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# A CONTROL SYSTEM FOR THE FERMILAB MASTER-SLAVE SERVO MANIPULATOR

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## Summary

A control system for the Fermilab Master-Slave servo manipulator has been developed. This new system offers a significant improvement in operational performance over the extant servo design with additional emphasis on simplicity of operation and maintainability. The servo manipulator is force-reflecting in each of the seven independent bilateral motions. Master force multipliciation is automatically increased as the slave force is increased to its fifty pound capacity. The design incorporates triac control of the low inertia two-phase servomotors and makes extensive use of digital circuits in the servo loops. The manipulator is utilized in servicing radioactive beam-line targeting equipment.


## Background

Since 1974, a pair of ANL Mark E4A manipulator arms[1] has formed the nucleus of the remote handling aspect of servicing radioactive beam line targeting equipment.[2] The Slave arms are mounted on an overhead bridge and carriage support which provides full coverage of the main servicing area. The Master arms, together with controls for both Master and Slave, are located in a separate building beyond the shielded servicing facility. Television and audio systems link the Master and Slave visually and acoustically. An increased work load for the servicing facility, coupled with operational difficulties with the obsolete E4A electronics,[3] mandated a second and more reliable manipulator system. Two sets of Master-Slave arms identical to the E4A's, were available from prior development efforts and were assigned to the second system. Cost constraints and the desire to keep both manipulator systems compatible dictated the retention of the split-phase ac servo motors. Since no operational electronics existed for the spare manipulator, the design of a new control system was initiated.

The several years' experience of operating and maintaining the E4A manipulators provided clear guidelines as to desirable improvements. Most prominent among these was to approach the manipulator controls from a systems standpoint stressing simplicity and failsafe operation with adequate diagnostic facility. Improvement of individual servo loop performance was also anticipated. Desired system improvements included simplifying start-up and sequencing procedure, modularizing of electronics, creating a soft-start capability, and providing a reduced power mode for the Master to allow null alignment of the Master to the Slave position. Desired individual servo loop improvements included automatic force ratioing of Master and Slave forces, increasing sensitivity at low forces, allowing for separate control of Master and Slave loop performance, creating a facility for minor position and counterbalance adjustments, and limiting servo motor power as a motion is overloaded and forced to slip out of null. Force ratioing between Master and Slave is required to enhance the sensitivity of the Master at low applied Slave forces, and to decrease Master force and operator fatigue at high levels of Slave applied force. The E4A electronics provide for operation in distinct force ratios of 1:1, 2:1, or 5:1. Most remote servicing tasks have been performed in the 5:1 mode, resulting in maximum Slave force of 50 lbs as desired, but at a loss of sensitivity. Gearing and servo motor configuration limit Master force to 17 lbs.

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## Design Concept and Implementation

The initial and pervading design consideration was the choice of output drive configuration. The servo motors require 60 Hz reference and control fields of up to 150 volts at more than 2 amps. The reference field remains constant in relative phase as the control field is phase-offset by plus or minus 90°, thus determining the direction of servo motor torque. Output torque is proportional to the product of the reference and control field magnitudes. The design goal of automatic force ratioing and a desire to minimize motor heating suggested the separation of output drives for Master and Slave reference and control field windings. Some initial consideration was given to ac transistorized power amplifiers. This approach was thwarted due to unavailability of suitable high voltage power transistors necessary for a directly coupled output stage. Transformer coupling was judged impractical due to the power requirements and attendant consequences of size and weight. These and other considerations led to the selection of triacs as the basic controlling elements, each servo motion requiring only six such devices for individual control of motor windings. The triac's 120 Hz control bandwidth, a full order of magnitude above the bandwidth of any manipulator motion, obviated concern of a discernible pulsing effect to the operator.

The subsequently derived control system for a Master-Slave manipulator consists of a 1 kHz three-phase voltage source, a Power Module, and an Amplifier Module. The three-phase source (Elgar Model 153A) provides excitation to synchro motors that furnish positional information to the servo loop. A single three-phase source is capable of driving two sets of Master-Slave arms. The Power Module, powered from a single 208 Vac 3$\phi$

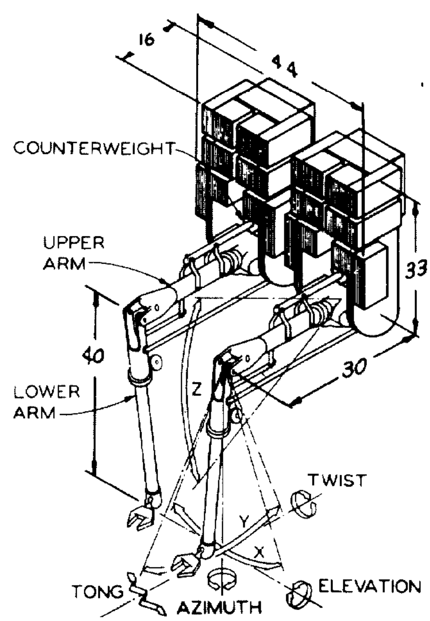


Fig. 1. Outline drawing of a pair of Slave arms showing motions.

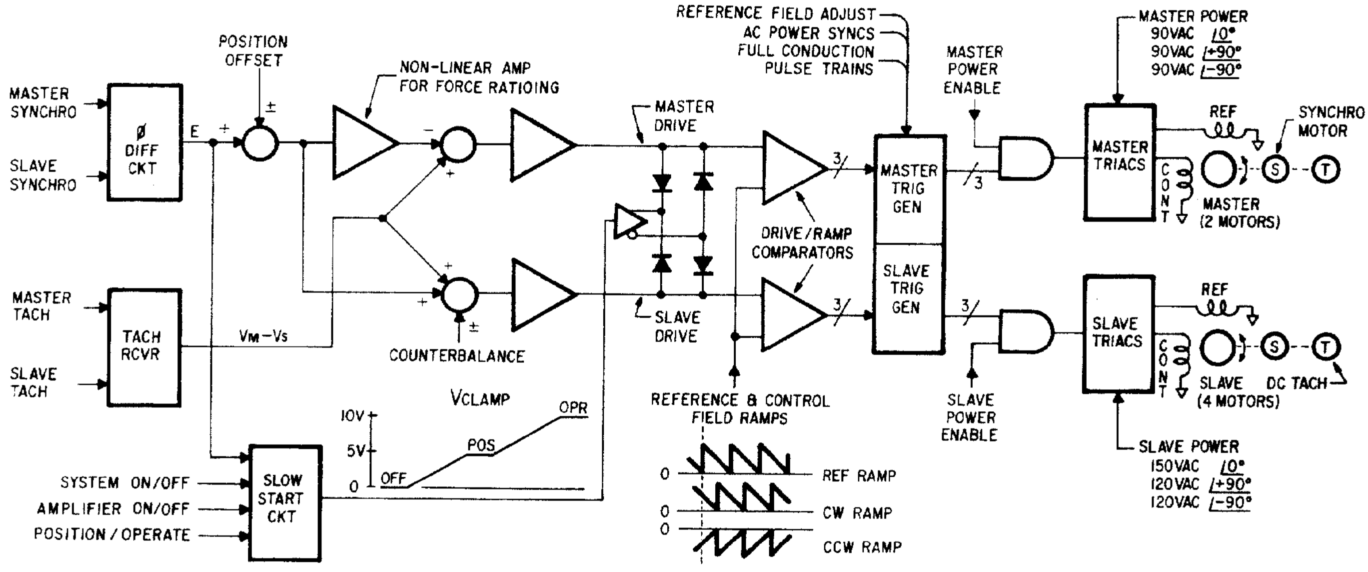


Fig. 2. Functional configuration of an individual servo loop.

source, contains two custom wound transformers in a Scott-T configuration which provides reference and control fields of up to 150 Vac. The power module also contains dc power supplies and solid-state relays to commutate Master and Slave motor power and Slave brake release power. The Amplifier Module contains seven servo systems, each controlling independent bilateral motions of X, Y, and Z coordinate space, azimuth, wrist twist and elevation, and grasp. A spare eighth servo system is also provided, which is normally used as a TV pan or tilt positional servo. Each servo system consists of a low level processor card and a triac output card. A single third type of card provides overall system control and sequencing, as well as providing three 120 Hz sawtooth ramps for all of the individual triac triggering circuits.

The Master and Slave cable directly to the Amplifier Module, each requiring a 19 shielded twisted-pair signal cable and a 19 twisted-pair drive cable. The Slave can easily be remoted to more than 300 feet, IR losses being the only significant limitation. Controls for a left and right arm Master-Slave manipulator system, consisting of a single synchro excitation source, two Amplifier Modules, and two Power Modules, occupy less than four vertical feet of rack space.

## The Servo Loop

Synchro control transformers, geared to both Master and Slave motors, provide positional information. Excitation of the synchro stator with a three-phase ac source yields a rotor signal of the same frequency but of varying phase angle with respect to the excitation. The servo loop acts to maintain minimum phase difference between the Master and Slave synchro rotor signals. One full turn of the synchro rotor yields a 360° signal phase shift and corresponds to about 40 turns of a Slave servo motor. All manipulator motions, with the exception of grasp, have more than a single null position within the mechanical limits of travel. The time-honored criteria for loop gain is that maximum Slave force be obtained in one revolution of the Slave servo motor. This corresponds to a Master-Slave synchro phase difference of 9°.

Figure 2 indicates the functional configuration of an individual servo system or loop. The primary error signal is a bipolar analog signal generated by the phase difference circuit of Fig. 4. Not shown in Fig. 2 are identical phase difference circuits that compare Master and Slave synchro signals to one of the synchro excitation phases to produce separate position signals. These signals are not integral to the servo loop but provide valuable response and stability information. Separate dc generator tachometers provide velocity information. The derived differential velocity is applied to both Master and Slave feed-forward paths providing second order stability. Automatic force ratioing, as indicated in Fig. 3, is accomplished by nonlinear amplification in the Master feed-forward path. Synchro phase differences up to 1° have higher feed-forward gain in both Master and Slave legs to overcome system friction and thereby increase sensitivity at low applied forces. Gradual delimiting of both Master and Slave drive signals provides the desired soft-start and reduced power features. Synchro phase differences in excess of 90° cause an individual servo system to turn off. The servo system will gradually reenergize subsequent to the synchro phase difference being reduced to less than 90°.

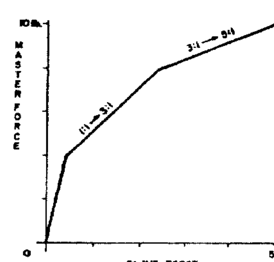


Fig. 3

Control of the firing angle of the triacs is determined by comparison of Master and Slave drive signals to appropriate sawtooth ramps. Both Master and Slave reference field triacs may be adjusted to a minimum conduction angle thereby yielding some linearization of the displacement versus force characteristic.

Position and counterbalancing adjustments are provided and enter the servo loop as shown. On/Off control of individual servo systems is provided at the front panel of the Amplifier Module. Absence of either Master or Slave synchro signal will turn off an individual servo system.

## Start-Up Procedure

Operator action sequences the Manipulator System through Power On and Position conditions to the Operate mode, providing simultaneous control of all servo systems within an Amplifier Module. The Power-On mode

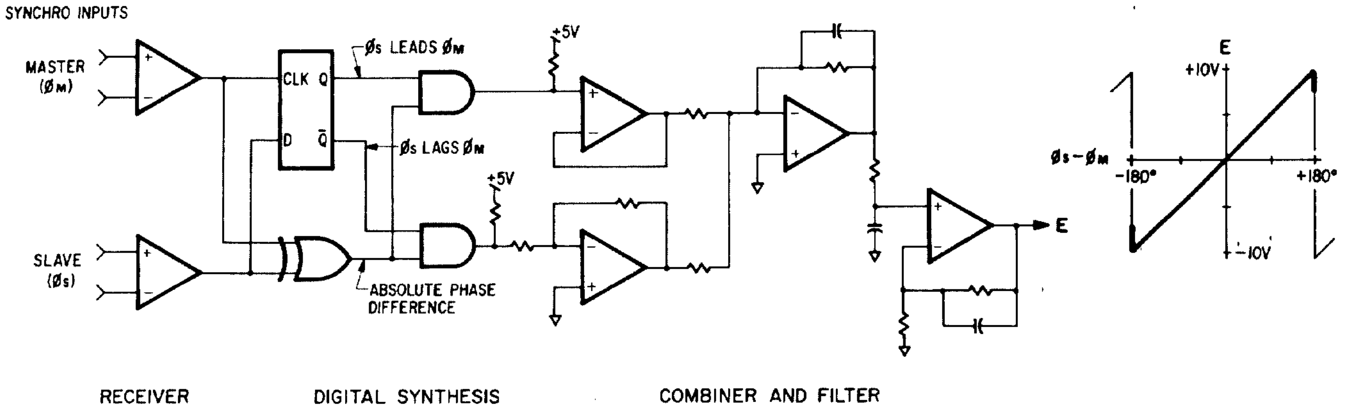


Fig. 4. Phase difference circuit.

provides for establishment of the Scott-T, synchro excitation, and dc power supplies. Master and Slave motor power remains off and the Slave remains mechanically locked in position. Observable, however, are all low-level position, error, and velocity signals, as well as the 120Hz sawtooth ramps. In the Position mode, all enabled servo systems proceed to reduced power and Master motor power is applied. The Master is now moved into proper null alignment with the locked Slave. Advancing to Operate allows full Master power and permits the application of Slave motor power with the release of brakes. Facility is provided for remote sequence and brake control. The status of dc voltages, synchro excitation, and Scott-T power is continously monitored. Improper status forces the manipulator system back to the Power-On state.

Fig. 5. Master operator at work.

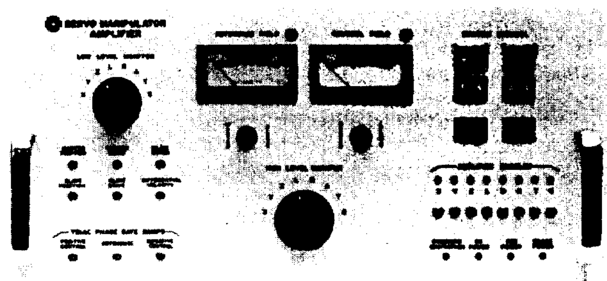

Fig. 6. The Amplifier Module.

## Conclusion

Operational experience with the new control system, though limited thus far, has proved highly favorable. From the user's standpoint, control of the manipulator was greatly simplified. Stability of individual motions was greatly improved at no sacrifice of sensitivity or gain. The separate adjustments of servo loop parameters allowed precise tuning of desired performance. Inherent linearity of applied reference and control fields permitted a reduction of Slave control field magnitude from 150Vac to 120Vac, while still maintaining maximum desired Slave force. The conduction lag of servo motor current led to some unanticipated problems in the commutation of the control fields. Slew rate limiting of the drive signal provided a workable solution to the problem.

Hardware costs for a Master-Slave manipulator control system are roughly $4200 plus $2000 for a single synchro excitation source which is capable of driving two systems.

## Acknowledgements


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## References


[1]Currently manufactured by Central Research Laboratories, Inc., Red Wing, MN, 55066, as the "Model M".

[2]John Simon et al; "Design of the Fermilab Neutrino Remote Target Maintenance System," Proc. of 23rd Conf. of Remote Systems Technology (1975).

[3]R. Goertz et al; "ANL Mark E4A Master-Slave Manipulator," Proc. of 14th Conf. on Remote Systems Technology (1966).