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HAND CONTROLLERS FOR TELEOPERATION.
A STATE-OF-THE-ART TECHNOLOGY SURVEY AND EVALUATION

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Hand Controllers for Teleoperation

A State-of-the-Art Technology Survey and Evaluation

T.L. Brooks
A.K. Bejczy

March 1, 1985

National Aeronautics and Space Administration

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

FOREWORD

The human hand is a key communication medium in teleoperator control. With hand actions, complex position, rate, or force commands can be expressed to a remote robot arm and hand in all workspace directions. At the same time, the hand can also receive force, contact, or touch information from the remote end effector in action. Furthermore, the fingers provide capabilities by which new commands can be conveyed to a remote robot from a suitable hand controller. Hand-controller technology is, therefore, an important component technology in the development of advanced teleoperators. Its importance is particularly underlined when one considers computer control which connects the hand controller to the remote robot arm.

This study was motivated by the increasing role that space teleoperators will have in Space Station development, satellite servicing, and maintenance operations. New space application scenarios involve the use of computers in the control of single or multiple arm teleoperators. It seems necessary, therefore, to take a new look at existing hand-controller capabilities, to evaluate alternatives, to generate new concepts, and to view hand-controller technology in the perspectives of new teleoperator control strategies which will rely upon increased use of computers. The new perspectives show that hand controllers integrated with computers in teleoperation become new man-machine system interface devices which also will require the consideration of human factors issues.

This study was supported by the National Aeronautics and Space Administration, Office of Aeronautics and Space Technology RTOP #506-57-25/B, entitled "Coorperative Dexterous Teleoperation for Space Station."

LEXICON

Anthropomorphic	- having human-like charateristics
Bilateral	- two way control, i.e., the control device commands the remote manipulator and the remote manipulator commands the control device
Configuration Feedback	- remote manipulator's joint and link configuration feedback to operator
Cross Coupling	- interaction between degrees-of-freedom
DOF	- Degree-Of-Freedom
FFB	- Force Feedback
FRHC	- Force Reflecting Hand Controller
Isometric	- used with respect to control input devices to indicate that output signals correspond to forces applied to an immobile handle (i.e., handle motion cannot be perceived by the operator)
Isotonic	- constant force over operating range, e.g., isotonic joystick (see p. 34)
OTS	- Off-The-Shelf technology
Proprioceptive Feedback	- feedback of the remote-end effector spatial location and orientation to the operator
Slave	- remote arm being controlled by input device
SOTA	- State-Of-The-Art technology
TRA	- Technology Readily Available
Unilateral	- one-way control signals, as opposed to bilateral, i.e., the controller commands the remote manipulator, but the remote manipulator cannot affect the controlling device

ABSTRACT

Hand-controller technology for teleoperation is surveyed in three major categories: (1) hand-grip design, (2) control input devices, and (3) control strategies. In the first category, 14 hand-grip designs are reviewed and evaluated in light of human factor considerations. In the second, 12 hand-controller input devices are evaluated in terms of task performance, configuration and force feedback, controller/slave correspondence, operating volume, operator workload, human limitations, cross coupling, singularities, anthropomorphic characteristics, physical complexity, control/display interference, accuracy, technological base, cost, and reliability. In the third category, control strategies, commonly called control "modes," are surveyed and evaluated. The report contains a bibliography with 189 select references on hand-controller technology.

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SECTION 1

INTRODUCTION

This report is the result of a technical search directed toward classifying and categorizing hand-controller technology. This effort was supported by the National Aeronautics and Space Administration, Office of Aeronautics and Space Technology RTOP #506-57-25/B, entitled "Cooperative Dexterous Teleoperation for Space Stations," in preparation for Space Station repair and servicing by teleoperated manipulators.

The objective of this study was to determine the technological areas of manual manipulator control which need further research and development to meet the requirements of Space Station teleoperation.

The approach taken in this review was: (1) to identify and describe existing hand grips, control input devices, and control techniques; and (2) to identify and describe new components and techniques, which in the future will or may become building elements of advanced hand controllers, in order to satisfy increasing performance requirements for remote teleoperation. This effort was initiated by performing a broad computer search of hand-controller technology in three data bases (i.e, NTIS, COMPENDEX, and NASA RECON). After pruning irrelevant and/or unwanted citations, the search had uncovered 293 references on hand controllers and joysticks specifically related to manual control, robotics, teleoperators, and manipulators. Of these, a number were considered to be directly applicable to our task and copies were obtained and reviewed. Upon review it was felt that an earlier hand-controller survey performed at JPL for the Oak Ridge National Laboratories in 1981 was very apropos; hence, it was decided to incorporate the previous work in this effort. Two other important surveys were uncovered in our search. The first is a thorough search on tracking controls, dated 1971, by Mehr and Mehr of Measurement Systems of Norwalk, CT. The second is a literature and laboratory survey conducted by McKinnon and Lippay in 1981, under NASA contract No. NAS 9-15939, in which they toured sixteen laboratories engaged in six-degree-of-freedom manual-control research and development. Their effort includes a detailed writeup of their visits with each laboratory and a computer search which is heavily oriented to the human-factor issues of manual control. References for both of these reports can be found in the Bibliography at the end of this report.

In Section 2, hand-grip design is reviewed and human factors considerations are discussed. Fourteen hand-grip designs are presented and evaluated relative to four major categories: (1) engineering development requirements, (2) controllability, (3) human-handle interaction, and (4) human limitations made apparent by the particular handle design.

In Section 3, hand-controller input devices are reviewed and evaluated without regard for the control technique typically used with the device. Evaluation independent of the control technique insures that the device is rated on its characteristics and not that of a particular control technique. Twelve hand controllers are evaluated in terms of 17 parameters: (1) task performance, (2) configuration feedback, (3) force feedback, (4) controller/slave correspondence, (5) operating volume, (6) operator workload, (7) human limitations, (8) cross coupling, (9) singularities, (10) anthropomorphic characteristics, (11) physical complexity, (12) control implementation complexity, (13) control/display interference, (14) accuracy, (15) technological availability, (16) cost, and (17) reliability.

In Section 4, control techniques are reviewed and evaluated independently of the input device and remote manipulator. This section considers only the control "modes," not specific servo controls such as proportional, pseudo-derivative, PID, etc. The control modes have been divided into four primary categories which are representative of the more successful techniques: rate, unilateral position, bilateral position, and operator aiding control.

Section 5 considers a number of observations made from this technology review.

Appendix A proposes a number of simple first-phase experiments directed toward the development of an optimal controller design for space teleoperation.

An extensive list of references supporting the state-of-the-art review can be found at the end of this report. The citations are organized as references quoted within the text and as a general bibliography of related literature.

SECTION 2

CONTROL HANDLE CONCEPTS

This section presents a number of alternative control-handle configurations. The first section considers general design and human factors guidelines. The second section presents the results of a handle concept generation phase of this study.

2.1 GENERAL DESIGN AND HUMAN FACTORS CONSIDERATIONS

The general handle design guidelines were: (1) the handle must strive for stimulus-response compatibility, (2) the handle must not be fatiguing under normal usage, (3) the design shall incorporate force feedback, (4) the design shall have proportional position feedback, (5) the handle shall be compatible with the intended controller structure, and (6) the handle shall be useable by 5th to 95th percentile operators. In order to design to these requirements, it is necessary to consider a number of human limitations and their implications.

One of the most important human limitations is endurance. As known from experience, the endurance of an operator to maintain a given muscular force is related to the magnitude of the force and the time over which it must be exerted. Figure 2-1 illustrates this relationship between force and time.

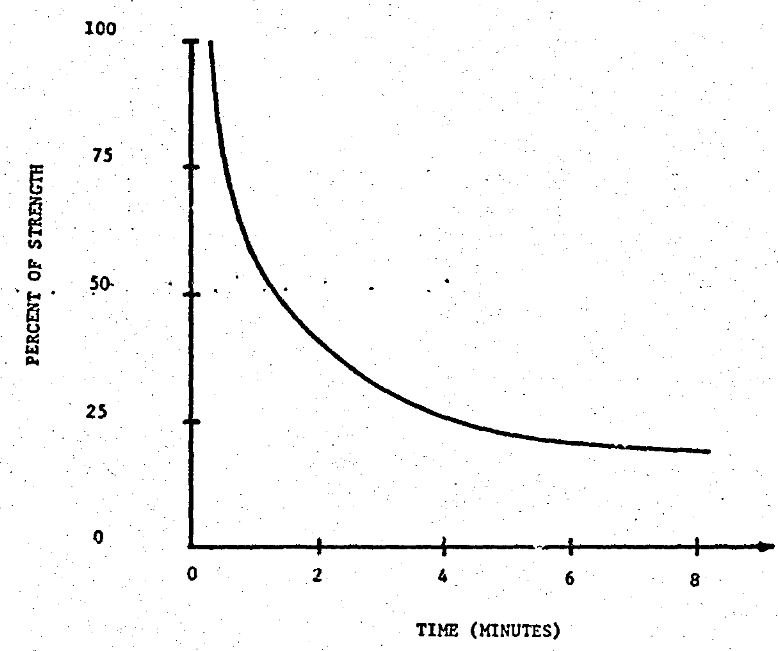


Figure 2-1. Endurance as a Function of Time and Force Requirements Ref. [1]

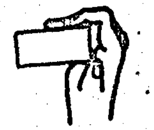
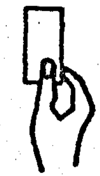
The figure illustrates that people can maintain their maximum effort only briefly, whereas they can maintain a 25% force or less for an extended period. The implication of this relationship is fairly obvious — since the operator may be required to exert a grasp force over long periods of time, the force should be well below the individual's maximum force capability [Ref. 1].

Figure 2-2 shows a number of human grasping methods along with relevant data on grasp capabilites. As shown, the maximum grasp force, the ability to generate torques, and the operator's endurance are functions of the grasping technique used. If it is assumed that the maximum grasp force will correspond to a maximum controller force of 20 pounds, we see that only the finger-heel and wrap-around techniques will be capable of producing the required forces. Unfortunately, even these grasp techniques will not be sufficient to meet the endurance requirement, since the maximum allowable endurance force for the 5th percentile female will be on the order of 11 pounds. The result is clear, a force-scaling ratio greater than 1 will be required from the slave to the controller handle. Since grip forces must be scaled anyway, all of the grasp techniques will be considered as potential candidates, rather than exclude them on the basis of maximum grasp force. However, since the operator must also produce significant torques through the control handle, we will not consider the pincher or lateral grasps further.

Human variability is another constraint which will affect the design considerably. In particular, a requirement that the handle be useable by 5% female to 95% male users probably will be impossible to achieve with one universal handle. This is evident when the variations in human hand size are considered, as shown in Figure 2-3.

Another important handle design factor is stimulus-response compatibility. Simply stated, the operator's gripping action should have a "natural" correspondence to the grasping action of the slave. Stimulus-response compatibility is essential for good control, and to prevent operator confusion. With respect to master-slave manipulators, stimulus-response compatibility is the rule rather than the exception. In fact, the squeeze grasp, which has been used as a nuclear industry standard for years, has direct stimulus-response compatibility with the grasping action of the teleoperator. Unfortunately, the squeeze grasp does not have good endurance capability due to the stress placed on the operator's hand when maintaining a fixed position. This is due to the natural tendency of the human hand to wrap around an object rather than remain open in the squeeze position. Hence, holding one's hand in this open position can be very fatiguing even when force is not being exerted. The squeeze grasp has an additional drawback in that the thumb, index finger, and middle finger cannot be used to control auxiliary functions, leaving only the pinky and third finger for function switching -- a less than desirable situation from a control standpoint.

Another important human factors consideration is the attachment of the handle to the master controller. Should it attach at the base of the handle or the top (see Figure 2-4). Clearly, placement of the handle should be dictated by its effect on controllability. Any interference between the operator and master structure which impedes the operator's ability to reach particular orientations will have a negative effect on manipulator control.

	FINGER-HEEL GRASP	WRAP-AROUND GRASP	SQUEEZE GRASP	PINCHER GRASP	LATERAL GRASP	TRIGGER INDEX FINGER
						
5% FEMALE	53 lbs	53 lbs	7.5 lbs[?1]	7.5 lbs	9 lbs	4 lbs[?3]
95% MALE	147 lbs	147 lbs	30 lbs[?1]	30 lbs	32 lbs	13 lbs[?2]
TORQUE CAPABILITY	EXCELLENT.	EXCELLENT	GOOD	POOR	SOME	EXCELLENT
ENDURANCE @ 25% LOAD	GOOD	GOOD	POOR	FAIR	FAIR	GOOD

? – DATA UNAVAILABLE
1 – VALUES ASSUMED TO BE ABOUT THE SAME AS PINCHER GRASP BUT SUPPORTING EVIDENCE NOT AVAILABLE
2 – MEAN VALUE 100 MALE SUBJECTS
3 – VALUE ASSUMED TO BE 1/3 OF MALE VALUE

Figure 2-2. Human Grasp Capabilities [Refs. 1, 2, 3, 4]

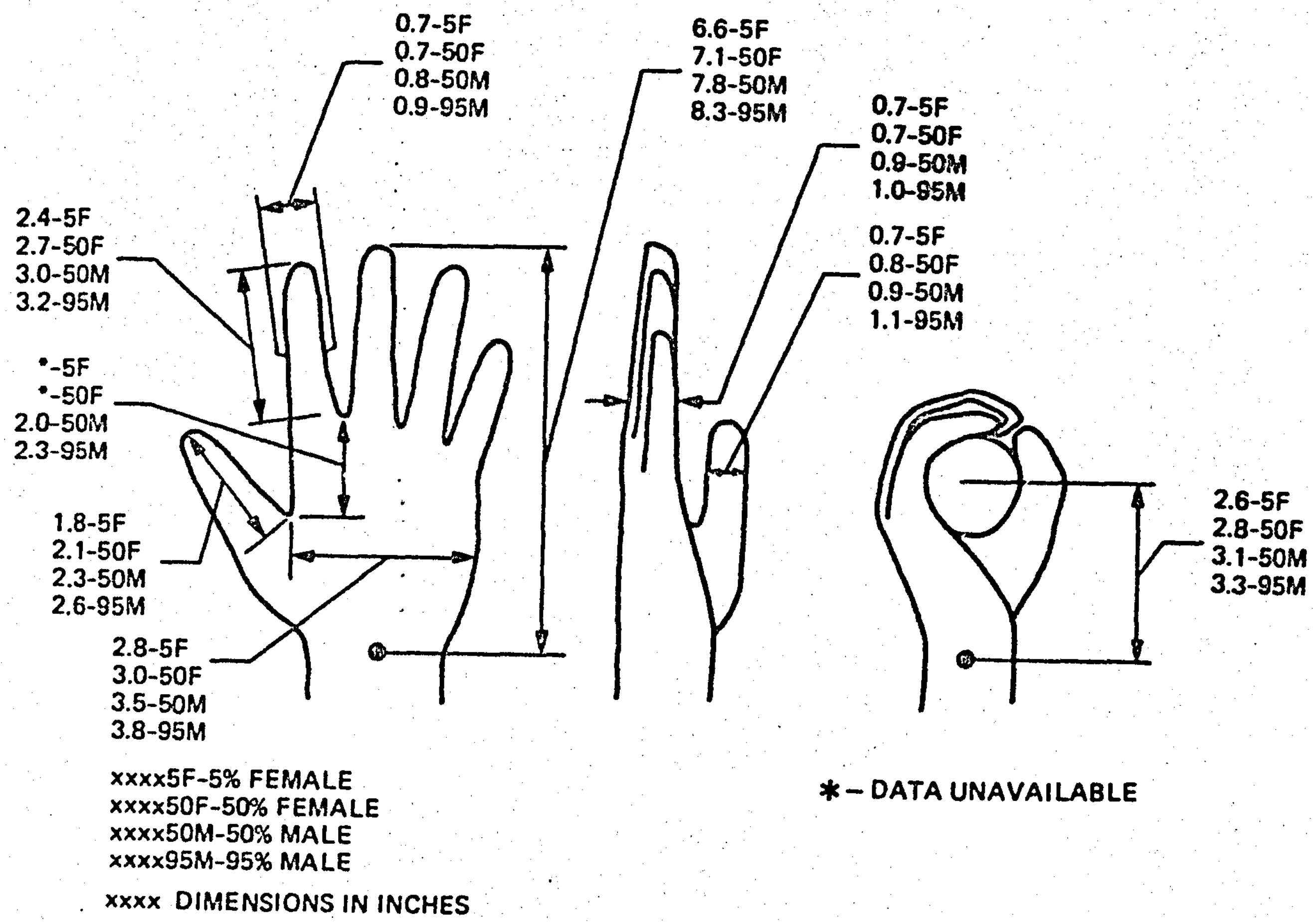


Figure 2-3. Human Hand Variability [Ref. 4]

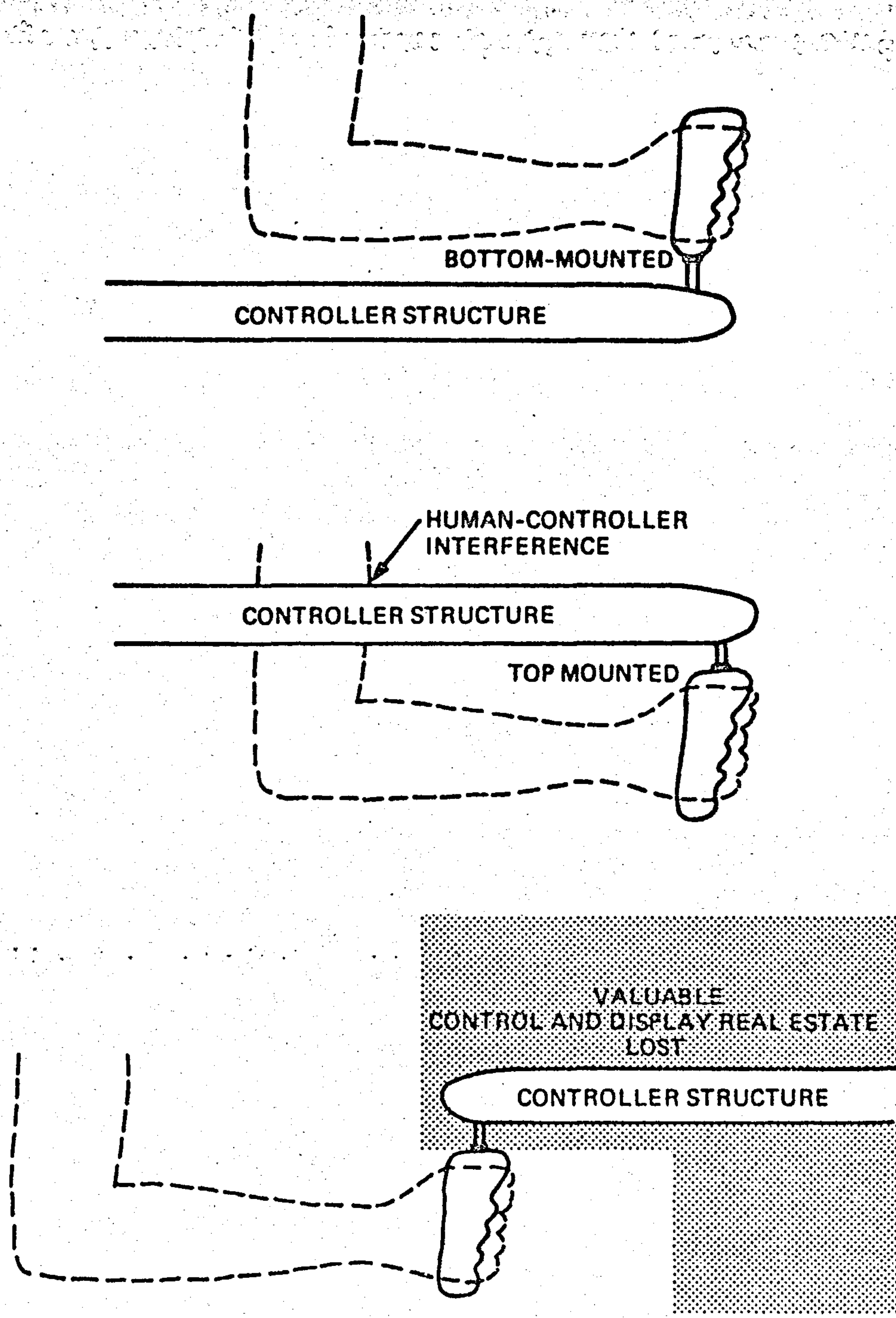


Figure 2-4. Handle Mounting Considerations

Placing the handle below the controller structure results in a rather obvious interference problem, since the operator's forearm is below the controller while his upper arm is above it (see Figure 2-4, middle illustration). Hence, the location where the operator's arm drops below the level of the controller structure is a point of potential human-controller interference. (This interference was in fact observed on a mockup master controller made for Oak Ridge National Laboratory.) On the other hand, if the top-mounted controller structure is placed forward of the operator, valuable control and display real estate is lost.

An equally valid argument against placing the handle on top of the controller is that the operator must support the weight of the load in his hand, creating the potential that (1) the grip will slip out of the operator's hand or (2) the operator will fatigue easily because he must squeeze the handle harder to support the load. Both of these objections can be solved, however, by designing the upright handle with a support for the operator's hand at the top of the handle. The interference problems which occur when the handle is in the down position cannot be solved as easily; hence, the handle designs to follow consider bottom-mounted devices of the type shown in the upper illustration of Figure 2-4.

As a final consideration before looking at alternative handle designs, it should be noted that an operator's grip strength is not only a function of physical attributes and sex, but also the grip dimensions and attributes. For example, Figure 2-5 shows that a relationship exists between the separation of the grip elements and the average grip strength of the male population. Other relationships exist with the overall controllability of the handle, and grip attributes such as handle width, contour, height, surface texture, and grip location. Figure 2-6 illustrates, for example, that a contoured handle has distinct advantages in controllability. Many of these effects on controllability, as they apply to teleoperators, have not been studied sufficiently in the past to have a sound data base from which to work. In fact, although our survey has revealed a large body of human factors literature relating to control sticks, few have dealt with the problems of six degree-of-freedom manipulators with simultaneous trigger and secondary function control. It is believed, therefore, that an experimental study of various handle configurations should be undertaken to insure that subtle human factors are not overlooked.

2.2 ALTERNATIVE HANDLE CONFIGURATIONS

This section presents a number of alternative controller-handle configurations. Most of these configurations were derived during the conceptual design phase of the Oak Ridge project. Some of the designs to follow, although not considered to be viable options, are nonetheless included for completeness.

Figure 2-7 shows 14 basic handle concepts. Most of the concepts are shown in the bottom-mounted configuration since this is the preferred position, as discussed in section 2.1 (note -- most of the designs can be used in a top-mounted configuration). Each design is briefly described below.

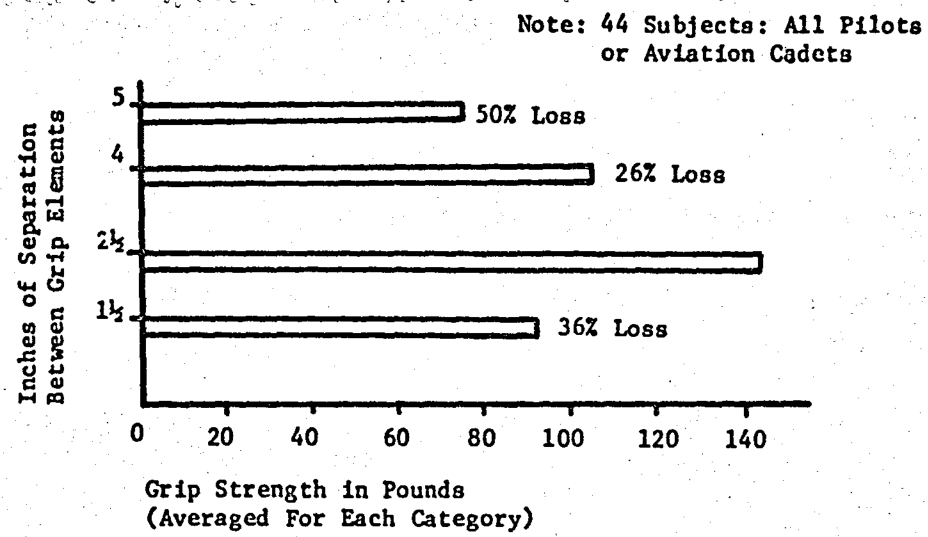


Figure 2-5. Grip Strength as a Function of Separation Between Grip Elements [Ref. 2]

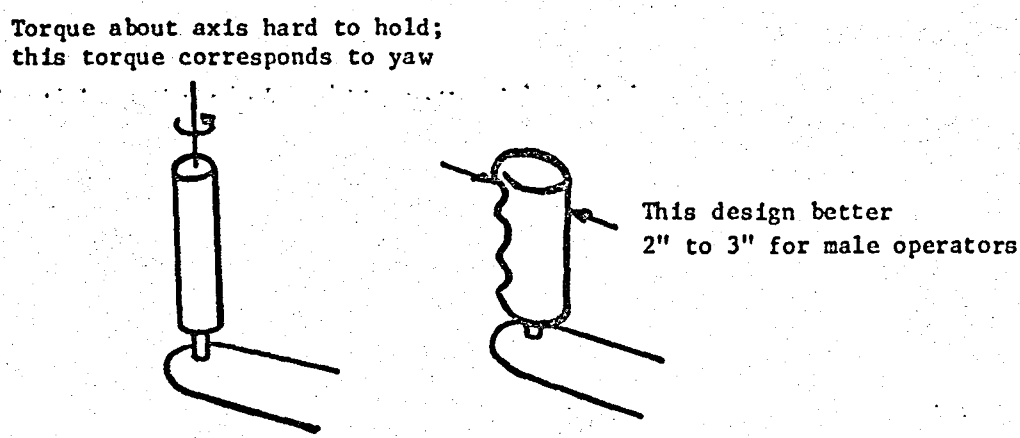


Figure 2-6. Effect of Handle Design on Controllability

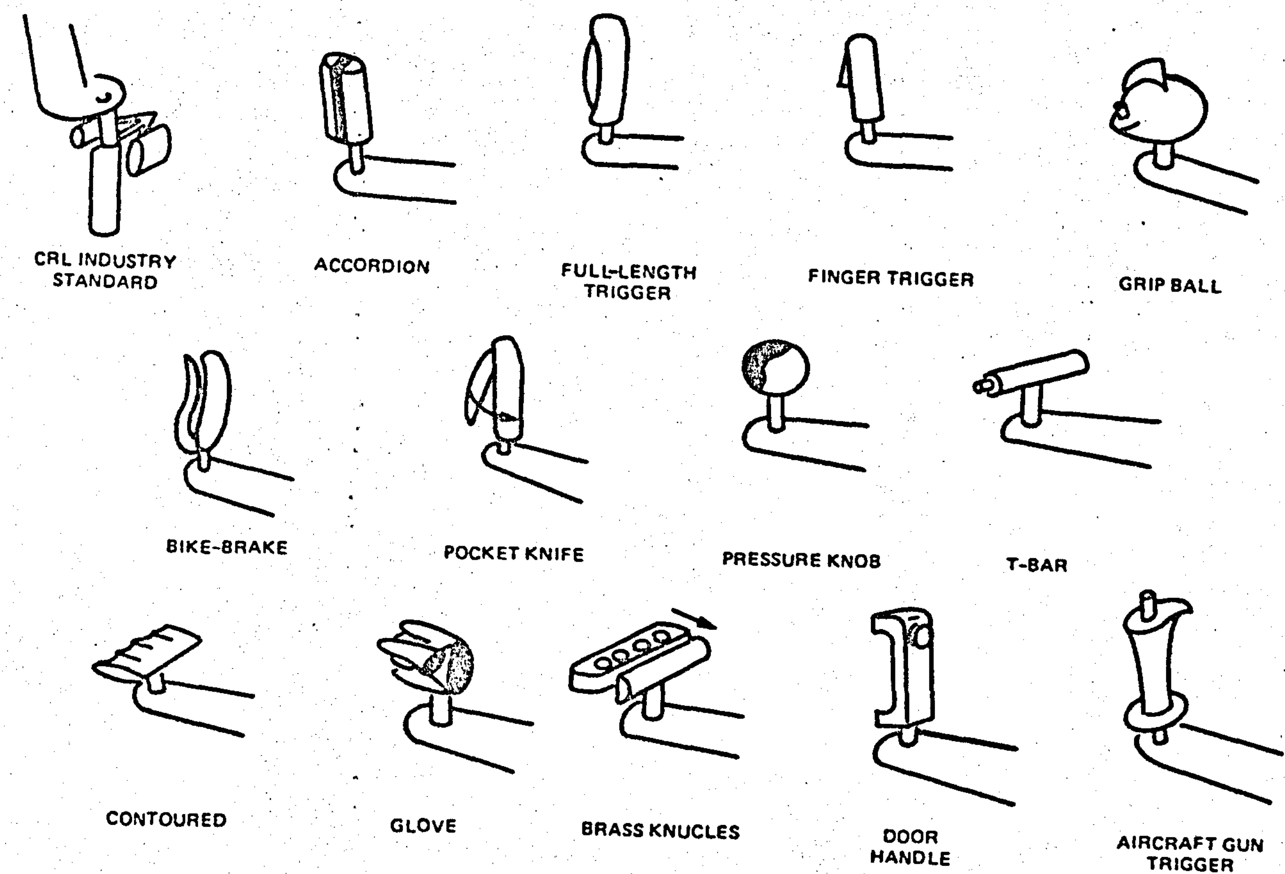


Figure 2-7. Basic Grip and Trigger Concepts

1) Nuclear Industry Standard: A squeeze grasp gripper control which simulates the slave end effector motion exactly. The operator grips the control handle with the third and fourth fingers while the thumb opposes the first and second fingers in a squeeze grasp trigger control. Secondary functions are difficult or impossible to implement when used for single-handed control. See section 2.3.2.1.

2) Hydraulic Accordian: A finger-heel grasp using a linear motion trigger driven by hydraulic pressure. To insure leak-free motion, an accordian-like bellows acts as the actuator. Secondary switch functions can be located on the top or side of the main body. Details and auxiliary switch arrangements are shown in section 2.3.2.2.

3) Full-Length Trigger: A finger-heel type, linear-motion, gripper control driven by a mechanical mechanism. Secondary switch functions can be located on the top or side of the main body. The figure in section 2.3.2.3 shows one possible version of this design.

4) Finger Trigger: A linear or pivoted gripper control which only requires one or two fingers for grasp actuation, and thus allows the remaining fingers to securely hold onto the handle. Secondary switch functions can be located on the top or side of the main body as shown in the figure in section 2.3.2.4.

5) Grip Ball: A ball-shaped handle with a vane-like protuberance which prevents slippage of the ball when sandwiched between two fingers. The trigger is controlled by a thumb switch. Secondary function switches can be located at the fingertips, but are difficult to control. See section 2.3.2.5.

6) Bike Brake: A gripper control using a finger-heel-type grasp in which the trigger mechanism is pivoted at the base of the handle. Secondary switch functions can be located on the top or side of the main body as shown in section 2.3.2.6.

7) Pocket Knife: A gripper control using a finger-heel grasp in which the trigger mechanism is pivoted at the top of the handle. Secondary switch functions can be located on the top or side of the main body. See figure in section 2.3.2.7 for one configuration.

8) Pressure Knob: A unibody ball-shaped handle consisting of a rigid mainbody (white in Figure 2-7) and a semi-rigid rubber balloon gripper control (black in Figure 2-7). The gripper control utilizes the wrap-around grasp in which the trigger surface is driven by hydraulic pressure. Location of secondary function switches can be on the side of the handle as shown in section 2.3.2.8.

9) <u>T-Bar</u>: A one-piece T-shaped handle with a thumb-button gripper control. This type of control handle combines the wrap-around grasp for firm spatial control and the lateral grasp for gripper control. The index finger can be used to actuate secondary switch functions as shown in section 2.3.2.9.

10) <u>Contoured</u>: A one-piece contoured T-type handle with a gripper control surface located on the underside. The gripper trigger is actuated by the fingers wrapped around the front of the wing-like handle. Secondary switch functions can be controlled by thumb switches on the side. The figure in section 2.3.2.10 shows a possible configuration of this control handle.

11) <u>Glove</u>: An undefined device which encases the operator's hand and gives the operator the sensation of being in direct contact with the task. See section 2.3.2.11.

12) <u>Brass Knuckles</u>: A two-piece T-type handle in which the operator's fingers slip into recesses or holes in the gripper control. This is a horizontal implementation of the finger-heel-type grasp. Secondary switch functions can be controlled by thumb activated switches on the side of the handle as shown in section 2.3.2.12.

13) <u>Door Handle</u>: A C-shaped handle with a thumb-button gripper control. This device is based on a modified lateral grasp. The thumb and index finger can be used to actuate switches on the side of the handle as shown in section 2.3.2.13.

14) <u>Aircraft Gun Trigger</u>: A vertical implementation using a lateral grasp for trigger control combined with the wrap-around grasp for firm spatial control. The index finger can be used for secondary function control as shown in section 2.3.2.14.

2.3 HANDLE CONCEPT EVALUATION

2.3.1 Selection Criteria

The basic handle specifications were as follows:

1) Handle must supply kinesthetic and force feedback.

2) Handle shall incorporate (a) grip lock/release switch, (b) secondary function switches, and (c) deadman switch.

3) Handle shall not fatigue the operator during relaxed states of operation and shall minimize fatigue during gripping actions.

4) Handle shall accommodate the full range of operators.

5) Gripping action shall have direct proportional correspondence to the grasping action of the slave.

6) Handle configuration shall be compatible with the controller structure and will allow a full range of movement.

7) Switches and feedback mechanisms shall be designed and placed to allow direct and uncumbersome actuation without regripping actions by the operator.

8) Pressure required to activate switches and gripper shall not approach the requirements of the least capable operator within 25%.

9) Switches shall be designed to prevent accidental activation.

10) Handle shall be lightweight.

The selection criteria, which are based on the handle specifications, were broken down into four categories: (1) engineering development, (2) controllability, (3) human-handle interface, and (4) human limitations. Each of these major categories is described below:

1) Engineering Development — This category considers the handle's developmental requirements in terms of (i) design simplicity, (ii) difficulty of implementation, (iii) extent to which a technological base has been established, and (iv) cost.

2) Controllability — This category considers the operator's ability to control the motion of the slave manipulator through the handle. Two major categories were used as selection criteria: (i) stimulus-response compatibility and (ii) cross coupling between the desired arm motion/forces and the grasp action. The first category, stimulus-response compatibility, considers the extent to which the handle design approaches the stimulus-response compatibility of the industry standard. This category only considers the desirability of stimulus-response compatibility from a motion-in/motion-out standpoint; it does not take into account its effect on fatigue (fatigue is considered in category 4). The second category, cross coupling, considers the extent of cross coupling between the motion or force being applied to the arm and the desired motion or force of the gripper.

3) Human-Handle Interaction — This category considers the effects of the interface and the interaction between the human and the handle. Four major categories were used as selection criteria: (i) secondary function control, (ii) force-feedback ratio, (iii) kinesthetic feedback, and (iv) accidental activation potential. The first category, secondary function control, considers the appropriateness of secondary switch placement from the standpoint of the operator's ability to

activate a given function. The second category, force feedback, considers the extent to which the remote forces must be scaled for a given handle configuration. The third category rates the degree of kinesthetic feedback, particularly with regard to the range of trigger motion with respect to an assumed 3-inch open/close motion of the end effector. The fourth category deals with the potential for accidental switch activation for a given design. The lower the rating, the more potential exists for accidental activation.

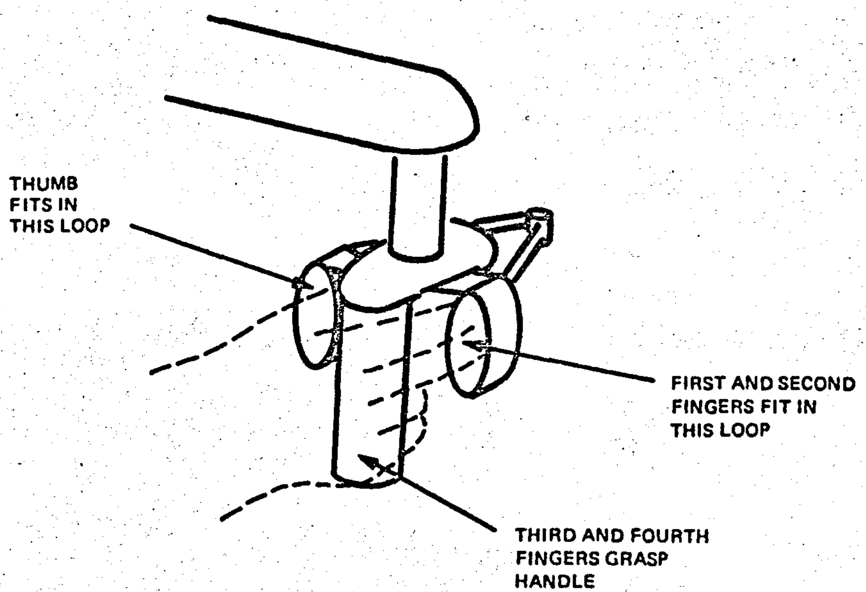
4) Human Limitations -- This category considers the limitations of the operator as a function of each design (assuming a normalized operator). Two areas were of concern in the handle selection: (i) endurance capacity and (ii) operator accommodation. The first category deals with the relative duration with respect to the other handle configurations during which an operator can use a given design without fatiguing or being stressed. The second category considers the extent to which a given design can accommodate a wide range of operators.

2.3.2 Concept Tradeoffs and Subjective Evaluations

This section considers the tradeoffs between the 14 handle configurations, based on the criteria outlined in the previous section. Subjective evaluations of the selection criteria are given on the following pages for each candidate design. The subjective ratings for each category are as follows:

	RATING 1	2	3
I. Engineering Development			
i) Design simplicity	complex	moderate	simple
ii) Difficulty of implementation	difficult	moderate	easy
iii) Technology base	unproven	R&D	proven
iv) Cost	high	medium	low
II. Controllability			
i) Stimulus-response compatibility	some	good	excellent
ii) Cross coupling	severe	some	little
III. Human-Handle Interaction			
i) Secondary function control	poor	acceptable	good
ii) Force feedback	poor	acceptable	good
iii) Kinesthetic feedback	poor	acceptable	good
iv) Potential for accidental activation	high	modest	low
IV. Human Limitations			
i) Endurance capacity	low	moderate	high
ii) Operator accommodation	poor	acceptable	good

2.3.2.1 Nuclear Industry Standard



PRIMARY ADVANTAGE(S)
– STIMULUS-RESPONSE COMPATIBILITY

PRIMARY DISADVANTAGE(S)
– LOW HUMAN ENDURANCE

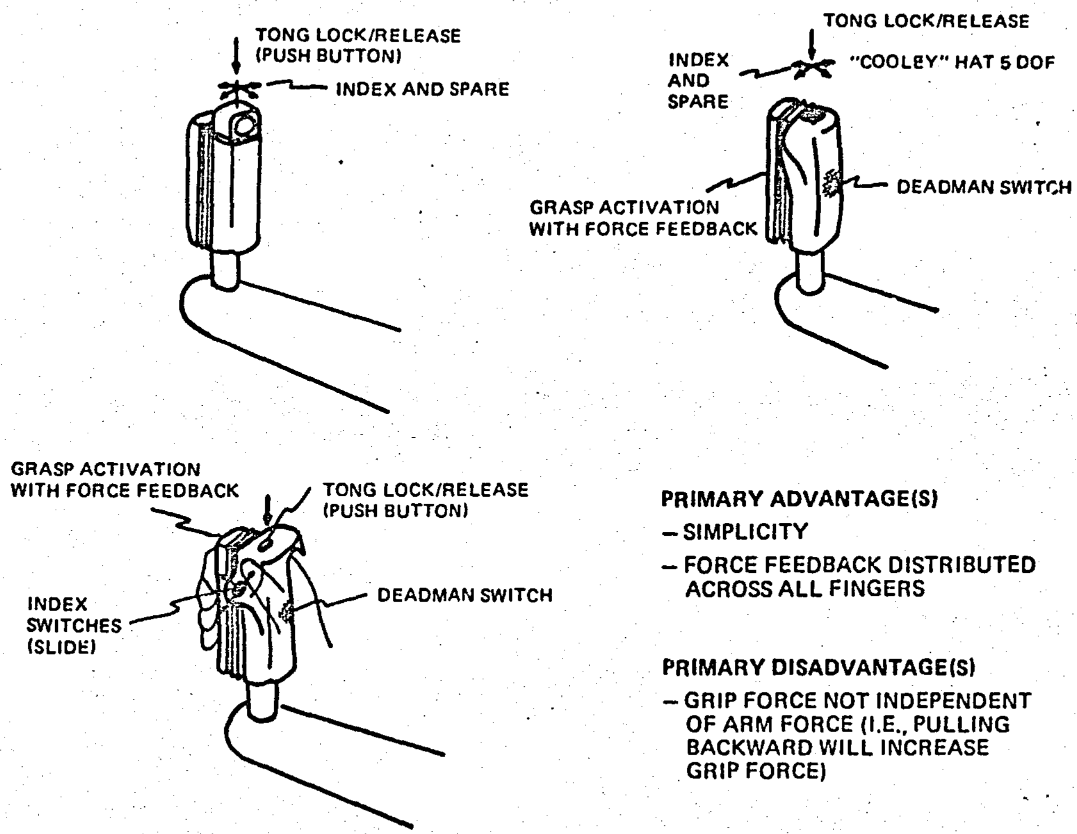
1) Engineering Development
   i) Moderate design complexity
   ii) Moderate implementation effort
   iii) Proven technology
   iv) Medium cost

2) Controllability
   i) Excellent stimulus-response compatibility
   ii) Little cross coupling

3) Human-Handle Interaction
   i) Poor secondary function control
   ii) Good force feedback
   iii) Good kinesthetic feedback
   iv) Modest potential for accidental activation

4) Human Limitations
   i) Low endurance capacity
   ii) Acceptable operator accommodation -- can be adjustable

2.3.2.2 Hydraulic-Accordion Handle



PRIMARY ADVANTAGE(S)

– SIMPLICITY

– FORCE FEEDBACK DISTRIBUTED ACROSS ALL FINGERS

PRIMARY DISADVANTAGE(S)

– GRIP FORCE NOT INDEPENDENT OF ARM FORCE (I.E., PULLING BACKWARD WILL INCREASE GRIP FORCE)

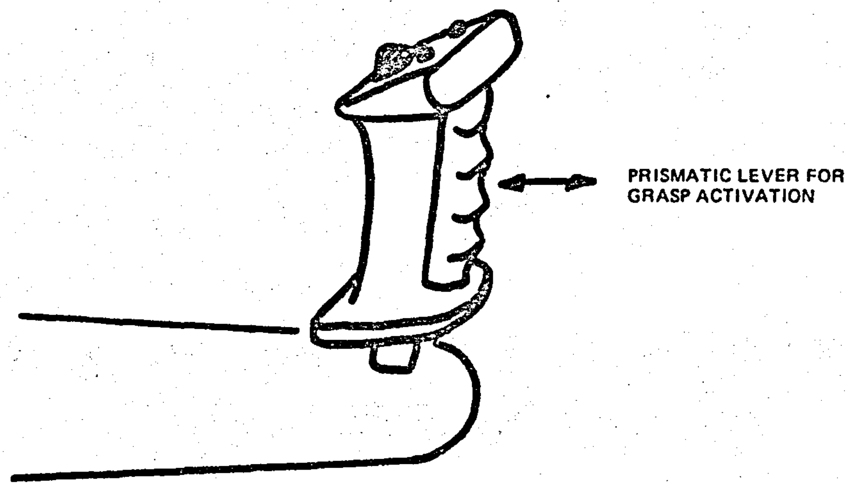
1) Engineering Development
   - i) Simple design -- bellows actuator
   - ii) Easy to implement
   - iii) Unproven concept of force feedback through hydraulic bellows
   - iv) Low cost

2) Controllability
   - i) Good stimulus-response compatibility
   - ii) Severe cross coupling unless grasp force is locked in place before manipulation

3) Human-Handle Interaction
   - i) Good secondary function control
   - ii) Good force feedback
   - iii) Good kinesthetic feedback
   - iv) Low potential for accidental activation

4) Human Limitations
   - i) Moderate endurance capacity
   - ii) Acceptable operator accommodation

2.3.2.3 Full-Length Trigger



PRIMARY ADVANTAGE(S)
- PRISMATIC MOTION
- FORCE FEEDBACK DISTRIBUTED ACROSS ALL FINGERS
- FIRM GRIPPING SURFACE

PRIMARY DISADVANTAGE(S)
- GRIP FORCE NOT INDEPENDENT OF ARM FORCE (I.E., PULLING BACKWARD WILL INCREASE GRIP FORCE)

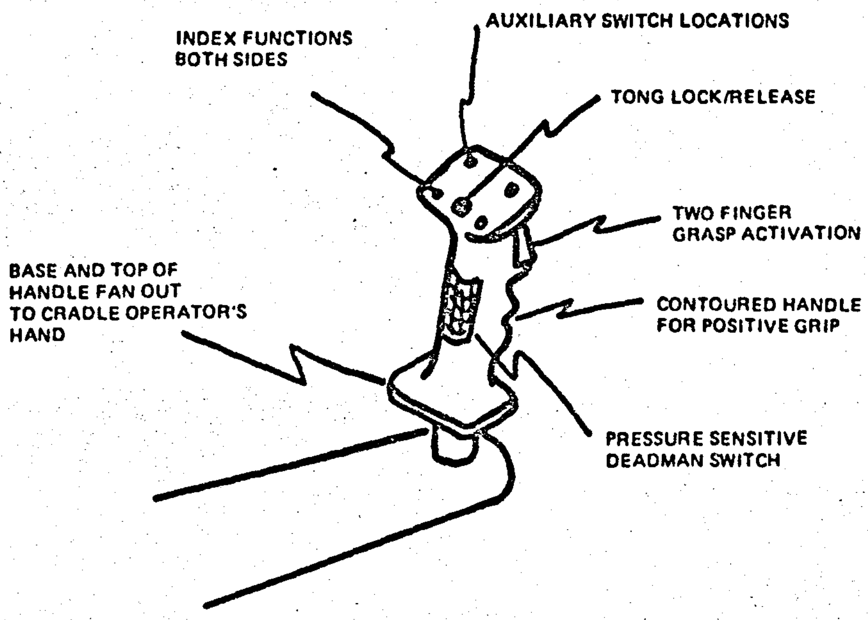
1) Engineering Development
   - i) Moderate design complexity due to linear motion of trigger
   - ii) Moderate effort to implement
   - iii) Proven technology
   - iv) Medium cost

2) Controllability
   - i) Good stimulus-response compatibility
   - ii) Severe cross coupling unless grasp force is locked in place before manipulation

3) Human-Handle Interaction
   - i) Good secondary function control
   - ii) Good force feedback
   - iii) Good kinesthetic feedback
   - iv) Low potential for accidental activation

4) Human Limitations
   - i) Moderate endurance capacity
   - ii) Acceptable operator accommodation

2.3.2.4 Finger-Trigger Handle



PRIMARY ADVANTAGE(S)

– OPERATOR HAS HEEL OF HAND AND TWO FINGERS SECURELY HOLDING HANDLE AT ALL TIMES

PRIMARY DISADVANTAGE(S)

– SMALL RANGE OF FORCE FEEDBACK DUE TO HUMAN INDEX FINGER LIMITATIONS

– SMALL TRIGGER DISPLACEMENT

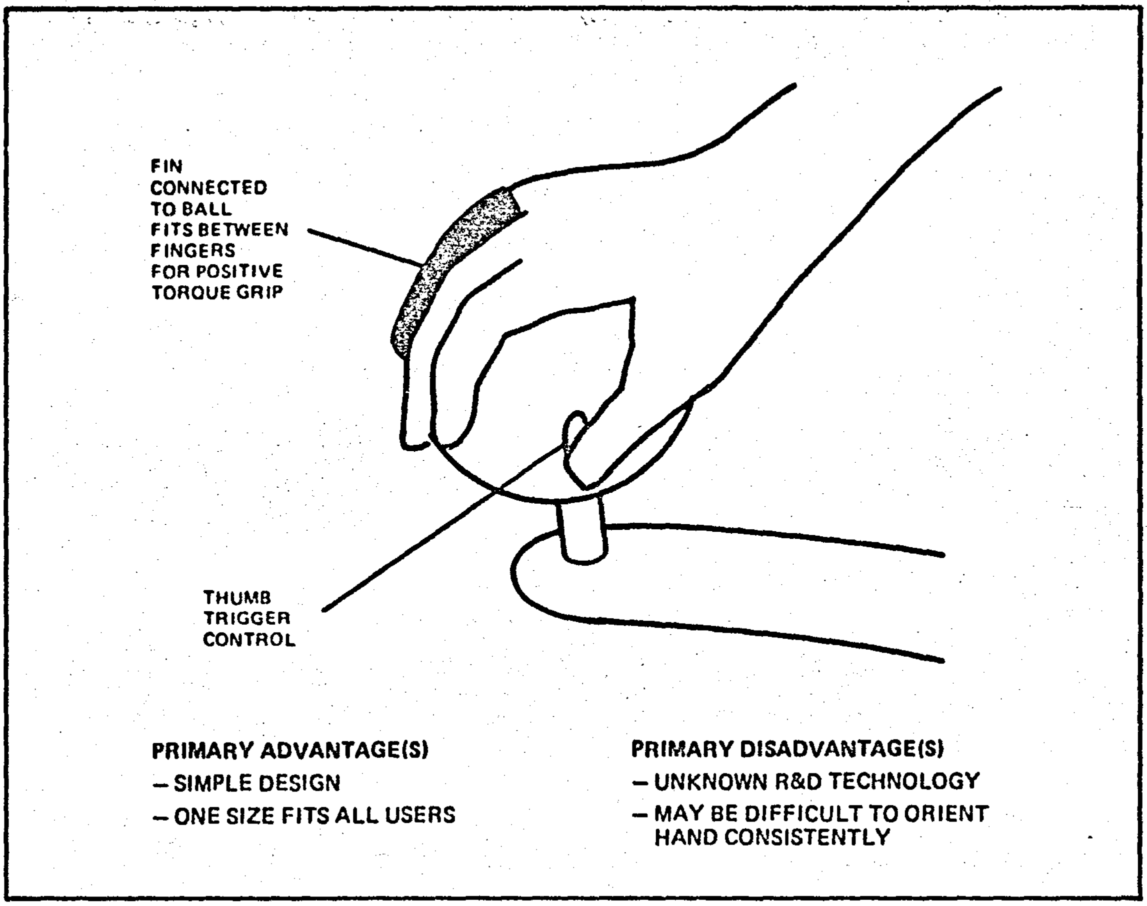
1) Engineering Development
   i) Simple design
   ii) Easy to implement
   iii) Proven technology
   iv) Low cost

2) Controllability
   i) Good stimulus-response compatibility
   ii) Little or no cross coupling

3) Human-Handle Interaction
   i) Good secondary function control
   ii) Acceptable force feedback
   iii) Good kinesthetic feedback
   iv) Low potential for accidental activation

4) Human Limitations
   i) High endurance capacity
   ii) Acceptable operator accommodation

2.3.2.5 Grip Ball



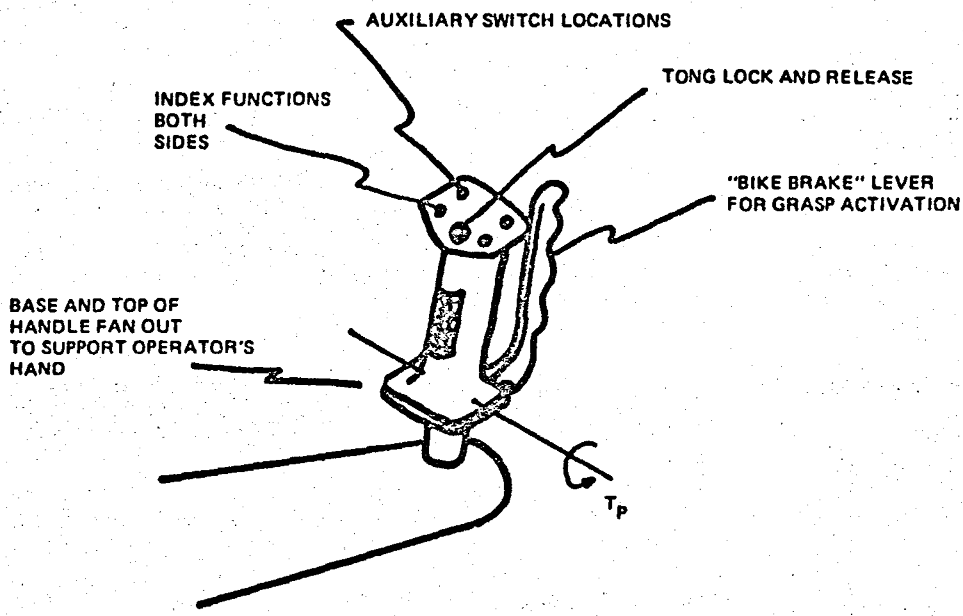
1) Engineering Development
   - i) Simple design
   - ii) Easy to implement
   - iii) R&D technology
   - iv) Medium cost

2) Controllability
   - i) Good stimulus-response compatibility
   - ii) Little cross coupling

3) Human-Handle Interaction
   - i) Poor secondary function control
   - ii) Acceptable force feedback
   - iii) Acceptable kinesthetic feedback (limited range of movement)
   - iv) High potential for accidental activation of secondary functions when controlled by fingers

4) Human Limitations
   - i) Moderate endurance capacity
   - ii) Good operator accommodation -- one handle fits all users

2.3.2.6 Bike-Brake Handle



PRIMARY ADVANTAGE(S)

- OPERATOR CAN EXERT LARGE GRASP FORCES
- GRASP LEVER HAS LARGE RANGE OF MOTION

PRIMARY DISADVANTAGE(S)

- GRIP FORCE NOT INDEPENDENT OF ARM FORCE (E.G., IT IS DIFFICULT TO MAINTAIN A LIGHT GRASP WHILE EXERTING A BACKWARD PITCH TORQUE T_P)

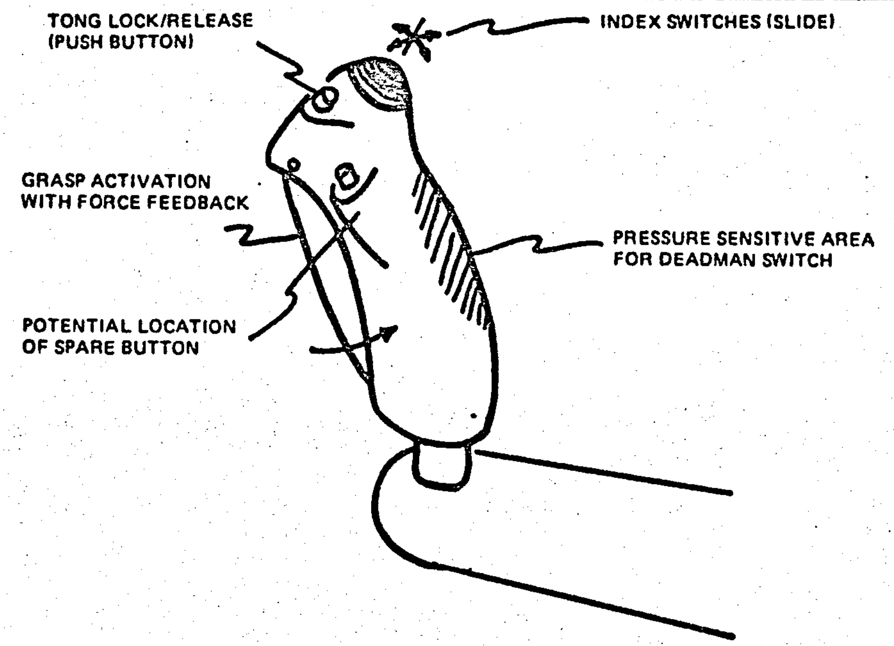
1) Engineering Development
   i) Simple design
   ii) Easy to implement
   iii) Proven technology
   iv) Low cost

2) Controllability
   i) Good stimulus-response compatibility
   ii) Severe cross coupling unless grasp force is locked in place before manipulation

3) Human-Handle Interaction
   i) Good secondary function control
   ii) Good force feedback
   iii) Good kinesthetic feedback
   iv) Low potential for accidental activation

4) Human Limitations
   i) Moderate endurance capacity
   ii) Acceptable operator accommodation

2.3.2.7 Pocket-Knife Handle



PRIMARY ADVANTAGE(S)

- CONTOURED HANDLE HELPS REDUCE FATIGUE
- OPERATOR CAN INCREASE/ DECREASE HIS LEVERAGE ON GRIPPER BY MOVING FINGERS DOWN OR UP ON GRIPPER-CONTROL LEVER

PRIMARY DISADVANTAGE(S)

- GRIP FORCE NOT INDEPENDENT OF ARM FORCE (E.G., PITCH TORQUE AND LIGHT GRASP ARE INCOMPATIBLE)
- HANDLE OFFERS LITTLE SUPPORT WHEN LIFTING LOADS

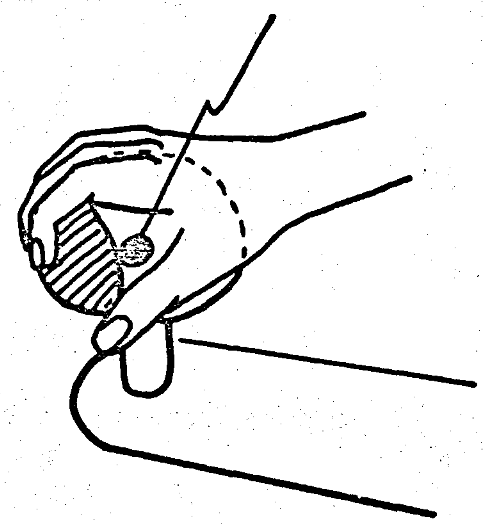
1) Engineering Development
   i) Simple to design
   ii) Easy to implement
   iii) Proven technology
   iv) Low cost

2) Controllability
   i) Good stimulus-response compatibility
   ii) Severe cross coupling unless grasp force is locked in place before manipulation

3) Human-Handle Interaction
   i) Good secondary function control
   ii) Good force feedback
   iii) Good kinesthetic feedback
   iv) Low potential for accidental activation

4) Human Limitations
   i) Moderate endurance capacity
   ii) Acceptable operator accommodation

2.3.2.8 Knob-Type Handle



PRIMARY ADVANTAGE(S)
- SIMPLICITY
- ONE SIZE FITS ALL USERS

PRIMARY DISADVANTAGE(S)
- OPERATOR'S ABILITY TO CONTROL TORQUES LIMITED
- GRASP LOCATION ILL-DEFINED
- GRIP FORCE NOT INDEPENDENT OF ARM FORCE (E.G., BACKWARD CONTROLLER FORCE WILL INCREASE GRIP FORCE)
- SMALL RANGE OF GRASP MOTION

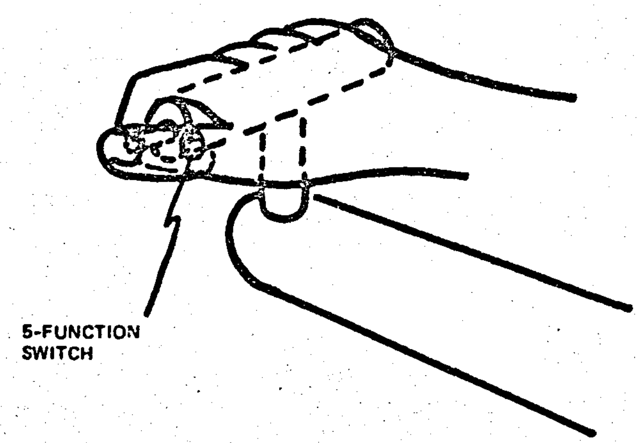
1) Engineering Development
   - i) Simple design -- balloon actuator
   - ii) Easy to implement
   - iii) Unproven concept of force feedback through hydraulic balloon
   - iv) Low cost

2) Controllability
   - i) Some stimulus-response compatibility
   - ii) Severe cross coupling

3) Human-Handle Interaction
   - i) Poor secondary function control
   - ii) Poor force feedback since handle is essentially an isometric controller
   - iii) Poor kinesthetic feedback -- distribution, number, and placement of fingers determines squeeze displacement
   - iv) High potential for accidental activation

4) Human Limitations
   - i) Low endurance capacity -- rubber ball squeeze is tiring
   - ii) Good operator accommodation -- one "nub" fits all users

2.3.2.9 T-Bar Handle



PRIMARY ADVANTAGE(S)
- HIGH TORQUE CAPABILITY
- CONTROLLER FORCES COMPLETELY INDEPENDENT OF GRASP FORCE

PRIMARY DISADVANTAGE(S)
- SWITCH FUNCTIONS DIFFICULT TO ACTIVATE WHILE MAINTAINING GOOD CONTROL

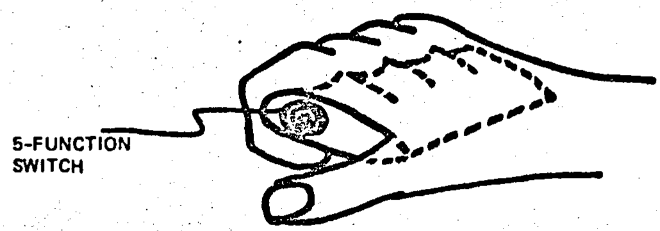
1) Engineering Development
   i) Simple design
   ii) Easy to implement
   iii) Proven technological base
   iv) Low cost

2) Controllability
   i) Good stimulus-response compatibility
   ii) Little or no cross coupling

3) Human-Handle Interaction
   i) Poor secondary function control by index finger
   ii) Acceptable force feedback
   iii) Acceptable kinesthetic feedback (limited range of movement)
   iv) High potential for accidental activation of secondary functions by index finger

4) Human Limitations
   i) Moderate endurance capacity
   ii) Good operator accommodation -- one handle fits all users

2.3.2.10 **Contoured Handle**



PRIMARY ADVANTAGE(S)
– HIGH TORQUE CAPABILITY
– FIRM GRIPPING SURFACE

PRIMARY DISADVANTAGE(S)
– GRIP FORCE NOT INDEPENDENT OF ARM FORCE (E.G., LIFTING ACTION WILL INCREASE GRIP FORCE)

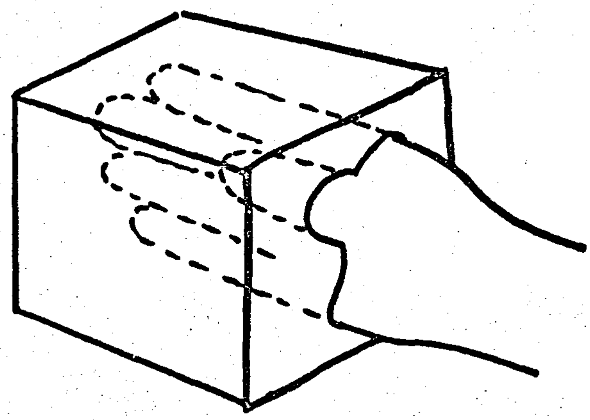
1) Engineering Development
   i) Moderate design complexity
   ii) Moderate effort to implement
   iii) Unproven concept of force feedback through hydraulic balloon
   iv) Medium cost

2) Controllability
   i) Some stimulus-response compatibility
   ii) Severe cross coupling

3) Human-Handle Interaction
   i) Good secondary function control
   ii) Poor force feedback -- trigger essentially isometric controller
   iii) Poor kinesthetic feedback due to small displacement of trigger
   iv) Modest potential for accidental activation since all functions are on one switch

4) Human Limitations
   i) Low endurance capacity since squeeze by fingertips
   ii) Good operator accommodation -- one handle fits all users

2.3.2.11 Glove-Control Handle



PRIMARY ADVANTAGE(S)
- TELEPRESENCE

PRIMARY DISADVANTAGE(S)
- ILL-DEFINED CONCEPT
- SECONDARY FUNCTION SWITCHES UNAVAILABLE
- TECHNOLOGY UNAVAILABLE
- OPERATOR'S HAND IS CAPTIVE

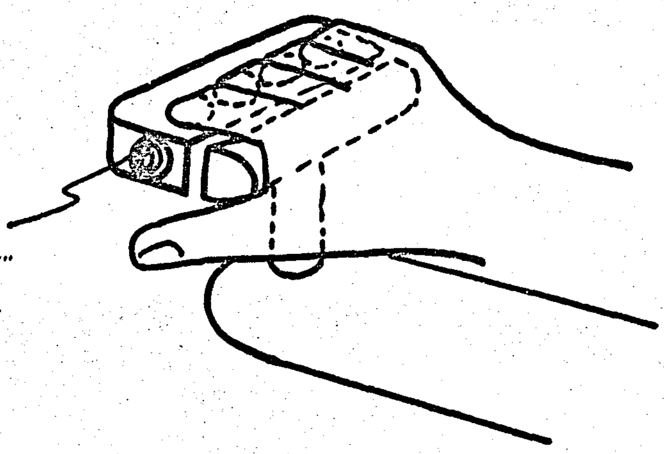
1) Engineering Development
   - i). Complex design
   - ii) Difficult to implement
   - iii) Unproven technological base
   - iv) High cost

2) Controllability
   - i) Excellent stimulus-response compatibility
   - ii) Little cross coupling

3) Human-Handle Interaction
   - i) Poor secondary function control
   - ii) Good force feedback
   - iii) Good kinesthetic feedback
   - iv) Potential for accidental activation unknown

4) Human Limitations
   - i) Moderate endurance capacity
   - ii) Poor operator accommodation

2.3.2.12 Brass-Knuckle Handle



PRIMARY ADVANTAGE(S)
- HIGH FORCE/TORQUE CAPABILITIES
- FIRM CONTROL

PRIMARY DISADVANTAGE(S)
- OPERATOR'S FINGERS CAPTIVE
- GRIP FORCE NOT INDEPENDENT OF ARM FORCE (E.G., PULLING ARM BACKWARD WILL INCREASE GRIP FORCE)

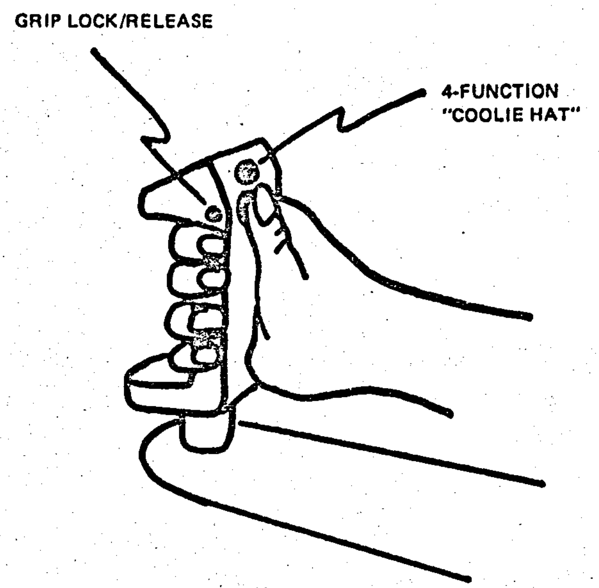
1) Engineering Development
   i) Moderate design complexity
   ii) Moderate effort to implement
   iii) Proven technological base
   iv) Medium cost

2) Controllability
   i) Good stimulus-response compatibility
   ii) Severe cross coupling unless trigger is locked before moving

3) Human-Handle Interaction
   i) Good secondary function control
   ii) Good force feedback
   iii) Good kinesthetic feedback
   iv) Modest potential for accidental activation since all functions are on one switch

4) Human Limitations
   i) Moderate endurance capacity
   ii) Good operator accommodation -- one handle may be sufficient for all users

2.3.2.13 Door Handle



PRIMARY ADVANTAGE(S)

– CAPTIVE-TYPE GRIP WITHOUT ACTUALLY ENCASING OPERATOR'S HAND

PRIMARY DISADVANTAGE(S)

– POTENTIALLY FATIGUING CONFIGURATION

– THUMB PERFORMING TOO MANY FUNCTIONS

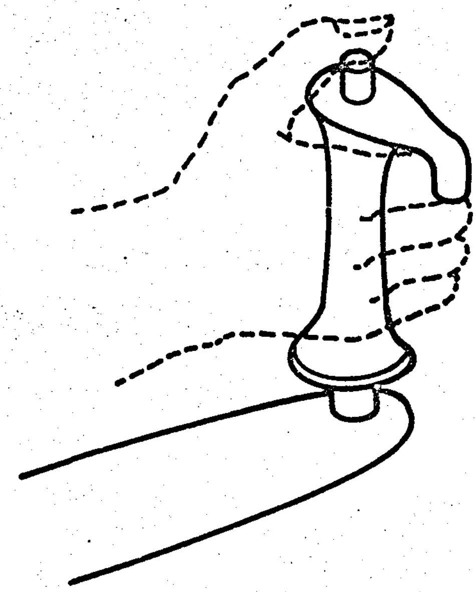
1) Engineering Development
   - i) Simple design
   - ii) Easy to implement
   - iii) Proven technology
   - iv) Low cost

2) Controllability
   - i) Good stimulus-response compatibility
   - ii) Little or no cross coupling

3) Human-Handle Interaction
   - i) Acceptable secondary function control
   - ii) Acceptable force feedback
   - iii) Acceptable kinesthetic feedback (limited range of movement)
   - iv) Modest potential for accidental activiation (thumb performs too many functions)

4) Human Limitations
   - i) Moderate endurance capacity
   - ii) Good operator accommodation

2.3.2.14 Aircraft Gun Control



PRIMARY ADVANTAGE(S)
- HIGH TORQUE CAPABILITY
- CONTROLLER FORCES COMPLETELY INDEPENDENT OF GRASP FORCE

PRIMARY DISADVANTAGE(S)
- SWITCH FUNCTIONS DIFFICULT TO ACTIVATE WHILE MAINTAINING GOOD CONTROL

1) Engineering Development
   i) Simple design
   ii) Easy to implement
   iii) Proven technology
   iv) Low cost

2) Controllability
   i) Good stimulus-response compatibility
   ii) Little or no cross coupling

3) Human-Handle Interaction
   i) Poor secondary function control
   ii) Acceptable force feedback
   iii) Acceptable kinesthetic feedback (limited range of movement)
   iv) High potential for accidental activiation by index finger

4) Human Limitations
   i) Moderate endurance capacity
   ii) Good operator accommodation -- one handle fits all users

2.3.3 Analysis of Handle Concepts

A value analysis was performed on the subjective evaluations of the previous section (Section 2.3.2). The subjective evaluations described in Sections 2.3.2.1 thru 2.3.2.14 were assigned a score between 1 and 3, and each of the selection criteria were given a value indicating importance from 1 to 5. Then a figure of merit was obtained by summing the products of each of the scores and values for each category. Table 2-1 shows the results of the value analysis. The value analysis selects the finger-trigger design as the most promising candidate.

In the previous analysis we used cross coupling as only one of many important parameters. Considering the effects of cross coupling on seven-DOF control it may be wiser to weigh it heavily. If we view cross coupling as an overriding factor, then only seven proposed designs meet our requirements:

A) Nuclear Industry Standard
B) Finger Trigger
C) Grip Ball
D) T-Bar
E) Glove
F) Door Handle
G) Aircraft Gun Control

The glove concept can be dropped for the present, due to the lack of a technological base and the scarcity of end effectors capable of being driven by a multifinger controller. (It is felt, however, that a long-term effort in this area should be undertaken at a future date.)

The remaining concepts all share one thing in common; that is, the handle is held firmly by some of the digits while other independent digits perform trigger actuation. Based on a simple analysis of these promising candidates it would appear that the most viable techniques for controlling a trigger DOF while simultaneously controlling six spatial DOF's obey the following guidelines:

1) The handle must be held firmly with at least two fingers and the heel of the hand at all times to adequately control the six spatial DOF's,

2) At least one of the stronger digits of the hand (i.e., thumb or index finger) must be dedicated to the function of trigger actuation and force feedback; that is, it must be independent of spatial control functions,

3) The index finger, having restricted lateral mobility, makes a good candidate for single-function dedication since it cannot move as freely as the thumb from one switch to another, and

4) Likewise, the thumb makes a better candidate for multiple switch activation.

Table 2-1. Tradeoff and Value Analysis of Handle Designs
(1 -- Lowest Rating; 3 -- Best Rating)

	ENGINEERING DEVELOPMENT				CONTROLL-ABILITY		HUMAN-HANDLE INTERACTION				HUMAN LIMITA-TIONS		
	DESIGN SIMPLICITY	DIFFICULTY OF IMPLE-MENTATION	TECHNOLOGY BASE	COST	STIMULUS-RESPONSE COMPATIBILITY	CROSS COUPLING	SECONDARY-FUNCTION CONTROL	FORCE FEEDBACK	KINESTHETIC FEEDBACK	ACCIDENTAL ACTIVATION	ENDURANCE CAPACITY	OPERATOR ACCOMMODATION	TOTAL FIGURE OF MERIT Σ VALUE X SCORE
VALUE	2	1	5	4	3	5	5	4	4	4	3	2	
A) INDUSTRY STANDARD	2	2	3	2	3	3	1	3	2	2	1	2	97
B) ACCORDIAN	3	3	1	3	2	1	3	3	3	3	2	2	98
C) FULL-LENGTH TRIGGER	2	2	3	2	2	1	3	3	3	3	2	2	101
D) FINGER TRIGGER	3	3	3	3	2	3	3	2	3	3	3	2	117
E) GRIP BALL	3	3	2	2	2	3	1	2	2	1	2	3	85
F) BIKE-BRAKE	3	3	3	3	2	1	3	3	3	3	2	2	108
G) POCKET KNIFE	3	3	3	3	2	1	3	3	3	3	2	2	108
H) PRESSURE NUB	3	3	1	3	1	1	1	1	1	1	1	3	60
I) T-BAR	3	3	3	3	2	3	1	2	2	1	2	3	94
J) CONTOURED	2	2	1	2	1	1	3	1	1	2	1	3	67
K) GLOVE	1	1	1	1	3	3	1	3	3	2	2	1	81
L) BRASS KNUCKLE	2	2	3	2	2	1	3	3	3	2	2	3	99
M) DOOR HANDLE	3	3	3	3	2	3	2	2	2	2	2	3	103
N) AIRCRAFT GUN TRIGGER	3	3	3	3	2	3	1	2	2	1	2	3	94

SECTION 3

CONTROL INPUT DEVICES

This section surveys hand-controller input devices without consideration of specific control strategies. Control strategies are surveyed in Section 4. To consider hand-controller characteristics it will at times, however, be necessary to refer to the control technique commonly used with the device. The hand controllers identified in this study are:

- Switches
- Potentiometers
- Joysticks
  - Isotonic
  - Isometric
  - Proportional
  - Hybrid
- Replica
- Master-Slave
- Anthropomorphic
- Nongeometric Analogic
- Universal
  - Control Stick
  - Floating-Handle

(See "Lexicon" at the beginning of this report for definitions of terminology used in this report.)

The following state-of-the-art survey is based on a number of previous, but incomplete surveys [Refs. 12, 13, 14, 15, 62].

3.1 SWITCH CONTROLS

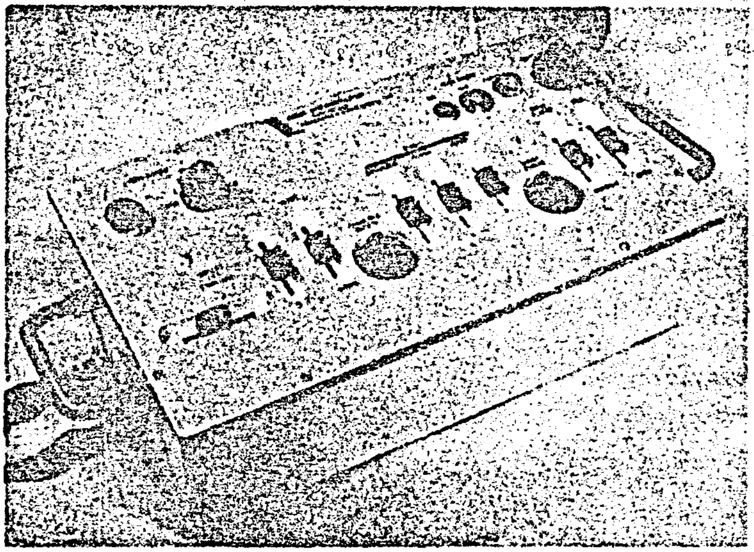
Switch controls generally consist of simple spring-centered, three-position (-, off, +), discrete action switches (toggle, push/pull, or slide), where each switch is assigned to either a particular manipulator joint or spatial degree-of-freedom of the end effector. Typical switch controls are shown in Figure 3-1 (related Refs. 12, 13, 14, 15, 17).

ADVANTAGES

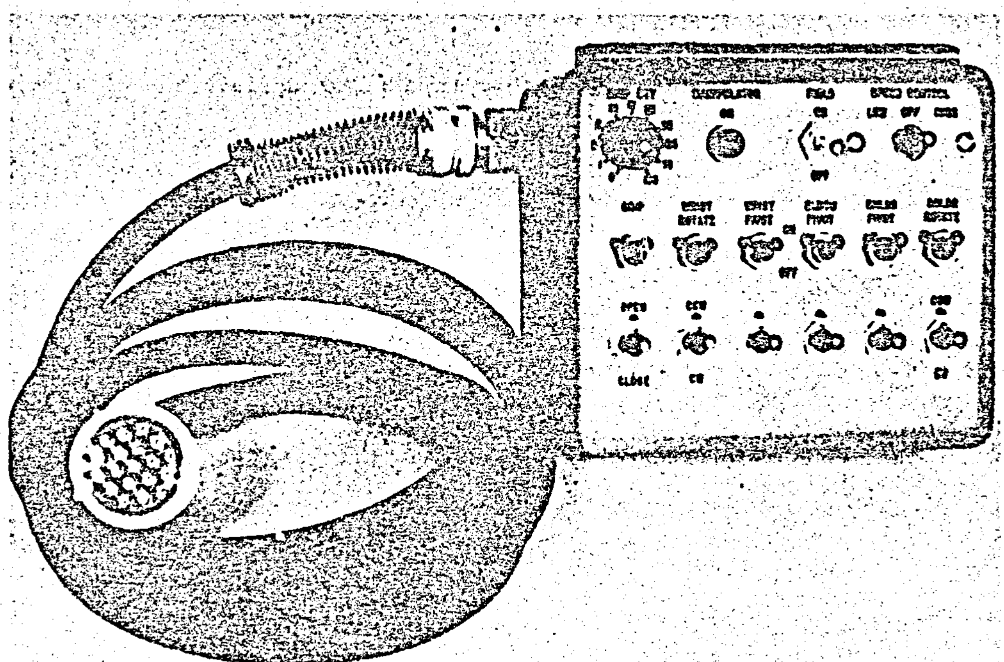
- Simplicity
- Low cost
- Reliability
- Minimum operating volume
- No cross coupling

DISADVANTAGES

- Open loop control
- No force feedback
- No proprioceptive or configuration feedback



(a) Switch-Type Control Box Used for the PaR Model 3000 Manipulator



(b) Early Model of ALVIN's Manipulator Controls (WHOI) [16]

Figure 3-1. Typical Switch Controls

Nonanthropomorphic
High operator workload
Coordinated end effector motion difficult
Operator response limited
High probability of operator disorientation
Increased probability of error

3.2 POTENTIOMETER CONTROLS

Potentiometers are used for proportional control inputs. They can be either force-operated (e.g., spring centered) or displacement-operated. Typically each pot is assigned to one manipulator joint or a spatial degree-of-freedom of the end effector. Figure 3-2 shows a generalized control console which uses displacement-operated potentiometers for either rate or position commands (related Refs. 12, 13, 14).

ADVANTAGES

Simplicity
Small operating volume
No cross-coupling
Control output feedback as a function of displacement
Closed-loop control
Well-defined zero position (spring-centered, detent, etc.)
Small input capability

DISADVANTAGES

Limited proprioceptive and configuration feedback cues
No force feedback
Operator workload moderately high
Coordinated multiple degree-of-freedom motion difficult
Operator response limited (better than switch control?)
High probability of operator error (less than with switch control?)

3.3 ISOTONIC JOYSTICK CONTROLLERS

An isotonic joystick is a position-operated fixed-force (isotonic) device used to control two or more degrees-of-freedom single-handedly, from within a limited control volume. The controller output does not correspond to the forces applied by the operator and the control lever remains in the last position set (the joystick usually maintains a set position by virtue of sliding friction [14]). A "trackball" is is a well-known example of an isotonic joystick. Figure 3-3 illustrates a joystick control device which has three isotonic rotational degrees-of-freedom.

In many cases the distinction between an isotonic joystick and unilateral master-slave is not clear. For example, Brooks [18] simulated an isotonic joystick at MIT with a six degree-of-freedom master-slave by turning the force feedback off and locking all but the wrist degrees-of-freedom;

OVERALL VIEW

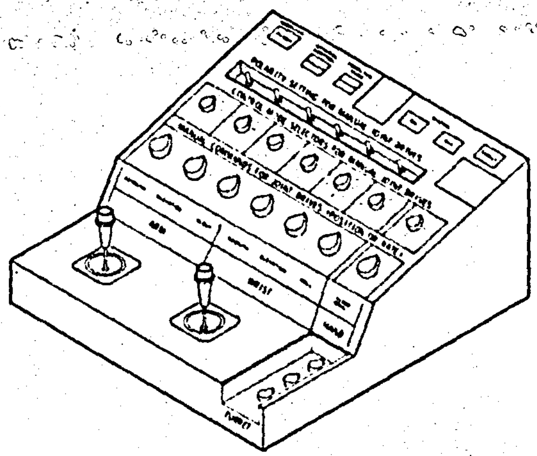


Figure 3-2. JPL's General Purpose Control Console for Both Manual and Computer Control

hence, creating an isotonic joystick which controlled the rotational degrees-of-freedom of the end effector from within a small operating volume (related Refs. 12, 13, 14, 15, 18, 19, 20, 21).

ADVANTAGES

- Small operating volume
- Proprioceptive and/or configuration feedback as a function of displacement
- Variable control gains
- Potentially anthropomorphic
- Small controller input forces -- reduced operator fatigue

DISADVANTAGES

- Accidental activation possible
- Control does not provide clearly defined zero
- Restricted hand excursions
- Peculiar wrist positions may be necessary to achieve orientation
- Cross coupling may be significant due to lack of maintenance force on neighboring degrees-of-freedom

3.4 ISOMETRIC JOYSTICK CONTROLLERS

An isometric joystick is a force-operated minimal-displacement (isometric) device used to control two or more degrees-of-freedom single-handedly from a fixed control. The controller output corresponds directly to the forces applied by the operator, and drops to zero unless manual force is

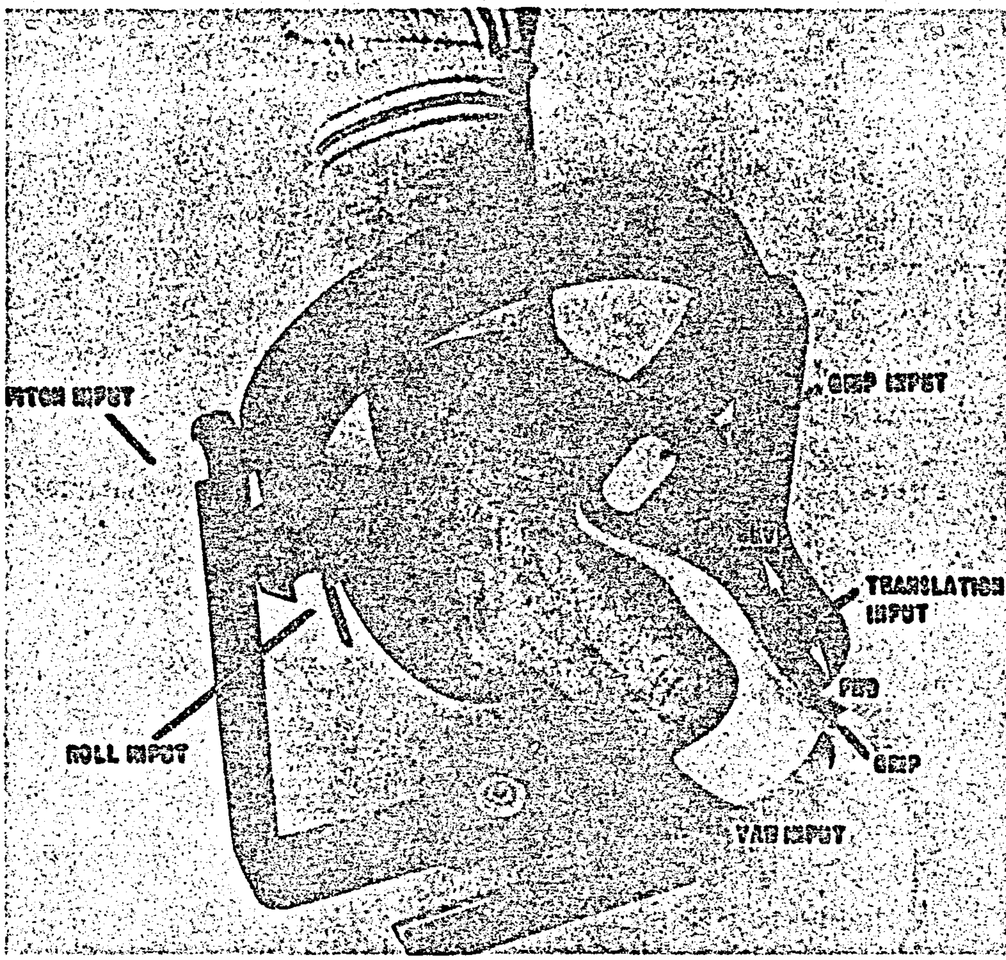
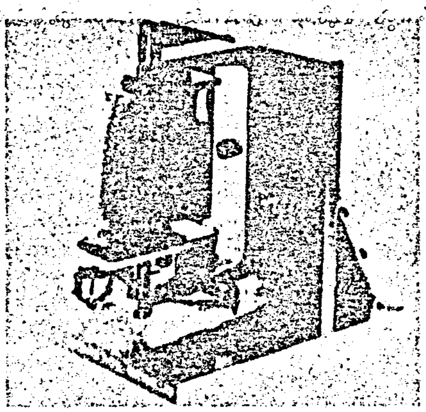


Figure 3-3. URS/Matrix Terminal Pointer Hand Controller

maintained [14]. Figure 3-4 illustrates two isometric joysticks developed at the Draper Lab (related Refs. 12, 13, 14, 15, 17, 19, 20, 22, 23).

ADVANTAGES

Compact operating volume
Little control movement
Small-signal input capability, i.e., high resolution
Variable control gains
Output returns to zero on removal of force



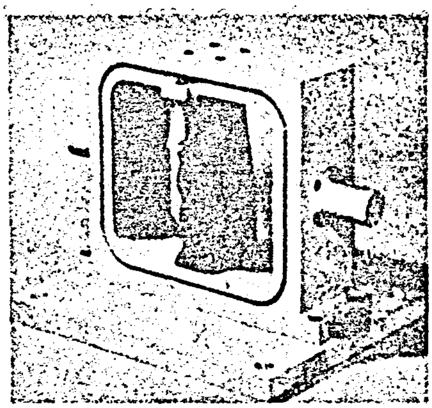


Figure 3-4. MIT/Draper Six Degree-of-Freedom Isometric Controllers

DISADVANTAGES

- Restricted hand excursions (near zero movement)
- No capability for force feedback from remote device
- No proprioceptive or configuration feedback
- Requires high degree of computational logic
- High degree of cross-coupling
- Operator fatigue
- Possible loss of spatial correspondence
- Operator disorientation

3.5 PROPORTIONAL JOYSTICK CONTROLLERS

A proportional joystick controller is a single-handed, two or more degree-of-freedom device with a limited operational volume in which the displacement is a function of the force applied by the operator (F=kx). The controller output corresponds directly to the displacement of the device. Figure 3-5 shows both a transitional and a rotational proportional joystick. A six degree-of-freedom proportional joystick developed by CAE Electronics of Canada is shown in Figure 3-6 (related Refs. 12, 13, 14, 15, 19, 21, 24).

ADVANTAGES

- Small operating volume
- Sense of control movement
- Minimal cross coupling (with moderate spring rates and less than 3 DOF's on one control stick)
- Variable control gains
- Output returns to zero on removal of force

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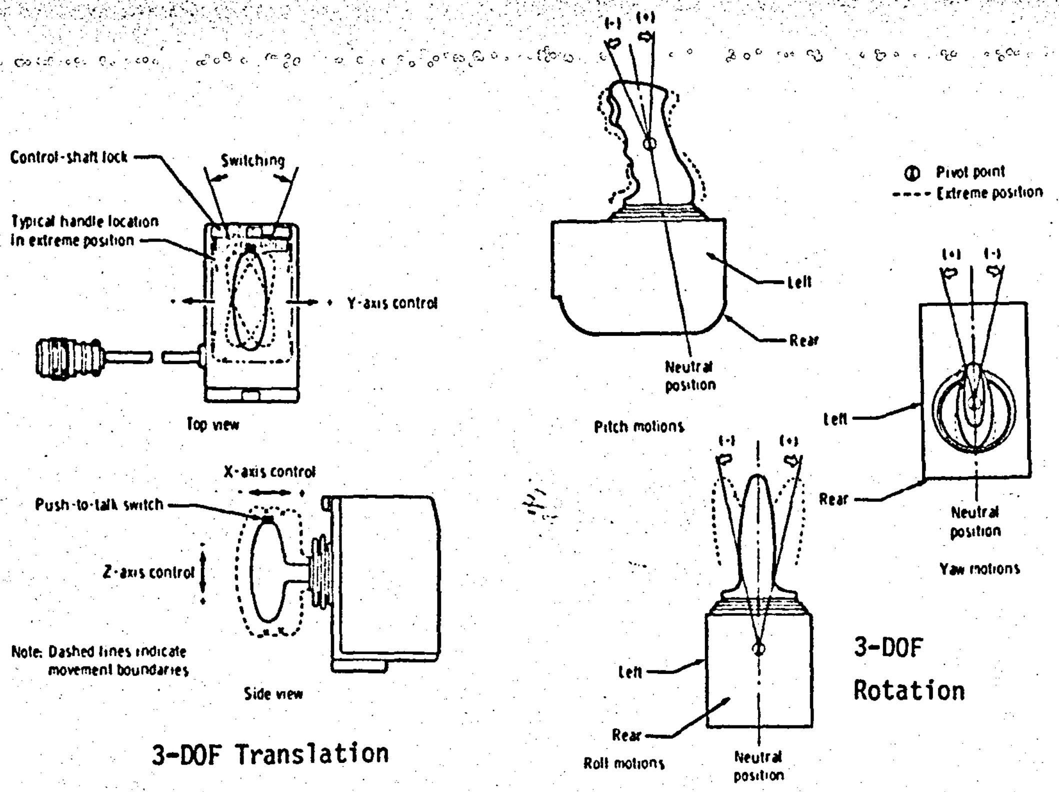

Figure 3-5. Apollo-Type Spring-Centered Joysticks [24]

DISADVANTAGES

- Restricted hand excursions
- No force feedback
- No configuration feedback
- Limited proprioceptive feedback
- Can require computational logic
- Cross coupling (with high spring rates)
- Operator fatigue (with low or high spring rates)
- Possible loss of spatial correspondence
- Operator disorientation

3.6 HYBRID JOYSTICK CONTROLLERS

A hybrid joystick is a controller composed of isotonic, isometric, and proportional elements (which are mutually exclusive for a given DOF), used to control two or more degrees-of-freedom from within a limited volume with a single hand. There are two basic implementation philosophies: concurrent and sequential.

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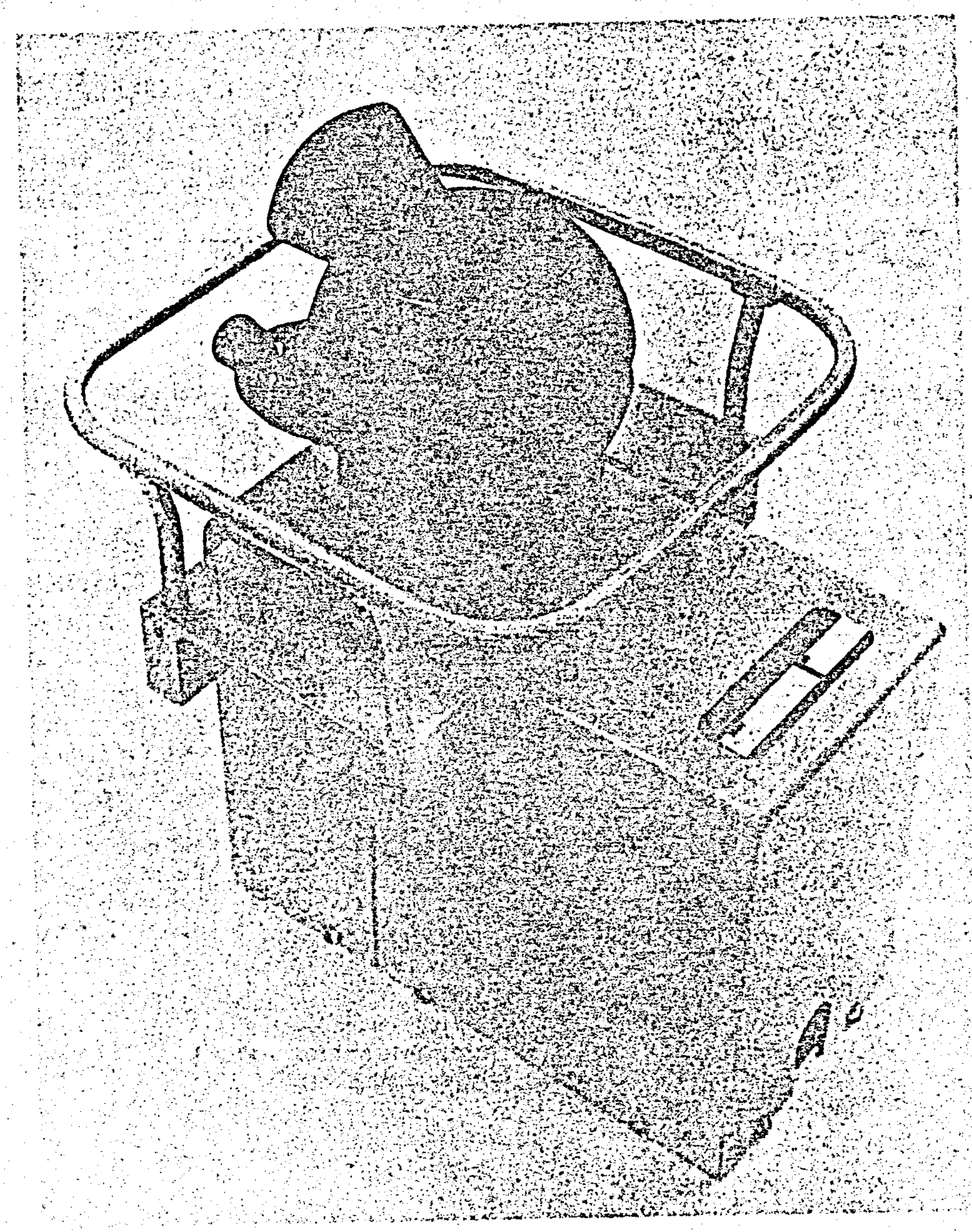


Figure 3-6. CAE Six Degree-of-Freedom Proportional Joystick
[CAE Electronics Ltd]

A concurrent controller has some degrees-of-freedom which are position-operated and others which are force-operated (isometric or proportional). For example, Brooks [18] simulated a concurrent hybrid joystick in which "the master acts as a springloaded joystick in the X, Y, and Z axes, giving rate commands to the X, Y, and Z axes of the slave proportional to the displacement of the master . . . while the remaining degrees of freedom (rotation, elevation, azimuth)" were controlled in an isotonic (position) mode. Figure 3-3 is another example of such an implementation. The three rotational degrees-of-freedom of the URS/Matrix hand controller are used to isotonically orient the end effector while a pressure sensitive area under the thumb acts as a proportional input to translate the end effector along the hand-pointing axis using rate control.

A sequential implementation, on the other hand, switches between force and position inputs. A simulation of a six degree-of-freedom auto-indexing sequential hybrid joystick was suggested by D. Jelatis in 1977 and implemented by Brooks in 1978 with a master E2 manipulator as the control input. The implementation "allowed a 1:1 isotonic (position) correspondence but only within a small volume of the master's motion; if the operator pushed the master outside that volume, the slave was driven at a rate proportional to how hard the operator pushed" against the force boundary. Once the operator returned to the small operating volume position-operated control resumed automatically [18] (related Refs. 12, 13, 14, 15, 20, 21).

ADVANTAGES

- Small operating volume
- Some proprioceptive and/or configuration feedback as a function of displacement possible (isotonic inputs only)
- Variable control gains
- Potentially anthropomorphic
- Isotonic regions or DOF's reduce operator fatigue

DISADVANTAGES

- Limited or no proprioceptive or configuraion feedback
- Can require high degree of computational logic
- Possible operator disorientation (sequential mode)
- Cross coupling (concurrent mode)
- Possible loss of spatial correspondence

3.7 REPLICA CONTROLLERS

A replica controller in a device which has the same geometric configuration as the controlled manipulator but which is built on a different scale. Hence, there is a direct correspondence between the joint movement of the replica and the teleoperated arm without an actual 1:1 spatial correspondence of the controller handle and the end effector. The replica can be either smaller or larger than the controlled arm (related Refs. 12, 13, 14, 15, 25).

ADVANTAGES

Moderately small operating volume (miniature replicas)
High positional accuracy (oversized replicas)
Can incorporate force feedback
Proprioceptive feedback
Configuration feedback
Can have anthropomorphic attributes
Limited control logic required
Operated by movement of master handle or individual linkages
Can be counterbalanced

DISADVANTAGES

Generally increased operating volume over previously considered controls
Scaled proprioceptive feedback can result in operator disorientation
Possible cross coupling
Human arm limitations (oversized replicas)
Amplification of errors (miniature replicas)
Moderate to high cost
Complex
Require brakes/locks to hold position
Joint-to-joint motion correspondence not readily changed (i.e., indexed) without operator disorientation

3.8 MASTER-SLAVE CONTROLLERS

The master-slave controller is a device which has the same geometric configuration and physical dimensions as the controlled manipulator, as well as a direct 1:1 correspondence between the joint motion of the master and the slave. Hence, a master controller has a 1:1 spatial correspondence with the controlled slave. Generally, master-slave systems are bilateral, i.e., bidirectional master-slave control signals result in the master arm being commanded by the slave to push back on the operator by an amount proportional to that which the slave is being pushed by the operator through the master (force feedback). However, master-slave systems may also be unilateral, i.e., master to slave control only (no force feedback).

Figure 3-7 shows a state-of-the-art bilateral master-slave system manufactured by Central Research Labs (related Refs. 12, 13, 14, 15, 18, 26 through 40).

ADVANTAGES

Can incorporate force feedback
Proprioceptive feedback
Configuration feedback
Anthropomorphic characteristics
Operated by master handle or individual linkages
Limited control logic required

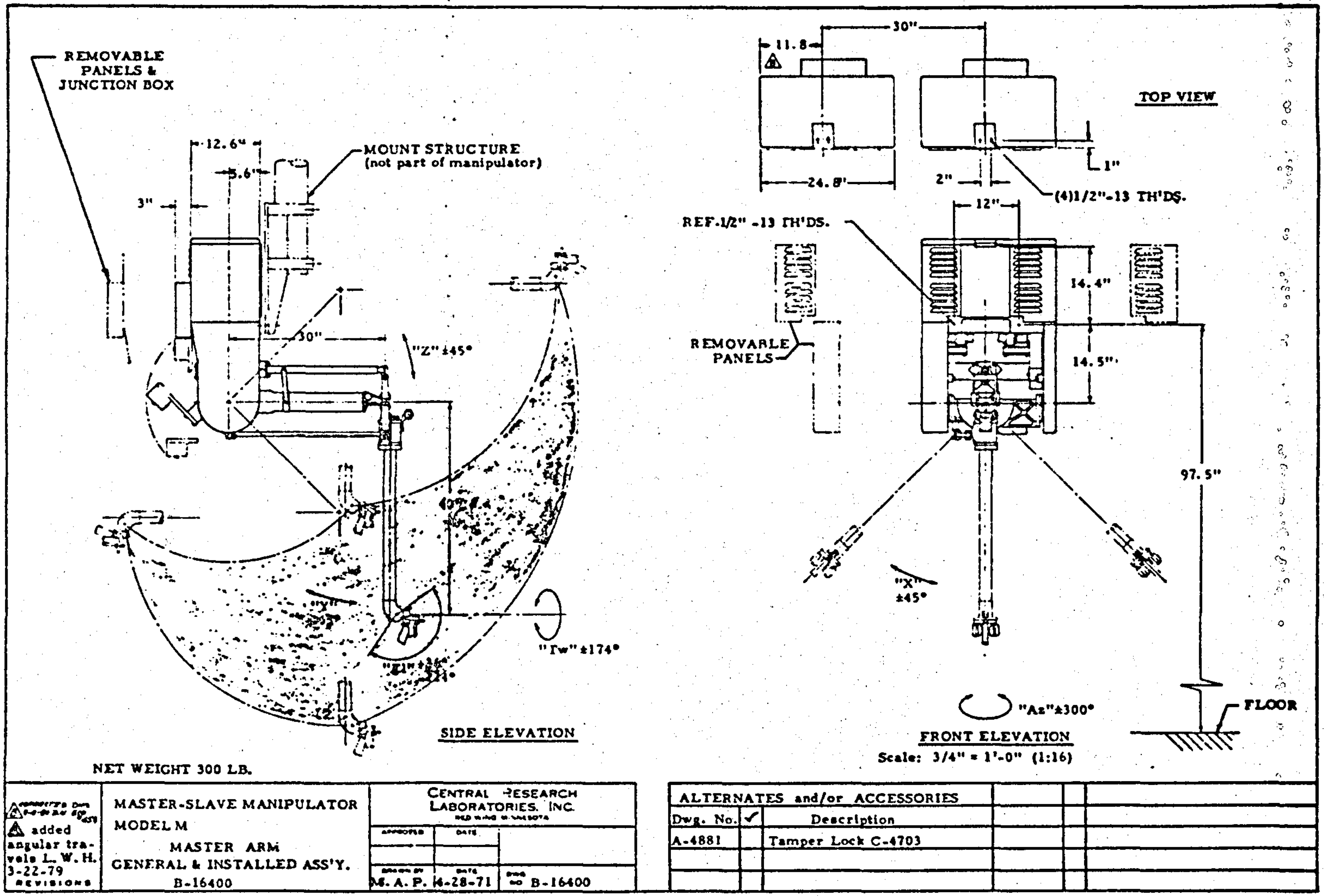


Figure 3-7. Central Research Labs' Model M Master-Slave Manipulator

"Natural" control
Reduced operator workload
Reduced probability of error
Can be counterbalanced

DISADVANTAGES

Large operating volume
Possible cross coupling
Human arm limitations (reach, rotation, configuration)
Moderate to high cost
Complex
Require brakes/locks to hold position without operator fatigue
Interference with control/display access

3.9 ANTHROPOMORPHIC CONTROLLERS

An anthropomorphic controller is a device which derives the manipulator control signals from the configuration of the human arm. The device may or may not have a geometric correspondence with the controlled manipulator. However, when a geometric correspondence does exist, anthropomorphic controllers have the added advantage that they provide direct configuration feedback to the opera- tor through his arm. Properly designed anthropomorphic controllers can control as many as seven independent degrees-of-freedom (excluding gripping actions) corresponding to the seven degrees-of-freedom of the human arm (3 shoulder, 1 elbow, and 3 wrist). Figure 3-8 shows an anthropomorphic exo-skeleton controller (related Refs. 12, 13, 14, 15, 40, 41, 42, 43, 44).

ADVANTAGES

Anthropomorphic (approaching telepresence)
Direct proprioceptive feedback
Direct configuration feedback possible
Motion and spatial correspondence can be achieved
Can incorporate force feedback
Natural human motions
Reduced learning time
Limited control logic required
Reduced cognitive workload on operator

DISADVANTAGES

Human arm limitations (reach, rotation, configuration)
Can be unwieldy and restrictive
Can increase physical workload on operator if he must support controller's weight
Moderate to high cost
Complex
Require brakes/locks to hold position without operator fatigue
Interference with control/display access
Safety hazards

Figure 3-8. Ames Anthropomorphic Exoskeleton Controller and Geometrically Similar Slave [41]

Slave manipulator in direct joint-to-joint applications must have anthropomorphic characteristics
Difficult to counterbalance

3.10 NONGEOMETRIC ANALOGIC CONTROLLERS

A nongeometric analogic controller is a device which does not have the same geometric configuration as the controlled manipulator, but which maintains joint-to-joint or spatial correspondence between the controller and slave. These devices generally take advantage of the spatial correspondence which can be achieved over limited regions of the dissimilar controller and arm workspace (see Figure 3-9(a) for example). However, a few controllers have been coupled to the slave arm through control circuits which resolve the controller motion into the desired manipulator motion [12] (see Figure 3-9(b) for example). Typically, a nongeometric controller is used when the general characteristics of a master-slave manipulator are desired, but where overriding design constraints, such as available controller volume, mounting location, etc., preclude the use of that option (related Refs. 12, 13, 14, 15, 43, 44).

ADVANTAGES

Moderate size operating volume
Can incorporate force feedback
Can have anthropomorphic attributes
Joint correspondence with slave can be achieved*
Proprioceptive feedback possible
Can be counterbalanced

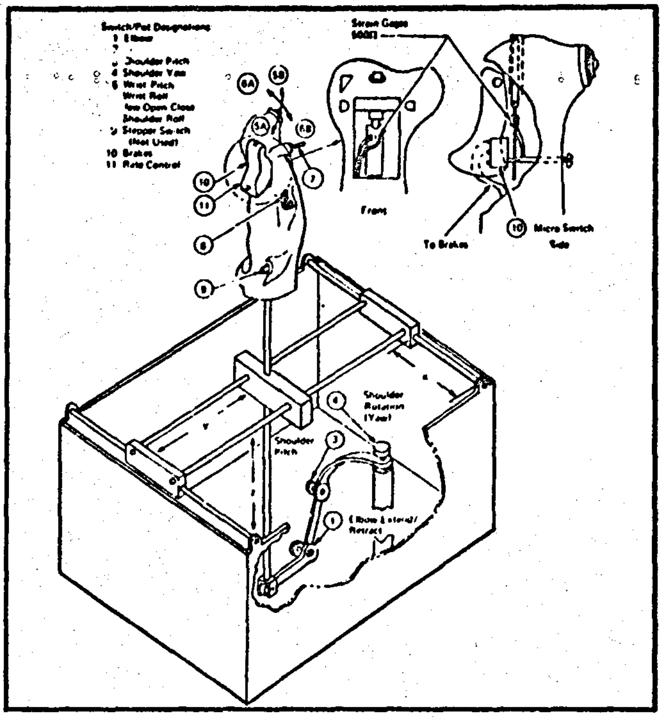
DISADVANTAGES

Spatial correspondence (i.e., proprioception) typically occurs over a limited range of the device
Gimbal lock/singularities frequently occur
Output of controller can be nonlinear
Requires unique mechanical or electrical design to achieve geometric coupling
Limited or no configuration feedback
Cross coupling
Response characteristics of controller (friction, actuation, force, etc.) can be nonlinear
Complex
Moderate to high cost

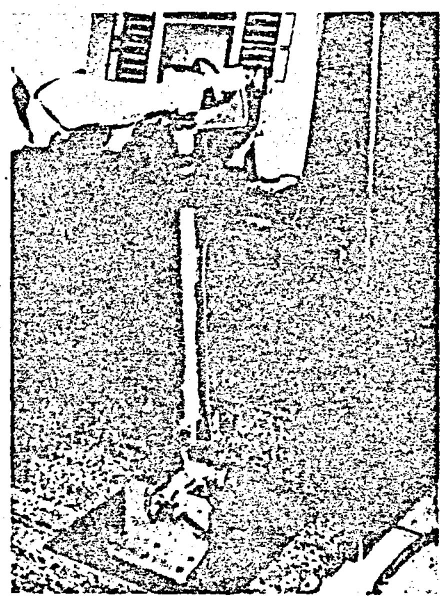
3.11 UNIVERSAL FORCE-REFLECTING HAND CONTROLLERS

A universal force-reflecting hand controller is a six degree-of-freedom control device which, through computational logic, is capable of controlling the end effector of any geometrically dissimilar manipulator.

*Joint correspondence does not result in configuration feedback, since link geometry between controller and slave are different.



(a) Marshall Space Flight Center's Analogic Controller Concept [44, 61]



(b) Martin Marietta's Nongeometric Analogic Controller Which Electronically Resolves Operator Commands Into Desired Spatial Slave Motion [12]

Figure 3-9. Nongeometric Analogic Controllers

Additionally, the device can command a manipulator with greater than six degrees-of-freedom provided the computation logic specifies the redundant degrees-of-freedom according to some criteria. The device is essentially a large volume joystick, except that it can be endowed through the computational machinery with isotonic, isometric, proportional, and hybrid characteristics without modifying the device itself. The universal controller evolved naturally from the nongeometric controller concept. In fact, the nongeometric controller shown in Figure 3-9(b) would be considered a universal controller except that the computational logic consisted of analog circuits, thus limiting the versatility of the device. Figure 3-10 shows a universal force-reflecting hand controller at the JPL teleoperator laboratory (related Refs. 12, 13, 14, 15, 45, 46).

ADVANTAGES

- Versatility
- Moderate size control volume yet sufficient for spatial-position feedback
- Isotonic, isometric, proportional, and hybrid controller characteristics easily generated
- Motion and spatial correspondence
- Proprioceptive feedback
- Human arm limitations never exceeded
- Can be integrated into system without control/display interference
- Force feedback can be incorporated
- Can be counterbalanced mechanically or electronically
- "Natural" control
- Position-hold brakes can be achieved by computer

DISADVANTAGES

- Absolute proprioceptive feedback can be absent
- Limited or no configuration feedback
- Interface transparency limited by large controller inertia if mechanically counterbalanced
- High degree of computational machinery necessary
- Moderate to high cost
- State-of-the-art not well developed

3.12 UNIVERSAL FLOATING-HANDLE CONTROLLERS

A completely nongeometric six-degree-of-freedom control device, without joints or linkages, which is used for controlling the slave end effector in hand-referenced control. As with the universal control stick, the floating-handle controller can control more than six degrees-of-freedom and simulate isotonic, isometric, proportional, and hybrid controllers through appropriate computational techniques. A unilateral controller could conceivably be built which consists simply of a palm-sized handle with no physical attachments to the control environment (e.g., handle position might be determined by signals emitted from the handle). However, to achieve bilateral control it is necessary to provide mechanical connections to handle. Figure 3-11 shows a concept developed at the University of Florida which is

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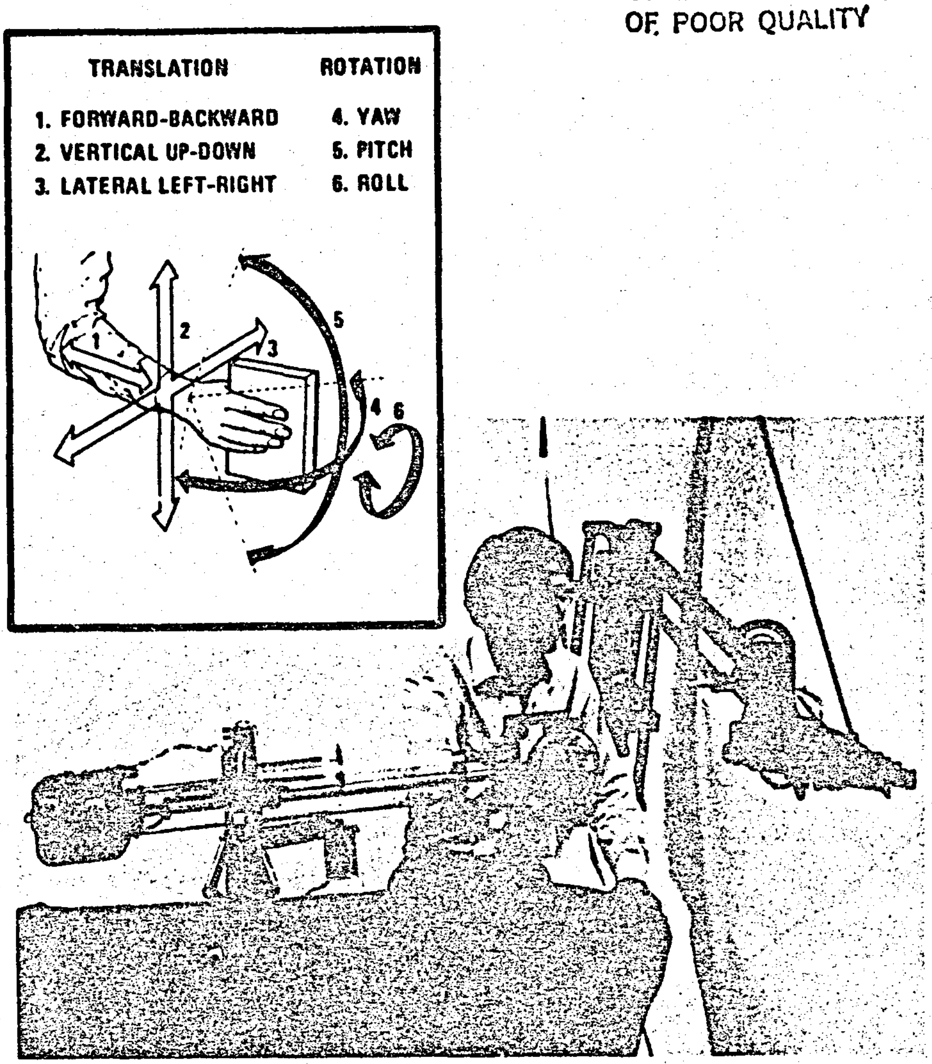

Figure 3-10. Six Degree-of-Freedom Universal Force-Reflecting Hand Controller at JPL [45]

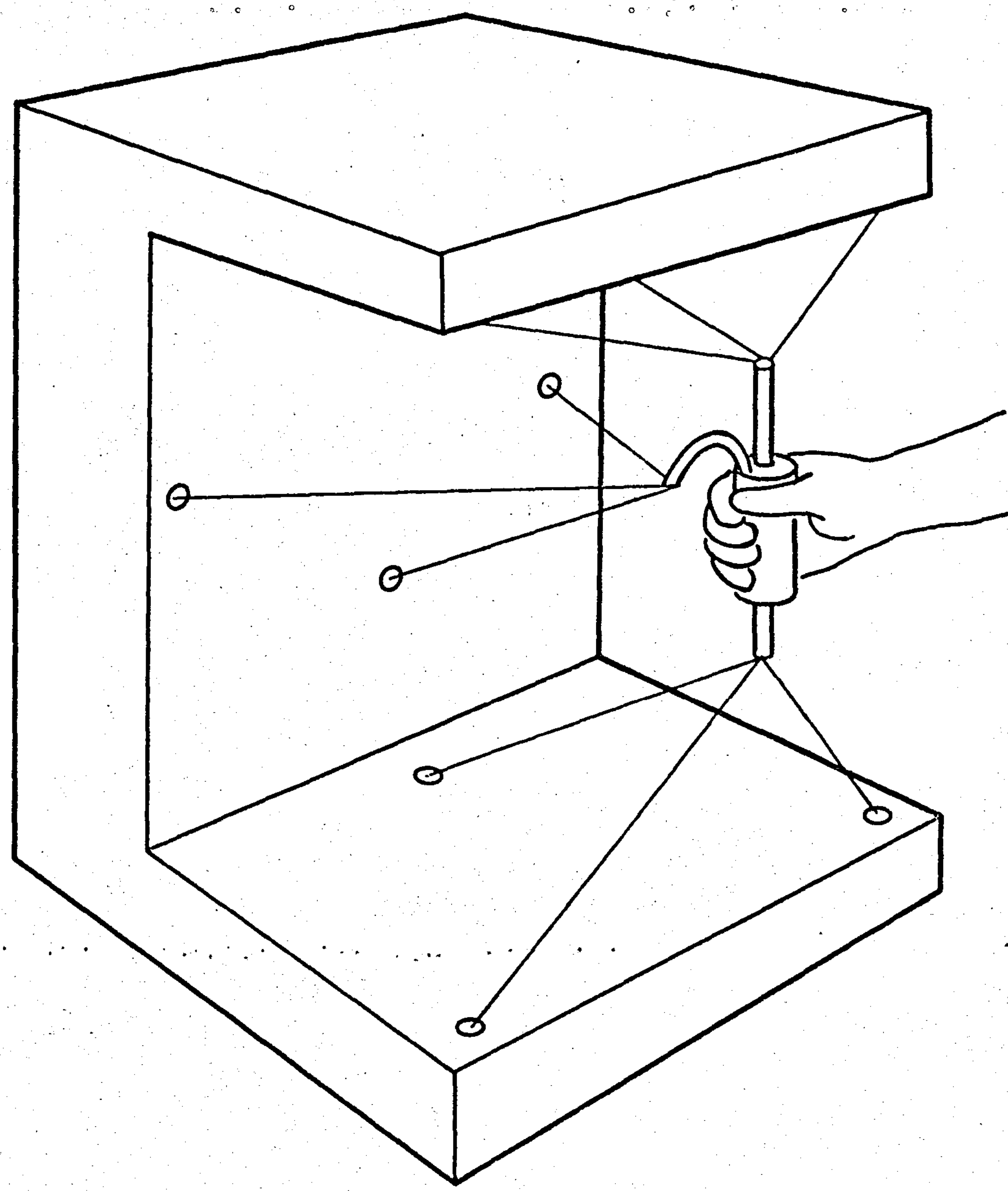

Figure 3-11. University of Flordia Universal Floating-Handle Controller [13]

capable of bilateral control (note -- the UF device does not at present have bilateral control) (related Refs. 13, 47, 48).

ADVANTAGES

- Versatility
- Moderate size control volume, yet sufficient for spatial-position feedback
- Isotonic, isometric, proportional, and hybrid controller characteristics can be generated
- Motion and spatial correspondence
- Proprioceptive feedback
- Human arm limitations never exceeded
- Force feedback easily incorporated
- Can be counterbalanced electronically
- "Natural" control
- Position-hold brakes can be achieved through computer
- Mechanical design simple
- Moderate cost

DISADVANTAGES

- Absolute proprioceptive feedback can be absent
- No configuration feedback
- Possible interference of strings (signals) and handle
- Limited rotation of handle
- Requires 9 degrees-of-freedom to unambiguously specify six spatial degrees-of-freedom
- High degree of computational machinery necessary
- Support frame could interfere with control/display interface
- State-of-the-art not well developed

3.13 HAND-CONTROLLER COMPARISON

A great variety of hand controllers based on the concepts outlined in the previous sections have been developed with a specific set of performance characteristics in mind. The foldout chart on the following page presents the more important performance characteristics in a column format to allow direct comparison between controllers.

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(A) Complicated analog circuits are typically used to achieve the desired slave motion.
(B) Higher potential exists with poor design.
(C) Data not available. Ratings extrapolated from common experience, but unsupportable.
(D) Inertia, friction, force feedback level, and balance of controller, which are design specific, contribute to this rating.

PT - Performance Time
ER - Error Rate
DOM - Direction of Movement
FFB - Force Feedback
PW - Physical Workload
CW - Cognitive Workload
DOF - Degree-of-Freedom

Control Device and Technique	Evaluation Criteria	Performance										
		Task Performance Time and Error Rate	Slave Configuration Feedback	Force Feedback	Controller/Slave Correspondence	Operating Volume	Operator Workload	Human Arm Limitations	Cross Coupling DOF	Singular Controller Configurations	Anthropomorphic "Naturalness"	Control Device Physical Complexit
Switches (-/off/+)	DRC	Poorest PT	None	No	Joint-to-Joint DOM only	Minimal	Very High CW Minimal PW	Operator cannot easily control more than 4 DOF's with both hands simultaneously	None	No	None	Very Minimal
	RRC	High ER			Spatial DOM only		High to Very High CW Minimal PW					
Potentiometers	DRC	Poorest PT	None	No	Joint-to-Joint DOM only	Small	Minimal PW; Very High CW	Operator cannot easily control more than 2 DOF's with both hands simultaneously	None	No	None	Very Minimal
	RRC				Spatial DOM only		High to Very High CW					
	DUPC	High ER	Indirect through pot position		Joint-to-Joint spatial limited regions only		Very High CW					
	RUPC		None		Spatial 1 DOF per pot		Moderate to Very High CW					
Isotonic Joystick	DRC	Fair-Good PT	None	No	Joint-to-Joint DOM only	Small	Minimal to Moderate PW (D); High CW	Restricted hand excursions	Potential exists due to ill-defined zero (B)	Generally not a problem (B)	Potential exists	Minimal
	RRC				Spatial DOM only		Moderate CW					
	DUPC		Fair-Good		Joint-to-Joint							
	RUPC	Modest ER	None		Spatial			Peculiar wrist positions				
	DBPC		Fair-Good	Yes	Joint-to-Joint							Moderat
	RBPC		None		Spatial							
Isometric Joystick	DRC	Poor PT	None	No	Spatial DOF to slave-joint DOF DOM only	Minimal	Moderate to High PW; High CW	Continuous low-level force requirements not compatible with ballistic nature of human arm	High	No	Minimal	Modest
	RRC	Very High ER			Spatial DOF-to-DOF DOM only		Moderate CW					
Proportional Joystick	DRC	Poor PT	None	No	Joint-to-Joint DOM only	Small	Moderate PW (D); High CW	Generally not a problem (B)	Minimal (B)	Generally not a problem (B)	Modest	Modest
	RRC				DOF-to-DOF DOM only		Moderate CW					
	DUPC	Very High ER	Poor-Fair		Joint-to-Joint							
	RUPC				DOF-to-DOF							
Hybrid Joystick	Control technique can be a mixture of available methods	Function of Design and Specific Hybrid Components Used										
Replica	DUPC	Fair PT	Visual Fair to Good	No	Joint-to-Joint scaled spatial DOF-to-DOF (scale factor fixed by size of replica)	Small to Large	Minimal to Moderate CW; Modest PW (D)	Smallest achievable movement by operator may not be sufficient with miniature replica	Minimal (B)	Yes (B)	Modest to good depending on magnitude of scale factor	Moderate
	DBPC	Modest ER (C)		Joint-to-Joint FFB			Moderate PW (D)					Moderate to Very
Master-Slave	DUPC	Good PT Low ER	Visual Very Good	No	Joint-to-Joint and spatial DOF-to-DOF over entire range	Very Large	Minimal CW; Modest PW (D)	Generally not a problem (B)	Minimal (B)	Yes (B)	Very good	Moderate
	DBPC	Best PT Lowest ER		Joint-to-Joint FFB			Moderate PW (D)					Moderate to Very Hi
Anthropomorphic	DUPC	Fair-Good PT Modest-Low ER	Excellent Direct to Human Arm	No	Joint-to-Joint with spatial DOF-to-DOF if slave arm has similar geometric configuration	Large	Minimal CW; Modest to Very High PW (D)	Slave restricted to movements which can be achieved by human arm	Minimal (B)	Yes (B)	Excellent most natural	Modrate to High
	DBPC	Good-Best PT Low-Lowest ER		Joint-to-Joint FFB								Moderate to Very High
Nongeometric Analogic	DUPC	Poor-Fair PT	Limited	No	Joint-to-Joint with spatial DOF-to-DOF over limited regions	Moderate	Minimal to Moderate CW; Moderate PW (D)	Restricted hand excursions (B)	Minimal to high (B)	Yes (B)	Minimal to good depending on design	High
	DBPC	Modest-High ER (C)		Typically nonlinear Joint-to-Joint FFB								Very Hi
Universal Force-Reflecting	RUPC	Task Performance Data Unavailable TBD	None	No	Spatial only	Moderate	Minimal CW; Modest PW (D)	Generally not a problem (B)	Minimal (B)	Yes (B)	Very good	Moderate
	RBPC			Spatial DOF-to-DOF FFB			Moderate PW (D)					Very Hi
Floating Handle	RUPC	Task Performance Data Unavailable TBD	None	No	Spatial only	Moderate	Minimal CW; Minimal PW (D)	Restricted hand excursions (B)	Minimal (B)	No	Very good	Modest
	RBPC			Spatial DOF-to-DOF FFB			Moderate PW (D)					Moderate

FOLDOUT FRAME

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PT - Performance Time
ER - Error Rate
DOM - Direction of Movement
FFB - Force Feedback
PW - Physical Workload
CW - Cognitive Workload
DOF - Degree-of-Freedom

Control Techniques

DRC - Direct Rate Control
RRC - Resolved Rate Control
DUPC - Direct Unilateral Position Control
RUPC - Resolved Unilateral Position Control
DBPC - Direct Bilateral Position Control
RBPC - Resolved Bilateral Position Control

ormance

	Cross Coupling DOF	Singular Controller Configurations	Anthropomorphic "Naturalness"	Control Device Physical Complexity	Control System Implementation Complexity	Potential for Control/Display Interference	Attainable Accuracy	Availability	Cost	Reliability
	None	No	None	Very Minimal	Very Minimal Modest	Very Minimal	Potentially infinite limited only by slave arm stiction, backlash, etc.	OTS	Minimal	Very High
	None	No	None	Very Minimal	Very Minimal Modest Very Minimal Modest	Minimal	Potentially infinite limited only by slave arm stiction, backlash, etc. Resolution of potentiometer	OTS	Minimal	Very High
	Potential exists due to ill-defined zero B	Generally not a problem B	Potential exists	Minimal Moderate	Minimal Modest Minimal Modest Moderate High	Moderate	Potentially infinite limited only by slave arm stiction, backlash, etc. Resolution of joystick times scale factor	TRA Some OTS SOTA	Modest Moderate to High	High
	High	No	Minimal	Modest	Modest Moderate	Modest	Potentially infinite limited only by slave arm stiction, backlash, etc.	TRA Some OTS	Moderate	Fair
	Minimal B	Generally not a problem B	Modest	Modest	Minimal Modest Minimal Modest	Moderate	Potentially infinite limited only by slave arm stiction, backlash, etc. Resolution of joystick times scale factor	TRA Some OTS	Minimal to Moderate	High
cific Hybrid Components Used								TRA	Modest to High	Fair to High
	Minimal B	Yes B	Modest to good depending on magnitude of scale factor	Moderate Moderate to Very High	Modest High	Moderate with miniature versions Moderate to very high with oversized versions	Resolution of replica times slave-to-replica scale factor	TRA	Modest Moderate to High	Good
	Minimal B	Yes B	Very good	Moderate Moderate to Very High	Modest High	High to very high	Resolution of master	OTS	Moderate Moderate to High	Good
ted	Minimal B	Yes B	Excellent most natural	Moderate to High Moderate to Very High	Modest High	Modest to high little more than normal interference due to human arm	Resolution of controller times slave-to-controller scale factor	TRA	Moderate Moderate to High	Good
	Minimal to high B	Yes B	Minimal to good depending on design	High Very High	High A Very High A	Modest to high	Resolution of controller times nonlinear scale factor	TRA	Moderate to High	Fair to Good
	Minimal B	Yes B	Very good	Moderate Very High	High Very High	Modest to high	Near infinite resolution by virtue of adjustable scale factor	R&D	Moderate High	Good? TBD
	Minimal B	No	Very good	Modest Moderate	High Very High	Moderate to very high	Near infinite resolution by virtue of adjustable scale factor	R&D	Modest Moderate to High	High? TBD

Table 3-1. Comparison of Hand Controllers

2 FOLDOUT FRAME

SECTION 4

TELEOPERATION CONTROL STRATEGIES

This section surveys available techniques by which the hand controllers surveyed in Section 3 can be coupled to a remote arm. This section will not consider specific servo controls, but only general manipulator-control strategies (e.g., position control is a manipulator-control technique which can be implemented by a number of servo controls such as proportional, pseudo-derivative, PID, etc.). The strategies are also called "control modes." Although a number of control techniques have been suggested or implemented in the past, this state-of-the-art review will only consider the more successful methods for teleoperator control:

- Rate control
  - Direct
  - Resolved
- Unilateral position control
  - Direct
  - Resolved
- Bilateral position control
  - Direct
  - Resolved
- Operator aiding control
  - Filtering
  - Scaling
  - Rereferencing
    - Controller
    - Control coordinates
  - Motion constraints
  - Motion compensation

Many of the advantages and disadvantages cited in the literature for these techniques are usually a function of the control device normally associated with the technique more than the control technique itself. Therefore, since the controller is for the most part independent of the control mode, this section will only consider the characteristics of the control mode and not the control device, which has been considered separately in Section 3.

4.1 DIRECT RATE CONTROL

Direct rate control occurs when the controller output is relayed directly to the manipulator servos where it is interpreted as an actuator velocity command. The controller degrees-of-freedom typically have a one-to-one correspondence with the manipulator degrees-of-freedom. The commanded velocities can be either preset or continuously variable, depending on the controller used (Refs. 1, 12, 13, 14, 15, 16).

ADVANTAGES

A small controller motion can cover large workspace accurately
Accuracy of manipulator positioning not dependent on joint resolution
Simple implementation

DISADVANTAGES

Operator must mentally coordinate his input commands to obtain desired end effector motion
Generally not compatible with force feedback
End-effector location must be obtained visually or through mental integration of controller action (a near-impossible task)

4.2 RESOLVED RATE CONTROL

Under resolved rate the controller output is interpreted by a computer as velocity commands in a convenient coordinate frame (e.g., the commands can be referenced with respect to the manipulator base, the end effector, or a convenient frame within a grasped object). To achieve the desired end-effector motion the computer transforms the controller output signal into the necessary joint velocities through an incremental transformation, such as a Jacobian or Newton-Raphson technique. Typically, each controller degree-of-freedom corresponds to one spatial degree-of-freedom. As with direct rate, the commanded velocities can be preset or continuously variable, depending on the controller used (related Refs. 13, 17, 20, 22, 23, 25, 49 through 54).

ADVANTAGES

Choice of control coordinate frame
Relieves operator burden of coordinating joint activation
Linear or nonlinear gains can be employed
Small control motion can cover large workspaces accurately
Accuracy of manipulator positioning not dependent on arm resolution
Allows operator to think in hand coordinates avoiding loss of spatial correspondence in unfamiliar viewing conditions

DISADVANTAGES

End-effector location must be obtained visually or through mental integration of controller action
Moderate to high degree of computation necessary
Generally not compatible with force feedback

4.3 DIRECT UNILATERAL POSITION CONTROL

Under this control technique, the controller output is relayed directly to the manipulator servo, where the signal is interpreted as the desired joint rotation. The controller degrees-of-freedom typically correspond on a one-to-one basis with the manipulator degrees-of-freedom (related Refs. 12, 13, 14, 15, 25, 41, 55).

ADVANTAGES

- Controller input corresponds to desired position of actuator
- Simple implementation

DISADVANTAGES

- Requires high-resolution position sensors on both controller and slave for electro-mechanical systems
- Spatial correspondence dependent on controller and manipulator configuration
- No force feedback
- Operator inputs can exceed the maximum velocity of arm
- End-effector control frame cannot be specified
- Limited use of scaling (see section 4.8)

4.4 RESOLVED UNILATERAL POSITION CONTROL

Under this control scheme, controller output is interpreted by a computer as the desired spatial position and/or orientation of a convenient coordinate frame attached to the manipulator (e.g., the end effector or payload). The computer converts the measured controller signals into the equivalent Cartesian spatial movement of the operator's hand, transforms the movement to the coordinate frame at the slave control point, and kinematically solves for the required joint commands. Typically, one controller degree-of-freedom corresponds to one spatial degree-of-freedom (related Refs. 13, 45, 46, 47, 48, 50, 51, 55).

ADVANTAGES

- Choice of control coordinate frame
- Spatial correspondence can be achieved regardless of controller design
- Motion scaling can be incorporated

DISADVANTAGES

- Moderate to high degree of computation necessary
- Since controller configuration is not required to be the same as the arm configuration, configuration feedback may not be available
- Requires high resolution position sensors on both controller and slave
- No force feedback
- Operator inputs can exceed the maximum velocity of arm

4.5 DIRECT BILATERAL POSITION CONTROL

Under this control scheme, the controller output is relayed directly to the manipulator servo where the signal is interpreted as a desired joint rotation. Simultaneously the arm's actual joint position is sent directly to the hand-controller servo where it is interpreted as the required controller position. This bidirectional control results in force reflection in the hand controller and force generation in the slave arm when the controller and manipulator are in disparate positions (related Refs. 12, 13, 14, 15, 18, 26 through 40). Figure 4-1 is a block diagram illustrating the implementation of direct bilateral position control at MIT [Ref. 18].

ADVANTAGES

Controller input corresponds to desired position of actuator
Simple implementation
Force feedback

DISADVANTAGES

Requires high-resolution position sensors on both controller and slave for electro-mechanical systems
Spatial correspondence dependent on controller and manipulator configuration
Increased controller complexity over unilateral position control
End-effector control frame cannot be specified
Limited use of scaling (see section 4.8)

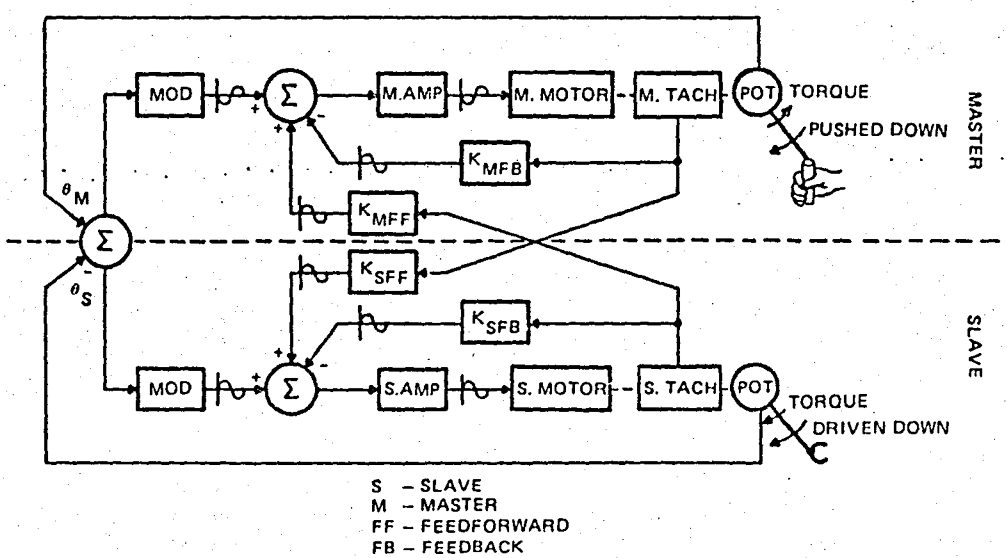

Figure 4-1. Generalized Block Diagram of Direct Bilateral Position Control

4.6 RESOLVED BILATERAL POSITION CONTROL

Under this control scheme, the computer converts controller joint signals to an equivalent Cartesian spatial movement of the operator's hand, transfers the movement to the control-point coordinate frame of the remote manipulator, and solves for the manipulator joint commands necessary to position the arm accordingly. Simultaneously, the computer transforms the position and forces encountered by the remote end effector into hand-controller coordinates and determines the commands necessary to position the hand controller accordingly. As with direct control, this bidirectional control results in force reflection in the hand controller and force generation in the slave arm when the controller and manipulator are in disparate positions.

However, in the case of resolved bilateral position control, the disparate positions are computed in spatial coordinates, not joint coordinates, thus allowing direct spatial scaling of geometry and force ratios. Resolved bilateral control can also be achieved by measuring the forces exerted by the slave directly and then transforming those forces into feedback signals to the controller. Figure 4-2 illustrates such a scheme developed at JPL (related Refs. 45, 46) where:

K_f = stiffness constant
K_v = velocity feedback
J = Jacobian
f = force/torque vector
e = error vector
T_B^A = homogeneous transformation from frame A to B
CURV = controlled remote arm

ADVANTAGES

- Choice of control coordinate frame
- Spatial correspondence can be achieved regardless of controller design
- Motion and force scaling can be easily incorporated

DISADVANTAGES

- High degree of computation necessary
- Since controller configuration is not required to be the same as the arm configuration, configuration feedback may not be available
- Requires high-resolution position sensors on both controller and slave

4.7 FILTERING

Filtering is a "process in which extraneous motion that is superimposed upon the control signal by the operator is detected and subsequently deleted" [13]. Filtering can be particularly advantageous when a miniature replica is being used.

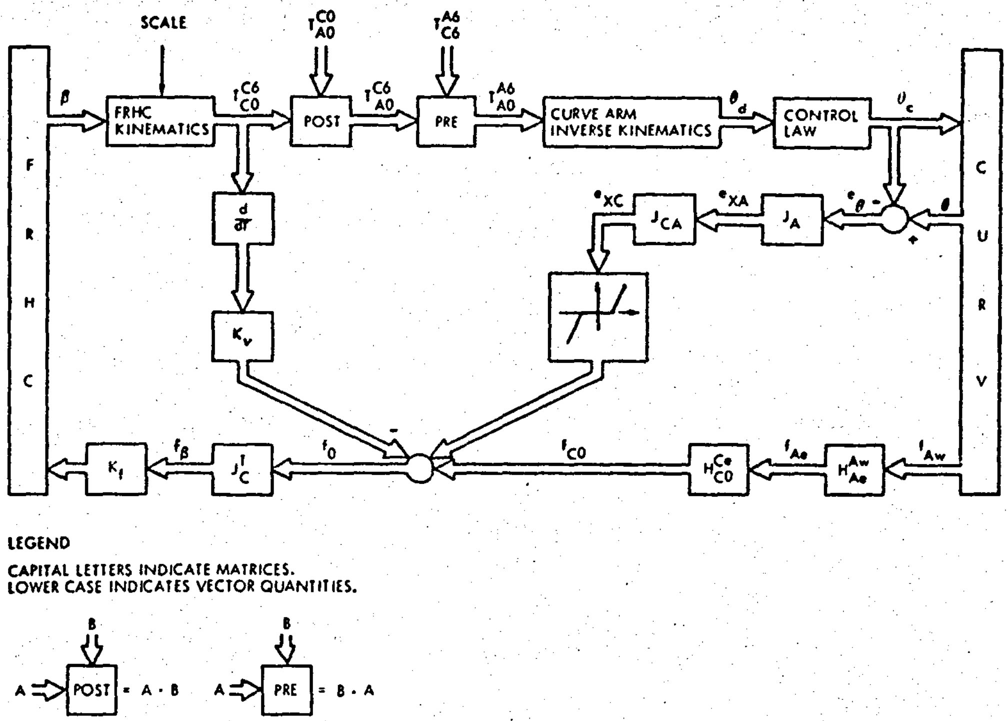

Figure 4-2. Force Reflecting Hand Controller (FRHC) Multi-Axis Control Strategy

ADVANTAGES

- Removes unwanted control signals
- Smooths operator inputs

DISADVANTAGES

- May remove desirable control signals
- Can introduce phase errors
- Moderate to high degree of computation depending on filter scheme

4.8 SCALING

Scaling is a control aid in which the geometric gain between the controller and manipulator can be varied. A gain of greater than one allows a controller to perform gross motions over a workspace which is larger than the control space. Conversely, a gain of less than one allows the same controller to perform precision motions with greater accuracy than achievable with the unaided human hand (assuming, of course, that the slave resolution is capable of this accuracy).

ADVANTAGES

Single controller can perform both gross and precision movements in limited control volume

DISADVANTAGES

Probability of operator error increased at high gains
Extraneous input during high gain requires filter
Resolution of slave must be at least that of controller resolution times the lowest gain
Direct position control can only use scaling over limited regions without loss of spatial correspondence

4.9 CONTROLLER REREFERENCING

Controller rereferencing is a control strategy in which the operator can rereference the control device with respect to the control coordinates. One form of this technique maintains the control device and its movements within an optimum volume to insure that the operator can "assume a comfortable and stable configuration for his arm" [13]. This form of rereferencing is sometimes called indexing. Another form of controller rereferencing allows the operator to change the spatial relationship of the controller while maintaining consistent control coordinates. This technique is used, for example, with the JPL universal force-reflecting hand controller to change between a horizontal table mounting and a vertical chair mounting configuration. It has also been suggested that this technique could be used to reorient the control-display relationship when switching between two or more cameras [13, 56].

ADVANTAGES

Operator can work in physically- and mentally-convenient coordinates

DISADVANTAGES

Discontinuity in control during change
Operator may lose spatial correspondence
Operator may experience conceptual difficulty in switching between different coordinate systems

4.10 CONTROL COORDINATE REREFERENCING

Control coordinate rereferencing is a control strategy in which the operator can change the control coordinate location. For example, this technique is being used in the shuttle system to allow changes between payload, end-effector, and orbiter-located control coordinates [Refs. 13, 17, 49 through 54, 56].

ADVANTAGES

Operator can work in mentally-convenient control coordinates
Can simplify tasks by working in natural coordinates

DISADVANTAGES

Can only be used with resolved control techniques
Moderate computational requirements
Provision must be made for unique specification of desired control frame

4.11 MOTION CONSTRAINTS

Motion constraints place artificial constraints on the manipulator to either improve control or protect the system. Motion constraints can be based on a model of the environment, directly-sensed data, or both. Force accommodation [22, 57] is an example in which control is improved through adaptive motion constraint based on the forces and torques sensed at the end effector (related Refs. 13, 22, 56, 57, 58).

ADVANTAGES

Improved control
Overall system protection
Partially relieves operator concern for system protection
Simplifies operator inputs

DISADVANTAGES

Can require high degree of computation
Can require a priori knowledge of environment

4.12 COMPENSATION TECHNIQUES

Compensation techniques are a group of control strategies in which the dynamic effects of the controller, manipulator, or task are removed or compensated for to prevent burdening the operator and to improve control. For example, a force/torque sensor could be mounted on the controller handle and the measured operator force inputs could be used to compensate for controller inertia and friction effects. Another example of compensation is a control system which tracks the motion of a moving task and superimposes that motion on the control signals, effecively "freezing" the end effector in task coordinates. Hence, although the manipulator base and task are continuously moving relative to one another, the end effector remains stationery with respect to the task unless commanded to move by the operator [59, 60]. Other candidates for compensation include arm dynamics, coupling, gravity, drift, nonlinear actuator characteristics, etc. (related Refs. 13, 14, 18, 56, 59, 60).

ADVANTAGES

Unwanted effects can be removed from the system

DISADVANTAGES

Can require high degree of computation
Undesired effect must be understood well enough to be compensated
Possible danger of compensating important data

SECTION 5

OBSERVATIONS AND CONCLUSIONS

5.1 HAND-GRIP OBSERVATIONS

In Section 2, we reviewed control-handle concepts and found that although there are a number of interesting possibilities, only the finger-trigger control handle appears to meet the requirements of trigger control without cross coupling, firm grip surface for good spatial control, and simultaneous secondary function control independent of trigger and manipulator degrees-of-freedom. If the requirement for simultanteous multi-function secondary switch control is dropped, a number of other designs showed clear promise: (1) the nuclear industry standard, (2) the grip ball, (3) the T-bar handle, (4) the glove, (5) the door handle design, and (6) the aircraft gun-type handle. The glove design must be rejected, however, due to the lack of available technology. Other variations on the basic handle types outlined in Section 2 may form the basis for an acceptable six degree-of-freedom control-handle design.

This survey has revealed a number of unanswered control-handle questions which remain to be studied. (Appendix A contains four proposed experiments designed to answer many of these questions.) The following are representative of these questions:

1) Is there a trigger shape and location on the handle which is "optimal" for both static and dynamic conditions?

2) Will one trigger design be sufficient for all tasks, or should the trigger be changed for different tasks?

3) Should one finger or two be used for trigger control? One may fatigue faster, but two could mean less spatial control.

4) If it is assumed that all secondary functions are voice controlled, is the thumb better than the index finger for trigger control?

5) Is the effect of cross coupling under time and psychological stress greater for thumb triggers or finger triggers?

6) What is the optimal force feedback level for finger-controlled versus thumb-controlled triggers?

7) Which results in better resolution, finger or thumb triggers?

8) It is predicted that the thumb's lateral dexterity would make it a better candidate than the index finger for multiple secondary function control. Is this true?

9) What are the changes in position and force resolution under static versus dynamic conditions?

10) How does a zero-gravity environment affect trigger control?

5.2 CONTROL INPUT DEVICE OBSERVATIONS

Control input devices were surveyed in Section 3. Although specific conclusions or recommendations were not derived, a few generalizations can be made.

All of the control devices appear to have their merits and weaknesses under the right conditions and, hence, one input device cannot be recommended as a panacea for all manipulator control problems. For example, even the simple switch controls find use in the cramped quarters of research submersibles like ALVIN at Woods Hole, Massachusetts. However, in the specific case of teleoperation from earth or a space station, few of the controllers appear to have clear advantages. Specifically, master-slave, anthropomorphic, and universal controllers offer the advantages of "natural" control with force and proprioceptive feedback, reduced operator workload, quick training, and reduced probability of errors. The primary differences between the three being that master-slave controllers have configuration feedback but may lack in anthropomorphism and compactness; anthropomorphic controllers are anthropomorphic but lack compactness and versatility and may encumber the operator; and universal controllers are versatile and compact but lack direct anthropomophism and configuration feedback. It is also interesting to note that a master-slave controller can mimic all the features of a universal controller except compactness with the correct software (see Brooks [Ref. 18] for example), but a universal controller cannot be made to mimic the master-slave's direct kinematic configuration feedback.

There are a number of input device questions remaining to be answered:

1) Given the limited space available for the manipulator controller, a universal controller would appear to offer most of the advantages of a master-slave without the associated control volume. When using a universal controller, can visual configuration feedback compensate for or equal that of the master-slave?

2) Assuming configuration feedback can be obtained visually, is there any significant differences between a universal versus a master-slave controller, other than operating volume?

3) Is there an optimal operational volume for a universal controller if one does not consider volume limitations? Is the optimal operational volume smaller than that required for a master-slave controller?

4) Current space shuttle systems use rate control with separate rotational and translational joysticks to alleviate cross coupling between wrist and large motion degrees of freedom. Is there truly an advantage to independent joysticks over a single-handed six-axis controller such as shown in Figure 3-6?

5) Can a kinematic and dynamic model of the coupled human hand and controller be used to predict "optimal" controller designs?

6) At the simplest level, a nongeometric analogic controller can be defined as using one nonlinear device to control another kinematically different nonlinear device. An interesting kinematic question can be posed: Is there a mathematical method by which two different nonlinear arms can be synthesized which can directly position control each other over a large work volume with no apparent disparity?

5.3 TELEOPERATION CONTROL STRATEGY OBSERVATIONS

The control techniques surveyed in Section 4 represent the most commonly used methods of teleoperator control, but are by no means an exhaustive list. In particular, one area which is conspicuously missing is that of traded supervisory control (i.e., control which is traded from man-to-machine and back again [Ref. 61]). Only forms of shared supervisory control (shared functions by man and machine) have been included since this report deals specifically with manual control. For a survey of supervisory control techniques see References [61] and [62]. There are many control-technique questions which remain to be resolved:

1) Should a hybrid auto-indexing scheme, in which the universal controller is bilateral position controlled over a limited range and resolved rate controlled at the extremes, be used to allow slave-arm indexing over large operational volumes? Or should the control mode simply be selected directly as the task conditions demand?

2) In order for bilateral control to represent a true "picture" of the force/torque state encountered by the remote manipulator, the controller feedback to the human operator must have a minimum stiffness. For example, touching a solid object will not be conveyed as solid if the control loop presents it to the operator as a spongy surface due to insufficient servo stiffness. What is the minimum control-loop stiffness which is acceptable for routine teleoperation in space?

3) A motion compensation technique, as suggested by Brooks [Refs. 18, 59, 60], would allow the operator to manipulate a moving task in apparently stationary coordinates while the teleoperator system automatically adjusted for the task movement. As long as the forces exerted on the task by the teleoperator system were small compared to the inertial properties of the task, motion compensation and station keeping should be practical. If the task requires significant reactive forces, however, motion compensation could quickly become an unstable, double-mass, coupled spring oscillator (particularly in space applications). Considering the complicated structural configuration of the task and teleoperator systems, can a model predict the total task-teloperator system behavior? Could this model be used to then restabilize the system after repairs were completed?

APPENDIX A

SUGGESTED HAND-GRIP EXPERIMENTS

This Appendix suggests a number of simple experiments directed toward resolving many of the unknowns uncovered in this search. The experiments make no claim to be all-inclusive determinants — merely an incipient effort to develop empirical design rules for space-teleoperator controllers.

A.1 SUGGESTED HAND-GRIP EXPERIMENTS

The objective of these experiments is to determine a handle and trigger configuration which enhances operator performance of six degrees-of-freedom manipulation systems, for both static as well as dynamic task conditions. Parameters such as cross coupling of the trigger with the spatial degrees of freedom of the arm (and vice versa) must be investigated to develop an appropriate handle/trigger design. Factors such as operator fatigue, maximum trigger force, gripping resolution, "naturalness" of the gripping action, and kinesthetic/proprioceptive considerations must be taken into account in the basic design. To this end, four experimental procedures are proposed for the purpose of determining an optimal handle/trigger mechanism: (1) compliant test, (2) free-motion test, (3) tracking test, and (4) tracking test with noise. The experimental design should utilize modular components so that multiple-handle designs which plug into a standardized interface can be tested. The standardized interface should consist of a means for transferring mechanical servo/power to the modular handle trigger.

A.1.1 Compliant Test

In this test the subject must maintain a predetermined force on the trigger while complying to a semirandom trajectory generated by the manipulator. The purpose of this test is to determine the operartor's ability to follow (comply with) the manipulator's motion while holding the trigger with a prescribed force.

Objective — The objective of this experiment is to determine the ability of the operator to sense and maintain prescribed trigger forces while complying to seemingly random motions.

Implementation — The subject will be asked to maintain a specified trigger force under static conditions for a period of five minutes. Data relating to the subject's ability to hold the specified force over time will be recorded. After the subject has rested, (s)he will be asked to maintain the same prescribed force while simultaneously complying to the manipulator's motion. The control handle will follow a path which specifically tests the handle controllability under all six degrees of freedom; however, the path will appear to be random to the subject. Data on subject's ability to follow the path will be recorded based on readings from a force/torque sensor at the base of the handle. Trigger force as a function of time and as a function of tracking error will be plotted for analysis.

A.1.2 Free-Motion Test

In this test the subject must hold a prespecified trigger force while moving an unencumbered hand controller in a random motion. This task will help determine the subject's ability to sustain a trigger force while moving in an unconstrained manner.

Objective -- The objective of this experiment is to ascertain the ability of an operator to sense and maintain prescribed trigger forces while moving in an unrestrained and arbitrary manner.

Implementation -- The subject will be asked to maintain a specified force level for five minutes while fatigue data is recorded. Then, after the subject is rested, (s)he will be asked to simply move at random as (s)he sees fit while maintaining a specified force level. The computer will track the subject's motion, looking for specific trajectory legs, such as x motion with yaw and pitch. Dynamic data will be recorded to determine controllability of each handle design during free spatial movement.

A.1.3 Tracking Test

In this test the subject must maintain a predetermined force on the trigger while tracking a moving target. The purpose of this test is to determine the operator's ability to maintain a prescribed force while concentrating on another task.

Objective -- The objective of this experiment is to determine the ability of the operator to sense and maintain prescribed trigger forces while performing a tracking task.

Implementation -- The subject will be asked to maintain a specified force level for five minutes while fatigue data is recorded. Then, after the subject is rested, (s)he will perform a tracking task in which (s)he must maintain a specified force level while tracking a moving target on the screen. The target will move in three dimensions at a minimum and, provided a suitable display can be devised, may have six degrees of freedom. (A stereo display would result in the most meaningful data; however, a mono display of x, y, and z, where z depth is given by object size, will suffice.) Dynamic data will be recorded for the x, y, and z legs of the movement to determine controllability of each handle design in the three degrees of spatial movement. The subjects will be tested under three forms of trigger-force feedback: In the first, the cue will be direct kinesthetic feedback through the trigger; in the second, the force level will be fedback to the subject through a visual display; finally, in the last set of experiments, the feedback will consist of both visual and kinesthetic cues.

A.1.4 Tracking Test With Noise

In this test the subject must maintain a prescribed force on the trigger while tracking a target moving in two degrees of freedom, while simultaneously complying with orthogonal noise impulses placed on the controller.

The purpose of this test is to determine the operator's ability to maintain a prescribed force while simultaneously performing and complying to another task.

Objective -- The objective of this experiment is to determine the ability of the operator to sense and maintain prescribed trigger forces for a given handle while performing a tracking task with superimposed noise.

Implementation -- The subject will be asked to maintain a specified force level for five minutes while fatigue data is recorded. Then, after the subject is rested, (s)he will perform a tracking task in which (s)he must maintain a specified force level while tracking an actual moving target with external noise forces randomly applied to the controller. Data on the subjects ability to track the object and maintain trigger force will be recorded and analyzed.

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16. Abstract

Hand-controller technology for teleoperation is surveyed in three major categories: (1) hand-grip design, (2) control input devices, and (3) control strategies. In the first category, 14 hand-grip designs are reviewed and evaluated in light of human factor considerations. In the second, 12 hand-controller input devices are evaluated in terms of task performance, configuration and force feedback, controller/slave correspondence, operating volume, operator workload, human limitations, cross coupling, singularities, anthropomorphic characteristics, physical complexity, control/display interference, accuracy, technological base, cost, and reliability. In the third category, control strategies, commonly called control "modes," are surveyed and evaluated. The report contains a bibliography with 189 select references on hand-controller technology.

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