HUMAN FACTORS IN THE DESIGN OF REMOTE MANIPULATORS

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A remote manipulator may be defined as a machine capable of performing tasks in an inaccessible area or hostile environment — at an operator's command — with the manipulator and operator physically separated by distance or by a protective barrier.

Human engineering, as it pertains to remote manipulation, can be thought of as the design of a manipulator and its controls to obtain maximum utility from the manipulator-operator combination.

Our company has been concerned with the development and manufacture of electromechanical manipulators, as opposed to master slaves which are controlled through direct, mechanical linkage. This paper will discuss the design considerations as they apply to powered manipulators, or more specifically, to General Mills' Mechanical Arms.

The natural way to provide a remote-manipulating capability is to transmit the motions of the human arm into the inaccessible or hazardous environment. This is accomplished by providing a machine that functions essentially as an extension of the human arm. Therefore, the simplest manipulator needs grasping, lifting, and maneuvering capabilities. If requirements so dictate, capabilities far greater than those of the human arm can be designed into the manipulator. For instance, a heavy load can be positioned carefully, smoothly, and accurately, using the steady power of electric motors; or the manipulator's "wrist" can be designed to rotate continuously under heavy torsional loads.

Though the versatility and capability of manipulators may vary from site to site and environment to environment, the three basic motions of grip or grasp, rotation, and pivot are common to all.

The basic tasks normally accomplished in remote manipulation are: handling objects of varying weight, strength, and rigidity; operating or manipulating tools; and positioning or adjusting scientific apparatus. Hence, the manipulator must be capable of both a light touch and a strong grip. Obviously, no one grip configuration is adequate, so special grips are designed to best suit the operator's needs. For maximum versatility, it is imperative that these gripping devices be remotely interchangeable.

For general-purpose manipulation, two sets of interchangeable grips are provided. The parallel-jaw type, consisting of two rigid fingers that remain parallel to each other as they open and close, is capable of grasping flat objects with parallel sides. The movable-hook type of grip, a movable hook that nests into a stationary anvil, will grip and hold irregularly shaped objects. Because of the variety of tasks to be performed in many installations, it is often convenient to design or adapt special tools so they can be gripped by either the parallel jaw or the movable-hook type grip.

As the need for dexterity increases, we add manipulator arm components. Shoulder rotation is added. Next is the link from shoulder to wrist, including a pivoting but non-rotating elbow. This gives the manipulator five motions: namely, shoulder rotation, shoulder pivot, elbow pivot, wrist rotation, and grip. This configuration, with its five motions, is most common in electromechanical manipulators.

The next step is to add wrist pivot, a sixth motion. The manipulator now has all motions of the human arm. Thus, we have shoulder rotation, shoulder pivot, elbow pivot, wrist pivot, wrist rotation, and grip.

Beyond this point, joints or members may be added as required to perform special tasks. These would provide supplemental pivots, rotations, or extensions.

As the operator is at some distance from the manipulator, and not infallible, each motion is protected from overload and damage by a slip clutch. To avoid the need for any quick corrective action on the part of the operator, the drive of the overloaded motion will "slip," but the link or affected portion will hold its pre-slip position.

Because the lifting and holding capacities of the manipulator are great — greater than those of the human hand and arm — irreversible drives or drives with brakes are used. These afford "fail safe" protection as all motions hold their positions upon relaxation of the controls.

By using parallelogram linkages for the shoulder and elbow pivot motions, the hand will stay parallel to the plane it was in at the start of the motion. This eliminates the need for an operator to integrate two motions when moving an object — for example, a liquid-filled beaker — from one position to another. If the operator is to direct the remote manipulator efficiently, he must be able to maneuver it into the desired position in a smooth and positive manner.

No one method of mounting is best for all applications. Therefore, a variety of mounts are designed. Where great vertical travel is needed, a boom — mounted on a vertically traveling carriage — may be desirable. Or, if the work area is relatively small, an elevator mount or simple post mount may suffice. At the other extreme, if the work area is extensive, mobility is achieved by mounting the manipulator on a vehicle. The most universally employed mounting to date, and one we'll discuss in somewhat greater detail, is the overhead bridge and trolley mount. Coupled with rigid telescoping tubes, the bridge-mounted manipulator can be accurately and smoothly positioned anywhere in the X, Y, and Z axes.

Because vision may, at times, be restricted, or because of the ever-present possibility of human error, manipulator movements are held to pre-established limits or ranges, thus minimizing the probability of damage to the manipulator or adjacent equipment. Bridge longitudinal travel is limited by travel-limit switches. Carriages are protected from colliding with the bridge end-trucks by another set of limit switches. Travel of the telescoping tubes is limited in the up position by a positive limit switch. The lower limit switch of the tubes is actuated by a "slack cable."

By pressing an override button, the operator can carefully resume motion stopped because a pre-set travel limitation had been reached.

Should more than one manipulator system be used on a single set of tracks, operational damage is prevented by collision switches that cut the power when a collision is imminent.

When it's possible to facilitate the remote-handling operation by enabling the operator to employ, simultaneously, his senses of sight and hearing, equipment must be so designed.

Proper vision is all-important to successful in-cell operations. Lights are mounted on manipulators where required. When direct viewing is not possible, television cameras with telescopic lenses or zoomer-type lenses mounted on remote pan and tilt mechanisms are utilized. It is essential that the cameras be placed so that the object can be viewed from two angles. While true perspective is not obtained in this manner, proper placement of the cameras does provide adequate viewing so that the manipulator can be properly oriented. Though stereo TV is available, the dual-camera approach normally provides sufficient definition without the more cumbersome equipment and fatiguing operator position associated with stereo viewing.

The ability to hear the operation of the manipulator as it moves to a location or performs a task may at times be very helpful to the operator. When this is the case, manipulators are equipped with microphones to pick up sounds in the working area. Motor loading can be estimated by the change in motor sound as the motor loads up. Initial contact of the manipulator with the object to be handled can sometimes best be verified by sound.

In directing the motions of a manipulator from his remote location, the operator, of course, is in physical contact with the controls. Here, then, is an area where human engineering must be given prime consideration.

General Mills provides either a control console or a portable, fingertip control station. Selection of the type of control unit to be employed may be dictated by a number of factors.

The control console features two "natural-movement" pistol-grip handles. The five precise motions of the manipulator itself are controlled by the right hand, while positioning of the bridge, trolley, and rigid crane are accomplished by movements of the left hand.

Natural arm movements guide the manipulator to the correct position and direct it to perform a specific task. Raising or lowering the left-hand control causes the rigid crane to move correspondingly. Moving the same control in or out moves the trolley away from or toward the operator. Left or right movement will produce a corresponding motion of the bridge. The right-hand control simililarly governs the manipulator movements. Moving the control lever right or left will rotate the shoulder in the corresponding direction. In or out movement will pivot the arm at the shoulder. Up or down will move the elbow pivot. Twisting clockwise or counter-clockwise will similarly move the wrist. Squeezing the top of the handle will close the grip, while squeezing the bottom will open it. By introducing displacement in any or all axes simultaneously, the manipulator can be positioned quickly and accurately.

Speed is varied by displacement from neutral — the further the displacement, the greater the speed. In order to help the operator avoid over-shooting or reversal while trying to find neutral, all controls are spring-loaded to return to center off-position when released.

Since, as we mentioned previously, items of varying strength and rigidity are handled, some indication or control of grip force is essential. As most electromechanical manipulators can exert and sustain a grip force in excess of the human hand's capability, direct force reflection is not used. Rather, two indicators are usually provided in the control console. One of these is visual, the other audio. In the visual method, a comparative meter indicates the grip by displacement of an indicating needle from center. The greater the grip force, the further the displacement. This meter is located on top of the console where it can be viewed easily. The audio indicator enables the operator to sense the gripping force without glancing away from the object being manipulated. Here, the frequency of a beep increases with the applied force. For use in handling operations where the desired grip force can be pre-determined, a variable grip-force dial is provided.

The "power-on" button is key-locked to prevent unauthorized or inadvertent use. A light indicates "power-on." "Power-off" is a large red-colored button, readily seen and easily depressed. Thus it serves as a "panic" button as well as an off button.

More than one console, at different physical locations, may be used in a system to control one manipulator. This type of system is made "fool-proof" by an electrical interlock such that the first control unit powered remains in control until the power is turned off.

The portable fingertip control station was developed for use where space limitation is a factor, as in certain vehicular applications, or where it is desirable in more standard applications for the operator to move closer to the viewing window. Here, an individual lever switch controls each individual motion of the manipulator. Direction and extent of switch displacement from a neutral position will control corresponding direction and rate of manipulator motion. The operator can use fingers of both hands for simultaneous control of any or all manipulator motions. On systems where special motions are required, additional lever switches are added.

Designers of remote manipulators must consider reliability and ease of maintenance as important human factors. If, as was mentioned previously, maximum utility is to be obtained from the manipulator-operator combination, the equipment must inspire the operator's confidence. The manipulators must be designed as small as is practicable for proper maneuverability, and yet be rugged enough to handle the desired loads. They must be readily serviceable to minimize "down time." As much of the equipment as possible should be located outside of the cell where it can be serviced quickly and easily. In addition to travel limit switches and slip clutches which protect the manipulator itself, each in-cell power motor is protected by a fuse or circuit breaker located outside the hazardous environment. Thus, some momentary overload or external short can be serviced without entrance into the contaminated area.

Newer systems for use in space, underseas, and over rugged terrain have been developed recently or are in the design state. In these new systems, all the human-engineering factors we have just discussed retain their fundamental importance. Whether the operator and manipulator are separated merely by a hotcell shielding window, by many thousands of feet of ocean water, or by limitless miles of outer space, we have the same two basic components of the system:- the man and the machine. And the efficiency of that system is directly proportional to the degree of compatibility between the two.