ANTHROPOMORPHIC TELEMANIPULATION SYSTEM IN TERMINUS CONTROL MODE

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Summary

The paper describes a prototype anthropomorphic kinesthetic telepresence system that is being developed at JPL. It utilizes dexterous terminus devices in form of an exoskeleton force-sensing master glove worn by the operator and a replica four finger anthropomorphic slave hand. The newly developed master glove is integrated with our previously developed non-anthropomorphic six degree-of-freedom (DOF) universal force-reflecting hand controller (FRHC). The mechanical hand and forearm are mounted to an industrial robot (PUMA 560), replacing its standard forearm. The notion of "terminus control mode" refers to the fact that only the terminus devices (glove and robot hand) are of anthropomorphic nature, and the master and slave arms are non-anthropomorphic. The system is controlled by a high performance distributed controller. Control electronics and computing architecture were custom developed for this telemanipulaton system. The system is currently being evaluated, focusing on tool handling and astronaut equivalent task executions. The evaluation revealed the system's potential for tool handling but it also became evident that hand tool manipulations and space operations require a dual arm robot.

introduction

This telerobotic system was designed to perform dexterous manipulations in hazardous environments. In order to perform a large variety of tasks, it must be able to use tools. Most tools can only be handled by fingered hands. The robot's fingered hand provides tool handling and other dexterous manipulation capabilities.

An obvious hazardous environment is space. Cost savings might result by performing certain space tasks by robots because they don 't need life support systems and can operate for long time periods in hostile environments. For space operations, the robot must be able to perform typical Extra Vehicular Activity (WA) astronaut tasks which require to use the same EVA tools and equipment that are available and certified for astronaut use [1]. Evaluating the robot's tool and EVA equipment handling skills thus became a major task. In fact, the success of this robot depends to a large degree on its ability to handle EVA equipment.

Besides using the system as a telemanipulator, it is also noted here that there is a strong medical interest for the backdrivable glove as a rehabilitation physical therapy aid for helping patient's recovery from hand injuries or for rehabilitating grasp and fine movement control in stroke patient's paralytic hand.

The paper describes the system's principal components, its control and computing architecture, discusses findings of the tool handling evaluation and explains why common tool handling and EVA space tasks require dual arm robots.

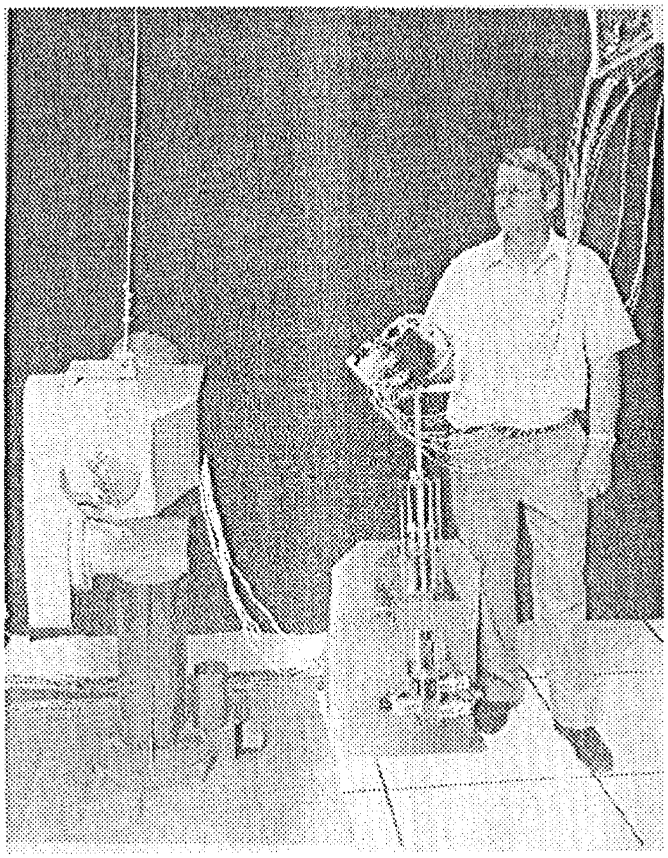

Fig 1: The Anthropomorphic Telemanipulation System in Terminus Control Mode

System Description

The telemanipulation system can be seen in Fig. 1. It consists of a master controller, a manipulator arm and the control electronics. The control electronics is not visible in this picture. The master arm/glove and the slave arm/hand have 22 active joints each. The manipulator arm has five additional drives to control finger and wrist compliance. This Active Electromechanical Compliance (AEC) system provides the muscle equivalent dual function of position as well as stiffness control. The overall sensing and control information flow block diagram is depicted in Fig. 2. It enables automatic hybrid position/force control and compliance control of the robot. The outside influence occurs at hand contact with the outside world, causing slight joint deflections which arc sensed by the compliance deflection sensors. It tells the controller that the robot is in contact with its environment, prompting it to switch to the force control mode automatically.

Master Controller

The master controller is comprised of the six DOF FRHC, controlling the robot arm and the 16 DOF glove controller, controlling the anthropomorphic robot hand. The FRHC [2] is a freestanding device used here in a vertical orientation. It controls the robot's wrist in either position/orientation or force control and provides equivalent force feedback to the operator. The telescoping part of the FRHC is gravity compensated so that the operator does not feel any gravitational effects from the master controller, The operational space at the wrist is a 45 cm cube working area.

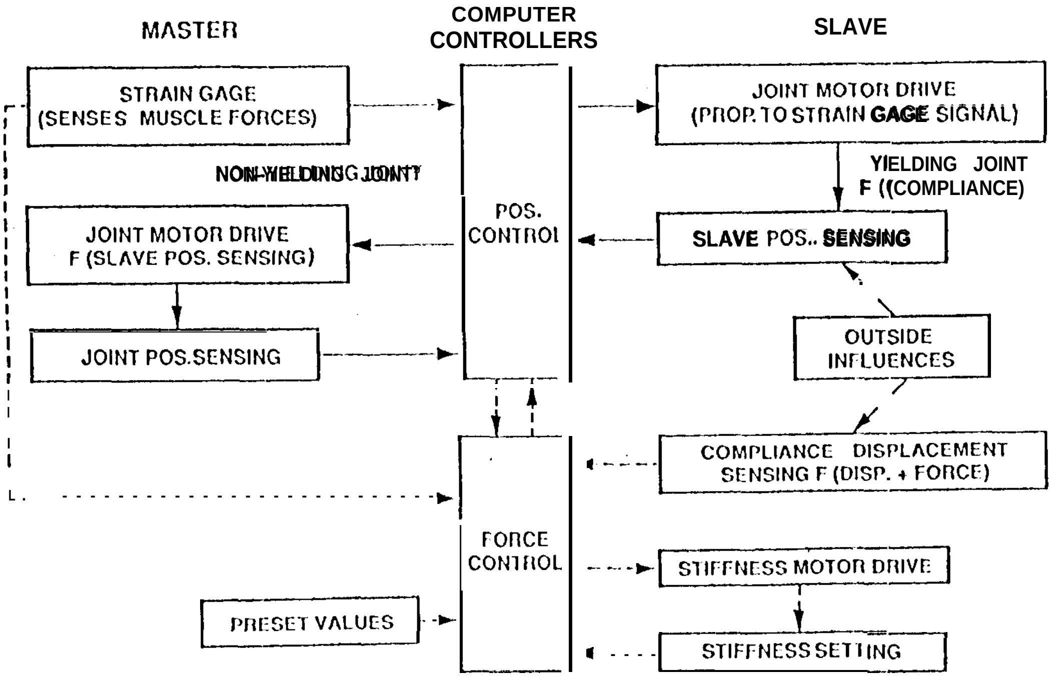

Fig. 2: The Overall Sensing and Control information Flow Block Diagram

A glove-type device [3] is worn by the operator (Fig. 3). Its force sensors enable hybrid position/force control and compliance control of the mechanical hand, Four fingers are instrumented, each having four DOF. Position feedback from the mechanical hand is providing position control for each of the 16 glove joints. The glove's feedback actuators are remotely located and linked to the glove through flex cables. A one-to-one kinematic mapping exists between master glove and slave hand joints, thus reducing the computational efforts and control complexity of the terminus subsystem. The exceptions to the direct mapping are the two thumb base joints which need kinematic transformations.

Manipulator Arm

The manipulator arm consists of a PUMA 560 robot with its forearm replaced by the new forearm assembly. The forearm weighs approximately 50 kg. A cable links the forearm to an overhead gravity balance suspension system, relieving the PUMA upper arm of this additional weight. The forearm has two sections, a rectangular and a cylindrical. The cylindrical section, extending beyond the elbow joint, contains the wrist actuation system, The rectangular cross section houses the finger drive actuators, all sensors and the local control and computational electronics. The wrist has three DOF with angular displacements similar to the human wrist. The wrist is linked to an AEC system that controls the wrist's stiffness. It is noted that the slave hand, wrist and forearm form a mechanically closed system, that is, the hand cannot be used without its wrist.

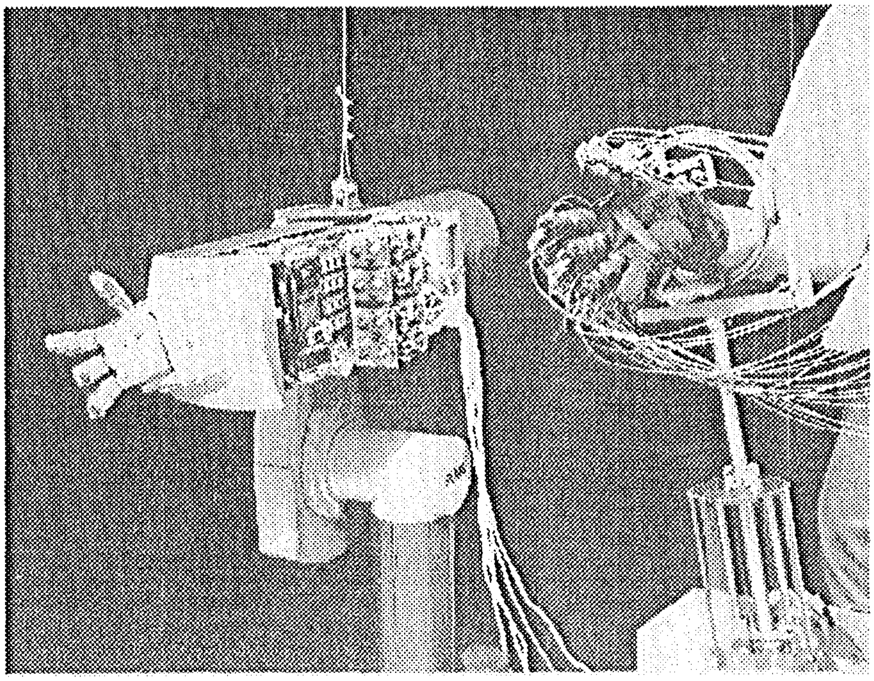

Fig. 3: The Master Glove Controller and the Anthropomorphic Hand

The mechanical hand has four fingers with four DOF at each finger (Fig. 3). Its thickness and configuration is comparable to a large male hand but increases in size toward the wrist. Angular displacements at each joint are similar to the corresponding human hand joints. The hand is almost completely enclosed, preventing object intrusions that could jam its mechanism. All finger joints are linked to the actuating system through flex cables. Each finger is linked to its own AEC system, enabling human-like soft grasping, The hand's kinematics is similar to the human hand, enabling tool manipulations and direct human control through the glove, A more detailed description of the hand can be found in publication [3].

Control Electronics

Early robotic control systems used parallel microprocessors to satisfy computational needs. Typically, one processor was devoted to each joint. In addition, a host processor provided mass storage, a user interface and coordinated joint motion. This configuration provided a cost effective solution to meet the processing requirements.

The dramatic performance increase of modern processors has had a major effect on the computational architecture of modern robots. It is now evident that using a large number of simple processors is not optimal. Today's Digital Signal Processing (DSP) chips represent a cost effective solution to handle all computational needs. The high performance of the DSP chips allows the functionality of a large number of simple processors to be consolidated onto one chip, thus reducing system complexity.

For this anthropomorphic telemanipulation system, the Texas Instrument TMS320C40 (C40) processor was selected to handle the digital control system computation and to provide user services. Key features that make the C40 DSP chip an attractive processor for robotics use are: 1) 40-50 MFLOPS performance 2) Six 20 MBYTES/sec communication ports, each with a separate Direct Memory Access (DMA) processor

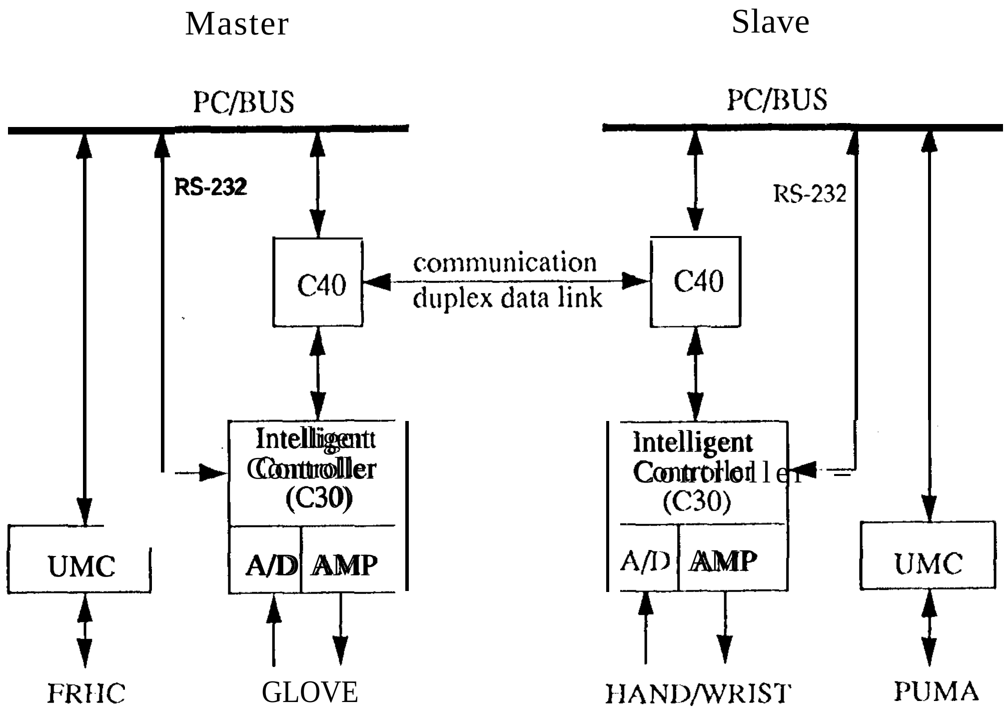

Fig. 4: Control Architecture Overview

capable of communicating with other processors without additional interface logic (i.e. glue logic) 3) Optimized for multiplications and accumulative type operations (i.e. A*B +...) 4) Availability of high performance real-time operating system 5) Low latency interrupt service and 6) Low cost PC based development environment.

The C40 is an attractive alternative to the use of a general purpose processor for robotics control (i.e. Motorola 68040). A consideration in designing a high performance computing architecture is upgradability. The C40 has been designed to be the building block of larger, higher speed computing networks, Its concept it is very similar to the Transputer, manufactured by Inmos and SGS-Thompson, which has been a popular parallel computing building block, particularly in Europe.

The control electronics (Fig. 4) for the master glove and the anthropomorphic hand/wrist are comprised of PC based computational engines, using TMS320C40 (C40) processors and 2 custom designed intelligent controllers. The interface to the FRHC and the PUMA upper arm joints is provided by two separate Universal Motor Controllers (UMC). The UMC has been described previously in [4].

The C40 development system is comprised of Texas instrument Modules (TIM), daughter boards, a PC and software tools. The C40S are placed on daughter boards that provide communication to a supervisory program on the PC. The development system also provides C source level debugging capabilities. All programs were written in the C language, assembly language programming was not necessary. In this implementation, the SPOX Real-Time Operating System (Spectrum Microsystems) was used to facilitate the development of multi-process programs.

The C40S communicate with each other via a single duplex communication channel. This communication link will be the connection between the control station and the remote site. In the future, it might be a satellite communication link.

The intelligent controllers (Fig. 5) are based on the Texas instrument TMS320C30 (C30). The C30 was selected for this task because of its low cost and high performance (33 MFLOPS). The C30 is very similar to the C40 except that it lacks the 6 high speed communication ports. Since these ports are not necessary in this controller application, the lower cost C30 was used instead.

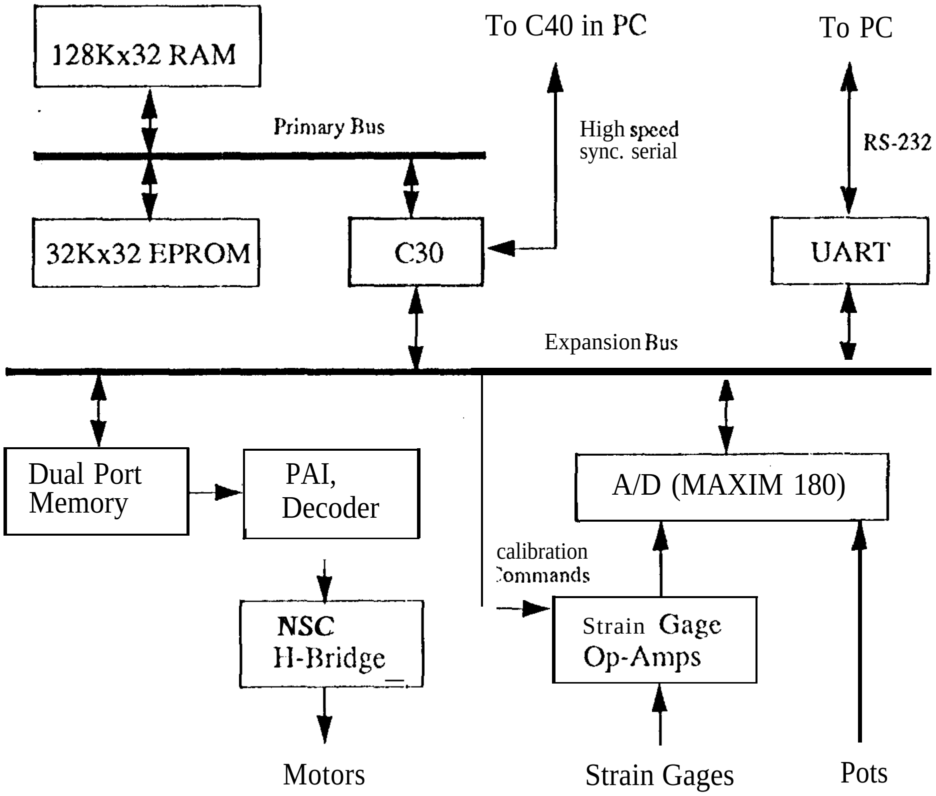

Fig. 5: Schematic of Intelligent Controllers

The two intelligent controllers are placed near the system's sensors, one is near the master glove, the other is near the anthropomorphic hand and wrist. The function of the controllers are to provide sampling of analog signals, filtering of these signals, to provide digital calibration of strain gages, modeling the actuator voltage-velocity curve, the generation of PWM signals and to communicate with the PC based computational engine.

Sensor signals are sampled at 2 kHz using 12-bit, 8 channel A/D converters (MAXIM 180). All strain gage signals are amplified by digitally-calibrated signal stage OP-AMP circuits. The motors are driven by a custom designed PWM circuit, composed of a Dual Ported Memory and several PALs (Programmable Array logic). The circuit generates the 16 PWM signals needed to backdrive the exoskeleton glove and the 20 signals necessary to drive the anthropomorphic hand, including the four compliance drives (one for each finger) and 4 PWM signals for the 3 DOF wrist and its compliance control. In addition, the controller monitors joint and force limits and can stop the system if preset limits are exceeded. The amplifier drive circuits, based on the National Semiconductor 18201 H-Bridge (PWM amplifier) provides power signals to the motor.

The C30 uses a UART (Universal Asynchronous Receiver/Transmitter) to provide an RS-232 serial line communication to the PC. The N-232 serial interface between the Intelligent Controller and the PC is used to download programs. Communication of sensor data and actuator commands to the computational engine is via a custom built 4 MHz synchronous serial interface between the C30 and one of the six parallel communication ports of the C40.

A monitor program was written for the C30 and resides in the EPROM. This program boots the computer, provides functions such as memory test, calibration and program downloading. Programs are downloaded via the RS-232 into the RAM memory.

Computing Architecture

The computing architecture (Fig. 4) was designed as an efficient means of handling the computational requirements for this system, currently with 49 DOF. It supports several distinct functions: 1) Filtration of sensed signals 2) Modeling of voltage-velocity curves for motor control 3) Control law implementation and 4) Inverse kinematics.

Filtration of Sensed Signals- Sensed signals include joint encoder signals, compliance deflection signals, compliance setting encoder signals and strain gage signals. Sensed values require filtration to estimate the true signal value. In this system, an Infinite Impulse Response (IIR) filter was used and is given by the following equation:

$$\hat{y}_n = \hat{y}_{n-1} + K \cdot (x_n - \hat{y}_{n-1}) \qquad (1)$$

where $\hat{y}_n$ is an unbiased estimate [5] of the true signal y_n at sample time n, K is a gain factor that depends on the signal noise and X_n is the value of the raw, unfiltered A/D converted sample.

Modeling of Voltage-Velocity Curve-A model of each actuator system is necessary for achieving high performance control. Each actuator system is comprised of a motor, a gear train, flex cables to the joint and the joint itself. For the hand, the joint's position pot, which is driven by the joint actuator cable, is the actual controlled quantity. For the glove, the positional output of the gear train is measured and the position of its joints are inferred from this measurement. Any other variable, i.e. true motor position, motor torque or true joint position are not measured in this system and hence are not considered in the model.

To obtain a first approximation, a voltage-velocity curve can be modelled by using two straight lines interrupted by a discontinuity at the origin. This model is given by the following equation:

$$f_{model}(Y, voltage) = k_1(Y) \cdot voltage + v_0^+(Y) \qquad if(voltage) \geq 0 \qquad (2)$$

$$f_{model}(Y, voltage) = k_2(Y) \cdot voltage + v_0^-(Y) \qquad if(voltage) < 0 \qquad (3)$$

where f_m is the modelled velocity of the position sensor, k_1 and k_2 are gains, the v_0's are the minimum starting voltages required to move the joint, and Y is an estimated value depending on the hand configuration. The values k_1, k_2, and v_0 are estimated by a calibration procedure. Note that back EMF and other velocity dependent terms are not included. Also note that the k_1, k_2 and v_0 variables are configuration dependent due to friction variations throughout the range of motion of each joint and due to interactions between joints. To simplify the problem, the variables were regarded as configuration independent at this time. In the near future, the calibration procedure will be augmented to generate several configuration dependent models for each actuator in the terminus devices.

Control Law Implementation- There are two modes of operation of the control system. In the first mode, called "free motion", the anthropomorphic hand/wrist assembly moves freely without contacting the environment. Once a finger comes into contact with a surface, its deflection sensors inform the controller of an externally induced finger deflection which causes the controller to automatically switch to the "force control" mode for that finger: Instead of specifying a joint position, joint torques and compliance settings are being servoed (force control of the wrist functions in similar fashion). Experimentation in this mode are still ongoing, the theory behind this control mode will be published at a later date.

In the "free motion" mode, the control laws are PD (positional and derivative) control laws. The input to the control law is the desired position, the current position and its time differential (which approximates velocity). Once a command is computed using the PD control law, the command signal is mapped through an inverse model of the motor. In this way, the motor's behavior is linearized. The equation for the control law is given in equation (4) and the equation for the inverse model is given in equation (5):

$$u = K_p \cdot (\hat{y}_n - y_d) + K_v \cdot (\hat{y}_n - \hat{y}_{n-1}) \qquad (4)$$

$$u' = f^{-1}{}_{model} \, . \, u \qquad (5)$$

where u is the control command to the actuator model, $\hat{y}_n$ is the estimated position of the joint being controlled, and y_d is the desired position of the joint. The variables K_p and K_v are gain factors for the Position error and the velocity error respectively. In equation (5), u' is the control output after being transformed by the inverse of the motor model f_{model}.

In the "free motion" mode, the desired position command y_d is derived from various sources: For most joints in the anthropomorphic hand, the desired position is given by the integral of the torque, sensed at the corresponding joint in the glove. This torque is a measure of the force exerted by the human operator. The equation for the desired position "is given by the equation below:

$$y_{danthro} = \int_0^T K_{sg} \, . \, \hat{y}sg_n dt \qquad (6)$$

Here $y_{danthro}$ is the set point command to the motor, K_{sg} are gain factors for strain gages at individual joints and $\hat{y}sg_n$ is the estimated strain gage value which is derived from the torque at that joint of the exoskeleton glove,

The lateral motion of the three fingers is position controlled and follows the same concept as described below for the glove.

The position of each joint in the exoskeleton glove is determined by the position of each corresponding joint in the anthropomorphic hand. That is:

$$y_{dglove} = y_{anthro} \qquad (7)$$

where y_{anthro} is the actual position of the corresponding anthropomorphic hand joint.

Finally, the position and orientation of the PUMA and the wrist is determined by a kinematic mapping of the FRHC to the PUMA and the wrist. Likewise, the FRHC is backdriven by the PUMA and the wrist in similar fashion.

Inverse Kinematics- The closed form inverse kinematics solution for the 6 dof robot arm (first 3 joints of the PUMA and the 3 dof wrist) are computed by standard methods.

'I'he computation is distributed between the C40s and the C30s. The C40S perform the bulk of the computations which are equations (4) through (7). Equation (1) and the inverses of the motor model, given by equations (2) and (3) are performed by the C30 in the intelligent interface controller. The C40S subdivide the computational load according to the natural division of master and slave, thus minimizing the bandwidth requirements of the communication link between the two C40s. If, in the future, additional processing requirement are desired, 2 or more C40S can be built into the system, thus forming a high performance parallel machine. The closed loop bandwidth of the system is approximately 1 kHz. This will increase as the code is optimized.

Performance Evaluation

The following discussion describes some of the handling skills that were demonstrated in the initial performance evaluation of this telemanipulation system, Testing is still in progress and actual test data will be published at a later date.

Object Grappling- Grasping objects with the hand in compliant mode simplifies the grappling process because compliance enables self-alignment of the hand to the object, easing positional accuracy requirements during final approach and grappling. Compliance also enables multi point object contact because individual fingers self-align to objects, resulting in a tight grip. The hand grasps objects primarily from one side, enabling a better oversight over the hand's activities while requiring less workspace around objects.

7001 Guidance- Tools that need to be guided along linear paths (i.e. knife) can be handled quite well due to the hand's compliance. Tools requiring tightening motions around an axis (i.e. a wrench moving around the screw axis), could also be handled. Two key capabilities make this possible: The hand's articulation enables it to embrace the tool handle, thus holding it without using much clamping force. To tighten the screw, the wrench has to move around the screw axis in a circular path but the hand does not have to follow this path accurately because the hand, formed as a hook around the embraced tool, allows some relative motion between itself and the tool without loosing contact with the tool. Additionally, the wrist's compliance provides some self-alignment of the hand's orientation w.r.t. the tool orientation. Not having to follow the tool path accurately simplifies this tool guidance operation considerably, In order to use a tool with the hand, it first must be placed into the hand properly. An often overlooked fact is that orienting and placing the tool handles correctly into the robot hand requires assistance from a second hand. Also, tools often need to be regrasped, held and guided or held and manipulated which requires a second hand as well. It was found that EVA-type remote tool operations are only meaningful if a second hand is available to assist the tool handling operation.

7001 *Manipulations*- Hand tool manipulations are surprisingly difficult to perform, even with the articulation this hand has. However, some tool manipulation tasks have already been demonstrated (i.e. scissor). 'l'he lack of tactile sensing was quite evident in tool manipulations: human tactile sensors not only sense the locations of contact but also sense the strength and direction of the applied forces, enabling the hand to exert proper reactive forces. This makes human tool manipulations easy. 'l'he lack of tactile sensing in the mechanical hand severely hampers tool manipulations.

Most tool manipulations will require two hands, For instance, a pliers can be held near its hinging point by one hand while the other hand operates the tool at the handles. In essence, tool manipulations will be transformed into two simpler tasks: tool holding and tool actuation.

Number of fingers needed- In most cases, it takes at least three fingers to rigidly hold an object within the hand while a fourth finger performs a manipulaton such as squeezing a trigger. Likewise, object manipulations require three fingers to firmly hold the object while the fourth finger is free to regrasp. 'Jests with the four fingered hand proved that most hand tools could not be held and operated by using only three fingers. Thus, the minimum number of fingers is four, one being a thumb.

EVA tool evaluation- An evaluation was undertaken [1], analyzing the feasibility of handling astronaut tools by a general purpose space telerobot. Major findings were that of the 195 astronaut EVA items evaluated, only 6 could be handled be an industrial type end effecter. A one arm robot with a fingered hand could handle 29 items whereas a dual arm robot with fingered hands would be capable of handling 171 items.

The following listing states the EVA items that can be handled by one fingered hand (excluding the tethering operation): Battery, bolt puller, camera actuator, connector tool, door latch, door stay, drill (on handle), drive unit preload tool, fastener (1/4 turn), force measurement tool, hammer, J-hook, hydrazine brush, loop pin extractor, probe, pry bar and wrenches (open, box ends and allen).

Other EVA items that are being considered for robot testing include: bolt puller, connector demate tools, connector pin straightener, power drive disconnect tool, ratchet wrenches, screwdrivers with shroud, sockets, bags, connector and cap, mirror, tape caddies, tool boards, knobs and switches.

Prerequisite for dual arm manipulations- Redundant 7 DOF arms are needed to reach around obstructions and to properly align the arms w.r.t. each other, avoiding arm interferences. Full arm compliance is needed for tool guidance operations (see above) ant] for cooperative dual arm manipulations of rigid objects. (Seven DOF anthropomorphic master arm controllers already exist),

Tethering operations- Shuttle safety manifests require that all loose items must be tethered in space to prevent free floating. All tethers securing tools or equipment while being used are lock-lock tethers which require two simultaneous operations to unlock the tether's hook, requiring two handed operations even for the astronaut. Tethering operations with the robot also require dual hands.

Conclusions

The initial evaluation revealed the system's potential for multifunctional operations, including tool handling and manipulation tasks. However, hand tool manipulations and EVA tasks require a dual fingered hand system with at least four fingers and 7 DOF compliant arms. The system can only reach its full potential after its expansion into a dual arm system with active electromechanical compliance, enabling human-equivalent telepresence in space, including tool use.

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