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DUAL ARM MASTER CONTROLLER CONCEPT*

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ABSTRACT The Advanced Servomanipulator (ASM) slave was designed with an anthropomorphic stance, gear/torque tube power drives, and modular construction. These features resulted in increased inertia, friction, and backlash relative to tape-driven manipulators. Studies were performed which addressed the human factors design and performance trade-offs associated with the corresponding master controller best suited for the ASM. The results of these studies, as well as the conceptual design of the dual arm master controller, are presented.

I. INTRODUCTION

The dual arm master controller (master) is the out-of-cell half of the Advanced Servomanipulator (ASM) teleoperator system. It will be used to operate the ASM slave from the control room, safely behind the biological shielding as shown in Fig. 1. It is primarily controlled by inputs from the human operator with computer augmentation. The motions of the master are reproduced in the cell by the slave using bilateral position-position servoloops.[1] The slave was designed to be remotely maintainable in-cell with another ASM slave.[2] This was achieved by designing the ASM slave with remotely replaceable modules and with gear/torque tube force transmission. These functional requirements increase manipulator inertia, friction, and backlash in comparison to conventional tape-driven servomanipulators. It was also felt that conventional systems needed an improved man/machine interface.

Therefore, the development of the dual arm master controller was intended to optimize both the mechanical design and the human factors aspects. It was designed to minimize inertia, friction, and backlash to offset the increase of these parameters in the slave. This combination will allow the entire master/slave system to perform comparably to the conventional systems. The human factors of the master were also studied to enhance the man/machine interface. The kinematics, handle type, and joint cross coupling were designed to conform to these results of the studies.

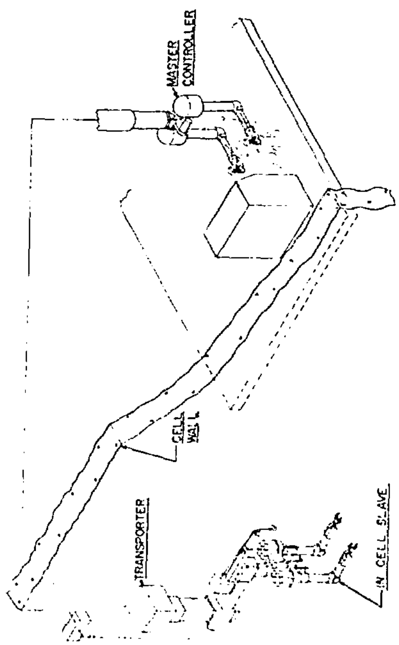

Fig. 1. Ambidextrous master handle

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II. KINEMATICS

The most basic criterion for designing a manipulator is the kinematic arrangement. The joint relationships and the length of the links can greatly influence the performance and dexterity. These factors were studied in detail,[3] and master kinematics were recommended that were similar to the ASM slave. The kinematics were investigated from a variety of viewpoints, but the overall objective was to maximize the dexterity and transparency to the operator. If this objective is met, it will maximize the operator's performance and efficiency by providing human-like flexibility and by minimizing his fatigue and frustration. The master must be capable of motions comparable to a human and should not interfere with the operator's body. Since several kinematic arrangements can achieve this objective, other criteria were established to evaluate these arrangements more closely. One such additional criterion was implementation complexity. Some of the arrangements, though geometrically similar, were not kinematically identical and therefore were difficult to implement. Geometric similarity consists of identical link lengths and joint orientations. Kinematic similarity includes this, but goes further than the structural linkages to include identical force and torque transmission. This also means that the entire manner in which forces are transmitted through the master, including joint interrelations must be identical to the slave.

The difficulty of implementation that arises when trying to use a geometrically similar (not kinematically identical) arrangement is the type of control loop that must be used. A position-position control loop is presently employed in the ASM control system.[1] This loop is very simple if the master is a kinematic replica of the slave but becomes very complicated if a non-replica master is chosen. With identical kinematics, the positions of the individual joints in both the master and in the slave are sensed and compared directly. If a position difference (error) exists, a command is derived from the control algorithm and is given to the master/slave pair to eliminate it. With non-replica kinematics the position difference must be derived since the individual joint positions cannot be directly compared. Such a derivation requires motor/joint transformations with significant calculations. Once the positions differences are determined, a similar transformation procedure is necessary to obtain the command for each corresponding joint. Since this method is theoretically feasible, an analysis was performed to determine if such a control loop could be closed fast enough to be stable. The analysis indicated that the loop could be implemented but would require development of complex software. Since the non-replica kinematic arrangement offered little advantage over the replica arrangement and since the non-replica option carried with it the need for increased software complexity, a kinematic replica master was chosen.

III. HANDLES

To properly design the handle for the master, the kinematic arrangement must be considered. Many handle designs were concepted,[3] Once the kinematics were chosen, several possibilities were eliminated. For the replica master kinematics four handle types were evaluated. The criteria for this evaluation were primarily concerned with the human factors that affect the performance of the operator. The handle must be comfortable and non-fatiguing and provide the operator with a transparent man/machine interface to the master. From previous studies[4] it was shown that an operator often uses either hand on either handle, so the design must also be ambidexterous. Although none of the final four possible designs showed a clear advantage, once a new tong actuator control concept was selected (Sect. VIII), the pistol-type handle (Fig. 2) looked most favorable. Before this new tong control concept was

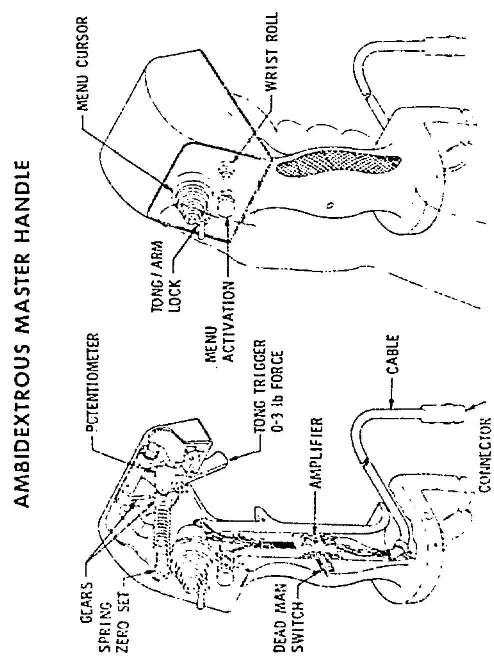

Fig. 2. ASM teleoperator system

chosen, it was believed that the tong actuator would be a backdriveable electromechanical gear train just like the rest of the joints. However, once the conceptual design of the master was begun, it became apparent that such a gear train could not be designed with a force-reflection threshold as low as the rest of the joints. In fact the threshold with this gear train would be more than three times higher. Therefore, it was decided to control the tong with a new concept that employs a trigger with a position sensor. This control concept can be easily implemented with the pistol-type handle. This handle also provides a good location for the operator to reach the remaining control switches. A prototype of the chosen handle will be built and the human factors thoroughly studied to design the final version for the master.

IV. CROSS COUPLING

A cross-coupled joint is one in which the torque in that joint is a function of the load in that joint and the load in another joint. For example, the summation of torques about the elbow joint is equal to the torque supplied by the elbow motor, PLUS an amount proportional to the torques supplied by the wrist motors. Another way to look at it is that the torque required from the elbow motor to support the elbow depends on how the wrist is being loaded. So the force reflected to the operator in the elbow of the master would be changed as the load in the slave wrist changed. The implications of this coupled relationship (as well as the coupling itself) are subtle, but it results in reduced controllability and inaccurate force reflection unless properly handled.

In the first design study[3] a concept was recommended for the master controller. This design was light, with low inertia, and almost no backlash. Nevertheless, there was one subtle aspect of this design that was not similar to the ASM and this made the design unacceptable. In the slave, all the wrist motors are located above the shoulder on the gear pod and the forces required for the wrist are transmitted through the elbow, which results in elbow/wrist cross coupling.[5] However, in the first master conceptual design, the wrist motors were located behind the elbow attached to the forearm. This completely eliminated the elbow/wrist cross coupling in the master. In most manipulator systems, this would be an advantageous feature, but in actuality it was detrimental to the performance of this master/slave system. Since the slave would be coupled but the master would be uncoupled, this unsymmetrical coupling would give the operator of the master a very confusing force and positional response.

The only way to account for this coupled-uncoupled relationship would be to employ motor/joint transformations. This would also require development of the transformation software. Therefore, a new concept was developed based on all the knowledge that was gained through the conceptual design efforts on the master and the design of the slave. This new concept is coupled, and it coupled identically as the slave. The coupling effects will then be reproduced in the opposite direction and cancelled out by the position-position loop. This will give the operator an accurate force and positional response, because all the coupling effects have been effectively "eliminated." As electronic advances continue in the future, such motor/joint transformations that we now shy away from may be routine enough to reconsider an uncoupled master. If this transformation option is chosen, then other kinematic arrangements should also be reconsidered.

V. MOTORS

The motors used on the master are the same as those used for the slave.[5] These motors have the highest continuous torque to friction torque ratio of any available motor. This is their most important feature, since they will obtain the lowest static friction possible for the master. This is very desirable in order to offset the increased friction in the slave. The gear ratio required with these motors range 2:1 to 12:1.

The only disadvantage is that the weight of the motors is approximately 50% of the estimated total master weight. This high weight contribution is due to the master being much lighter construction than the slave. This is an unusually high contribution but it is warranted by the low overall friction of the motor. A smaller motor (less weight) with a higher gear ratio was considered to reduce the high contribution. This was not done because it would actually increase friction. This is because the absolute value of the motor friction torque (approximately 42 N.mm) is the same in both the smaller and the larger motor. Since the smaller motor has lower continuous torque, it yields a lower continuous torque/friction torque ratio. This lower continuous torque/friction torque ratio increases the static friction, and therefore, degrades the force reflection. The present slave motor then provides the minimum static friction, and therefore the minimum force-reflection threshold. In essence, the motor development effort for the slave system identified a nearly optimal servomotor in terms of capacity and friction characteristics. Using this motor on both the slave and the master will assist in producing the best force reflection possible.

VI. CABLE CHAINS

A variety of techniques and hardware are available for transmitting forces from the centralized motors to their respective joints. The most likely possibilities that were considered were metal tapes, cables, and polyurethane cable chains. Cable chains are relatively new compared to the metal tapes or cables. They are available commercially and have been successfully used in many critical applications.[6] They provide low friction and inertia with zero backlash. They were chosen because their performance equals or exceeds the performance of the tapes or cables and are much easier to implement. Standard sprockets and chains can be purchased and a very simple design was developed around these components. This greatly reduces the complexity and fabrication cost of the master.

The only disadvantage of the cable chains is that they are not as stiff as existing systems (metal tapes or cables). It is the author's opinion that a master does not need to be as stiff as existing masters. This will of course be evaluated when the master is tested. But even if a higher stiffness is necessary, it can be accomplished with a larger size cable chain, a double row of the present size, or stiffeners (such as steel bars) added in the free-length sections of the chains.

VII. DESIGN OBJECTIVES

As stated earlier, the objective of the master design was to provide a system that was best suited for the gear driven slave. Therefore, the master was designed to minimize friction and inertia with zero backlash while enhancing the man/machine interface. All these features can be grouped under the single category of improving the operator's performance. Consequently, it is also important to achieve a very clear and aesthetically appealing master, which is comfortable to operate. In addition, the design options for the master considered simplicity and low cost as high priorities to balance the cost of the slave. This effort was then solidified and documented as a conceptual design in the detailed design requirements document. This document was the basis for the work by Jet Propulsion Laboratory, which further developed and finalized the concept.

VIII. DESIGN CONCEPT

The conceptual design for the dual arm master controller is shown in Fig. 3. The master has a capacity of 6 kg, approximately one-fourth the capacity of the ASM slave. It has 7 degrees of freedom and features the anthropomorphic (elbows down) stance to mimic the slave. The structural tubes are made of graphic composites to increase their stiffness and decrease their weight. The master will use an advanced handle developed from rigorous human factors analysis and experimental tests of a prototype handle. The force-reflection threshold has been analytically determined to be about 1/4 kg. A 1-degree-of-freedom test stand that simulates the wrist roll joint is being fabricated to verify these analytical results.

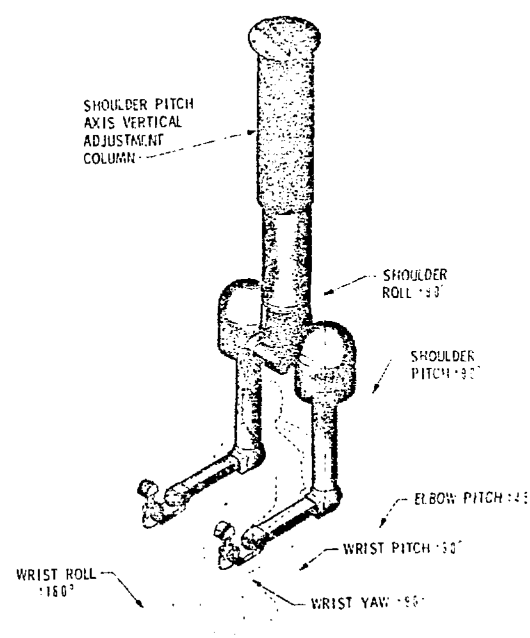

Fig. 3. Dual arm master controller conceptual design

The kinematic arrangement of the joints is identical to the slave. All the force transmission, the length of the links, and the location and orientation of the joints are identical, except for the wrist L-housing. Here the distance from the wrist pitch axis to the tong actuator is only 200 mm (50 mm less than the slave) to allow the slave tongs to touch without the master handles interfering. The master is mechanically counterbalanced to reduce friction. This is accomplished with a 4-bar linkage located inside the upper arm tube.

The two upper degrees of freedom are all gear driven as in the slave. Since the capacity of the master is much less than the slave, the gear trains are smaller and simpler. Precision gears with weight and inertia minimized, and precision bearings are used throughout. This results in a gear train with very low backlash and low inertia.

The elbow is partially gear driven. It uses the 4-bar counterbalance linkage to also transmit the drive forces to the lower arm structure in the elbow joint. This yields a very clean, compact design which is much easier to implement than a bevel gear/drive shaft arrangement.

The three wrist motions (pitch, yaw, and roll) are driven by 1:1 ratio gears to translate and rotate the torque from the motor at the edge of the gear box to the sprocket assembly in the center of the gear box. From the sprocket assembly to the wrist, the forces are transmitted using commercial cable chains (see Sect. VI). One chain transmits forces from the sprocket assembly to the elbow, and a second chain continues the transmission from the elbow to wrist gearing. In the wrist itself the traditional differential is used to drive pitch and yaw motions, and a partial second differential is nested inside of this to drive the roll. The roll forces are transmitted from its differential through the L-housing with a special 3-dimensional cable chain. This 3-dimensional chain can turn corners and is a very simple way to provide the wrist roll forces to the handle interface.

Another unique feature is the "unilateral loop" that is used to control the slave tong. Traditionally the slave tong is controlled similarly to the other joints, with a bilateral force-reflecting drive train. With this method the force-reflection threshold for the tong would be on the order of 1.0 kg. Since this threshold level is so high, a new idea was pursued that was much simpler and more reliable.

The new tong actuator is electromechanical but it is not a backdriveable gear train. Instead it incorporates a position sensor with a spring to give the operator an artificial force reflection. The slave tong is driven by sensing the position of the tong actuator (trigger) and using this information to calculate a current command to the tong motor. The control system then servos the tong about this resulting force. Since the position of the tong actuator is related (through the spring constant of the actuator spring) to the force applied by the operator to the trigger, this is actually a force-force loop. This control method is very flexible since the gains can be changed in the software to make the tong very sensitive to the tong actuator force for fragile jobs, or insensitive for heavy tasks. The spring in the handle itself can also be changed for various tasks or for individual operators. Overall this method is deemed very acceptable for the function it is to perform, but will be thoroughly evaluated during the testing of the master.

IX. SUMMARY

Overall the master represents a significant engineering achievement. It provides a major performance improvement by employing high performance commercial components and human factors engineering. This will result in an ASM master/slave system that provides increased performance and capabilities that are competitive with existing servomanipulator systems.

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