLER WITH FORCE-REFLECTING TELEPRESENCE"

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ABSTRACT

A thorough understanding of the requirements for successful master-slave robotic systems is becoming increasingly desirable. Such systems can aid in the accomplishment of tasks that are hazardous or inaccessible to humans. Although a history of use has proven master-slave systems to be viable, system requirements and the impact of specifications on the human factors side of system performance are not well known. In support of the next phase of teleoperation research being conducted at the Armstrong Research Laboratory, a force-reflecting, seven degree of freedom exoskeleton for master-slave teleoperation has been concepted, and is presently being developed.

The exoskeleton has a unique kinematic structure that complements the structure of the human arm. It provides a natural means for teleoperating a dexterous, possibly redundant robotic manipulator. It allows ease of use without operator fatigue and faithfully follows human arm and wrist motions. Reflected forces and moments are remotely transmitted to the operator hand grip using a cable transmission scheme. This paper presents the exoskeleton concept and development results to date. Conceptual design, hardware, algorithms, computer architecture, and software are covered.

INTRODUCTION

The purpose of a teleoperation system is to project an operator's manipulative and sensory functions into a remote environment, with the goal of performing work or extracting information. When using the system, an operator should feel that he has been projected into the remote environment. He should feel that he is at the work site, performing work with his own, unencumbered hands. Telepresent systems, through the use of sensors and manipulative capabilities, try to achieve this goal.

Perhaps the most important element in a teleoperation system is the interface between the human operator and the mechanical components of the system. This interface strongly influences both the system's performance the operator's perception of a remote environment. In the past, most master controllers have had six or less degrees of freedom and were kinematically similar to the devices they controlled. The human arm, however, is minimally represented by at least seven degrees of freedom.

Adequate feedback to the operator is essential for successful teleoperation. For example, the addition of stereo vision makes most remote, video teleoperated tasks significantly easier, if not possible. Force and/or audio feedback have been shown to be essential for tasks that involve a relatively high degree of physical interaction with a remote environment.

In support of research being performed at the Armstrong Research Laboratory on human factors issues in teleoperation, a better interface, in the form of a novel, seven degree of freedom, force reflecting master controller, is presently being developed.

Background

Teleoperation systems have historically allowed the accomplishment of tasks that were hazardous or inaccessible to humans. Master-slave systems have been used by the nuclear and other industries to remotely handle hazardous materials for over thirty years. The use of teleoperation technologies in submersibles has allowed man to explore and work in the deep sea, an environment that would oth-

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erwise have been inaccessible. As such, the idea of a person projecting manipulative and sensory functions into a remote environment is not new.

The application of teleoperated system technologies in space has been a focus of research within the Nasa centers for much of the past decade. Teleoperation technologies, if sufficiently developed, could greatly facilitate satellite construction, servicing, and refueling. For defense applications, it could be advantageous to remotely operate in chemical, biological, or nuclear environments. In the commercial area, hazardous waste removal and other broadening markets demand advances in teleoperation technologies. With advances in computer, sensory, and manipulative technologies, the science of teleoperation is evolving.

Manipulative technologies have recently progressed beyond those currently used for teleoperation purposes. Dexterous, redundant degree of freedom manipulators are now commercially available. Dexterity implies that a manipulator has a relatively high payload capability. This quality is essential for the successful completion of many teleoperation tasks. Redundancy in the degrees of freedom (seven or more joints to control six degrees of freedom) allows one to influence the configuration of a manipulator in addition to controlling position and/or forces at the endpoint (in this paper, position refers to position and orientation and forces refers to forces and moments.) Configuration control can, among other things, be used to increase the dexterity of a manipulator or to avoid obstacles when working in a cluttered environment. Of the redundant manipulators that are currently under development, many are somewhat anthropomorphic in design, containing spherical joints at the shoulder and wrist, and a single revolute joint at the elbow. These manipulators, with high performance joint torque servos and anthropomorphic kinematics, are well suited for the application of kinesthetic master-slave teleoperation.

Progress in cable driven actuators has also pushed the state of technology that is available for teleoperation systems. An early example of a cable driven master is that of the Salisbury/JPL hand controller. Other, more recent examples are the Utah-MIT hand and WAM manipulator. Each digit of the hand is servoed to the position of an operator's finger joint through an antagonistic cable/tendon arrangement. The WAM manipulator demonstrates that cable transmissions can allow remotely mounted motors to apply relatively high torques at the joints of a compact, light weight manipulator structure. There are benefits that suggest the use of cable transmissions. Cable transmissions are relatively efficient, do not contain backlash and are relatively smooth in operation.

EXOSKELETON CONCEPT

The exoskeleton has seven degrees of freedom that anthropomorphically map those of the human arm. The shoulder roll, pitch, and yaw joints intersect at the approximate center of rotation of the operator's shoulder. The exoskeleton elbow pitch joint, although slightly offset from the human elbow for practical kinematic reasons, very closely and spatially follows rotations of the operator's elbow. The wrist roll, pitch, and yaw joints intersect at the approximate center of the operator's wrist. A conceptual rendering of the exoskeleton is presented in Figure 1.

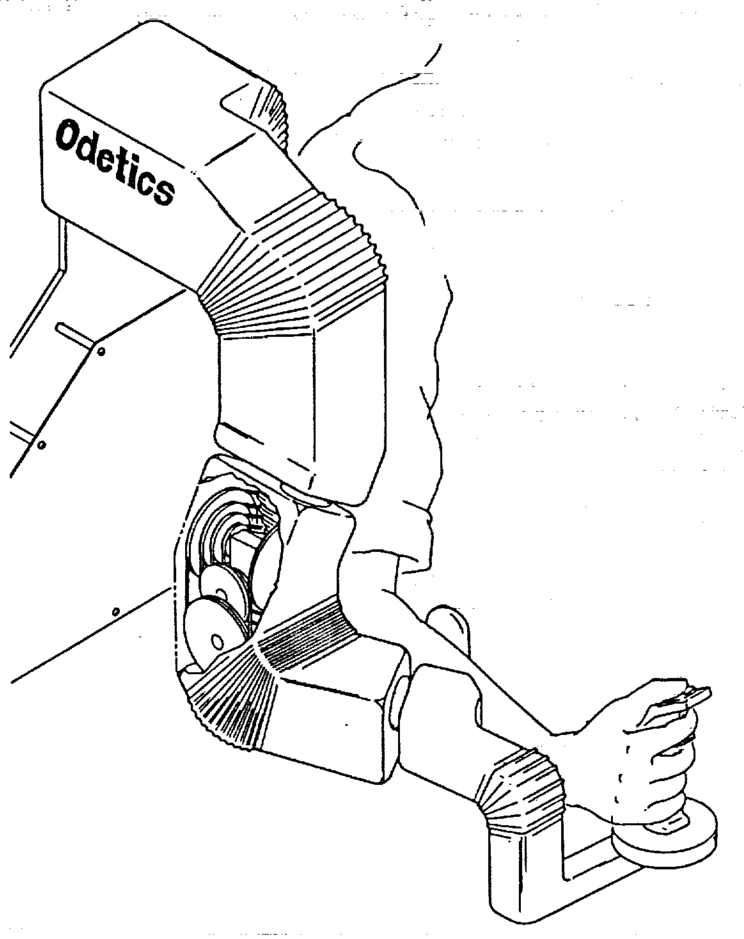

Figure 1 Exoskeleton Concept

Technical Description

Because the exoskeleton is designed to have a kinematic structure that complements the structure of the human arm, it provides a natural telerobotic interface. The system being developed has a number of unique characteristics:

- Because of the anthropomorphic similarity, the exoskeleton follows human arm motions. A single push plate is provided on the forearm. No straps or restraints are required.
- The exoskeleton is electrically actuated by remotely located motors. Torques are transferred to the joints through an antagonistic cable tendon transmission scheme. The use of cable transmissions will allow a very lightweight, low inertia master.
- Gravity forces on the master are compensated in software (at the joints). No additional mass or complex counterweighting scheme is required.
- Gravity compensation may be tuned by the operator. Additional compensation is available to cancel the operator's arm weight.
- The exoskeleton system exchanges data in base cartesian coordinates. The exoskeleton a generic master that may be coupled to any capable slave device.
- A force sensor, mounted at the exoskeleton grip, may provide data that can be used to servo out the effects of friction and/or compliance. Better force resolution will be available at the grip.
- A parameter that characterizes the exoskeleton arm configuration will also be generated. This parameter can be used to influence the configuration of a redundant slave arm.

The exoskeleton will provide a natural means for teleoperating a similar, possibly dexterous, redundant degree of freedom manipulator. It will allow ease of use without operator fatigue and will faithfully follow human arm and wrist motions.

BILATERAL ARCHITECTURE

The human operator is limited in his capacities to generate commands and perceive kinesthetic and proprioceptive sensory information in a bilateral loop. Component performance that surpasses the capacities of a human operator will not increase system performance. Telepresence thus provides a natural bound for master and slave performance requirements.

Relatively little research has been performed to directly determine the affects of sensory and command bandwidths on teleoperation system performance. One consensus is that the master, as a goal, should be capable of generating commands in the 5-10 Hz range. Although the human operator is able to perceive changes in vibrational frequency up to approximately 320 Hz, we are interested primarily in higher amplitude, kinesthetic force feedback. As a goal, the master should be capable of reflecting kinesthetic feedback in the 20-30 Hz range. Again, relatively little research has been performed in this area. These specifications are based primarily on the compiled opinions of scientists with previous teleoperation hardware experience [3]. An important point to note is that bandwidth requirements for the command and feedback sides of the loop are asymmetrical.

The physics of most bilateral systems are, in general, similarly asymmetrical. The slave usually has a relatively high inertia and the master has a relatively low inertia that is coupled to a stabilizing influence (the human operator). The master is thus able to meet higher bandwidth feedback requirements while the slave is generally capable of tracking only lower bandwidth commands.

Position-position, position-force, and force-force master-slave bilateral loops are theoretically feasible. Force-force loops, however, would not be practical for most situations.

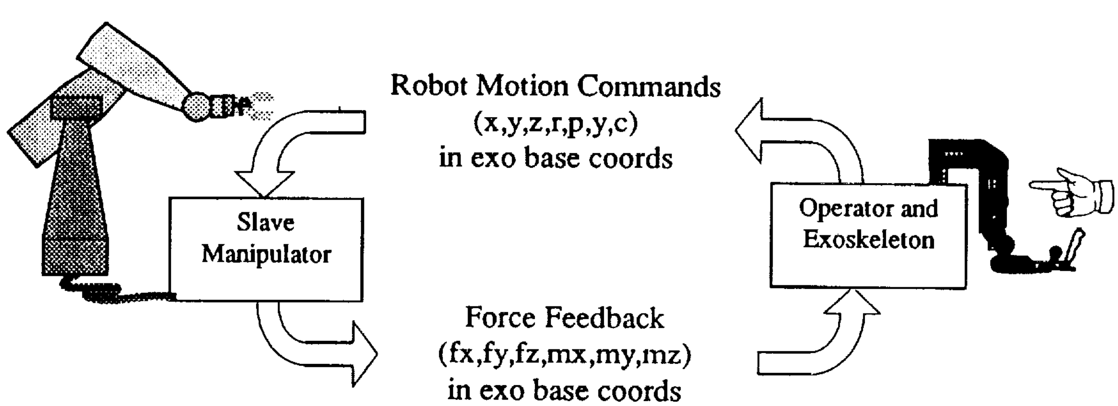

Figure 2 Position-Force Bilateral Architecture

When the master and slave are kinematically similar, position-position loops can be advantageous, as servos can be closed directly between the master and slave at each of the joints. In light of the asymmetrical bandwidth requirements for telepresence, however, a disadvantage is that feedback in such a system will be bandwidth limited by the slave inertia. Unless the bilateral slave has a relatively high position bandwidth, a position-force bilateral system (Figure 2) offers the greatest promise for telepresence.

Because we intend to create a generic master, one that could potentially be used with any capable slave manipulator, this consideration is deemed important.

Algorithms

Cartesian commands, based on the incremental position of the exoskeleton grip with respect to the exoskeleton base, are generated and sent to the slave. Cartesian forces, returned by the slave, are fed back to the exoskeleton operator by torque actuating the joints in a coordinated, controlled manner. A summary of these basic, open loop algorithms is presented in Figure 3.

Command Generation

Exoskeleton command generation algorithms consist of the forward kinematics and Euler angle transform algorithms. The forward kinematics routine solves the forward kinematics for the exoskeleton, generating a 4x4 matrix transform that relates locations in the exoskeleton grip coordinate frame to the base coordinate frame. The Euler angle transform routine extracts position and orientation commands in cartesian coordinates from the 4x4 matrix transformation.

Orientation angles in the exoskeleton command set are specified in terms of a Z-Y-X successive Euler angle representation.

The command set that is extracted by the Euler angle transform routine is absolute. However, commands that are sent to the bilateral slave are incremental, based on the difference between the absolute exoskeleton position and a set point that is selected when the grip deadman trigger is enabled (see REF for more information.)

The exoskeleton is a redundant degree of freedom device and, as such, more than one configuration may be possible for cartesian position set points in its workspace. A configuration command parameter is thus appended to the command set in order to pass information regarding the exoskeleton arm configuration to the slave.

If a redundant manipulator is coupled to the exoskeleton as a slave device, it should be possible to not only control the slave set point, but to influence the slave configuration. In teleoperation, the advantages of such a system would include natural master-slave obstacle avoidance and the ability to remotely configure the slave for maximum mechanical advantage.

Either an incremental wrist roll angle or an incremental elbow plane angle will be used to represent the exoskeleton configuration. The elbow plane angle is defined as the angle between a vertical plane passing through the exoskeleton shoulder apex and wrist apex and the plane formed by points at the shoulder apex, wrist apex, and a point at the center of the elbow joint.

Force Reflection

A recursive Newton-Euler formulation, similar to that suggested by Craig [4], is used to determine exoskeleton joint torques. At any instant in time, it is assumed that the

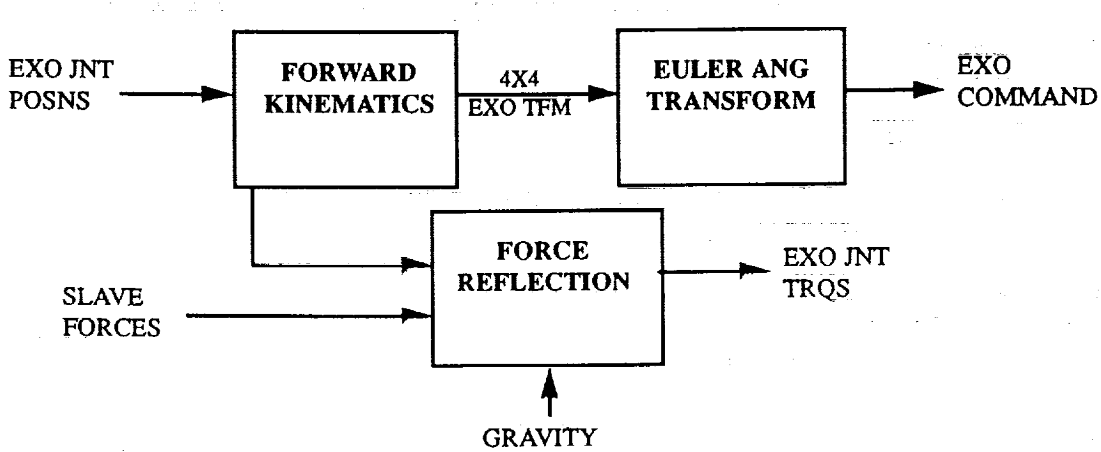

Figure 3 Exoskeleton Algorithms

exoskeleton joints are locked so that the arm becomes a structure. A force-moment balance for static equilibrium is then computed for each link in that link's coordinate frame. The inclusion of dynamic (velocity and/or acceleration dependent) forces in the calculation is not precluded.

Gravity forces on the arm are included by linearly accelerating the base frame of the exoskeleton upwards by a gravity acceleration constant. For the exoskeleton implementation, the gravity constant can be varied by the operator using a knob on the hardware user interface panel. Compensation may thus be tailored to the preferences of the operator or additional compensation can be added to support the operator's arm weight.

Algorithm Development Tools

Real-time software development for the forward kinematic and joint torque reflection expressions was inherently simplified by using the software tool Mathematica as a symbolic engine. Scripts have been developed to aid in the generation of real-time kinematic and dynamic models. Given a file of kinematic and mass parameters describing a system, the scripts generate real-time C subroutines.

Future Control Concepts

The implementation of more advanced control algorithms to alleviate the effects of friction and joint compliance may enhance future system telepresence. The arm is being developed so as not to preclude the implementation of such algorithms. Actuators and sensors for the arm have been chosen appropriately.

One concept that has been proposed would be to close a torque servo at each of the joints. Although closing the loops could prove to be a significant undertaking, this type of architecture would yield a very telepresent system and may be worth an investigation.

An additional control concept that has been proposed is that a six degree of freedom force sensor be placed at the grip of the exoskeleton. Conceptually, a force loop could be closed around the arm using this sensor. Friction in the joint transmissions effectively decreases the force resolution available at the exoskeleton grip. If the force at the grip were servoed to the commanded force, parasitic friction, compliance, and inertial forces would be negated. The exoskeleton system being developed will have provisions for the inclusion of a force sensor.

HARDWARE

Realization of the exoskeleton concept has provided significant engineering challenges. At the present time, engineering design is well underway and the procurement of mechanical and electrical system components has begun.

Mechanical Hardware

The exoskeleton arm and associated support structure, although integrally connected, were developed with somewhat different philosophies. Performance and cost were of primary importance in the design of the system. Where possible, arm mass and volume were minimized. Arm stiffness was maximized. Additionally, transmission stiffness, friction, and backlash were considered in the design of the arm. The support structure was also designed for performance, but mass, volume, and other packaging concerns were not deemed as important in light of system costs.

At the present time, link structural and transmission components, including shafts, bearings, pulleys, cables, and other associated hardware have been designed, and are presently being procured. Actuator hardware has been specified and is presently being procured. The exoskeleton support structure, including actuator mounting and electronic packaging has also been designed.

Exoskeleton Arm

The exoskeleton arm is the primary human interface to a teleoperation system. Design of the exoskeleton arm thus, arguably, has the greatest impact on telepresence as perceived by an operator.

Cable Transmissions

In order to transfer torques to the exoskeleton joints, a unique cable transmission scheme has been developed (see Figure 4). Antagonistic cable tendons, routed along the exoskeleton structure through banks of pulleys, transfer torques from remotely mounted motors to each of the joints. Remotely mounting the motors allows a minimal exoskeleton link structure. Additionally, a motor size limitation no longer precludes the active cancellation of gravity forces or the development of advanced control concepts for the arm. No counterweighting for the arm is required.

Early in the design effort, it was realized that double groove pulleys were required to allow joint rotations in excess of 90 degrees (cables are terminated at the driving and driven pulleys for positive power transmission.) In order to effectively transfer torques using a cable tendon transmission, the cables must be preloaded to half of their working load (to avoid hysteresis due to cable slack [5].) To satisfy cable loading requirements and, at the same time, minimize bending friction, 7 by 19 multi-stranded 1/16th inch diameter wire rope was selected. Figure 4 presents a mock-up that was fabricated to verify the transmission concept. Because existing cable hardware could not satisfy volumetric packaging requirements for the arm, a custom termination scheme was also developed.

Exoskeleton Arm Joints

Another issue that was resolved relatively early in the design phase was how to efficiently mount pulleys on the exoskeleton structure. All shafts and non-driving pulleys rotate on bearings in order to minimize friction in the drive train. Conventional mounting schemes, however, do not satisfy packaging requirements for the concept (strict packaging requirements are evident in Figure 5.)

Previous experience at Odetics suggested that retaining compound could be used to fasten the bearings. Although the specification for Loctite R680 Aluminum-Aluminum bonds did not meet requirements for the arm, testing revealed that diametral clearance and surface finish significantly impact the strength of the bond. It was determined that shear load carrying requirements for the exoskeleton joints could be met if Aluminum surfaces were hard anodized and if design tolerances could be tightly held.

Exoskeleton links appear similar to those roughly shown in Figure 4, with the exception that some additional structure is required at the upper and lower arm twist joints. A photograph of the first two links, presently under assembly, is presented as Figure 6.

Joint Torque Actuators

Force reflection requirements have been selected to be 5 lb_f and 25 in-lb_f for each axis at the grip. Simulations, developed with conservative estimates for mass properties, transmission efficiencies, and actuator efficiencies, suggested that relatively large torques would be required for a successful system. Such torques would typically be obtained through the use of small motors coupled to sizable reductions. However, reflected actuator friction, linearly related to the reduction ratio, and reflected inertia, related to the square of the reduction ratio, will not be servoed out of the present, open-loop system. Small ratios are thus required to minimize reflected forces that would be perceived by an operator. Additionally, and perhaps more importantly, large reductions would limit actuator velocity and acceleration capacities, thus precluding the application of future servo concepts.

Figure 4 Transmission Mock-up

A number of actuator configurations were considered. Because the actuators are remotely mounted, packaging was not a priority in light of performance and cost requirements for the system. A relatively large, high performance brushless motor (Industrial Drives B206A) has been selected to meet system requirements. Low ratio, low backlash, low friction spur gear reducers (Bayside) are coupled to the actuators to obtain larger torques for the first four axes. The last three axes are directly driven.

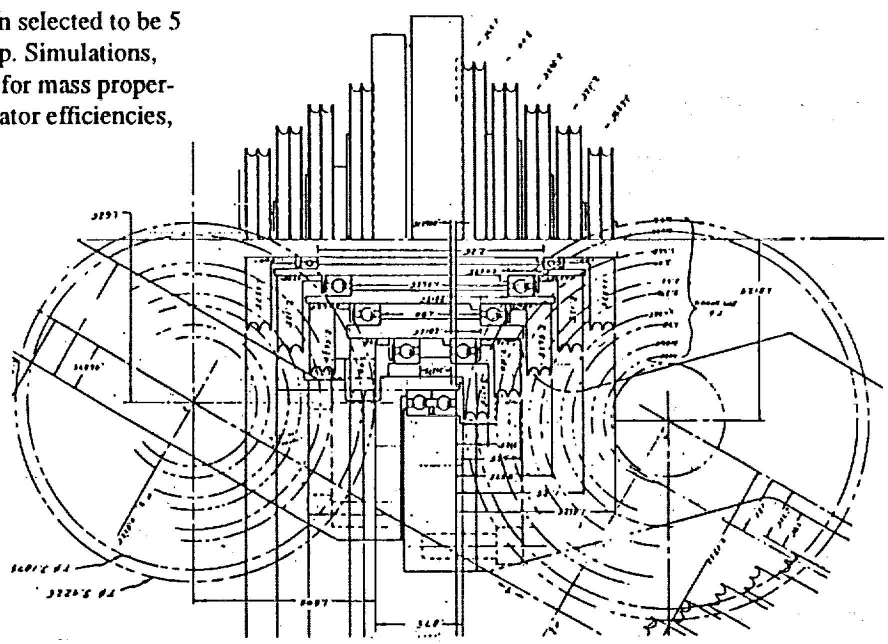

Figure 5 Shoulder Yaw Joint

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Because the actuator hardware is commercially available, costs are not as prohibitive as the cost of a custom actuator. The motor has a high continuous torque capacity. Low armature friction and inertia allow the use of a gearhead without compromising system telepresence. A full sine-wave motor driver provides smooth, low speed DC torque. The motors that are being procured are modified to reduce cogging torque without compromising power density or linearity.

Because the gearheads use involute profile spur gears, high efficiencies can be realized. An additional benefit is that spur gear reductions are relatively linear and stiff, compared to harmonic or other reduction methods. This quality is very desirable from a control system perspective. We plan to use gearheads having minimal backlash so as not to preclude the future application of a torque loop or other compensation.

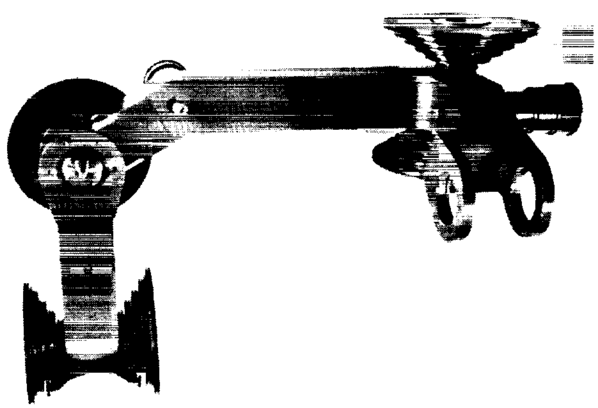

Figure 6 Shoulder Links

The present actuation scheme reflects a compromise between performance and cost. Although the development of custom actuators was considered, the benefits would have been primarily in packaging. Potential increases in system performance were deemed marginal in terms of the present goals and requirements for this program.

Support and Drive System

The exoskeleton support and drive system consists of a rigid aluminum structure that provides support for the arm, a mounting surface for the torque actuators, cable transmissions to couple the actuators to the exoskeleton shoulder pulley set, and a servo enclosure for the motor drivers, servo power supplies, and interface electronics. The support and drive system is presented as Figure 7.

The actuators are mounted to the rear, middle portion of the exoskeleton support structure. The position of each actuator can be adjusted in order to pretension the support structure pulley transmissions. Drive pulleys are located on the front (operator) side of the support structure and are covered by a clear plastic shield. At the lower portion of the support, an enclosed box houses the motor drivers, servo power supplies, and servo interface electronics. Space for a fan module is also provided. Removable panels have been designed into the sides of the enclosure to allow easy driver tuning or maintenance.

Although the support and drive system were also designed for performance, other packaging concerns (mass, volume, etc.) did not have as high a priority.

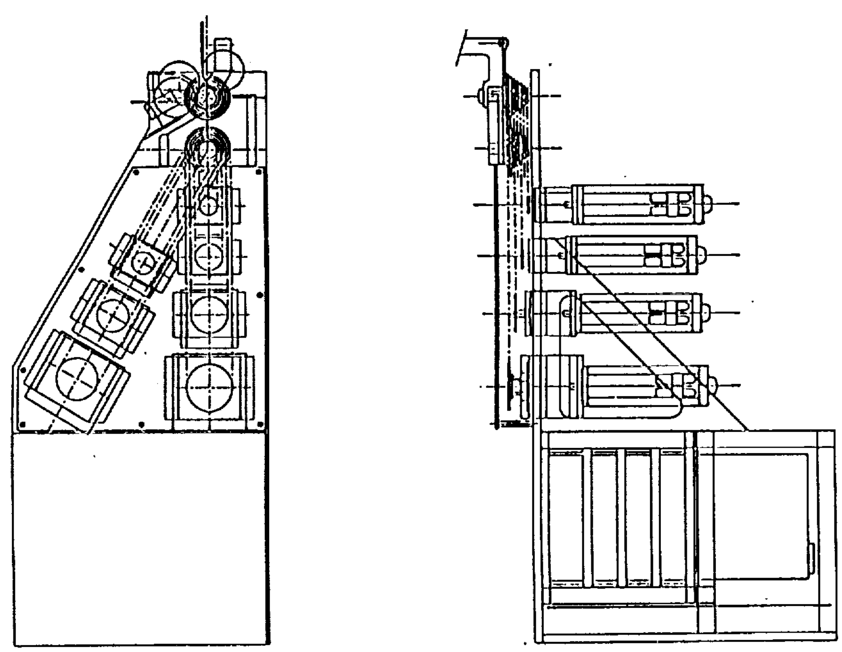

Figure 7 Support and Drive System

Electrical Hardware

Servo Electronics
The servo electronics consists of the motors, motor drivers, servo power supplies, servo power circuitry, and servo driver interface circuitry. Although components have been selected, the servo power interface circuitry has only been conceptually designed at this time. Detailed design of the interface circuitry is under way.

Computer / Interface Electronics
The computer and interface electronics consist of the processor enclosure and computer card cage, computer boards, instrumentation and computer power supply, the control panel, and the hardware interface electronics.

The exoskeleton controller enclosure contains 4 VME-based processor and I/O boards mounted in a 7 slot chassis. Three slots are thus available for future system expansion. The chassis has both J1 and J2 bus connectors in each slot. An integral fan cools the processor boards. Also housed in the exoskeleton processor enclosure are a 350 Watt computer and instrumentation power supply and custom signal conditioning and interface electronics.

The system hardware interface, consisting of the power switch, potentiometers for adjusting the command and force feedback gains, a potentiometer to adjust the gravity compensation gain, the emergency stop switch, a reset button, and status LEDs has been developed for the front panel of the processor enclosure.

In addition to the panel interface, two deadman switches are located on the exoskeleton grip. A Measurement Systems control grip has been specified to meet system requirements. The system has been designed so that emergency stop, motor temperature, and power supply error signals have authority over the Servo Enable deadman. Additionally, the Servo Enable deadman has authority over the Operate (bilateral communications) deadman. The Operate deadman output controls a relay that engages system communications. The states of both switches are available both at the hardware user interface and in software with other system states as semaphores.

In typical operation, the Servo Enable deadman will be depressed at all times to compensate for gravity. The Operate deadman will be used intermittently to initiate slave tracking of the master and to reflect slave forces.

Although servo enable and communications logic have been implemented in hardware to assure complete operator authority at all times, the real-time control loop also takes hardware states into consideration when generating position and joint torque commands. The gravity, command, and force feedback gains are scanned before being used in the real-time loop. there are thus no limitations on when the gains may be adjusted during normal use.

Computer System / Architecture

Exoskeleton computer hardware is VME-based. The VME (Versa-Multi-Europa) architecture offers an acceptable solution to a primary hardware/software problem in robotics. From a hardware standpoint, special purpose microprocessors (RISC based processors or DSP's) offer the best performance for inner control loop calculations. However, this hardware typically is not backed by mature software development tools. Additional and expensive software development time is usually required to write code for higher level tasks when these systems are used. For the higher level tasks, no additional performance is usually required. On the other hand, general purpose microprocessors provide good all around performance. Additionally, mature software development tools and a relatively large pool of experienced software developers exist for these processors. However, it is usually difficult to effectively implement both real-time and higher level code on a general purpose microprocessor and still meet real-time system demands. The VME bus architecture offers a solution: it allows several general purpose microprocessors to run in parallel. One or more processors can be dedicated to the real-time portion of the system, while others perform the higher level tasks.

A number of manufacturers offer off the shelf, high performance CPU and I/O boards for VME systems. This allows for flexibility in interfacing, expansion, and subsequent system modification. As advances in technology are made, higher performance SPU boards and higher density I/O boards can be integrated into the existing system relatively easily. Because a family of processors (Motorola 680x0) can be used, code is generally forward compatible and can be ported with minimal difficulty.

Computer and I/O Boards
A review of system requirements suggested that a single microprocessor would suffice for the present system. Figure 8 shows the configuration and hardware selected for the present system.

For development purposes, an Ethernet card has also been added to the VME system. This card allows a relatively transparent connection to an existing Sun workstation network. Because well documented, well used tools are available on the Sun network, the software development tasks are greatly simplified. Code can be designed, documented, compiled and tested in the workstation environment. Executable modules can then be downloaded to the vxWorks

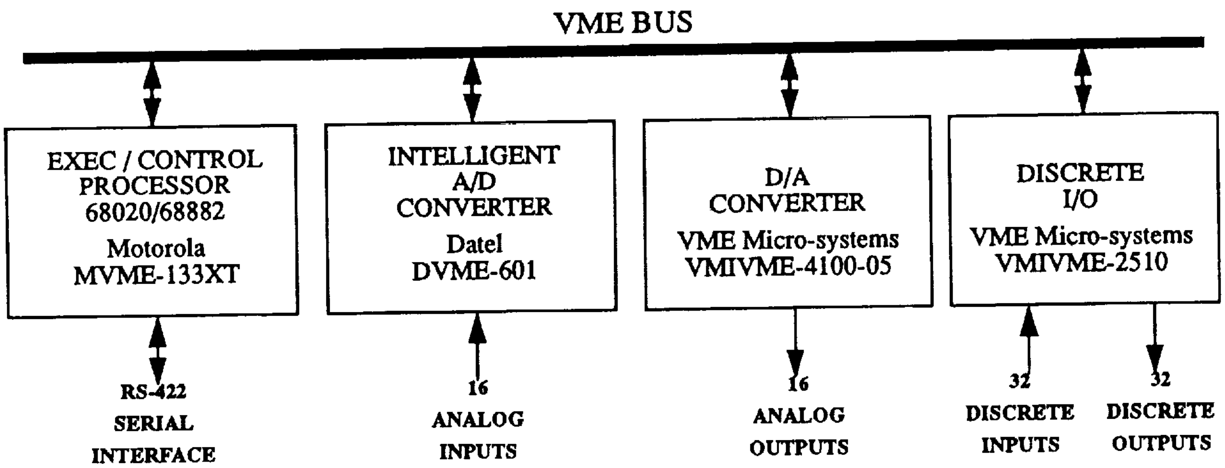

Figure 8 Computer Architecture / Hardware

real-time kernel on the host processor. The development interface, although not required for operation, provides the capability to adjust and display parameters while the system is in use.

Communications Interface

The communications interface between the master exoskeleton and robotic slave has been specified to be a high speed RS-422 serial interface. Thus, a single cable is all that is required to couple master and slave systems. The selected protocol calls for 192 kBaud, manchester encoded data. Data will be transferred in duplex between the systems. Routines are being developed to provide a buffered, interrupt-driven interface. The routines will provide a transparent software interface to the serial port. All data is transferred in scaled integral engineering units.

PROJECT RESULTS

Development is still underway and results are preliminary. Technical accomplishments that have been made to date include:

- Exoskeleton arm mechanical hardware has been fully designed. The transmission concept has been realized.
- Links 1 and 2 of the arm have been procured and assembly has commenced.
- The actuator concept has been developed and hardware has been specified. Parts are presently being procured.
- The support and drive system hardware has been designed and is presently being procured.
- The computer hardware architecture, software architecture, and communication protocols have been defined.
- Real-time computer system components have been specified, procured, configured, and assembled. Real-time software development is under way.
- All control algorithms required for basic bilateral teleoperation have been developed and ported to the real-time hardware.
- The hardware and software user interface protocols have been developed.

We are engineering a viable, working system based on the exoskeleton concept. At this time, we are confident that we will successfully meet program goals.

FUTURE POSSIBILITIES

The advantages and unique kinematic configuration of the exoskeleton suggest a number of interesting system possibilities.

- The kinematic redundancy in the exoskeleton is very similar to that in a spherical-revolute-spherical seven degree of freedom robotic arm. The exoskeleton may thus be used to naturally influence the configuration of a redundant slave arm based on the configuration of the operator's arm.
- Because the exoskeleton joints anthropomorphically map those of the operator, individual joint feedback (configuration force feedback) should be possible. This concept could be used for teleoperation with obstacle avoidance assistance.
- Right and left versions of the exoskeleton could be used together to allow natural, dual arm, coordinated control of teleoperated slave manipulators.

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