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AN ADVANCED REMOTELY MAINTAINABLE FORCE-REFLECTING SERVOMANIPULATOR CONCEPT*

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ABSTRACT A remotely maintainable force-reflecting servomanipulator concept is being developed at the Oak Ridge National Laboratory as part of the Consolidated Fuel Reprocessing Program. This new manipulator addresses requirements of advanced nuclear fuel reprocessing with emphasis on force reflection, remote maintainability, reliability, radiation tolerance, and corrosion resistance. The advanced servomanipulator is uniquely subdivided into remotely replaceable modules which will permit in situ manipulator repair by spare module replacement. Manipulator modularization and increased reliability are accomplished through a force transmission system that uses gears and torque tubes. Digital control algorithms and mechanical precision are used to offset the increased backlash, friction, and inertia resulting from the gear drives. This results in the first remotely maintainable force-reflecting servomanipulator in the world.

I. INTRODUCTION

The Consolidated Fuel Reprocessing Program (CFRP) at the Oak Ridge National Laboratory (ORNL) is responsible for the development of advanced nuclear fuel reprocessing. Remote maintenance technology development that will increase future plant operational availability, reduce personnel radiation exposure, and reduce environmental impact is an integral part of the CFRP. The Remote Control Engineering and Special Remote Systems tasks are major activities which are working toward a new remote maintenance system[1,2] based on force-reflecting servomanipulators and television viewing as principal maintenance tools. It is believed that the increased dexterity of servomanipulators will significantly increase the remote maintenance system's work efficiency, as well as allow more difficult tasks to be performed.[3]

This paper presents a new *remotely maintainable force-reflecting* servomanipulator concept which is intended to bridge the gap between the complexity of current force-reflecting manipulators and the degree of reliability and maintainability deemed necessary for use in reprocessing environments.

II. MOTIVATION

Servomanipulators and television viewing can provide a large-volume remote handling capability which approaches that of mechanical master/slave manipulators (MSMs) and shielded-window viewing.[4,5] Increased dexterity will influence remote facility design and operation by increasing the number of admissible work tasks, increasing the time efficiency, and enhancing the maintenance system's ability to respond to unexpected problems. These influences should reduce process equipment mean time to repair (MTTR) and thus increase overall plant availability. Servomanipulators' kinematics and dexterity should also allow equipment designers to reduce the degree of special remote provisions they normally are required to include.

Servomanipulator systems can extend MSM capabilities to a large-volume facility since the interconnection is electrical rather than mechanical between the master and slave arms, which allows the slave systems to be mobile using a transporter. The value of MSM-like dexterity as an additional large-volume remote handling tool is clear. The underlying concern is manipulator system reliability, particularly for the slave system. The added benefits of

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servomanipulator-based maintenance cannot be realized unless their reliability and maintainability are consistent with overall plant goals. Remote handling system failures increase plant downtime if they prevent process repairs to be completed. Consequently, process equipment MTTR is a function of both the remote handling system's functional capabilities and its inherent reliability. It is important for manipulators to operate *when* they are needed. In this regard, conventional servomanipulator slave designs have been inadequate. Current designs have used metal tape (or cable) and pulley drives to deliver motor torque to specific joint rotations on the arm.[6,7,8] This force transmission technique is an extrapolation of the tape linkages used in MSMs. Tape drives enhance teleoperation parameters by minimizing static friction and inertia, unfortunately at the expense of reliability and maintainability. Experience has shown that the tensioned tapes undergo fatigue failure after a few hundred operating hours. Tape replacement is a complex maintenance task which is almost impossible to accomplish remotely.[9] Replacement also results in significant personnel exposure. Overall system mean time between failure (MTBF) must be increased roughly an order of magnitude, and the slave manipulator itself must be remotely maintainable to reduce manipulator MTTR and minimize personnel exposure.

Recent advances in digital microelectronics and dc motors provide a foundation for more extensive use of gearing (rather than tapes) for motor torque transmission. Gear drives have been avoided in the past, particularly for the lower arm joints, because they undesirably increase friction, inertia, and backlash. These parameters are related to joint servocontrol performance and affect force-reflection fidelity. Since force reflection is considered a critical performance factor in remote maintenance efficiency, microprocessor servocontrol was used to implement compensation algorithms which offset the undesirable effects. Since only the remote slave system must be gear-driven and modularized, the master controller can be designed to help reduce overall friction, inertia, and backlash also.

The motivation for developing this new servomanipulator concept is the belief that increased control electronic capabilities and precise mechanical design can be implemented to offset detrimental effects inherent in this modular design. To this end, a specific Remote Control Engineering task activity was established for the development of a new servomanipulator system, called the advanced servomanipulator.

III. THE ADVANCED SERVOMANIPULATOR

The development of an advanced servomanipulator (ASM) concept began with an initial in-house ORNL study and subcontracts with Teleoperator System Incorporated and Martin Marietta Corporation for conceptual design of the in-cell slave manipulator. The results of these design studies were used in formulating the directions of the ASM research. The initial concept was based on a dual-arm anthropomorphic package where each manipulator arm consists of 7 degrees of freedom. The seven-joint arm concept incorporated shoulder-mounted actuators with combinations of gears and nested-torque tubes to transmit torques to lower degrees of freedom. The concept was mechanically too complex to modularize, but later ORNL revisions rendered a feasible approach. This approach was particularly attractive in that the gear/torque-tube force transmission would facilitate modularization for remote maintainability.

A. System Description

The ASM slave is a two-arm, all-gear-driven servomanipulator. The single most obvious difference in this system from traditional servomanipulators is the anthropomorphic or "manlike" stance as shown in Fig. 1. Reprocessing plants generally consist of very large

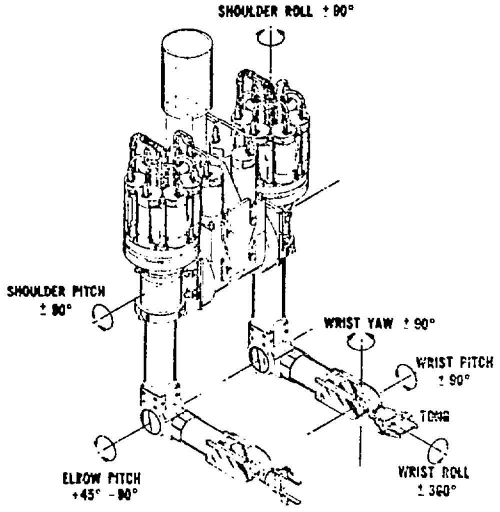

Fig. 1. Advanced servomanipulator

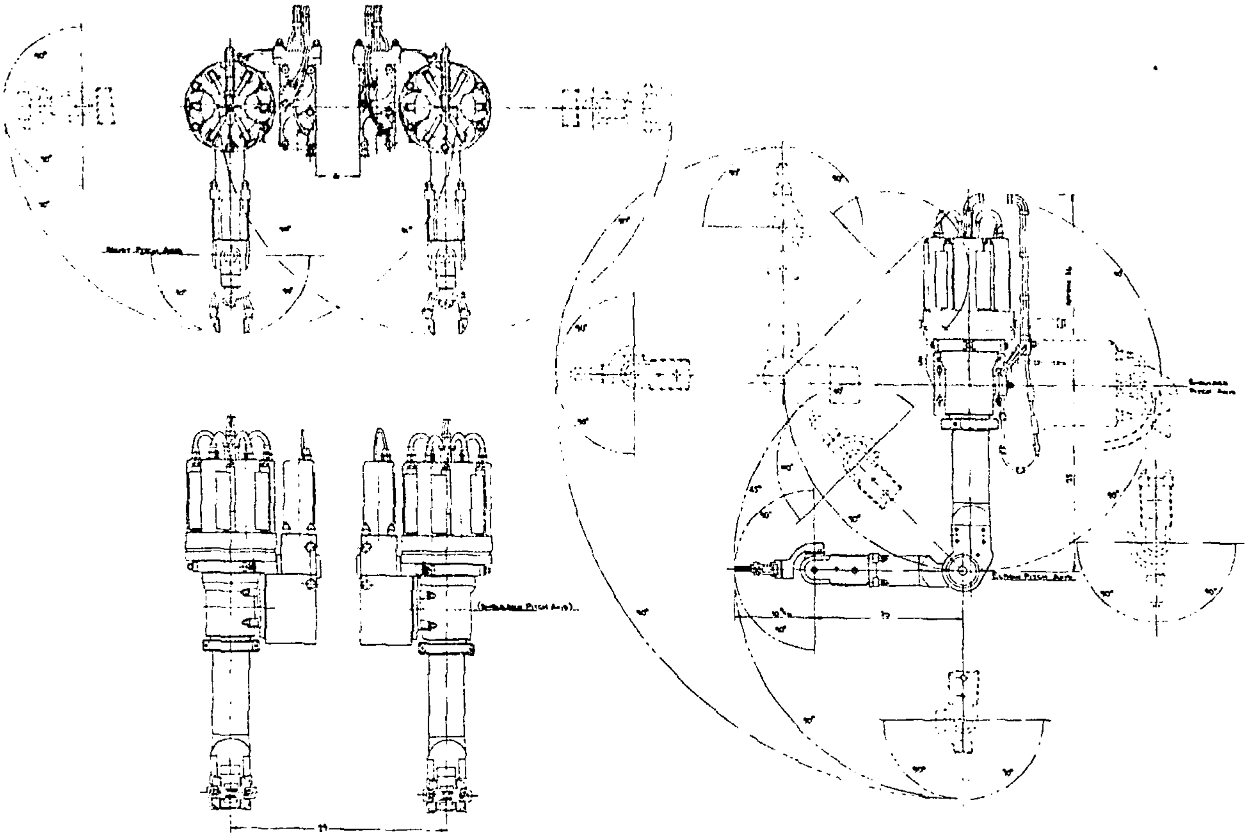

Fig. 2. Three-view motion range

chemical equipment such as tanks, heat exchangers and columns where horizontal manipulator access into the equipment is required.[1,10] The traditional "elbow-up" manipulator stance was derived from "over-the-wall" shielding penetration and was intended for tabletop operations. This kinematic configuration, so successfully applied to hot lab maintenance worldwide, is not amenable to horizontal reaching actions because of the obstruction created by the lower arm link.

The ASM kinematic configuration and ranges of motion are shown in Figs. 1 and 2. The upper 3 degrees of freedom (shoulder pitch, shoulder roll, and elbow pitch) provide wrist positioning in space. Three of the four wrist motions (wrist pitch, wrist yaw, and wrist roll) establish tong orientation. The fourth wrist motion, tong closure, supplies a grasping ability. This unique wrist design, with 4 degrees of freedom, provides very dexterous orientation of the tong by virtue of intersecting orthogonal axes and the pitch-yaw-roll kinematic sequence. Conventional MSM wrist kinematics (e.g., lower arm roll followed by wrist pitch and roll) could not be used in the elbows-down stance because the lower arm and end-effector axes of motion coincide at the normal operating position. When two joint axes align to form what is often called a singularity, they become redundant and difficult to control independently. The ASM lower arm does not rotate but has all the orientations occurring in the wrist body. In the ASM wrist, all the singularities occur at the extremities of the ranges of motion where they are of minimal concern.

The load capacity of the ASM slave arms is 23 kg, which is considered appropriate for reprocessing maintenance. The ASM design capacity presumes that it will be part of an integrated maintenance system including cranes, and is based on trade-off analysis of the packaging and envelope requirements of the manipulator and the reprocessing equipment needs. The ASM slave arms are designed with an end-effector maximum slew velocity of approximately 1.0 m/s and have sufficient dynamic response to follow an operator's normal range of input speed in real time.

Several other parameters associated with the ASM gear drives are critically important in terms of the ultimate performance of the manipulator. The disadvantages of the gear/torque tube force transmission system must be minimized for in the mechanical design and compensated for in the control development. These disadvantages include increased friction, increased backlash, increased inertia, and joint axis cross-coupling. Friction is of major concern because it directly affects the magnitude of the force-reflection threshold. The force-reflection threshold is that amount of back-driving force at the slave necessary to overcome static friction and to initiate master arm motion. Below this threshold the operator has no feedback from the remote environment. Therefore, minimizing the friction threshold is considered one of the most important performance-related design objectives. It is estimated that the ASM will have a force-reflection threshold on the order of 0.45 kg (2% capacity). For comparison, currently available servomanipulators have force-reflection thresholds ranging from 1 to 10% of capacity.

The sources of friction in the ASM are primarily bearings, gears, and motors. Friction magnitudes are dependent on bearing quality, gear quality, lubrication, and fabrication precision. Lubrication will be limited to light machine oil, and shaft seals are not used because they significantly increase friction. Gear friction is minimized with precision alignment, high-quality gears, and hardened gear materials. It has been estimated that the gear friction will be roughly an order of magnitude larger than the bearing friction. Drive motor friction must be minimized since its effects are amplified by the ratio and the efficiency of the associated gear train. A friction compensation algorithm will also be used to reduce the perceived static friction even further.

Backlash in gear-driven servo systems imposes undesirable nonlinear effects on the control system. This results in reduced positioning accuracy and can cause instability. Several methods can be used to reduce the magnitude and effects of backlash. Mounting the gear meshes with interference is often used in industrial robots to minimize backlash, but this significantly degrades force reflection. This approach is not possible for force-reflecting servomanipulators because the gear trains must be backdriveable. Other design solutions include selecting high-quality components that are manufactured to close tolerances, mounting feedback sensors at the drive motor shafts to close the control loop exclusive of backlash, distributing gear ratios such that the largest gear reductions occur near the output, and minimizing overall backlash by minimizing backlash in the master controller, which does not have to use gear drives. Each of these techniques was used to varying degrees in the design of the ASM.

A detailed parametric analysis was performed to determine the contribution of each mechanical component to the total system backlash. This study was the basis for the degree of precision chosen for each specific component. In general, the precision chosen is much better than standard components but is not the best that can be achieved.

Locating feedback sensors at the centralized motors circumvents most of the stability problems posed by backlash. This eliminates potential phase errors between motor position and actual joint position which could cause small amplitude jitter. The nonlinear load effects are still present, but the effect of gravity on the slave arm will reduce these effects in the majority of manipulator positions. Another advantage of motor-mounted sensors is the motor, brake, and sensors can be located in one package, enhancing the remote maintenance aspects.

A disadvantage caused by the centralized motors and magnified by the gear drives is joint axis cross coupling. The nature in which the gear drives transmit forces through manipulator arm joints results in the torques applied at the motor shafts becoming interrelated at the arm joints. Cross-coupling effects in the ASM are significantly larger (20 to 40% of the total torque) than in metal tape-driven servomanipulators. The implications of cross coupling are important and can result in more complex control requirements, especially for accurate force reflection to the operator. An analysis was performed to evaluate the impact of slave cross coupling on the master controller design and the overall control system. The most important conclusion obtained was that the master controller cross coupling must mimic the slave cross coupling to prevent the operator from being confused by sensing incorrect forces at the master controller. The analysis also showed that the cross coupling can be either additive or subtractive. The gear train designs are arranged so that cross coupling allows motor drives to assist one than another rather counteract each other.

Since gear/torque-tube force transmission systems have much larger inertia than conventional tape drives, special attention is being given to total weight minimization. Multiple control regimes will be implemented to reduce inertial effects and therefore operator fatigue. In addition, real-time servocontrol techniques will be used to eliminate mechanical counterbalancing weights and mechanisms. The ASM utilizes electronic counterbalancing by calculating the weight vectors of the various arm links in real-time based on joint position. The weight vector data are then transformed back to the motor-drive coordinate frame where they are treated as incremental additive torques necessary to offset the weight. The effective shoulder inertia was reduced 35% and the total arm weight was reduced 40% over a mechanically counterbalanced system. Electronic counterbalancing increases friction because of the additional gear train load. It also increases drive motor duty cycles, which leads to higher gear reduction and increased friction threshold.

Another important design trade-off occurs between gear ratios and motor size. Low gear reductions reduce perceived inertia but require large, heavy motors. High gear reductions with small motors are not only nonbackdriveable but result in large reflected inertia that is proportional to the gear ratio squared. The ASM design uses relatively large motors which operate at slow speeds through low gear reductions.

B. Components and Materials of Construction

The ASM will operate in an acidic environment requiring corrosion-resistant materials. All bearings will be 440 C stainless steel. Gears and shafts are fabricated from corrosion-resistant 17-4PH stainless steel, and various housings are passivated 6061-T6 aluminum.

Only spur and straight-bevel gears are used in the ASM to minimize friction and to achieve backdriveability. Bevel gears have slightly lower efficiency than spur gears but are necessary to transmit forces around joints. Helical, spiral bevel, and other gears which are known to be smoother and quieter are not used because they are less efficient. All gears conform to the American Gear Manufacturers Association (AGMA) standard and are either 16 or 12 diametral pitch. Gear stresses are limited to meet reliability and life requirements of the ASM. All gears are high precision (AGMA Quality Class 10C), based upon an overall manipulator precision and backlash analysis.

Precision antifriction ball bearings are used throughout the ASM, and they are almost exclusively the deep groove radial type. This low- friction bearing type was selected because of the vast number of sizes, variations, and suppliers available. The bearings are sized to provide a minimum 1000-h life at maximum load and speed with approximately 1% failures.

Since maximum load and maximum speed never occur at the same time, it is estimated that the ASM bearings will actually have an operating life of 10,000 h in normal use.

The ASM torque-tube drives were analyzed with respect to strength, deflection, and vibration natural frequency. Of these three, the deflection criterion was most severe, so the stresses are low and the stiffnesses (and natural frequencies) are high. The failure rate of these components should be very low.

Electric motors supply the drive torques for all the manipulator motions. The dc servomotors provide large torque capacity at low speed and are commonly used in precision servomechanisms. Two vastly different dc servomotor geometries were investigated: (1) the shell motor and (2) the rare-earth magnet, iron core motor. The geometries of these two motor types are shown schematically in Fig. 3. The key difference between the two geometries is the location of the motor windings where heat generation occurs. In the shell motor, the windings are at the exterior of the armature, where as in the iron core motor the windings are in the internal rotating armature. The motor parameters that are particularly important for force-reflecting servomanipulator applications are presented in Table 1. Of these parameters, the percent sensitivity is the most important factor because it determines the absolute friction threshold that the manipulator can ultimately attain.

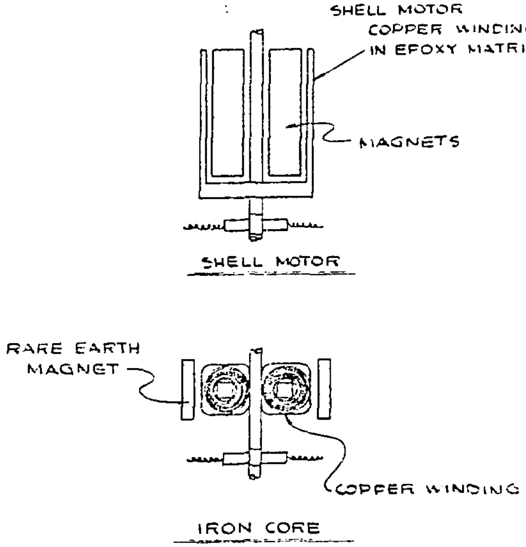

Fig. 3. Shell motor and iron core motor geometric comparison

Table 1. Important servomotor parameters

Parameter	Definition
1. Continuous torque capacity	Maximum torque that can be generated for a period of 2 h with an armature temperature ≤ 155°C.
2. Friction torque	Shaft torque necessary to backdrive motor.
3. Percent sensitivity	(Friction torque/continuous torque capacity) x 100%.
4. Torque density	(Continuous torque capacity/motor weight) x 100%.

An extensive motor market survey with product testing and development was performed at ORNL. This has enabled several performance improvements to be made in the ASM motors. Comparative testing between the two motor types was used to make the final selection. The friction torque and heat dissipation characteristics of the shell motor proved to be superior. A geometry change placed all magnets in the center of the motor, allowing the largest coil lever arm for torque generation and the best conductive path for thermal dissipation. The percent sensitivity of the shell motor is only 60% of the iron core motor and is the primary reason that it was selected as the baseline motor.

All electrical leads are terminated in the motor modules, so cabling is required to provide power and signal wiring from the shoulder to the motors mounted on the upper arm. Since the cabling will have a finite life due to radiation embrittlement and fatigue, external cable routing was chosen to simplify remote replacement. To reduce the possible snagging, cables are routed at the rear of the manipulators and away from the work site. A free length of cable has been selected to allow shoulder pitch and roll joints to have motion ranges of ±90°. If additional motion is required, the cable jumper can be redesigned for the different motion changes. If a different stance (e.g., elbows-up) is desired for a special task, the cable jumper can be used after the arm stance is changed.

The electronic controls have been designed so that they can be located away from the arms and shielded from the radiation. More details about the ASM control system can be found in ref. 10.

C. Modularization and Remote Maintenance

The ASM is designed to minimize remote handling system MTTR by using a module replacement scheme. The ASM is constructed in modules each of weighing less than 23 kg so that they can be handled by another ASM. Modularity is possible because the gear/torque-tube force transmission concept allows separation of modules at gear or spline interfaces. The ASM concept is based on the philosophy that a manipulator failure can be isolated to a particular module malfunction. The failed module would then be replaced with a working spare in situ by another ASM. Through spare module replacement, the failed ASM system can be returned to operation quickly (relative to removing the entire arm to a decontamination/repair station). The failed module would then be transferred to a repair station for further evaluation. All the ASM modules are designed for remote replacement using fixtures and tooling necessary for synchronization of gear meshes and intermediate arm supports.

As shown in Fig. 4, the ASM consists of eight remotely replaceable module types. The largest subassembly in the ASM, the shoulder, is actually made up of two modules: the shoulder gear box module and the lower pitch sleeve module. The shoulder is subdivided so that the individual module weight is below the 23-kg ASM capacity. Also, it was felt that the failure rate of the pitch sleeve will be much lower than the more complicated gear box.

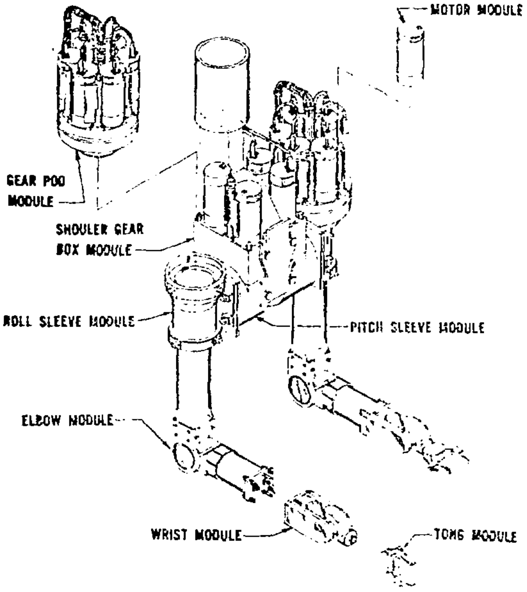

Fig. 4. Advanced servomanipulator modules

Since the pitch sleeve module supports the rest of the arm, it is designed to remain in place while the gear box is being replaced. The shoulder module provides the shoulder pitch motion for the arm. The shoulder pitch load is the largest and requires two of the standard ASM motor modules operating in tandem.

The roll sleeve module is attached to the shoulder. This module is basically a housing for the shoulder roll motion bearings and the internal torque tubes. These components have large design margins and should have a high reliability. The roll sleeve module can be removed from the shoulder pitch module with the elbow and gear pod modules attached. To replace the roll sleeve module, the elbow and gear pod modules must be removed first.

The gear pod module is removable from the roll sleeve and provides the appropriate gear reduction for the remaining 6 degrees of freedom. It also provides alignment for the remote coupling of the torque tubes and the motor modules.

The elbow module includes the upper arm, the elbow joint, and the lower arm. It is removable from the bottom of the roll sleeve through an attachment ring. It contains the torque tubes required to transmit power to the elbow motion and the four wrist motions and provides alignment for the remote coupling to the wrist module. The elbow module could be resized to provide different reach and capacity ranges for special applications.

Of all the modules in the ASM, the wrist module contains the largest number of gears, bearings, and other parts in a very small volume. It is also the most important module because it provides a degree of dexterity never before available in a manipulator. The ASM wrist has 4 degrees of freedom, whereas conventional MSM-type manipulators have only 3. This gives the operator a very human-like capability for performing his maintenance tasks. Since this module has the largest duty cycle and stress levels, it is expected to have the lowest reliability and therefore has been designed for remote replacement.

The tong module is based on a Sargent Industries, Central Research Laboratories Division, rotary drive two-fingered tong. This tong is modified to be remotely replaceable using a special changeout tool. This capability also allows direct attachment of special tooling to the wrist.

The motor module is identical for all joints. This simplifies spare parts inventory as well as remote replacement. The only disadvantage to using the same motor for all joints is that it increases the tong force reflection threshold. This is because the motor is larger than necessary; therefore, the friction is proportionately larger. The motor module includes all the necessary components, such as brake, position sensor, and tachometer required for joint control. The entire module will be replaced if any component fails. The motor module and its interface have been designed such that if significant commercial improvements are made in motors, sensors, or brakes, they can be incorporated by redesigning only the motor module.

D. Current Status

The initial design of the ASM slave manipulator has been completed. A 1-degree-of-freedom test stand has been built and extensively tested. Both the mechanical predictions and the performance of the control algorithms have been verified on this stand. The backlash and friction characteristics of this test stand have been as good or better than expected. Additional testing is continuing to optimize some remaining parameters. To gain further experience, two developmental units are being fabricated at ORNL. The ASM development arms will be used in preliminary testing with one unit acting as a replica master controller and the other as the corresponding slave. The objective of these tests will be to quantitatively evaluate basic gear-drive effects. Later, the two developmental slave arms will be combined as a dual-arm slave package and installed in an integrated demonstration of a complete advanced maintenance system including the mobile transporter, master controller, and operator station.[2]

IV. SUMMARY

It is believed that force-reflecting servomanipulators significantly improve the time efficiency and range of admissible tasks pertaining to remote maintenance and operations in advanced nuclear fuel reprocessing facilities. To be consistent with the basic objectives of the CFRP, servomanipulator reliability and remote maintainability must be improved. A new remotely maintainable servomanipulator, called the ASM, is being developed to meet these challenges. The ASM represents an entirely new concept that uses gears and torque tubes to transmit forces rather than conventional metal tapes. Improved control methods are used to compensate for gear and torque-tube shortcomings. The gear-drive approach allows the ASM to be subdivided into remotely replaceable modules. Remote modularization will allow failed manipulators to be repaired through (in some cases in situ) spare module replacement and thus decrease repair time. The mechanical design of the ASM slave manipulators has been completed, and fabrication of two developmental units is under way at ORNL. Experimental results are encouraging and fortify the expectation that the ASM can achieve the desired force-reflection performance while being more reliable and remotely maintainable.

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