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Teleoperator Hand Controllers: A Contextual Human Factors Assessment

John V. Draper

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FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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ENVIRONMENTAL RESTORATION AND WASTE MANAGEMENT PROGRAM

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TELEOPERATOR HAND CONTROLLERS: A CONTEXTUAL HUMAN FACTORS ASSESSMENT

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ABSTRACT

This document provides a human factors assessment of the efficacy of hand controllers for use with remotely controlled manipulators deployed to remove hazardous waste from underground storage tanks. The analysis concentrates on *controller technique* (i.e., the broad class of hand controller) and not on details of controller ergonomics. Examples of controller techniques include, for example, direct rate control, resolved unilateral position control, and direct bilateral position control.

Using an existing concept, the Tank Waste Retrieval Manipulator System, as a reference, two basic types of manipulators may be identified for this application. A long reach, gross-positioning manipulator (LRM) may be used to position a smaller manipulator or an end-effector within a work site. For a Long Reach Manipulator, which will have an enormous motion range and be capable of high end-effector velocity, it will be safest and most efficient to use a resolved rate control system. A smaller, dexterous manipulator may be used to perform handling work within a relatively small work site, (i.e., to complete tasks requiring near-human dexterity). For a Dexterous Manipulator, which will have a smaller motion range than the LRM and be required to perform more difficult tasks, a resolved bilateral position control system will be safest and most efficient. However, during some waste recovery tasks it may be important to support the users by restricting movements to a single plane or axis. This can be done with a resolved bilateral position control system by (1) using the master controller force output to restrict controller inputs or (2) switching the controller to a multiaxis rate control mode and using the force output to provide a spring return to center functionality.

These conclusions are based on available teleoperator performance literature, which is not entirely adequate to answer the question. Therefore, the conclusions should be verified by future experimentation.

1.0 INTRODUCTION

Hand controllers are a critical link between the human operator of a remote handling system and manipulators employed in a remote site. Just as most of the information used by the operator is displayed by television views of the remote area, most of the commands given to the remote system will be given by use of some sort of hand controller. For some systems, this may be as simple as a computer mouse; for others, this may require advanced, bilateral hand position sensing systems. This document provides a human factors assessment of the efficacy of hand control techniques for use with hazardous waste removal systems deployed in underground storage tanks. The analysis concentrates on *controller technique* (i.e., the broad class of hand controller) and not on details of controller ergonomics. Detailed explanations of controller techniques are given in the following subsections.

1.1 TANK WASTE RETRIEVAL MANIPULATOR SYSTEM

For the purposes of this report, the Tank Waste Retrieval Manipulator System (TWRMS) will serve as a reference manipulator concept. The TWRMS will comprise three key parts: the Long Reach Manipulator (LRM), the Dexterous Manipulator (DM), and end-effectors. The LRM will be used to position the DM and end-effectors within the storage tanks. It will be a large 5-degree-of-freedom (dof) manipulator capable of moving the DM and end-effectors to any location within the underground tank. The DM will be used to position end-effectors within work sites inside the storage tanks. It will be a high-performance manipulator capable of completing tasks requiring near-human dexterity.

1.2 CONTEXTUAL APPROACH

The basic premise of the contextual approach that this document follows is this: there is no "best way" to control a teleoperator; rather, the optimal controller must be selected on the basis of the tasks to be performed by the teleoperator and the level of control exercised by the human user. To help define the context for hand controller assessment, this subsection defines what a *teleoperator* is, introduces the concept *level of control*, identifies possible control metaphors during teleoperation, and describes performance issues that will be addressed in the remainder of the document.

1.2.1 Teleoperators

According to ref. 1, "a teleoperator is a general-purpose, dexterous, man-machine system that augments man by projecting his manipulatory and pedipulatory capabilities across distance and through physical barriers into hostile environments." Ref. 2 defines one common type of teleoperator, the master-slave manipulator, as a "general-purpose mechanical device used by a human operator in a normal environment to extend his hand and arm manipulative capacity into a ... remote hostile environment with the aid of direct or indirect visual observation, with movements characterized by [1] naturalness, to obviate the need for extensive training, [2] feel, to reflect the elastic characteristics of task objects and forces exerted on them, and [3] compliance, to follow task-constrained paths or orientations." These definitions emphasize three aspects of teleoperators that are important in distinguishing them from other similar systems. First, teleoperators are general purpose machines: they are capable of performing a wide array of tasks, a characteristic that distinguishes them from tools intended to have a small set of specific uses like shovels, forks, or scalpels. In fact, teleoperators can use these tools for the specific uses for which they were intended: teleoperators are tools that use tools. Second, teleoperators are dexterous: they have components that allow them to interact with their environment, a characteristic that distinguishes them from other remotely controlled systems like garage door openers. Third, teleoperators are human-machine systems: they combine powerful human perceptual and problem-solving capabilities with the hardiness of machines, a combination that distinguishes them from robots.

1.2.2 User Tasks

During teleoperation users carry out some varying mix of five generic tasks: (1) programming, storing a behavioral repertoire by use of symbols; (2) teaching, storing a behavioral repertoire by stepping through an example; (3) controlling, continuous manual control; (4) commanding, control by manipulating symbols to trigger behavioral repertoires; and (5) monitoring, observing the machine carry out commands and deciding to switch to one of the other tasks as required. The relative importance and frequency of these tasks will be determined by the *level of control.*

Level of control refers to the nature of human responsibility for machine functioning and ranges from total control to strategic control. During total control the user is responsible for all decisions—from strategic planning to trajectory control. At the other end of this continuum, the user is responsible only for relatively long-term plans, at least while the machine is performing the task (programming takes place before task execution).

Figure 1 shows some representative examples of points along the level-of-control continuum, labels regions of it, and identifies the salient machine responsibilities, user tasks, and user information requirements at each point. Ascending the continuum, the machine assumes more responsibility for subtask and task performance, and human interaction with the system becomes more symbolic and less energetic.

Starting at the bottom of Fig. 1, the first region is labeled *Manual Control.* At this level of control, the human user must control the entire range of system functioning—from trajectory guidance to planning; the task of the machine is to display information from the work site and to act on user inputs. The next region is called *Manual Control with Intelligent Assistance.* As more machine intelligence becomes available, the user may be able to teach the machine rudimentary information about the work site, such as defining regions that should not be entered. The machine is able to modify (1) information displays to enhance available video displays and (2) user inputs to provide guidance, perhaps in the

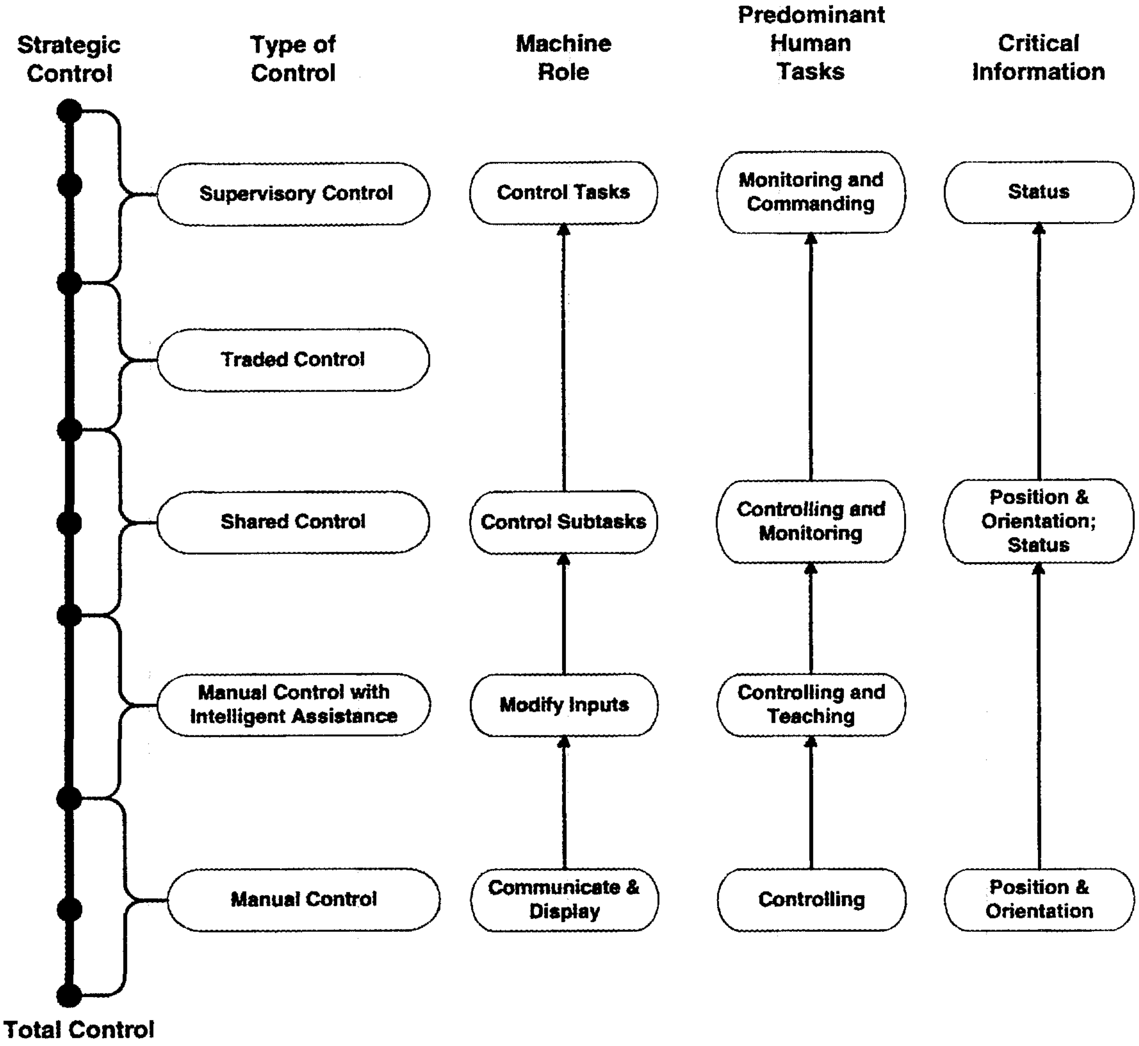

Fig. 1. Level of control continuum with control types, primary machine and human tasks, and critical information for the human operator.

form of movement restrictions (for further discussion see ref. 3 and for an example see ref. 4). Computer-assisted teleoperation [5] and shared compliant control [6] fit into this region. As the machine becomes more capable, the user is able to shed more responsibility; in the region labeled *Shared Control* the user is responsible for controlling some subtasks while the machine simultaneously controls others. An example is human control of horizontal velocity and machine control of pitch, yaw, roll, and vertical velocity for a submersible [7]. At the next level, labeled *Traded Control*, the machine and human are consecutively responsible for subtasks (i.e., , sometimes the machine is in complete control, and sometimes the human is in control). The TWRMS will most likely operate within this region of the continuum [8]. At this level the user may be controlling, commanding, or monitoring (with occasional programming or teaching) depending on the subtask. The next level, labeled *Supervisory Control*, was first described in ref. 9 and is defined as a control mode in which "one or more human operators are intermittently programming and continually receiving information from a computer" that controls a teleoperator [10]. The machine is responsible for controlling tasks, and the human is monitoring it—occasionally intervening to command, to teach, or to program; human interaction with the system is symbolic (i.e., it involves selection of teleoperator tasks and goals but does not involve direct control of teleoperator actions). Under normal conditions the user's role at the highest level of control is not so much teleoperation as it is managing robots. The human user will enter the control loop only if abnormal situations arise. Figure 2 further illustrates the nature of human involvement in the control loop for each level of control.

User interfaces for a teleoperator must be able to accommodate human-machine interactions at the appropriate levels of control for the system. Note that future teleoperators will not generally occupy one point on the continuum but will move up and down on it in response to mission requirements and machine capability. However, it is not true that a teleoperator capable of operating at one level of control is automatically capable of operating at lower levels. User interfaces must be flexible enough to accommodate a range of human tasks corresponding to the levels of control that the teleoperator will exhibit during a mission.

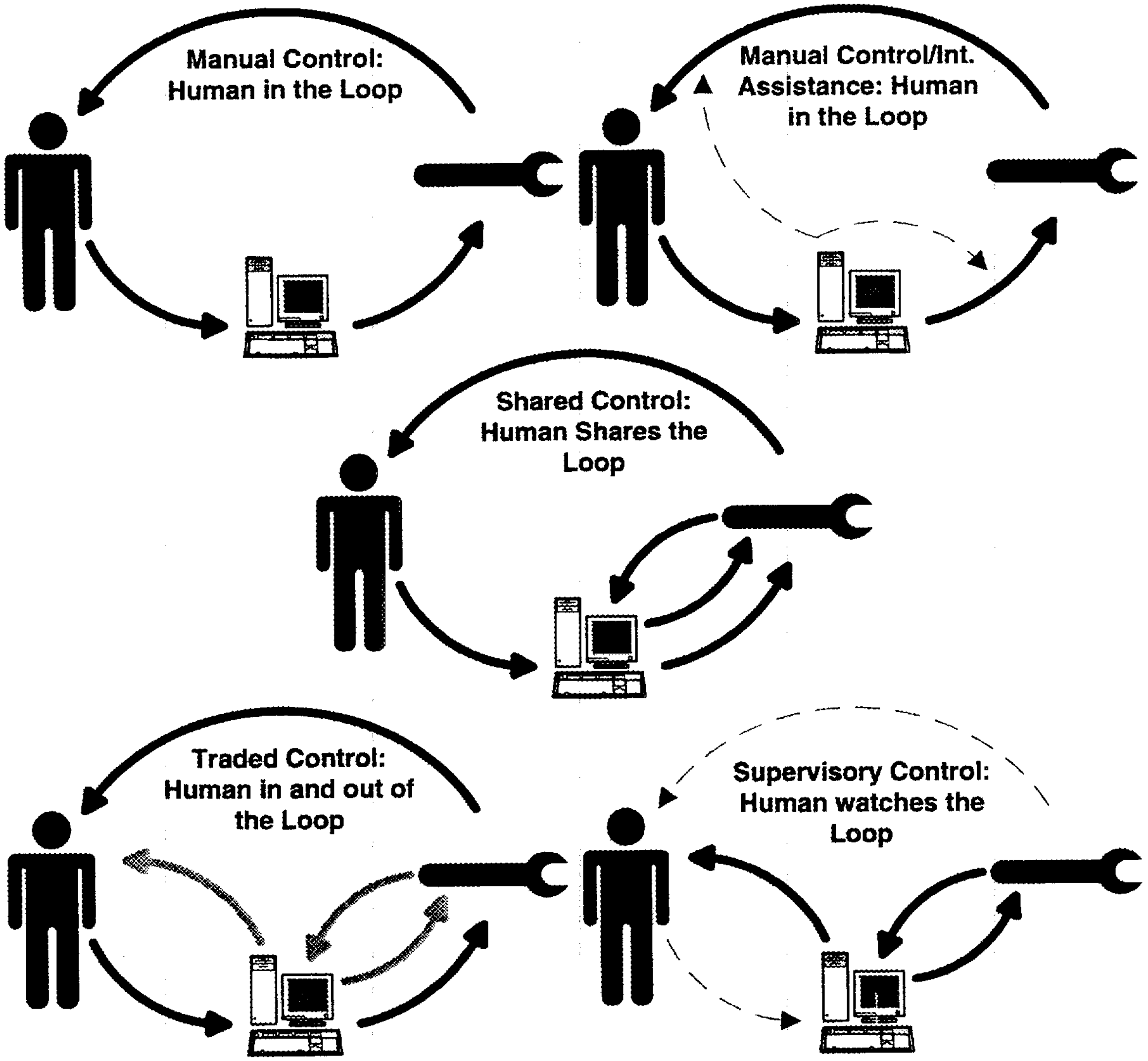

Fig. 2. Human and computer roles within each control type. Dark arrows indicate primary responsibility, shaded arrows indicated intermittant responsibility, and dashed lines indicate monitoring or modifying only.

1.2.3 Control Metaphors

When operating in *Supervisory Control*, user inputs should be optimized for human-computer interaction and most likely will involve picking items from a menu or clicking on objects on a tank map or other graphics display. The appropriate control metaphor for this case is normal computer operations.

When in constant manual control of a teleoperator, the user should be in control of the end-effector and not individual joints, and one of two control metaphors should be applied. The user may move the machine as if it is an extension of his arms into the remote area (or as if it is a suit that he has donned); or he may fly the end-effector as if it is a vehicle in three-dimensional space. Discrete control of individual joints, whether by joystick, switches, potentiometers, or other method, should be avoided because it is inefficient [11,12,13,14]. The performance capabilities of the machine should determine the choice of the optimal control metaphor (i.e., suit or flying).

Responsiveness is the ability of a manipulator to reproduce user arm trajectories and impedance in time and space. Assuming a series of hypothetical human arm trajectories, teleoperators fall into three categories according to how well they can follow the trajectories: (1) *user-paced teleoperators* are highly responsive and capable of executing any human trajectory in real time; (2) *machine-paced teleoperators* are moderately responsive and are capable of executing most, but not all, trajectories in real time; and (3) *non-real-time teleoperators* are not capable of keeping up with human trajectories at any pace. These categories represent regions on a continuum of responsiveness rather than fixed categories; while the boundaries are at present ill-defined, evidence indicates that (1) non-real-time teleoperators are characterized by maximum end-effector velocity below 0.65 m/s [15,16,17] and acceleration bandwidth below 1.28 Hz [18] and (2) user-paced teleoperators are characterized by acceleration bandwidth above 9 Hz [19].

User-paced teleoperators and machine-paced teleoperators in the upper range of responsiveness for the category are more efficient when controlled using position control than when using rate control [20,21,22] (i.e., the arm-extension metaphor is better than the flying metaphor). Rate control (i.e., the flying metaphor) is best for machine-paced teleoperators that are in the lower range of responsiveness for the category and non-real-time teleoperators because unresponsive systems develop dangerous lags between master and slave. However, the work envelope for a position controller must be adequately large to span the task area. If the user frequently meets a work envelope barrier and must index the master and slave (indexing ratchets the slave position relative to the master controller), performance is no better than with a rate controller. For example, in ref. 23 no statistically significant performance differences were found between position controllers and rate controllers for the same slave arm, and subjects complained of the constant indexing necessary to complete the task with the small-volume master controller. Recordings of master controller joint angles during performance of three typical remote maintenance tasks show that nearly all operations take place within a volume (resting on the user's lap) approximately 3/4 m wide, 3/4 m high, and 1 m deep [24]. Smaller work envelopes require indexing and reduce efficiency.

1.2.4 Performance Issues

Specifying a hand controller for the LRM and DM requires understanding the total implications of the decision including (1) safety and user errors, (2) task completion time efficiency, (3) user fatigue, and (4) feedback. Safety issues include (1) the likelihood of damage to the tank or manipulator system and (2) the safety of human users of the manipulator system. User errors indicate the likelihood and severity of errors that users may commit; this includes psychomotor errors (e.g., misjudgment by a user of the distance to an object in the remote area) and cognitive errors (e.g., a bad decision by a user). Task completion time efficiency, or simply efficiency, covers how rapidly waste retrieval tasks may be completed. User fatigue is related to user difficulty in operating the manipulator system; systems that are difficult to use will be, in the long run, more fatiguing than systems that are easier to use. Feedback concerns whether the hand controller can provide feedback to the user. Some controllers are not capable of providing feedback (e.g., a mouse); others can provide some feedback but in a sub optimal fashion (e.g., rate control joysticks can provide only limited force feedback); and some are capable of providing very rich feedback (e.g., exoskeleton controllers can provide joint-by-joint force reflection). In the following subsection, each controller technique is evaluated on each of these performance issues.

1.3 CONTROL TECHNIQUES

Although a minimal taxonomy of hand controllers includes only two control modes, position control and rate control [25], a categorization that includes feedback provided directly by the hand controller [26] and that accounts for all user tasks is more useful. Such a taxonomy might include the following: digital input, position control pointing devices, direct rate control, resolved rate control, direct unilateral position control, resolved unilateral position control, direct bilateral position control, and resolved bilateral position control (most of these categories are suggested by ref. 26). Using the available teleoperator and human performance literature this subsection describes each of these control techniques and evaluates each on the basis of the five criteria listed above.

1.3.1 Digital Input

1.3.1.1 Description

Digital inputs are single-action inputs to change a state or to enter an alphanumeric character. Examples of digital input hardware include keyboards and switches.

1.3.1.2 Applications

Digital input is appropriate wherever a digital decision must be entered (e.g., turn on the system power) or for unstructured data entry (i.e., where data to be entered cannot be restricted to a known set and placed on a menu). It is also the preferred method for system programming. It is not appropriate for controlling teleoperators in real time. It is appropriate for programming and commanding, and perhaps teaching, but not for controlling. It would be the optimal control technique during monitoring when users must interrupt automated task completion quickly.

1.3.1.3 Safety and User Errors

During programming, teaching, commanding, or monitoring, this control technique provides adequate safety. However, it would not be as safe for controlling as the other techniques. Digital input implies two things that raise safety issues: (1) joint-by-joint control is implied by the on/off coding, and this often leads to problems when users attempt to judge the implications of activating one joint for end-effector position; and (2) control by an on/off switch requires two decisions and two actions by the user, which would make it more difficult to respond in the event of an emergency.

Operators using this control technique during commanding, programming, or monitoring may commit fewer errors with this control technique than with any other; during controlling they will commit more errors because of the cognitive burden imposed by joint-by-joint control

1.3.1.4 Efficiency

Keyboard data entry is the most efficient and accurate way to enter large amounts of data off-line. For binary parameters (e.g., system power on/off) switches are the most intuitive interface. These devices are inherently one-dimensional and therefore are not good for controlling trajectories in real time. Joint-by-joint control of teleoperators has been shown to be extremely inefficient [27,28].

1.3.1.5 Fatigue

Joint-by-joint control imposes greater cognitive workload on a user than resolved control, and this may be more fatiguing. The impact of a single joint movement on end-effector position is not always obvious; thus planning, executing, and monitoring a movement can be taxing.

1.3.1.6 Feedback

The feedback possible from these devices is limited to visual and audio signals.

1.3.2 Position Control Pointing Device

1.3.2.1 Description

Position control pointing devices are used to move a cursor on a computer screen and to select or to mark a region of the screen. A personal computer mouse is a good example.

1.3.2.2 Applications

This control technique is often used for menu selection, screen highlighting, etc. These devices are appropriate for programming, teaching, and commanding but not for controlling.

1.3.2.3 Safety and User Errors

Errors committed with these devices during programming, teaching, or commanding will be mostly cognitive and not due to the controller per se; positioning errors that may occur will impose slight delays but not seriously challenge system efficiency or safety.

1.3.2.4 Efficiency

Position control pointing devices are very common, and they are efficient for cursor control; this control technique will probably be the optimal technique during commanding. The current body of knowledge about these devices allows specification for applications. Many options are commercially available. These devices have occasionally been used for controlling but are inefficient [29].

1.3.2.5 Fatigue

This control technique is not likely to be more fatiguing than any other.

1.3.2.6 Feedback

The feedback possible from these devices is limited to visual and audio signals.

1.3.3 Direct Rate Control

1.3.3.1 Description

Direct rate control is joint-by-joint control of the velocity of individual dof's using spring-return switches or joysticks.

1.3.3.2 Applications

Direct rate control is often used for controlling heavy-duty links that may be operated independently or in small sets, as is done in backhoes. However, it is an inefficient control technique for dexterous teleoperation [30].

1.3.3.3 Safety and User Errors

Provided an appropriate gain is used, rate control avoids overshoots sometimes seen with unilateral position control. Rate control may enforce slower work pace, perhaps improving safety at the expense of productivity [31]. However, direct rate control makes it difficult for users to understand the implications of joint movements on end point position; this can lead to unexpected actions including collisions in the remote area. Furthermore, if the gain is too high, the user may have difficulty positioning the end-effector. When gain is too high, positioning movements will be characterized by overshooting and overcorrecting.

This control technique is more error-prone than the others because of the likelihood of cognitive errors that may be associated with misunderstandings of the control input-end-effector movement relationship.

1.3.3.4 Efficiency

Rate control has inherently lower bandwidth than position control because every movement requires two control inputs. In ref. 32 an experimenter examined the performance of a single highly DM controlled by a master controller and by a multi-dof joystick; in ref. 33 experimenters compared performance of a single hand controller and manipulator using rate control or position control combined with several different force feedback conditions; and in ref. 34 experimenters compared the performance of several different hand controllers (including a reduced-volume master controller) using a single medium-dexterity manipulator. In the two former experiments, position control was found to provide superior task performance; in the latter, performance was no better, but the hand controller was so small that it required "continuous indexing" during tasks. This may have eliminated any performance advantage for the position controller and illustrates that a position controller must be able to span the task space to be effective.

Rate controllers should be isotonic (i.e., elastic and position sensing) rather than isometric (i.e., immobile and force sensing) for greatest efficiency [35].

1.3.3.5 Fatigue

Rate controllers impose heavier workload because of the indirect controller/manipulator positioning linkage; this is exacerbated by joint-by-joint control. Joint-by-joint control requires heavy cognitive workload to understand the implications of moving one joint for the position of all the others. Because less movement is required to make a control input, however, joysticks may be less physically fatiguing than master controllers.

1.3.3.6 Feedback

It is difficult (perhaps impossible) to provide force reflection to rate controllers with the same consistent meaning that is possible with position controllers (i.e., force reflection can occur only when a velocity is inputted; the force that is fed back will vary with input as well as with force because of the summation of the spring return and the force reflection terms), although some force reflection is possible [33].

1.3.4 Resolved Rate Control

1.3.4.1 Description

Resolved rate control is similar to direct rate control in that the user controls the velocity of translation, but rather than directly controlling joint movements, the user's control is over positioning and rotational axes. Instead of controlling the rate of translation of a particular joint, the user controls the rate of translation on a single plane or around a single axis. The planes or axes may be referenced to the world or to the end-effector.

1.3.4.2 Applications

Resolved rate control may be used for controlling semidexterous manipulators or for slowing the pace of work.

1.3.4.3 Safety and User Errors

Safety must balance (1) the potential error-saving effect of rate control in slowing the pace of operations and (2) the potential for errors caused by requiring users to translate control inputs into slave arm positioning. Force reflection is also not provided as well by these controllers as it is by master controllers, which makes it more difficult for users to perceive and to control forces that they apply. This technique will be much safer than direct rate control but may be less safe than bilateral position control. Furthermore, if the gain is too high, the user may have difficulty positioning the end-effector. When gain is too high, positioning movements will be characterized by overshooting and overcorrecting.

Some evidence indicates that the slow pace imposed by rate control contributes to more accurate end-effector positioning; however, this evidence is weak.

1.3.4.4 Efficiency

Rate control has inherently lower bandwidth than position control because every movement requires two control inputs, the velocity input command and the zeroing command; thus it is a less efficient control technique for high-performance manipulators. However, rate controllers are usually less expensive than position control devices and occupy smaller cockpit volume.

1.3.4.5 Fatigue

Rate controllers impose heavy cognitive workload because of the indirect controller/manipulator positioning (e.g., pull back on the handle to go up). Instead of moving their hand naturally to a position relative to the starting point, users must translate the desired position into a trajectory and then translate the trajectory into commands along and around the three spatial dimensions. This is harder cognitively than moving one's hand. Joint-by-joint control also requires heavy cognitive workload to understand the implications of moving one joint for the position of all the others. Resolved rate control avoids some of the cognitive load associated with direct rate control by referencing control inputs to the world, the task, or the end-effector instead of to joints. During rate control user hand translations are typically smaller and work against less friction and inertia than is present for bilateral controllers; therefore, rate control may be physically easier to use than some position controllers.

1.3.4.6 Feedback

It is difficult (perhaps impossible) to provide force reflection to rate controllers with the same consistent meaning that is possible with position controllers (i.e., force reflection can occur only when a velocity is inputted; the force that is fed back will vary with input as well as with force), although some force reflection is possible [33].

1.3.5 Direct Unilateral Position Control

1.3.5.1 Description

Direct unilateral position control is direct mapping of controller position to manipulator position on a joint-by-joint basis. An exoskeleton master controller without force reflection is a good example.

1.3.5.2 Applications

This technique may be used for controlling or teaching but is not applicable for programming.

1.3.5.3 Safety and User Errors

Two safety issues are associated with unilateral exoskeleton master controllers. First, the safety of the in-cell equipment may be enhanced because of the direct control possible over each slave arm joint and the feedback that may be provided to each. However, this must be balanced against the potential for injuries (including chronic fatigue injuries) that are possible with this type of controller. Second, unilateral controllers are less safe than bilateral controllers, for two reasons. First, force reflection demonstrably reduces the forces exerted on objects in the remote area [36,37]; a unilateral system is less safe because a user cannot perceive and control the forces exerted by the remote system. This is true whether the force reflection is provided by position error signals or force sensors; it may be possible to provide other forms of force feedback (e.g., tones or graphs), but these techniques are less effective than force reflection. Second, force reflection provided by master—slave position error provides resistance to movement and allows the user to match his pace to the manipulator. This avoids *spatio-temporal decoupling*, a phenomenon in which the lag between master position and slave position is so large that it becomes difficult for the user to understand the implications of his control inputs.

spatio-temporal decoupling can lead to dangerous overshooting and unexpected contact with objects in the remote area, and leads to an inefficient "move-and-wait" strategy. This control technique may lead to more errors than others because of the potential for spatio-temporal decoupling.

1.3.5.4 Efficiency

Position control is the most efficient technique for manipulator control. However, the motion range of the master controller must be large enough to span the work site, or frequent indexing will be required. Frequent indexing reduces the efficiency of position control to the point that it is no more efficient than rate control, and can frustrate users.

1.3.5.5 Fatigue

Exoskeleton masters may be more fatiguing to use than resolved position controllers because they are more confining and will be less comfortable over the course of a waste retrieval campaign. Direct position control requires either joint-by-joint knobs/joysticks or an exoskeleton master controller; the former has all the disadvantages of direct rate control, while the latter is confining to the user and may require individualized controllers.

1.3.5.6 Feedback

Feedback may be provided aurally or visually.

1.3.6 Resolved Unilateral Position Control

1.3.6.1 Description

Resolved unilateral position control refers to direct mapping of the user's hand position relative to some reference point to manipulator end-effector position relative to some comparable remote reference point. The data glove is an example of a resolved unilateral position controller.

1.3.6.2 Applications

This should be avoided because of the potential of spatio-temporal decoupling of the hand controller from the end-effector.

1.3.6.3 Safety and User Errors

Movements made without resistance to the movements may lead to spatio-temporal decoupling. The resulting lag between the commanded hand controller position and the end-effector position may result in overshooting the target and is potentially dangerous to remote tasks and the manipulator. Controllers that provide force feedback but not force reflection (e.g., through force sensors mounted at the end-effector) provide feed back of contact forces but do not feedback position differences between controller and manipulator. To avoid decoupling in the absence of force reflection, the manipulator must be capable of very high velocities (i.e., about 1 m/s) and acceleration (i.e., in excess of 1 g).

1.3.6.4 Efficiency

Position controllers are more efficient than rate controllers for DMs because of the higher input bandwidth possible with them and the ease with which users can translate desired slave position into controller inputs. Unilateral position controllers are less expensive than bilateral controllers. Resolved control may be less expensive and more flexible than direct control.

1.3.6.5 Fatigue

This control technique is potentially the least fatiguing of all the techniques.

1.3.6.6 Feedback

This control technique may lead to more errors than others because of the potential for spatio-temporal decoupling.

1.3.7 Direct Bilateral Position Control

1.3.7.1 Description

Direct bilateral position control is joint-by-joint control of the manipulator with force reflection, such as that used in force-reflecting exoskeleton controllers. The EXOS controller is an example of this control technique [38].

1.3.7.2 Applications

This control technique is useful for controlling and teaching.

1.3.7.3 Safety and User Errors

Because of the rich feedback that this type of system can provide to the user, this is the safest control technique in terms of the remote area. However, because the user is confined within a system that imposes forces on his limbs, the safety of the user is poorest with this system.

Users will probably commit the fewest errors with position control techniques because of the intuitive relationship between controller movement and manipulator movement.

1.3.7.4 Efficiency

Position control is the most efficient method for controlling manipulators provided the controller range of motion spans an adequate work space.

1.3.7.5 Fatigue

This control technique has the potential for being the most fatiguing one because of the problems mentioned for unilateral direct position control and the addition of greater resistance to movement through the addition of force reflection.

1.3.7.6 Feedback

This control technique has the advantages of (1) easily understood relationships between feedback and events in the remote area, (2) the ability to provide contact (i.e., forces) and noncontact (i.e., inertia) feedback, and (3) the ability of providing a richer array of feedback because forces can be exerted on each limb link rather than just at the hand, as is done in resolved bilateral position control.

1.3.8 Resolved Bilateral Position Control

1.3.8.1 Description

This is classic master—slave manipulation with force reflection.

1.3.8.2 Applications

This is the most efficient and safest method for controlling manipulators.

1.3.8.3 Safety and User Errors

This control technique has the good safety characteristics of a force-reflecting system (i.e., force control and avoidance of spatio-temporal decoupling) and is safer for users than direct position control. Users will probably commit the fewest errors with position control techniques because of the intuitive relationship between controller movement and manipulator movement.

1.3.8.4 Efficiency

Position control is the most efficient method for controlling manipulators provided the controller range of motion spans an adequate work space.

1.3.8.5 Fatigue

Force reflection imposes resistance to movement; thus it can be more fatiguing than unilateral systems, but this is more than balanced by the greater safety inherent in force reflection.

1.3.8.6 Feedback

Resolved bilateral systems provide feedback with the advantages of (1) easily understood relationships between feedback and events in the remote area and (2) the ability to provide contact (i.e., forces) and noncontact (i.e., inertia) force feedback. Because the feedback is resolved at the controller handle, it is not possible to provide as rich an array of information with it as with a bilateral exoskeleton.

2.0 RECOMMENDATIONS

2.1 RECOMMENDATIONS BY TASK

2.1.1 Commanding

The safest and most efficient method for commanding manipulators to carry out programmed routines is by use of a position control pointing device and graphical user interface. A mouse or trackball should be considered the optimal controller for this task.

2.1.2 Controlling

The safest and most efficient method for controlling manipulator trajectories will depend in part on the manipulator. For the Long Reach Manipulator, which will have an enormous motion range and be capable of high end-effector velocity, it will probably be best to use a resolved rate control system. A rate control system will (1) allow control over the entire range of motion without requiring indexing, (2) slow the pace of operations to help prevent unexpected contact with objects in the remote area, and (3) allow the user to control movement on a single specified plane or along a single axis without cross-coupling. In other words, because of the size of the manipulator and the type of task to be performed with it (mostly tranporting the DM from work site to work site), the flying metaphor is best for this manipulator. For the DM, which will have a smaller motion range and be required to perform tasks requiring dexterity, a resolved bilateral position control system will be best. This will (1) allow the most efficient user of the manipulator, (2) be safest for remote equipment because it allows the best force control, and (3) be the least fatiguing for the users. In other words, the arm extension metaphor is best for this manipulator. However, during some waste recovery tasks it may be important to support the users by restricting movements to a single plane or axis. This can be done with a resolved bilateral position control system by (1) using force reflection to restrict controller inputs or (2) switching the controller to a multiaxis rate controller and using the force reflection to provide spring return to center.

2.1.3 Programming

The most efficient control technique for programming will be by keyboard; however, over time a library of actions will be built up such that programming can be done by combining sets of algorithms from a menu. In that case, a position control pointing device will be most efficient.

2.1.4 Teaching

For teaching, two control techniques should be used. For high-level supervisory control, a position control pointing device that allows the users to pick algorithms, work sites, etc., should be used. At the lower level of teaching movement combinations, a resolved position control device should be used.

2.1.5 Monitoring

The most important control input during monitoring will interrupt the execution of robotic routines; this will be something like an emergency stop button and should be a digital input.

2.2 RECOMMENDATIONS TABLE

Table 1 summarizes the recommendations from the preceding section in a tabular format. For commanding, the optimal controller technique is a position control pointing device; for this task the user will typically select options from a menu or graphical representation of the work flow. Input by keyboard or joystick is also applicable for this task.

For controlling, the optimal control technique depends on the tasks to be performed and the performance capability of the manipulator. For tasks requiring dexterity and high-performance manipulators, one of the bilateral position control options is optimal; for less challenging tasks and less responsive manipulators, resolved rate control may be optimal. Unilateral position control, direct rate control, digital input, and pointing devices are not applicable for this task because of inefficiency or potential safety hazards associated with their use.

For programming, keyboard data entry is the optimal control technique; menu item selection by pointing device or direct rate control (joystick) is also applicable.

For teaching, several control techniques may be applicable depending on the details of the teaching task. Unilateral controllers are applicable because force reflection is not needed, and the performance of the slave arm need not pace the teaching task. Direct control gives the most detailed control over manipulator actions, although it may be less efficient than resolved control. No single control technique is clearly the best suited for this task.

For monitoring, which requires only one control input (i.e., to interrupt the system to begin controlling, commanding, programming, or teaching), a single "routine pause" switch is optimal; this could also be done by pointing device, but less efficiently.

Table 1. Qualitative assessment of the relative merits of telemanipulator control techniques for each user task. Each technique is graded as optimal, applicable, or not recommended. The "optimal" technique is the best for the application; an "applicable" technique may be used, but at the cost of poorer performance; and a "not recommended" technique should not be used

Control Technique	Commanding	Controlling	Programming	Teaching	Monitoring	Example
Digital input	Applicable	Not recommended	Optimal	Not recommended	Optimal	Keyboard or on/off switches
Position control pointing device	Optimal	Not recommended	Applicable	Applicable	Applicable	Mouse or trackball
Direct rate control	Applicable	Not recommended	Applicable	Applicable	Not recommended	Joystick (direct joint to dof mapping)
Resolved rate control	Not recommended	Optimal*	Not recommended	Applicable	Not recommended	Joystick (coordinate frame to dof mapping)
Direct unilateral position control	Not recommended	Not recommended	Not recommended	Applicable	Not recommended	Exoskeletal master without force reflection
Resolved unilateral position control	Not recommended	Not recommended	Not recommended	Applicable	Not recommended	Master controller without force reflection
Direct bilateral position control	Not recommended	Optimal*	Not recommended	Applicable	Not recommended	Force-reflecting exoskeletal master
Resolved bilateral position control	Not recommended	Optimal*	Not recommended	Applicable	Not recommended	Force-reflecting master

*Depends on manipulator performance and task requirements.

2.3 LONG REACH MANIPULATORS

2.3.1 LRM Tasks and Level of Control

An LRM will either operate independently to position a DM and end-effectors at work sites within the tank or as a part of the integrated LRM-DM-end-effector unit positioning the end-effector within the work site. For the first case, the level of control will most likely be Supervisory Control; for the latter case, the level of control will range from Manual Control to Supervisory Control. This means that controllers for the LRM require (1) a pointing device and (2) a hand controller for manual .control.

2.3.2 Performance Specifications

The key LRM specifications are that it shall be capable of (1) end-plate velocity up to 30.5 cm/s (12 in./s) in all configurations and (2) 2-g acceleration in all configurations. These performance specifications mean that the LRM probably will not be a user-paced teleoperator. Furthermore, the LRM is not capable of positioning and orienting its end-plate at any point in space because it has only 5 dof; and moving a large [up to 454 kg (1000 lb)] end-effector inside a tank *must* be done safely.

2.3.3 Hand Controller Recommendation

For a Long Reach Manipulator, which will have an enormous motion range and be capable of high end-effector velocity, it will probably be best to use a resolved rate control system. A resolved position control system might be more efficient for this system provided the motion range of the controller matches the work envelope of the manipulator; however, because this would require considerable motion scaling or frequent indexing [the work envelope will be a cylinder 22.9 m (75) ft in diam and up to [7.3 m (24 ft) high], a master controller may not confer any efficiency advantage. Because the LRM will not be expected to perform tasks that require contact with the remote environment (in fact, such contact should normally be avoided during LRM operations), the force reflection capabilities of a position controller will not confer any safety advantages. A resolved rate control system will (1) allow control over the entire range of motion without requiring indexing, (2) slow the pace of operations to help prevent unexpected contact with objects in the remote area, and (3) allow the user to control movement on a single specified plane or along a single axis without cross-coupling.

2.4 DEXTEROUS MANIPULATOR

2.4.1 DM Tasks and Level of Control

A DM will operate independently to position end-effectors within a work site or to manipulate objects in the remote environment. These tasks will be carried out by a mixture of levels of control; emphasis will likely be on supervisory and manual control. This means that the key user tasks will be commanding and controlling.

2.4.2 Performance Specifications

The key DM specifications in the current TWRMS concept are that the DM shall be capable of (1) end-plate velocity up to 91.4 cm/s (36 m/s) in all configurations and (2) 2-g acceleration in all configurations. These performance specifications mean that the DM could be a user-paced teleoperator and, therefore, for most efficient operation should be equipped with a master controller.

2.4.3 Hand Controller Recommendation

For the DM, which will have a smaller motion range than the LRM and be required to perform more difficult tasks, a resolved bilateral position control system will be best. This will (1) allow the most efficient use of the manipulator, (2) be safest for remote equipment because it allows the best force control, and (3) be the least fatiguing for the users. However, during some waste recovery tasks it may be important to support the users by restricting movements to a single plane or axis. This can be done with a resolved bilateral position control system by (1) using the master force output capability to restrict controller movements or (2) switching the controller to a multiaxis rate control mode and using the force output capability to provide return-to-center functionality. If the DM is built to specification, it will perform well enough to be optimally controlled by a bilateral position controller. However, to allow optimal control during terrain- or path-following operations with waste retrieval end-effectors, it may be useful to include a resolved rate control mode, using the force output capabilities of the master controller to provide a return-to-center functionality for the handle. The control frame of references available should include world-referenced andend-effector referenced modes. It should also be capable of limiting control responses to a subset of the dofs.

3.0 RESEARCH ISSUES

Because of the paucity of available research on teleoperator hand controllers, the conclusions expressed in this document must be considered tentative and should be the subject of future research. Some important topics for future experiments might include the following:

- comparison of control techniques under varying levels of manipulator responsiveness;
- identification of responsiveness thresholds for user pacing, machine pacing, and real-time manipulation;
- measurement of the impact of motion range restrictions on position controller efficiency;
- measurement of relative workload imposed by controller types; and
- assessment of the impact of exoskeleton controllers on user workload and fatigue.

4.0 SUMMARY

This document provides a human factors assessment of the efficacy of hand controllers for use with the TWRMS. The analysis concentrates on *controller technique* (i.e., the broad class of hand controller) and not on details of controller ergonomics.

For a Long Reach Manipulator, which will have an enormous motion range and be capable of high end-effector velocity, it will probably be best to use a resolved rate control system. A rate control system will (1) allow control over the entire range of motion without requiring indexing, (2) slow the pace of operations to help prevent unexpected contact with objects in the remote area, and (3) allow the user to control movement on a single specified plane or along a single axis without cross-coupling.

For a DM, which will have a smaller motion range than the LRM and be required to perform more difficult tasks, a resolved bilateral position control system will be best. This will (1) allow the most efficient use of the manipulator, (2) be safest for remote equipment because it allows the best force control, and (3) be the least fatiguing for the users. However, during some waste recovery tasks it may be important to support the users by restricting movements to a single plane or axis. This can be done with a resolved bilateral position control system by (1) using the master controller force output capability to restrict controller inputs or (2) switching the controller to a multiaxis rate control mode and using the force output capability to provide return-to-center functionality for the handle. If the DM is built to specification, it will perform well enough to be optimally controlled by a bilateral position controller. However, to allow optimal control during terrain- or path-following operations with waste retrieval end-effectors, it may be useful to include a resolved rate control mode, using the force output capabilities of the master controller to provide a centering spring for the handle. The control frame of references available should include world-referenced and end-effector referenced modes. It should also be capable of limiting control responses to a subset of the dofs.

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