HUMAN FACTORS IN DESIGN OF REMOTE-HANDLING EQUIPMENT

R. C. Goertz

Argonne National Laboratory
Argonne, Illinois

I am going to start with the basic problem of what manipulation is. Any object in space has six independent motions. It has the three that can move it in space and the three angular motions, no more and no less. These motions must be independent or the position cannot be completely described. The first thing to consider about any manipulator system that is supposed to do general handling is that it must have all capabilities of this kind of action. It must also be able to attach to the object. That means that the basic movements of a manipulator are seven — additional movements would help in changing the shape of the arm or in adding fingers. The human arm has many more than seven, but the others are essentially redundant except for the extra fingers. When you handle a particular object, you use only seven.

We have used a term "general-purpose manipulator." By this we mean that a manipulator should be able to handle objects of various sizes and weights, to place them anywhere within the working volume of the manipulator, and to orient them to any angle desired. If it will do this, then we can say it is a general-purpose manipulator.

Let's look at manipulation in a little different way. We have to attach the manipulator to the object before we can move it or exert a force on it. This involves a collision. You might say that manipulation is a series of collisions with motions and forces mixed in. Because this is so, it is very important to control the collisions. It is also important to control the forces.

Argonne developed a rectilinear electric manipulator in the late forties. Many other rectilinear manipulators are produced commercially now. I want to talk about its good points and some of its limiting characteristics. It has the three motions to displace the tongs throughout the working volume and the three motions to orient the tongs in all of the lower hemisphere of angle. If you have to use the upper hemisphere, then you must grasp the object at a different position. The manipulator motions are each controlled by individual switches. These switches are oriented so that the motion of the switch corresponds to the motion that is activated. This is true in all but a few cases. The translational motions are easy to provide in this manner. The rotating motions of the wrist joints do not work out so well. For instance, the elevation which would be the motion of the tongs up and down is reasonably easy to accomplish. This is done by a lever that moves up and down. The rotation about the vertical axis is fairly easy to accomplish to keep in synchronism with the device by turning a knob at the top. The twist rotation, however, doesn't stay oriented properly. If we twist, for instance, in one direction, and then move in azimuth until the tongs are on the opposite side, the twist rotation will be reversed. We did not make provision for correcting this. Of course, at right angles, it wouldn't be oriented at all.

These manipulators have valuable functions for carrying loads and moving objects from place to place. They are fairly slow in performing tasks. The operator usually goes about the operation by trial and error methods rather than by the smooth operation that you use when you operate with your own hands. Because of these limitations, we stopped working on these manipulators. There was one other reason, of course: that other organizations were working on various types of these manipulators at about that time or slightly after. Therefore, there was no need for us to continue.

The next requirement is to keep the movement of the manipulator oriented with the motions of the control handle or knob, and to keep them oriented at all times. This suggests that the arm that does the work (that is, behind the shield or away from the operator) should be controlled by a similar arm located at the operator and that the movements correspond. We simply named this master-slave because of the master arm controlling the slave arm. Actually, the whole system becomes the slave of the human operator. By master-slave, we mean more than just the correspondence of position, because at the same time that we were working on this we started working on force-reflecting servos and mechanical linkages that were bilateral in mechanical aspects.

Our Model 8 Master-Slave Manipulator is the eighth one that was designed either partially or wholly. In only one case did we stop the design and go on to a new model. All others from 1 to 8 were actually built. Most of them were used, except the first one which was just a small experimental unit. It was never used, although duplicates of it were. This manipulator has the characteristics that you already know about. I would like to run through them just to refresh your memory. It has seven motions — no more. It could have more, but it doesn't. It has a natural control, the opposite forces are reflected, and it is bilateral. Let me explain bilateral again. If you move or push on the slave, you will get a reaction on the master. In fact, the manipulator is essentially symmetrical about the center as far as function is concerned. This is a very important feature. Let me explain why. If I were to move up to a desk with my arm as a slave arm, and I didn't have it so it could yield readily, then I would have high forces, not just because I have the mass of my arm, but because I may have the mass of my whole body involved if the arm doesn't yield and yield readily. For instance, if you turn cranks or operate on instruments, it is very important that the arm yield. I think it would be important in space vehicles and in servicing aircraft that these arms also be bilateral. Otherwise, it seems to me you could easily puncture holes in the skin of the craft, or do other damage.

Major Pigg mentioned yesterday that the Model 8 has been measured by the Aerospace Medical Laboratory. I think this is very good work that has been going on here: to find out how inefficient the Model 8 is compared to the human being. I think he was optimistic. I think he stated a number anywhere from 6 to 10 and probably averaged at 8 as the ratio of direct to remote handling time. However, I think that he selected jobs that the manipulator could do. There are many operations that the human hand could do that the manipulator could not do in an infinite period of time. So it has to be very limited when you discuss the operating speed of a manipulator compared to the human being.

I mentioned the rectilinear manipulator before. It is our estimate that the speed ratio for most operations in a laboratory, the ratio of master-slave to rectilinear, is about 10:1. This varies, of course. Again, there must be a provision, and the provision is that the master-slave can handle the load. In many cases, the master-slave couldn't do the job at all. But if it is within the load capacity and the reach capacity, then I would say about 10:1.

It is clear that a manipulator cannot always remain anchored to the wall through which it passes. It is very limited if it does and it would be desirable to free it from this. We found that the mechanical master-slave manipulators were very useful. They did quite a lot of laboratory work satisfactorily—that is, satisfactorily to most people. I am one of the people who are not very satisfied. In the late forties, we started working on force-reflecting servos to accomplish essentially the same thing as an efficient mechanical linkage.

A simpler system with two low-inertia, two-phase motors was developed. The motors are electrically connected so that the torque produced by one motor is opposite and equal to the torque produced by the other. By adjusting the condensors and a few other parameters of the motors and selecting or, if necessary, getting them designed properly, the desired valance can be brought about. Then the signal coming from a signal device, such as the synchro, connected in the gear train goes through the amplifier and feeds the power to each servo motor, causing one to drive one way and the second, the other way. This is now, essentially, a symmetrical, bilateral servo. If you turn one end, the other will turn. It works quite well, except that there is some inertia and some friction. Nevertheless, it is quite useful. This system has been built into a couple of different manipulators.

One slave robot has been built up using these servos. But, in place of one motor, we use four small motors. The capacity on the slave tongs is 50 pounds. Of course, you do not have to supply the 50 pounds at the master. In fact, it's a little hard to do, because of the mechanical coupling of the master handle to the human hand. It's quite easy for the human hand to lift 50 pounds or hoist 50 pounds, but it's not easy to use the grasping action and also do this. We had a master stand with similar arms mounted to control this, and we ran several experiments to see what the effects would be of displacing the arms with respect to the master. We found no trouble if the arms were at various locations with respect to the master. They could be high or low or to the side— it made no difference. However, if the angle, either of the wrist joint or of the motions, in what we call the XYZ direction (that is, the displacement motion) was out of synchronism by about 30°, then it became difficult to operate and it took considerably longer. You could still operate; you still had the feel; and so you did not have necessarily high collision forces. But the time increased, and you had to probe, as if you didn't have stereo vision. You made the wrong movement first and then corrected it.

Some of our new manipulators have been installed in caves and have worked out quite well. They have been in use now for about a year. The only trouble that we have had has been with the safety brakes in each gearbox. These brakes have to be adjusted once in a while. We've had a few other very minor troubles. The servo amplifiers are vacuum-tube type. We have now worked up a power amplifier which uses transistors, which should be some improvement. We have found in making these various checks that it is quite important to keep the stiffness of the system fairly high—that is, to make the slave follow the master reasonably well, not accurate in position, but accurate as far as not allowing very much error to occur until you get large forces. If the relationship becomes what we might call soft or springy, then it is hard to detect transient forces. We are also working on some hydraulic systems. In the hydraulic system, we tried putting in a lead network to emphasize the transient force. This seems to help, so it might be something to keep in mind. One thing that should be pointed out or kept in mind by facility operators and designers is that it cost us $90,000.00 to manufacture a complete pair of these arms. They are presently located in a relatively small cave. But, even so, the cost per unit working volume is less than the cost per unit working volume of a Model 8. And if the cave were as big as it should be, then the unit cost per volume would be even less.