GENERAL PURPOSE SERVO-MANIPULATOR FOR REMOTE MAINTENANCE OF ACCELERATORS*

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Introduction

The basic approach to the maintenance and modification problems of large, high intensity accelerators under conditions of induced radioactivity has been detailed several years ago[1,2] in connection with the "Proposal to Increase the Intensity of the Brookhaven AGS."[3] At that time the scope of the study went somewhat beyond the immediate problems of the AGS improvement program, and an attempt was made to find methods of operation valid for other high intensity circular machines and possibly for linear accelerators as well.

The conclusion was reached that one should take advantage of the modular nature of modern accelerators, augmented by quick and simplified disconnects for all modules. The removal of these modules should not be automated, for reasons of cost effectiveness, reliability, and the ability to cope with the many unexpected situations one encounters. Instead, the versatile remote operational capability of an appropriate telemanipulator system should be used.

Manipulator Requirements

The maintenance operation of a large accelerator installation is almost by definition a nonrepetitive one. Constant modifications required by experimental programs and by the desire to reduce maintenance frequency are the rule. Implementing such modification is certainly not a repetitive operation. This is so, despite any simplifications brought about by the modular design-quick disconnect philosophy and points up one of the reasons why automation will not solve this remote-handling problem. In addition to this, the large demand for accelerator operating time requires that maintenance periods be minimized, making it imperative that any manipulator system employed be as dexterous as possible.

From the very extensive experience in hot laboratories, we know that, at least within the limited degree of remoteness of the hot cell, the mechanical master-slave manipulator is the fastest, safest and most dexterous remote-handling tool available. This is due to the fact that the operator can apply complete proportional control on any and all available degrees of freedom while having all slave forces reflected at the master. Thus not only is complete positional and force control available on all degrees of freedom of a pair of standard master-slave manipulators, but all or any desired combination of motions can be used simultaneously to perform a given operation.

The geometry of the Brookhaven AGS and of other synchrotrons requires a larger degree of remoteness than is possible with mechanically-connected master-slave manipulators. The use of electrically-connected servo master-slave manipulators was difficult as existing prototypes were too bulky to fit into the very restricted spaces in which accelerator remote handling has to be performed. It was therefore decided to develop a compact servo master-slave manipulator specifically suited to accelerator requirements.

Design Objectives and Constraints

The constraints imposed by the typical accelerator installation on a manipulator system are rather different from those encountered in the average hot laboratory. An operating accelerator produces a wide spectrum of ionization radiation, much of it of sufficient energy to cause induced activity due to nuclear interactions. In addition to this, strong pulsed magnetic fields and very strong RFI are encountered. Under these conditions no personnel entry whatsoever is allowed. On the other hand, when the accelerator is shut down for maintenance purposes, one encounters only induced radioactivity consisting almost entirely of gamma radiation in the MeV region. No magnetic fields and RFI are encountered under these conditions.

Other constraints are geometrical. As has already been mentioned, the very crowded environment in hot areas requires a very compact manipulator system. The very large volume that must be covered demands that one have a good transport system capable of placing the manipulator system at any desired operational point. It also requires that the communication link be optimized both with regard to the number of channels required and signal levels, thus allowing truly remote operations. Since it was never intended that the manipulator replace a hoist or crane, but only that it do in the radiation environment the work otherwise done by human operators, a lifting capacity of 20-40 pounds was considered sufficient.

The design objectives called for a manipulator having truly proportional control and bilateral force reflection. Friction levels, force sensitivity, and frequency response should be at least as good as those available in any mechanically-connected master-slave manipulator. At program inception time it was anticipated that after an initial prototype further development would be able to take advantage of what had been learned. It was therefore decided to leave possible improvements in dexterity due to changes in the number of degrees of freedom and their arrangements to further development projects. It was desired, nevertheless, to take advantage of any possible minor improvements that promised to lead to better dexterity.

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The Manipulator System

Figure 1 shows the single arm with slave in foreground and master behind. The author would like to emphasize that he does not recommend the use of a single master-slave arm as these arms are at their best when used in pairs. However, budget limitations often force us to do things that are far from ideal. The arms are mounted in temporary test suspensions. The cabinet in the background contains the electronics in a test rack. The major features are:

Bilateral force reflection. True bilateral force reflection as is usual in master-slave arms.

Capacity. Capacity is 30 lb nominal. That means that 30 lb can be exerted in all directions with arms at essentially their maximum or near maximum extension.

Compactness. Compactness of the arm is apparent when compared to the background. Minimum operating volume is about 1 ft^3, which is estimated to be about a factor of four smaller than the volume required for other servo master-slave manipulators.[4]

Weight. With counterweights (the striped segments) slave weight is 120 lb. When counterbalancing will be changed to passive force linkages this will be reduced to 60 lb. As no structural design refinements have been used as yet the slave arm weight can easily be reduced to 30-40 lb. This is important because the size and complexity of the required slave transport system is a very strong function of slave capacity-to-weight ratio. The ability of a pair of master slaves to transfer themselves from one transport system to another is also strongly dependent on this ratio.

Degrees of freedom (Fig. 2). Conventional 7 degrees of freedom are employed. X motion only has been changed for reasons of simplifying counterbalancing and to provide better articulation. As long as master and slave are mounted similarly they can be hung from the top or supported from the bottom without modifications.

Complete articulation (Fig. 3). The figure is a multiple exposure showing the range of motions possible. This wide range makes overhead work possible and improves operating capability when space is restricted.

Servo actuators (Fig. 4). The compactness is primarily achieved at the system design level by the use of compact dc motors which will fit into the limbs of the arms themselves.[5] Harmonic drives are used for speed reducers of the translationary degrees of freedom. The figure shows motors and speed reducers for Y and Z motions.

Servo system. To compensate for higher friction levels and larger inertias an asymmetrical position-force servo scheme is used which has the properties of dividing the friction and inertia components on the motor side of the force transducers by the force loop gain. The result is that friction levels are 2-3 ounces and reflected inertias equal to or lower than in other servo manipulators.

Force ratio. The slave-to-master force ratio is not switchable but varies quasi-exponentially as a function of input force. The variation ranges from 1:1 at low forces to 3:1 at maximum forces. Preliminary tests show this to be a good system. It certainly makes interrupting work for force switching unnecessary.

Other features.

1. The tong is counterbalanced, which minimizes strain on the operator's wrists.
2. In addition to true master-slave twist motion, continuous twist with reaction torque reflected back to the master, like a remote torque wrench, is available.
3. Direct coupling gives good frequency response (10 Hz) at the output of motions. Servo stiffness is quite good. For instance, we have 7×10^{-5} rad/in.lb for X and Z motions.
4. Simple logic operations sort out motion redundancies which occur in certain positions.

Electronics (Fig. 5). This system has been designed for truly remote operation which requires electronics near the slave end as well as the master end. For testing convenience all this has been temporarily put in one rack. The paneled sections are power supplies of sufficient capacity to drive a pair of arms. Servo amplifiers are in the two bins above, one bin for the master and one for the slave. Only 15 low signal level wires per arm are required between master and slave, with no other connections between them. The coiled cable in the picture contains 22 wires, this being the nearest Brookhaven stock item. Indications are that this scheme is sufficient for distances of 1000 ft or so. Fifteen telemetering channels can fulfill this function just as well and should be used for larger distances. If the money and engineering time can be found we will do this. The operational arrangement for a pair of arms will have separate power supplies for master and slave with two bins on each end and 29 communication channels between them.

Performance and Capabilities

The prototype manipulator is in the early testing stages. Initial operational test results allow some conclusions on expected performance to be drawn. Sensitivity, balance and frequency response are generally at least as good or better than one would find on the best mechanical master slave. As far as all the above parameters are concerned, preliminary measurements indicate that actual performance will meet design requirements.

What conclusion can one draw on dexterity and capability to perform operations typically required in accelerators? Salsig[6] and Krevitt[7] at the Lawrence Radiation Laboratory have shown that master-slave manipulators can be extremely useful in servicing accelerator structures remotely. This was apparent despite the extreme limitation on spatial orientation brought about by the use of a shielded cab mockup (see Fig. 6). By introducing the Brookhaven servo manipulators with all the improvements cited above and the far superior capability for spatial orientation one should be able to perform an even wider range of useful operations.

Application to an Accelerator

In the original concept for this system only operation during maintenance shutdown was considered. The environmental constraints thus encountered are not too difficult to meet. This operational mode, however, comes at a price. A hindrance factor of about 3.5-8 is introduced for maintenance by manipulator. This means it will take 3.5-8 times as long to perform an operation remotely than it would take to do it manually. The exact factor applicable depends on the manipulator system used and the nature of the operation.

Most of the components of the Brookhaven manipulator are highly radiation resistant. Some few items are less so, with the lowest thresholds in the system at about 5×10^7 rads. These thresholds are certainly amenable to upgrading, but even at their present level we have at least a factor of 10^6 improvement over radiation personnel exposure limits. This figure assumes that a 10-year refurbishing period is reasonable for a manipulator system. Under such conditions it is desirable to do whatever operations possible while an accelerator is running. One should, however, take advantage of the localized nature of primary accelerator radiation and not go to within half a betatron wavelength or so downstream of regions where prime targeting or beam ejection go on. This allows access, not at all previously possible, to about 90% of the machine with the rest accessible by appropriate rescheduling of experimental operations.

Of course only those maintenance jobs can thus be performed that do not interfere unduly with machine operation. Nevertheless, maintenance times required with the machine shut down can be reduced. Analysis also shows that if only one hour a week of unscheduled shutdown is saved, one can pay for a very capable manipulator system with the money saved in about a year.

The Operational System

While the availability of a suitable manipulator is essential, it is only one of the required ingredients of an accelerator remote-handling system. Luckily the other ingredients are either commercially available or capable of being built with considerably less cost and development effort than the manipulator itself. The major subsystems required for accelerator remote handling are:

A pair of servo master-slave manipulators.
A good TV system with three cameras.
A transport system.
A good communication link between master and slave stations.

None of these other subsystems presents any fundamental problems. The design or selection of the transport system whose function it is to move the manipulator system to the desired location within the accelerator is eased by the weight savings mentioned above. About 85% of the Brookhaven AGS tunnel is covered by a crane which can be used for transport, but the remaining 15% is among the regions where a manipulator system will be most useful. The ability to transfer itself remotely from the crane to the light-duty transport system in the latter region will be of great utility.

Once self-transfer ability is accomplished one can also think of using an alternate transport system based on some novel vehicular systems of unusual obstacle-surmounting ability now being developed in various places in Europe. Some representative capabilities of such vehicles are: mobility while folded to profile of crawling man, ability to climb stairs and 45° grades, as well as novel collision-prevention schemes.

The viewing system used will initially be based on compact and radiation-resistant TV equipment now used at the Brookhaven AGS. The problems of integrating this into the over-all manipulator system are not considered to be extensive.

The communication link between master and slave can become a very substantial problem, as has been shown at CERN.[8] Optimizing manipulator communication channels as shown above is a first step in easing these problems. The same technique has to be extended to the transport system control and the viewing system. The trade-offs between cable systems with or without multiplexing vs complete radio control should be investigated.

References

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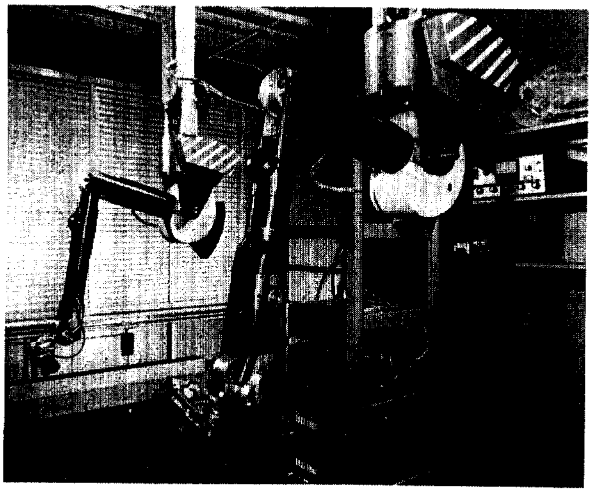

Fig. 1. Compact electric servo master-slave manipulator on test mounts. Slave arm is in front, master behind, electronics rack in background.

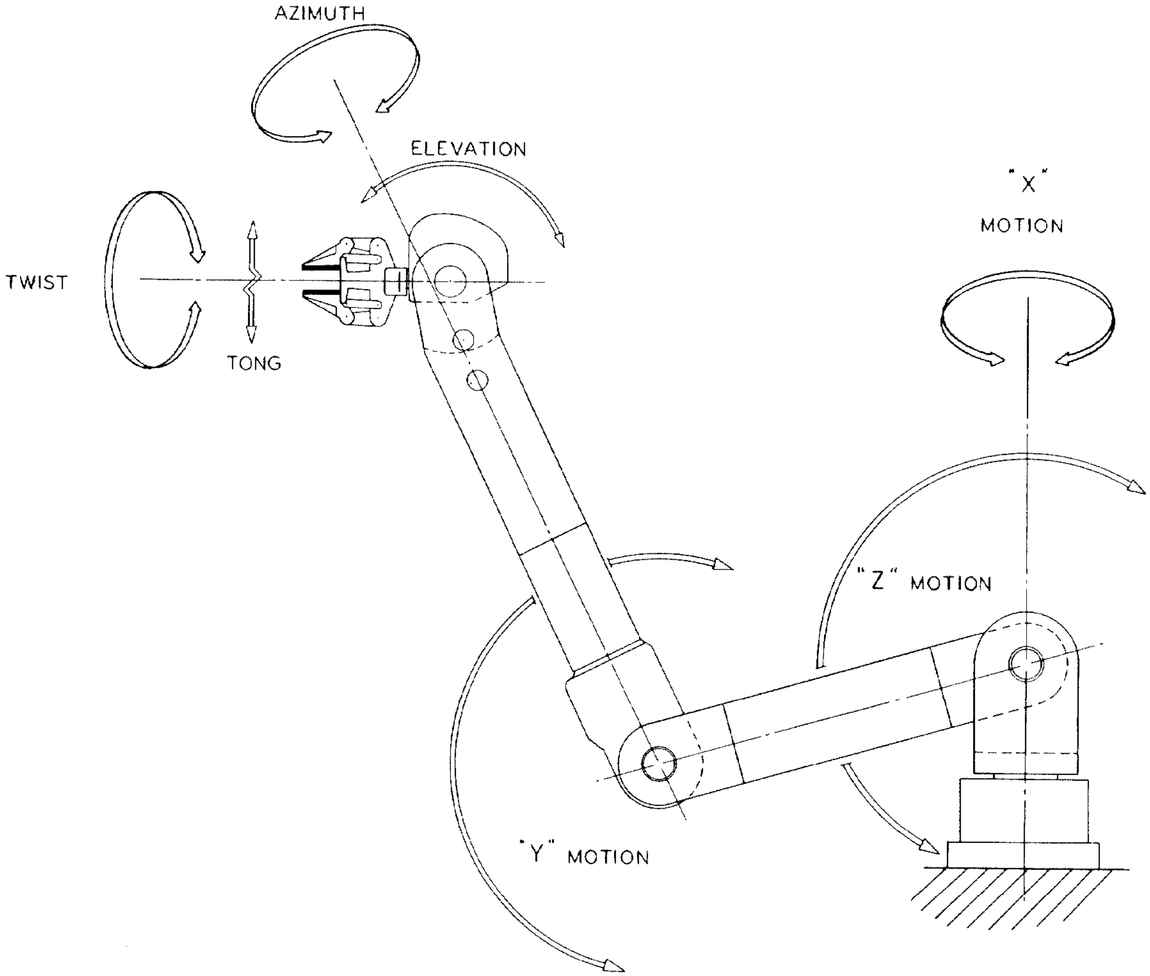

Fig. 2. Manipulator degrees of freedom.

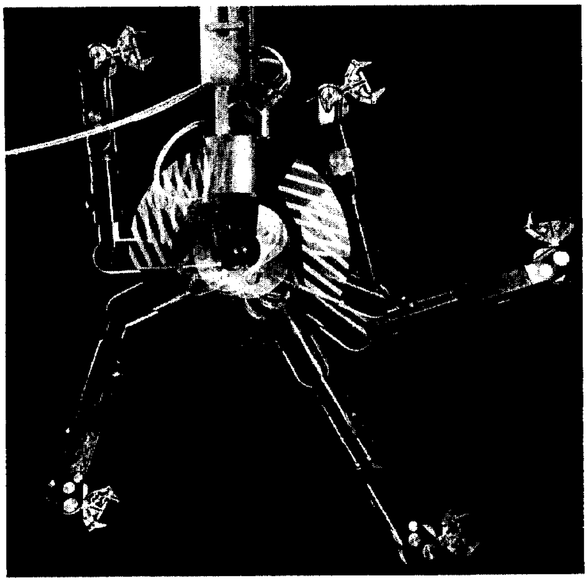

Fig. 3. Multiple exposure showing wide motion range of manipulator.

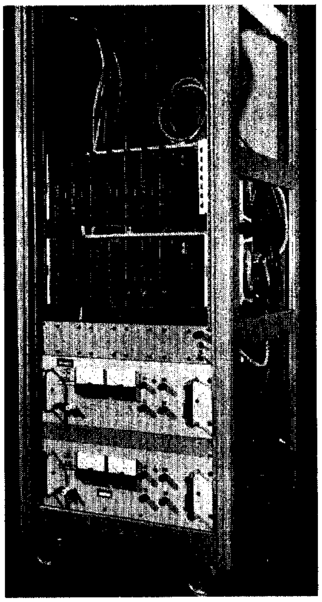

Fig. 5. Electronics for manipulator mounted in test rack.

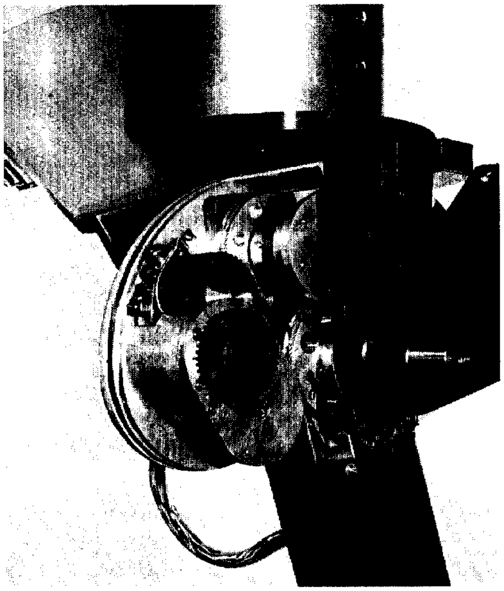

Fig. 4. Dc servo motors and drive trains for lower and upper arm motions.

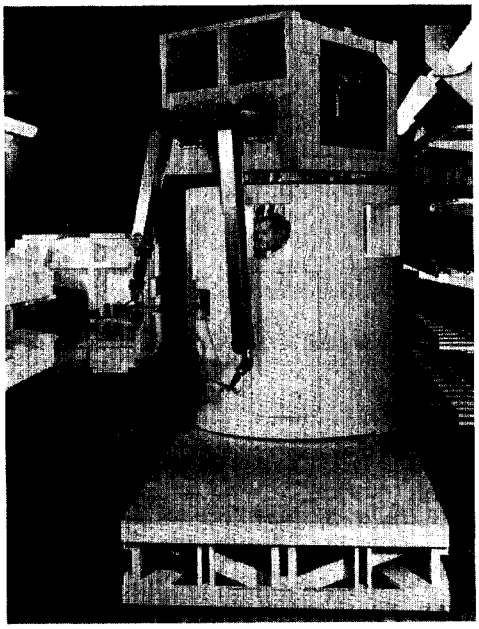

Fig. 6. Shielded manipulator vehicle mockup at LRL.