GRAPHIC-BASED HUMAN-MACHINE INTERFACE FOR CONSTRUCTION MANIPULATOR CONTROL

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ABSTRACT: Large-scale construction manipulators are important to productivity and safety on the construction site. Traditionally, manipulators are controlled by an operator, who pulls and pushes levers, which open and close hydraulic values. Recently, joysticks have begun to be used as a more sophisticated control method. In either case, the manipulator control utilizes the human operator's manual skills and experience because automation of the control is difficult in a unstructured task environment. An alternative to the traditional control methods, a human-machine interface can be used to combine the human operator's intuitive judgment and skills with intelligent machine control. The goal of this research was to understand the characteristics of the human-machine interface during the telerobotic operation of construction manipulators. The paper discusses a comprehensive control framework that describes the types of control systems for an interactive human-machine interface. A general remote control structure was developed to implement the framework to the telerobotic operation of a bridge maintenance crane. Field experiments were conducted to comparatively evaluate the performance of the general remote control structure in varying task complexities. The test results indicate that the human-machine interface can be implemented flexibly to cope with different task requirements on construction sites.

INTRODUCTION

Construction operation can be more easily automated if the flow of materials and activities is predictable and preplanned. In a cyclic operation both in the type of actions and in the type of materials, the manipulators can be provided with an autonomous capability to execute repetitive tasks and connect different construction tasks within scheduled time and spaces.

Many construction activities are, however, executed in a constantly changing task environment. The attempt to robotize construction operations and maintenance activities is often hindered by the unsteadiness and unstructured nature of the construction operation (Everett and Slocum 1993). The difficulty arises from two areas: development of the physical hardware and development of an intelligent control system. Since most construction projects are executed under different site conditions, the automated hardware system should be flexible and adaptive enough for various applications.

A subtle, evolutionary attempt to improve existing technologies may offer a more feasible improvement of productivity and safety than a revolutionary attempt to robotize the full process of the construction operation (Miller and Bernold 1991). It has been shown that integration of the human operator's strength with the robotic system's autonomous capability can offer more practical benefits than full automation can (ENR 1994). A robotic system in the construction process must therefore be designed and developed such that the system supports human operators rather than entirely taking over their roles.

The human-machine interface can be a more promising approach to operating large-scale construction manipulators than either the manual or the automated control alone. This control approach is based on the recognition that the role of the human operator is still important, even in autonomous robot control. In the human-machine interface, the operator works as a supervisor and intervenes in automated machine control whenever necessary to make decisions (Halpin 1990). The human operator and the computerized machine controller interactively share control responsibility to ensure flexibility and reliability. As Balagner et al. (1996) showed, this control paradigm has begun to be studied for the operation of construction manipulators. Graphic simulation often used for the interface can generate useful information when the direct view of the control environment is not available (Ujiie et al. 1996).

This paper discusses the concept of the human-machine interface during the telerobotic operation of large-scale construction manipulators. The research goal of this study is to understand how the performance of the supervisory control changes under varying construction task environments. A comprehensive control framework was developed as a control system for the human-machine interface. A general remote control structure was introduced as a means of implementing the interface. Field experiments were conducted on a testing bridge and a bridge maintenance crane at the North Carolina Department of Transportation. The experiments provided performance data for evaluating the effectiveness of the human-machine interface during the telerobotic operation of a bridge maintenance crane.

CHARACTERISTICS OF HUMAN-MACHINE INTERFACE

The task environment on construction sites is often unfavorable to large-scale construction manipulators. Construction obstacles and natural conditions make it hard for the operator to attain the desired level of machine control. An alternative to manual manipulator control is a telerobotic operation. This section discusses the concept of a human-machine interface for the telerobotic operation of construction manipulators.

Telerobotization of Large-Scale Construction Manipulators

In a construction operation, large-scale manipulators are needed to handle a large volume of construction materials such as soil, concrete, and asphalt. Currently, the operation of large-scale construction manipulators relies on manual control with direct manipulation by the human operator. This manual control is described as teleoperation, during which the human operator's sensing and manual capability are extended to operate construction equipment located in a remote area. Machine productivity is significantly affected by the human operator's decision-making ability and establishment of a strategic plan.

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Unlike teleoperation, telerobotic operation allows work to be executed remotely and automatically. In telerobotic operation, the operator can interactively direct telerobots in circumstances where direct action is not feasible or desirable. This remote control capability links the task space between the human operator at a control station and the telerobot at a work area (Moon and Bernold 1997).

The telerobotic operation can be implemented efficiently through the interactive function of the human-machine interface. In this control approach, the machine controller's electronic sensing and intelligence are enhanced by the human operator's decision-making and control strategies. The human-machine interface compensates for the imperfection that comes from either the human operator or the machine controller (Rasmussen 1986).

Supervisory Human-Machine Interface

In telerobotic operation the goal of the human-machine interface is to monitor the actual operating status and to keep it within a specified target domain through the interactive exchange of control responsibilities. Sheridan (1992) described the monitoring function as "supervisory" and offers this definition:

> The computer transforms information from human to a controlled process and from the controlled process to human, but only under the strict definition does the computer necessarily close a control loop that excludes the human, thus making the computer an autonomous controller for some variables at least some of the time.

The computerized machine controller may be faster than manual control in exchanging data, making decisions and executing tasks. The human operator still needs to preside in the control loop to observe real-time control status and to take over control responsibility whenever necessary. According to Sheridan, the motivation behind the human-machine interface control is to: (1) improve the accuracy and to speed up the machine control; (2) eliminate the demand for continuous human involvement and reduce the operator's workload; (3) provide a failure proof capability when the error in the operator's direct control or in the autonomous machine control is catastrophic; (4) eliminate the need for the operator to be present in hazardous environments; and (5) compensate the human operator's limited motor skills through a human-machine interface.

Roles of Human Operator and Machine Controller

During telerobotic operation, the human-machine interface enables the human operator and the automated machine controller to handle different aspects of the manipulator control. In a complex working environment, the human operator should monitor the actions of the telerobot and determine whether the manipulator is executing desired tasks. In a stable working condition, the machine controller takes over the control responsibility and automatically executes desired tasks. As Fischer (1990) argued, this cooperative problem-solving effort can improve the effectiveness of telerobotic manipulator control.

The compatibility of the human operator with the machine controller and vice versa is important and needs to be identified in developing an efficient human-machine interface. After the specific needs of the task requirements are identified, the control responsibility can be assigned to either the human operator or the machine controller. The human-machine interface should be designed to maximize system function. Although the two control identities have their own distinctive characteristics, the computerized machine controller can take over many of the traditional human operators' roles.

Assignment of control responsibilities, either to the human operator or to the machine controller, should be planned according to task requirements, task complexities, available technologies, etc. The assignment should increase the cost-effectiveness of the telerobotic system. The more responsibility the machine takes, the greater the cost of telerobotic system development. The increased role of the machine controller will also increase the level of risk during the control process. For example, if the controller breaks down, the telerobot may collide with obstacles in the manipulator path. Therefore, the operator's role should be increased whenever the cost exceeds the benefit of automation.

COMPREHENSIVE CONTROL FRAMEWORK

Efficient human-machine interface in the telerobotic operation requires dynamic assignment of control responsibilities to either the human operator or the computerized machine controller. Two control functions are required for the human-machine interface: monitoring and command execution. The monitoring function keeps track of the current status of the machine operation and provides guidance for real-time control. The command execution performs machine commands and maneuvers machine components in a consistent way to achieve desired goals. The human operator or the machine controller can carry out these control responsibilities depending on task requirements.

A comprehensive control framework (C^2F) conceptually describes the types of control systems for creating an interactive human-machine interface. The framework was developed combining the two functions (i.e., monitoring and command execution) with either the human operator or the machine controller (Fig. 1). The framework consists of four control types: manual, human-led, machine-led, and autonomous.

Manual control is employed when both the monitoring and command execution functions are executed by the human operator. Human-led control is employed when the monitoring function is performed by the human operator and the command execution function by the machine controller. Machine-led control is employed when the monitoring function is performed by the machine controller and the command execution function by the human operator. Autonomous control is employed when both the monitoring and command execution functions are performed by the machine controller independent of the human operator's involvement.

Each control system has a different degree of effectiveness that depends on the condition of the construction sites. Depending on the task requirements on construction sites, the

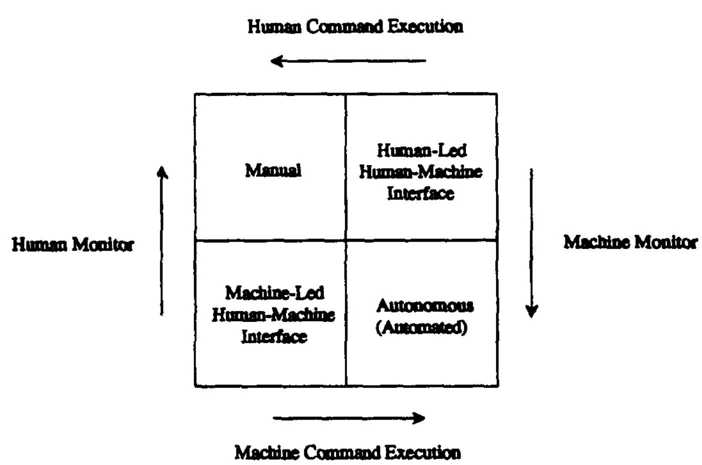

FIG. 1. Comprehensive Control Framework (C^2F)

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human operator or the machine controller may be better suited to telerobotic operation. The need for human control increases when the need for machine control decreases, and vice versa. Since each control system has different characteristics, selection of the appropriate control system should be based on the need.

GENERAL REMOTE CONTROL STRUCTURE FOR CONSTRUCTION TASK ENVIRONMENT

The C^2F can be applied to the telerobotic operation of construction manipulators using the general remote control structure (GRCS), as shown in Fig. 2. Using the control modes in the GRCS, the human operator functions as a supervisor in the overall control loop. The uniqueness of the GRCS is the integration of numerical control and graphic-based visual control. The graphic-based control takes advantage of CAD graphics, which depict the structural shapes. When the graphics are overlaid onto live camera images, the overlay creates a virtual control environment for real-time telerobotic operation. The graphic aid in the control environment can assist the human operator in visualizing the robot motion in relation to the actual site condition and in developing control strategies.

Fig. 3(a) and (b) show the conceptual model of the graphic overlay. The global view provides the overall picture of the manipulator path for a faster advancement of the telerobot. This far view is effective when the sight of view is available in the work space. The local view provides detailed live pictures of site conditions. This closeup view is effective when the overall view is blocked by temporary or permanent structures on construction sites.

The GRCS is capable of handling the four control types described in the C^2F: manual, human-led, machine-led, and autonomous. There are three modes of control: direct-view joint actuation, video-view joint actuation, and spatial. The other three modes in Fig. 2—the spatial, human-led, machine-led, and autonomous modes—are executed in the graphic-based control environment, or virtual-interface control environment (ViCE). Moon and Bernold (1996) discussed the basic concept of off-line path planning for the graphic-based manipulator control.

In the actual task environment, each control mode is operated in the following manner:

1. Direct-view joint actuation: Using a joint-actuation joystick, the operator deploys the crane manipulator to a location where overall view of the task space is available.

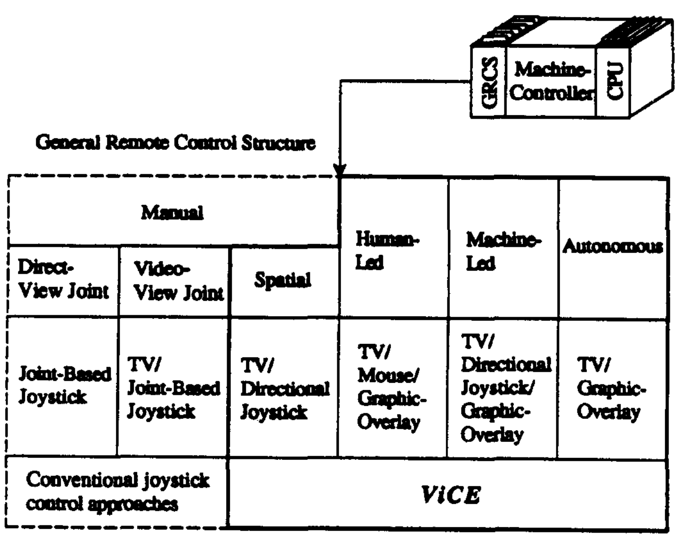

FIG. 2. General Remote Control Structure (GRCS)

   This conventional manual operation does not involve video cameras or TV monitors.
2. Video-view joint actuation: The operator deploys the manipulator using the same join-actuation joystick in the site office. A TV monitor and two video cameras, one for global view and the other for local view, provide video images.
3. Spatial: Watching a TV monitor, the operator deploys the manipulator with a directional joystick. The operator indicates the direction of the next intermediate path in 2D space. The machine controller then automatically actuates each joint of the crane boom to reach the designated position. The operator repeats this operation until the goal position is reached.
4. Human-led: Playing a supervisory role, the operator deploys the manipulator based on the graphic interface. Relying on visual and numerical sensory feedback, the operator monitors the advancement of the manipulator. If the human operator designates an intermediate point on the path with a mouse, the machine controller calculates the required joint angles according to inverse kinematics. The controller then automatically advances the manipulator to the designated position.
5. Machine-led: Assisted by the machine controller, the operator deploys the manipulator based on the graphic interface. In this approach, the controller uses distance sensors to monitor whether the predefined manipulator path is clear of obstacles and visually guides the human operator. If the machine controller displays the next intermediate path on the TV monitor, then the operator moves the end-point of the manipulator using a directional joystick.
6. Autonomous: The manipulator is automatically deployed from a starting position to a goal position. The trajectory data generated from an off-line path planning are used for the automated deployment of the manipulator. Potentiometers are used to measure the actual joint angles and understand the configuration of the manipulator. The manipulator path is constantly updated. During the navigation, the controller analyzes sensory feedback data and interprets the presence of obstacles. When the manipulator approaches an obstacle, the machine controller automatically creates a new path in order to avoid collision.

FIELD EXPERIMENTS

The goal of the field experiment in this study was to comparatively evaluate the human-machine interface in a variety of task environments. For this purpose, the performance of the control modes in the GRCS were compared at increasing levels of task complexity. Although accuracy can be a measure to evaluate control performance, the evaluation needs to consider the effects of task complexities as well as operator skills. This paper, therefore, focuses on task completion time as a performance measure.

Experimental Setup

For the experiments, the hydraulic system of a bridge maintenance crane at the North Carolina Department of Transportation (NC DOT) was retrofitted. Proportional valves and a hydraulic pump were installed into the existing hydraulic system of the crane for accurate and smooth actuation of joint cylinders. The improved controllability of the new valve system made it possible to computerize the boom operation.

An experimental facility was built utilizing the testing bridge at the Bridge Maintenance Division of the NC DOT. The development of the facility included installation of a steel beam, digging of a trench, and construction of a control station under the bridge deck (Fig. 4).

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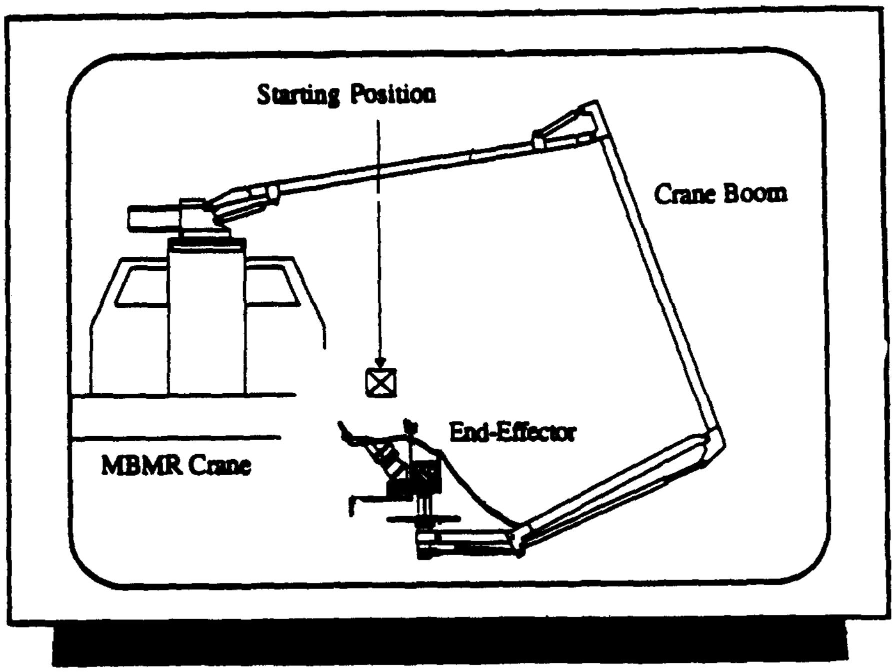
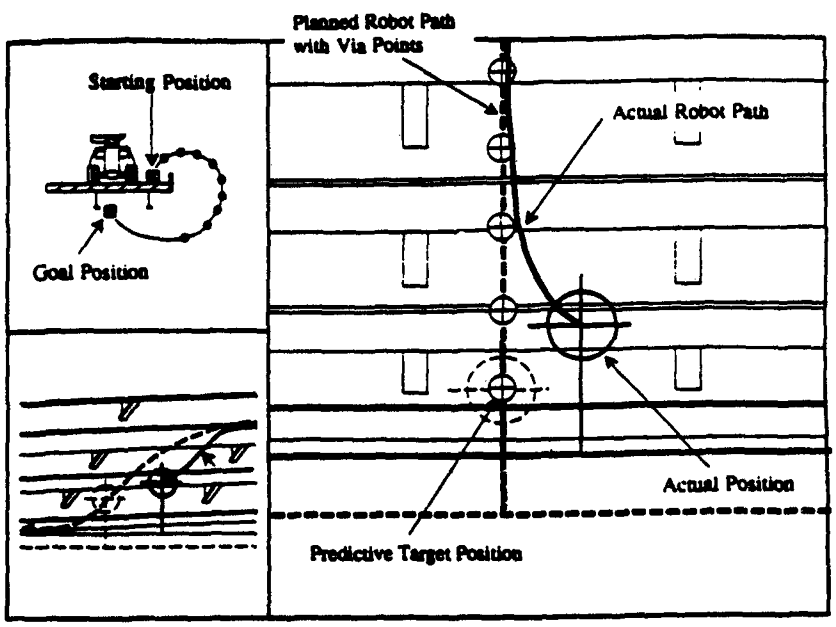


a)



b)

FIG. 3. (a) Global View of Graphic-Overlay for Virtual Human-Machine Interface; (b) Local View of Graphic-Overlay for the Virtual Human-Machine Interface

For joint sensing, potentiometers and inclinometers were installed on each joint of the crane. These sensor devices measured the position and orientation of the manipulator during the telerobotic operation of the crane. The data from the joint sensing were then used for automatic control of the manipulator as well as for juxtaposition of 3D CAD graphics onto live camera images.

For the graphic interface, the conceptual model discussed in the previous section was developed into an actual working model. Figs. 5(a) and (b) show the experimental setup. One TV monitor with two cameras presented graphic overlay from varying distances and view angles. The TV monitor was used for both the global view and the local view. The change from a global view to a local view, and vice versa, was made with a screen switcher.

Representation of Task Complexity

Five levels of task complexity were assumed for this experiment. Simulated obstacles were installed in the manipulator path (Fig. 6). The number of obstacles was increased to indicate the task complexity from level 1 to level 5. Complexity level 1 was represented without any obstacles except the bridge structure; complexity level 2, with an obstacle under the bridge beam; complexity level 3, with two obstacles under the bridge beam; complexity level 4, with the addition of one obstacle on the ground and another outside of the bridge deck; and complexity 5, with the addition of one more obstacle near the goal position. Since obstacles were added arbitrarily, the increment of increasing task complexity was not necessarily constant.

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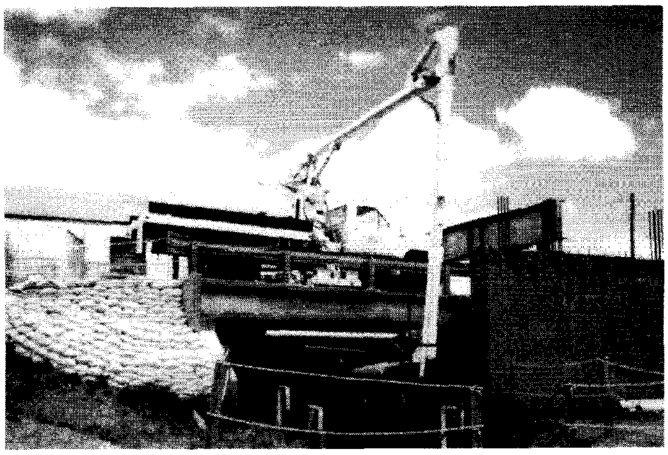
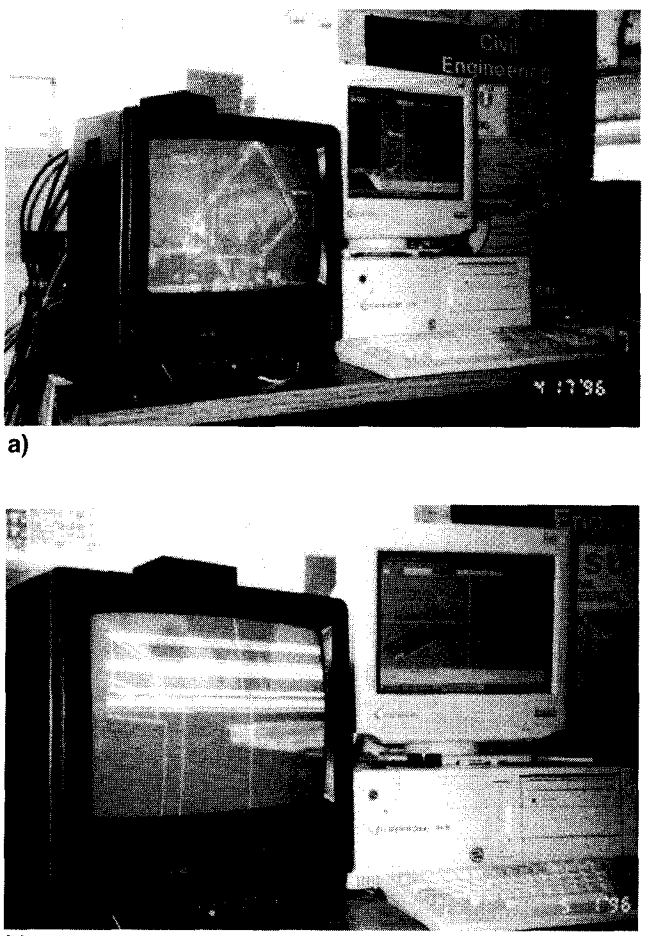


FIG. 4. Experimental Facility



a)

b)

FIG. 5. (a) Global View of Experimental Setup for Graphic Interface; (b) Local View of Experimental Setup for Graphic Interface

During the test, operators had to move the crane boom around the obstacles and reach the goal position. The obstacle interference caused a delay of task completion. The effects of task complexity on control performance were then analyzed to determine which control mode is more effective for a certain task requirement.

PERFORMANCE EVALUATION

This experiment was intended to explain the effects of task complexities on task completion time. The question in evaluating the effects is whether the approaches in the graphic-based control environment can provide a mechanism flexible enough to execute complex tasks. Consequently, the hypothesis for the experiment was that, since the proposed human-machine interface have different degrees of automation, the control systems in the C^2F have different sensitivities to the increase of task complexities.

Four skilled operators performed the tests varying the level of task complexities from level 1 to level 5. To eliminate learning effects, the sequence of the tests were selected randomly. All the operators deployed crane under the bridge deck using the six control modes in the GRCS: DVJA VVJA, spatial, human-led, machine-led, and autonomous. Each control mode was repeated 20 times, totaling 120 times for all six modes.

Regression Analysis

A regression model was developed to graphically represent the relation of expected task completion time with the increase of task complexities (Fig. 7). Linear regression appeared to be sufficient for this analysis because the data were scattered significantly. The simple function used for this representation is as follows:

$$Y = aX + b \quad (1)$$

Here, X indicates the level of task complexity, and Y indicates the predictable task completion time. The slope, a, indicates the rate of the performance variation as the level of task complexity increases. The intercept. b, represents the basic increment on which the additional amount of task completion time should be added on the next task level.

The result of the data analysis showed that DVJA mode was insensitive to the increase of task complexity with an initial value of 2.95 min. and a slope of 0.27 at complexity level 1. On the other hand, the VVJA mode has the highest slope, 0.98, with a task completion time of 7.52 minutes at complexity level 5. Spatial mode also resulted in a high slope of 0.63 with the task completion time of 6.96 minutes at complexity level 5. Although human-led and machine-led modes showed high task completion time of 5.48 and 6.07 minutes respectively at complexity level 1, their low slopes of 0.27 and 0.20 indicate slow learning effects. As a result, although VVJA and spatial modes performed faster than human-led and machine-led modes until complexity level 3, their performance became slower at complexity levels 4 and 5. The autonomous mode performed well, almost equaling the performance of DVJA mode at all complexity levels.

Trend Analysis

A statistical trend analysis, or contrast test, was used to quantitatively indicate whether there are any significant differences in control performance at any two levels of task complexity. This contrast test was based on statistical t test. The R^2 values show the correlation between the control performance and task complexity. In general, the larger the R^2 values are, the better the model fits.

The F values show how well the model as a whole accounts for the behavior of dependent variables. The overall p value, $P_r > F$, indicates the probability of getting a value larger than the F value if the parameter is truly equal to zero. A very small probability leads to the conclusion that the independent variable contributes significantly to the model. The p values for the contrast between two complexity levels indicate whether the result is significant enough to be within 5% confidence.

Table 1 summarizes the outputs of the statistical trend analysis. The VVJA, spatial, and autonomous modes showed significant correlation to task complexity, as evinced by the R^2 values 0.74, 0.74, and 0.73, respectively. Overall p values indicate that these three control modes were highly affected by a change in task complexity.

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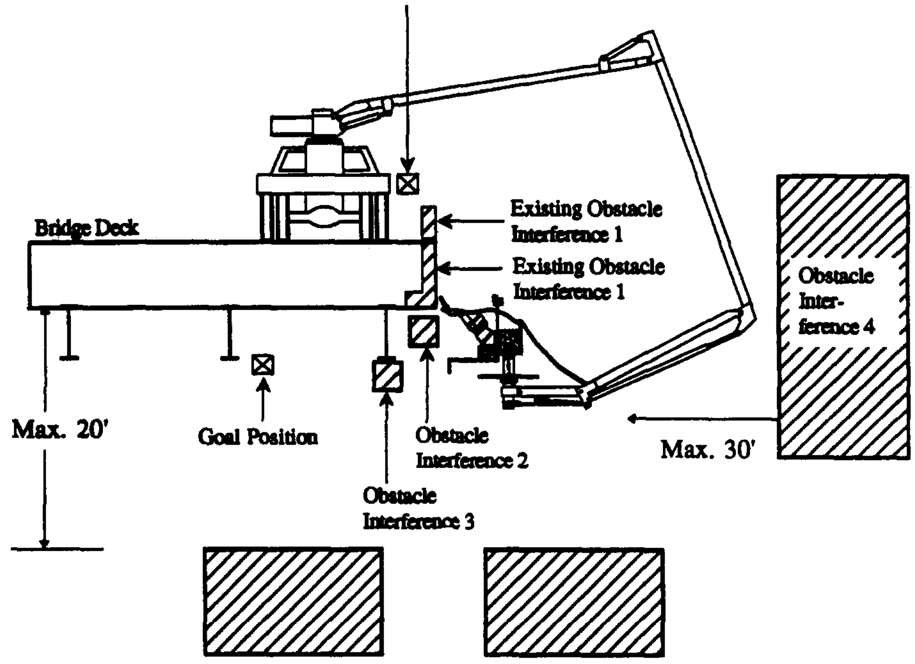

FIG. 6. Representation of Task Complexities Using Simulated Obstacles

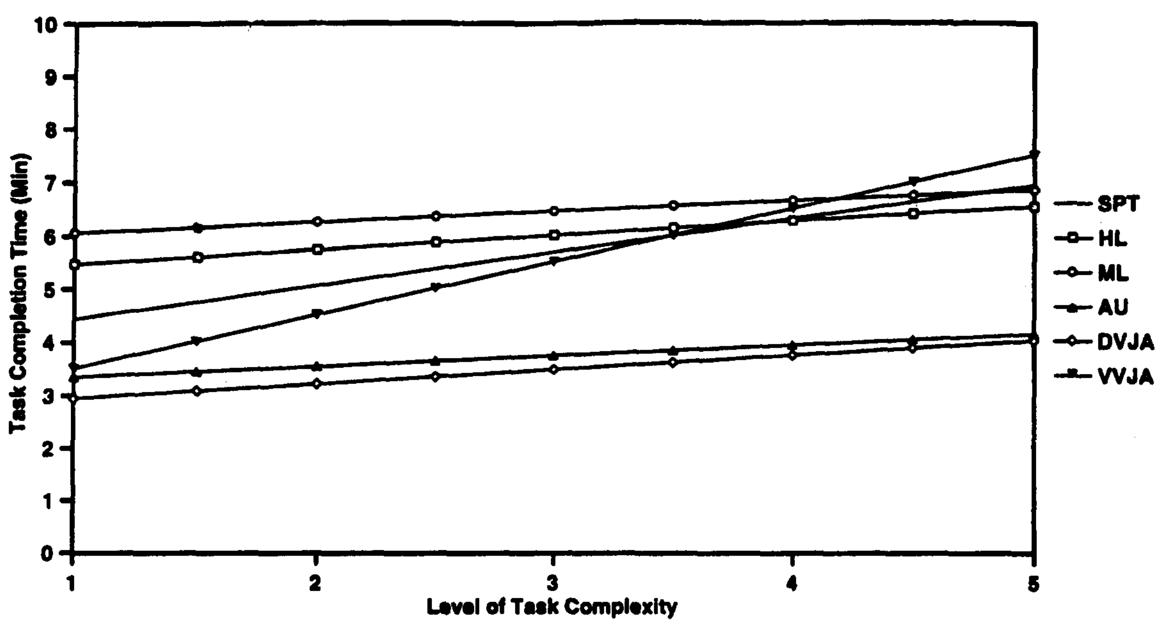

FIG. 7. Trends of Control Performance for Each Control Mode

TABLE 1. Summary Table of Parameters for Trend Analysis

Control mode (1)	R^2 (2)	F (3)	$Pr > F$ (4)	*p* Values for Contrast between Two Complexity Levels: Level 1–2 (5)	Level 2–3 (6)	Level 3–4 (7)	Level 4–5 (8)	Level 1–5 (9)
DVJA	0.32	1.75	0.19	0.95	0.44	0.23	0.74	0.12
VVJA	0.74	10.56	0.00	0.24	0.50	0.01	0.52	0.00
Spatial	0.74	10.71	0.00	0.55	0.29	0.01	0.25	0.00
Human-led	0.25	1.23	0.34	0.26	0.59	0.81	0.80	0.11
Machine-led	0.22	1.07	0.41	0.55	0.53	0.88	0.64	0.08
Autonomous	0.73	10.07	0.00	0.34	0.22	0.04	0.54	0.00

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In the contrast test between two complexity levels, the DVJA mode had relatively high p values—0.95, 0.44, 0.23, and 0.74. These high p values indicate that the control mode is slightly affected by an increase of task complexity except between level 3 and level 4. The VVJA and spatial modes are significantly affected by the increase of task complexity between level 3 and level 4 considering the low p values of 0.01. Human-led and machine-led modes had relatively low p values in every increment of task complexity. The autonomous mode is moderately influenced by an increase in task complexity except between level 3 and level 4. The contrasts between complexity level 1 and level 5 were significant for all control modes.

Discussion of Results

This experiment assessed the performance of the control modes in the GRCS. The results shows the expected behavior of the human-machine interface during the telerobotic operation of construction manipulators. In the regression analysis, the control modes responded differently to a change in control requirements. Fig. 7 indicates that human-led and machine-led modes are not very sensitive to a change in task complexity. Although their initial task completion time was higher than that of the VVJA and spatial modes, the graphic-based modes in the GRCS performed better as the complexity increased beyond level 3.

In the statistical trend analysis, the insensitivity of the human-led and machine-led modes to task complexity were quantitatively represented. In each increment of task complexity, the p values ranged above 0.50, indicating no significant changes in the output of control performance. The consistency in the output indicates that these control approaches can be effectively used even when there are obstacles in the manipulator path.

The varying sensitivity of each control mode in the GRCS is attributed to the fact that the human operator and the machine controller play different roles in the control loop. Since the control modes have different degrees of automated machine control, they response differently to task complexity. The partial automation in the human-machine interface enables the operator to flexibly advance the manipulator by sharing control responsibilities with the machine controller. Through the human-machine interface, the intelligence of the machine controller helps the operator to overcome obstacle interference. The increased controllability, in turn, suggests that the control system in the C^2F should be implemented flexibly depending on the task requirements on the construction site.

The overall results suggest that in real implementation a control method should be selected and implemented after a careful assessment of construction operation. The schedule of construction activities should be evaluated to identify possible work space interference with construction crews, equipment, and materials. The site conditions should then be assessed for the difficulty involved in carrying out manipulator control. Based on the assessment, the supervisory control should be applied flexibly to maximize the system effectiveness of telerobotic operation.

Limitations of Experiment

The task complexity was represented by installing obstacles around the manipulator path. The number of obstacles were increased to indicate the next level of task complexity. The simulated obstacles, however, do not necessarily reflect actual site conditions that may be encountered during manipulator control. As a result, although the study results provide general understanding of the human-machine interface, the control performance can vary for any particular situation as the task environment changes. It was assumed in this study that the structural shapes and the locations of obstacles were known; that is, the operator had knowledge of task environment. Under this assumption, the autonomous mode performed well despite task complexity.

CONCLUSION

There is a significant need to improve manipulator control in the construction industry. Advanced control methods can provide many opportunities to increase the safety and productivity of construction equipment. The human-machine interface presented in this paper permits human operators' decision-making and control skills as a part of the overall control architecture. This study demonstrates that it provides a mechanism for efficient manipulator control under increasing task difficulty on construction sites. The interface in the graphic-based control mode increased the controllability even for complex task requirements. The study results suggest that it could be implemented flexibly depending on the construction task and the preference of the operator. The identified problems and needs can be used as a reference point for exploring telerobotic construction operation.

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