Graphical Control Interface for Construction and Maintenance Equipment

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Abstract: This paper discusses graphical interfaces to improve equipment control in construction and facility/infrastructure maintenance environments. Most large construction and maintenance machines are difficult to control because of insufficient visual feedback to equipment operators. In many emerging applications such as hazardous waste cleaning, it is also necessary to control such equipment from a distance using teleoperation techniques. Initial evidence indicates that real-time updated graphical representation of equipment and work environments can enhance equipment control by providing better spatial perception to the equipment operator. Real-time simulation and task planning with graphical models can also ensure safe and reliable operation of equipment. However, graphical control interfaces require careful design for successful results as it is very difficult to generate exact graphical models of unstructured and dynamic environments such as construction and maintenance. Design of graphical control interfaces for construction equipment also requires knowledge in various technological areas. In this paper, design issues and principles for graphical control interfaces for construction and maintenance equipment are presented. The usefulness of graphical control interfaces is also presented through performance tests of a teleoperated clinker clearing robot for power plant maintenance.

INTRODUCTION

Equipment operated in construction and facility/infrastructure maintenance environments can be difficult to control. Large size and the operator's insufficient visual feedback on the constantly changing status of equipment and work environments make equipment control difficult. In addition, the operator often can be overwhelmed by the amount of information required for the equipment operation. This information involves work environments, equipment status, and tasks to be accomplished.

In many emerging applications such as hazardous waste cleaning, it is also necessary to control such equipment from a distance using teleoperation techniques in which the visual feedback is significantly limited. Teleoperated systems usually use video and audio feedback as well as control sticks and buttons at a remote operator workstation. Early systems were functional but were handicapped by lack of spatial perception and peripheral vision, and they quickly induced operator fatigue (Haas et al. 1995).

There have been many efforts to improve the control of construction and maintenance equipment. These efforts have usually involved the use of computers and sensors. The development of automated equipment or robots was also possible as control techniques advanced. Among the emerging technologies to improve equipment control is the use of graphical control interfaces with real-time updated graphical models of equipment and work environments. In the graphical interface based control scheme, the operator controls the equipment based on graphical representations of the current status of equipment and work environments updated by sensor data.

A graphical environment provides an excellent interface to equipment operators. Graphical features such as viewing and zooming provide better spatial perception to operators. Real-time simulation and task planning with graphical models can also ensure the safe and reliable operation of equipment. In addition, graphical interfaces can assist the operator to plan, measure, and record work progress by integrating design or as-built CAD databases with graphical models of equipment and work environments. In many construction cases, where specific goals are to be achieved, this feature of graphical control interface is very critical for equipment control. Design information stored in a CAD database, such as a grade line for excavation, tells the operator what to do by providing target information. Measurement activities involved in equipment operations can be eliminated by presenting the design information and the current status of work environments and equipment together.

The use of graphical models for equipment control in construction and maintenance environments, however, has limitations. It is very difficult to generate exact graphical models in such quickly changing environments (Haas et al. 1995). Therefore, graphical control interfaces for construction equipment should be carefully designed for successful results. Design of graphical control interfaces also requires knowledge in various technological areas. However, design issues for graphical interfaces for equipment control in construction and maintenance environments have not been previously identified, and necessary design principles have not been developed.

This paper presents design issues and principles for graphical control interfaces for construction and maintenance equipment. Existing graphical control systems for construction and maintenance equipment are reviewed. Based on the investigation of existing systems and the background information on other core technologies required for graphical control interface implementation, the design issues are identified and necessary design principles are proposed.

The usefulness of graphical control interfaces is also presented through performance tests of teleoperated power plant maintenance equipment. The teleoperated equipment is intended to break rock-like lignite ash-buildup, also known as "clinkers," in the power plant furnace hoppers. The robot was developed to improve conventional clinker clearing methods that are laborious, physically dangerous, unpleasant and dirty, and require large forces. The graphical control interface designed based on the proposed design principles improved the equipment control significantly over a direct video interface.

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J. Constr. Eng. Manage., 2000, 126(3): 210-218

EXISTING GRAPHICAL CONTROL INTERFACES

A total of 12 graphical control interface systems was reviewed. Table 1 shows the reviewed graphical control interfaces and their features. The first column of Table 1 shows types of equipment that utilize a graphical control interface. For two of the reviewed systems that were not developed for a specific type of equipment, descriptions of the graphical control interface with applicable types of equipment are included. The selected features for the reviewed systems are the key elements for graphical control interface design and implementation. These features were compared and analyzed to identify design issues and to develop design principles.

Many types of equipment utilize a graphical control interface including traditional earth-moving equipment and specialized maintenance equipment. In many cases, graphical control interfaces were used to improve the performance of teleoperation. However, two applications (road compactor and computer-aided earth-moving system) were on-machine type applications mainly designed for productivity improvement. Organizations developing graphical control interfaces appear to be broadly based, including academic institutes, government research institutes, and private firms. Most of the existing graphical control interfaces are in the prototype test stage except for two Japanese cases (pneumatic caisson excavator and dredger), and two U.S. cases (computer-aided earth-moving system and automated road maintenance machine). This reveals that the graphical control interface technique is still emerging.

DESIGN ISSUES AND PRINCIPLES

Various issues are involved in the design of a graphical control interface for construction and maintenance equipment. These design issues are discussed in this section. Alternatives for identified design issues are presented, and design principles are also proposed based on the review of the existing systems and background information on key technologies for graphical control interface. Three categories of design issues are discussed: architecture design, graphical representation design, and graphics update scheme design.

Architecture Design

A system including both hardware and software modules is required to implement a graphical interface for equipment control. System architectures of graphical control interfaces vary according to their functionality in assisting equipment operation. Necessary system components and different types of graphical interface architectures are discussed, and principles for selecting an appropriate graphical interface type are suggested.

Components

For the hardware, four classes of components are required: (1) Input devices; (2) displays; (3) computers; and (4) sensors. For the software of a graphical interface system, three different modules are required: (1) graphics module; (2) sensor data processing module; and (3) controller interface module. The graphics module stores graphical models and displays real-time updated graphics to assist equipment operation. The sensor data processing module is required to convert raw sensor data into usable data to update graphical models. The controller interface module is needed for the interaction between the graphics module and the equipment controller that has direct interaction with the mechanical subsystems of equipment.

Types of Architecture

The architecture of a graphical control interface varies according to its functionality in an equipment control system. In practice, however, graphical control interfaces can be divided into two architectural classes, active and passive.

Active Graphical Control Interface. A graphical control interface system forms a part of an equipment control system. The architecture of a complete equipment control system that employs an active graphical interface is described in Fig. 1. With this type of graphical interface, the operator can perform real-time simulation and task planning by manipulating graphical models. The simulated or planned commands are verified and then passed to the equipment through the controller interface module. The operation can then be monitored with the real-time updated graphical models or live views while the graphically generated motion commands are automatically executed. The graphical control interfaces with the path planning control mode, among the reviewed systems of Table 1, fall into this category. The control architecture with an active graphical interface fits into the supervisory control model suggested by Sheridan (1992).

Passive Graphical Control Interface. Graphical models are updated as the status of equipment and work environment change, but no task planning or simulation with graphical models are employed in this type of graphical interface. Fig. 2 shows the system architecture of a passive graphical control interface system. The operator gets enhanced visual feedback from a graphical display, but the operator controls equipment directly through the equipment controller. Therefore, a controller interface module is often not required, or minimal interactions between the controller interface module and the controller, such as emergency stop signals, exist. Graphical control interfaces with the monitoring control mode in Table 1 belong to this category. This type of graphical interface helps the operator's decision making simply by providing an additional source of visual feedback to a direct line of sight or closed-circuit television (CCTV) feedback. More than that, it also acts as a measurement system and a recorder of progress and work completed. An equipment control system that employs a passive graphical interface can be classified as the computer-assisted manual control model suggested by Sheridan (1992).

Comparison and Selection Criteria

For an active graphical control interface, entire objects in the work environment that could potentially affect the equipment operation should be modeled, which is often difficult to achieve in unstructured and dynamic construction environments (Haas et al. 1995). Graphically planned equipment operation based on false or incomplete graphical models could cause accidents including collisions between the equipment and objects not included in the graphical model. On the other hand, a passive graphical control interface can exclude some portion of the work environment if the operator can get visual feedback for the missing portion from other sources. For example, in the CAD integrated excavator case in Table 1, the desired grade line is graphically presented to the operator, but the actual soil profile is not presented. With the passive graphical control interface employed, the operator could improve the manual operation by intermittently comparing the graphically presented position of the excavator's cutting edge to the desired grade line during operation (Huang and Bernold 1997). For an active graphical control interface, however, the soil profile and obstructions such as underground pipes should be modeled because the operator cannot graphically simulate or plan the path of the excavator's bucket only with the graphical models of the excavator and the design information (the grade line). Therefore, passive type interfaces are more appropriate when complete work environment models are not available, and the operator must resort to live visual feedback frequently.

Because of difficulties in work environment modeling in construction and maintenance environments, an active graph-

J. Constr. Eng. Manage., 2000, 126(3): 210-218

TABLE 1. Existing Graphical Control Interface Systems for Construction and Maintenance Equipment

Equipment (1)	Graphics type (2)	Control mode (3)	Sensor (4)	Control station (5)	Live view (6)	Graphics model (7)	Developer (8)	Development stage (9)	Sources (10)
Nuclear waste cleaning robot	3D	Monitoring Path planning	Encoders[a] Ultrasonic[b] Structured lighting[b]	Remote	CCTV	Tank geometry Waste surface-profile Robot	Sandia National Laboratory	Full-scale test	Christensen (1993)
CAD-integrated excavator	3D	Monitoring	Encoders[a] 3D laser positioning[a]	On-board Remote	Direct view	Desired grade line Excavator	North Carolina State University	Prototype field test	Huang and Bernold (1997)
Pneumatic caisson excavator	2D	Monitoring	Encoders[a] Ultrasonic[b]	Remote	CCTV	Excavator Caisson Soil profile	Kajima Corp. (Japan)	In operation	Harada et al. (1990)
Road compactor	2D	Monitoring	2D laser positioning[a] GPS[a]	On-board	Direct view	Road profile Compactor	Road Test Center (France)	Prototype field test	Froumentin and Peyret (1996)
Space construction robot	3D	Monitoring Path planning	Encoders[a] Machine vision[b]	Remote	CCTV[c]	Space robot Satellite module	Jet Propulsion Laboratory	Full-scale test	Bejczy et al. (1994)
Computer aided earthmoving systems: dozer, scraper	3D	Monitoring	GPS[ab]	On-board	Direct view	Desired grade line Equipment	Caterpillar, Inc.	Prototype field test	Caterpillar (1996)
Dredger	2D	Monitoring	GPS[a] Ultrasonic[b]	Remote	CCTV	Underwater soil profile Desired bottom profile Dredger Sledge collector	Mitsubishi & MEC Engineering	In operation	Ogasawara et al. (1996)
Landfill compactor	3D	Monitoring Path planning	GPS[ab]	Remote	CCTV	Compactor Site profile	University of Wisconsin	Mapping module	Tserng et al. (1997)
Large scale manipulator	2D	Monitoring	Encoders[a]	Remote	Direct view	Work envelop Manipulator—wrist joint	University of Texas	Laboratory test	LeBlond et al. (1998)
Automated road maintenance machine	2D	Monitoring Path planning	Encoders[a] Machine vision[b]	Remote	CCTV[c]	Planned path	University of Texas	Field test	Haas et al. (1997)
Augmented display system: teleoperated equipment	3D	Monitoring Path planning	Encoders[a] Machine vision[b]	Remote	CCTV[c]	Robot manipulator	University of Toronto	Prototype field test	Rastogi (1996)
Construction manipulator	3D	Monitoring Path planning	Encoders[a] Machine vision[b]	Remote	CCTV[c]	Bridge geometry Manipulator	North Carolina State University	Prototype field test	Moon and Bernold (1998)

[a]Equipment sensor.
[b]Work environment sensor.
[c]Graphical models overlaid on CCTV.

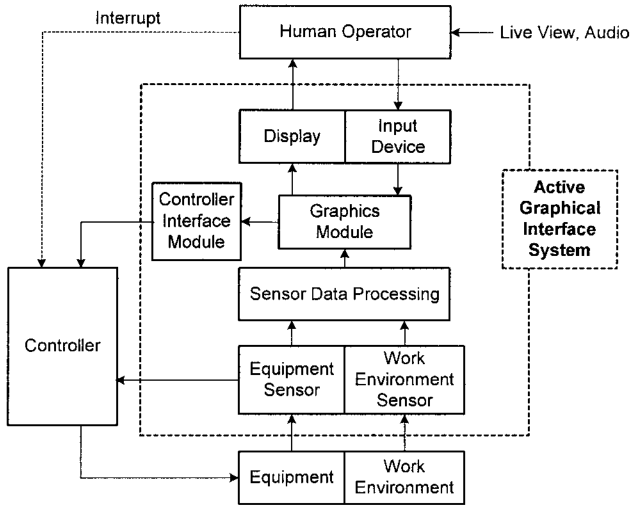

FIG. 1. Architecture of Active Graphical Control Interface

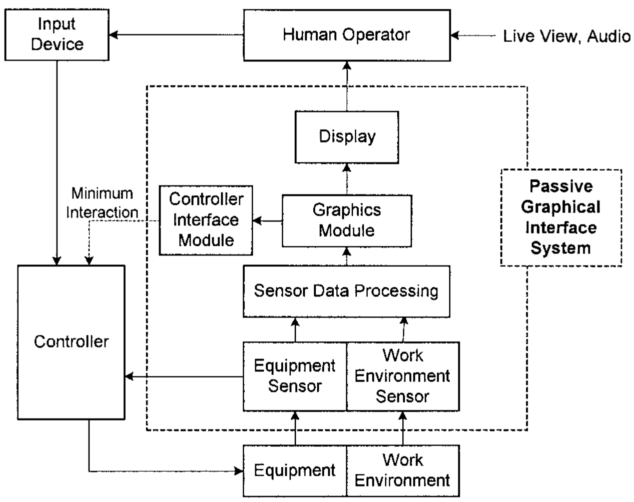

FIG. 2. Architecture of Passive Graphical Control Interface

ical control interface is more appropriate for situations where a real-time simulation and task planning functionality is absolutely required such as the time-delayed teleoperation of the space construction robot (Bejczy et al. 1994). When the motion planning of equipment is relatively simple, or the operator controls equipment while onboard, a passive graphical interface becomes a more appropriate approach.

With a hybrid-type interface that combines graphical models and live visual feedback into a single visual source, the operator can simulate equipment path before execution by running the graphical models of equipment over the video background. For 3D operations, however, serious calibration processes are required for the graphical models of equipment to be matched with the camera views, as found in the space construction robot and the augmented display system cases in Table 1 (Bejczy et al. 1994; Rastogi 1996).

Graphical Representation Design

Design of a graphical representation scheme is of great importance for the effective delivery of information on equipment and work environment. Research studies on graphics aids for teleoperation, which were performed in simulated environments, revealed that different graphical representation schemes, such as operator's response time and quality of decisions, greatly affect the operator's performance (Das et al. 1989; Browse and Little 1991). Design issues for this category are types of graphics, abstraction, viewing, and colors.

Types of Graphics

Graphics aids for equipment control can be classified based on dimensionality (2D or 3D). The graphics type should be carefully selected because 3D graphics with their high fidelity allure are often selected where 2D graphics can meet the needs (Ince et al. 1993).

2D Graphics. When equipment is operated on a flat surface or a relatively flat surface on which depth information can be ignored, the equipment operation can be described with 2D graphical representations. For the road compactor in Table 1, 2D rectangle elements were used to represent the equipment and the plan view of the roadway (Froumentin and Peyret 1996). In many cases, 2D representations of different views can satisfactorily describe equipment operation in 3D space. In the case of the dredger in Table 1, a top view was provided for the positioning of the ship, and a side view orthogonal to the path of the sledge collector was provided to the operator (Ogasawara et al. 1996). However, it becomes difficult to represent the equipment operation with 2D graphics as complexity of equipment geometry, its operation, and work environment increases.

3D Graphics. High fidelity graphics can be achieved with solid or surface model based 3D graphics. Three-dimensional geometry models with camera models and lighting models are utilized in this graphics category. Real-time simulation for planning motion of equipment, for which 2D graphics have many limitations, can be performed with 3D graphics with collision detection functionality. Various rendering schemes such as shade, texture, and transparent are available in 3D graphics. For the design of a graphical control interface, a rendering scheme that can provide the best spatial perception to the operator should be selected. A robotic simulation study revealed that it is more helpful to have simple shadowing than photorealistic rendering for the spatial perception of the scene (Neugebauer 1992). Another type of 3D graphics scheme is wireframe model based graphics where edges of 3D objects are represented with line segments. More details on that type of graphics can be found in Seo (1998).

Abstraction

Real-world objects should be abstracted using various graphical primitives. To abstract real-world objects with graphical models for equipment control, simplification based on equipment operational characteristics can be considered. The simpler the graphical representation, the better the operator's decision making for equipment operation. Therefore, the simplest representation without the loss of critical information for equipment operation is desirable. Neugebauer (1992), in his robotic simulation experiment, reported that peripheral environments that are not directly related to the robot's task can be simplified with a limited number of polygons, whereas the workpiece handled by the robot should be modeled in more detail. The level of detail for the equipment operation should also be considered to determine the level of detail for abstraction.

Viewing

Viewing design affects the effectiveness of a graphical interface for equipment control, because the degree of the spatial perception of the operator can be very different with different views. In the case of 2D graphics, the viewing design at the initial development stage must be well thought out because once design is fixed, it cannot be changed. A viewpoint that is orthogonal to the equipment operation plane inherently provides the best view for operation. The views chosen for the dredger control interface (explained previously) is a good illustration of this type of viewpoint.

J. Constr. Eng. Manage., 2000, 126(3): 210-218

Although the viewpoints can be dynamically changed in 3D graphics, preselection of the most needed views is very helpful, because the operator may not be able to select the best views for specific operations or the operator may not have enough time for view changes during operation. Preselected views can also serve as reference views to which the operator can quickly return after exploring different views.

Colors

Distinctive colors can be used for different graphical items to help operators understand the situation clearly. Basic principles for the effective use of color can be found in various references such as Birren (1978). For graphical control interfaces, colors can be used to better describe the equipment operation in the following ways:

- Work environment presentation. A complex work environment can be effectively presented by using different colors. Two important notions in the usage of colors in work environment presentation are grouping and distinguishing. Grouping related items together or differentiating unrelated items can effectively be achieved with color coding. Distinguishing an item from other items can also be achieved by using contrasting colors (Chua 1997).
- Localization of equipment and work target. Color should be used to distinguish equipment and its components in work environments. Targets for equipment operation within work environments should also be distinguished with different colors.
- Impending collision. Warnings on impending collisions can be provided by changing the color of the relevant portion of equipment or work environments.
- Motion status or configuration of equipment. The configuration or motion status of equipment can be effectively represented by colors. For example, a bulldozer moving forward or backward could be represented with two different colors that are different from the color for a stationary state.
- Work progress indication. Different colors can indicate the progress of the work. For example, the number of passes achieved by the road compactor in Table 1 was represented with different colors (Froumentin and Peyret 1996).

Graphics Update Scheme Design

Several design issues should also be resolved to update graphics as equipment operation progresses. Sensing schemes should be designed to effectively detect changes in the status of the equipment and work environment. A data structure that can process and present acquired sensor data is also required. Design issues for this category are sensing, equipment kinematics, and work environment modeling and updating.

Sensing

Sensing is required to update the graphical models of equipment and work environments. The commonly used equipment sensors are angle encoders for revolute joints, linear encoders for prismatic joints, gyroscopes for orientation of equipment body, and positioning systems for position and orientation of equipment base. The sensors for updating work environment models include machine vision systems, ultrasonic range sensors, laser range sensors, radar, and positioning systems.

Maintaining graphical models of construction and maintenance environments for equipment control purposes is difficult. For the design of sensing schemes, the equipment operational characteristics should be considered. Issues such as model accuracy versus computational efficiency should be studied to facilitate real-time implementation of the graphical models. Another issue that should be investigated is the desired update rate of the dynamic graphical model and its relationship to increased efficiency of a given equipment operation. The choice of the sensor system should also be based on issues such as expense, ease of implementation, and durability.

Equipment Kinematics

To update the equipment model based on sensor data, the motion of equipment components should be defined by kinematic models. In the case of a bulldozer, the roll and pitch motion of the blade should be defined in addition to the position and orientation of the bulldozer body. Sensors attached to the blade can measure the variation of the blade angles. A kinematic model that can represent the rotation of the blade with respect to the newly updated position and orientation of the bulldozer body is required. For equipment with multiple degrees of freedom, such as the space construction robot and the large scale manipulator in Table 1, more mathematically complex kinematic models are required. Many references on equipment kinematics are available (Craig 1993).

Work Environment Modeling and Updating

The following four cases may be considered for modeling and updating work environments: localization, parametric modeling, mapping, and occupancy array. The localization method can be used when the shape and size of the objects in the work environment are uniform, but their position and orientation change over time. The parametric modeling method can be used when objects in the work environment can be modeled with parametric graphical primitives such as cubes and cylinders, but the size or magnitudes of the objects are not known. The necessary parameters obtained from sensors are assigned to the parametric graphical primitives.

For objects with irregular and changing shapes, mapping with wire mesh or polygon mesh is required, because it is difficult to assign parametric graphical primitives to these shapes. The occupancy arrays can also be used to model irregular shapes. Three-dimensional space occupied by irregularly shaped objects can be filled with occupancy arrays. The most common array type is the cube (Foley et al. 1990). The size of occupancy arrays depends on the accuracy required for the equipment operation.

APPLICATIONS EXAMPLE

Graphical Control Interface of Teleoperated Power Plant Maintenance Equipment

A graphical control interface was designed for a teleoperated power plant maintenance robot based on the design principles proposed. The description of the power plant maintenance operation, the robotic equipment, the design of the graphical control interface, and the result of the performance test are presented in this section.

Description of Power Plant Maintenance Operation

Lignite-fired electric power facilities produce clinkers with varying hardness. The clinkers accumulate along the boiler hopper walls and continuously drop to the bottom into a cooling pool of water (Haas 1995). As shown in Fig. 3, the hopper is composed of a main structure that contains cooling water and a gate housing structure with a grinder and hatch opening. A sluice gate is used to allow the flushing of the hopper contents. Some clinkers get stuck before they reach the grinder, and others are simply too large to be handled by the grinder. These clinkers must be dislodged and broken into small pieces either to be processed by the grinder or to be manually removed.

Clearing clinkers is a dangerous operation. Workers are required to wear cumbersome, hot suits and to manipulate a long, heavy steel rod connected to a jackhammer. One worker should position the front end of the steel rod to a clinker through the hatch opening, and at least two workers should manipulate the jackhammer connected to the back end of the rod to dislodge and break clinkers. Controlling the jackhammer and steel rod combination with their hands while in heavy protection suits exposes the workers to several safety hazards. The vibrations from the jackhammer can cause severe fatigue and internal injuries. The hot and humid environment quickly induces worker fatigue. In addition, the end of the rod can swing upward and impact a worker if hit by a falling clinker. Clearing clinkers while the furnace remains in operation, even at reduced output, increases the danger substantially. The conventional clinker clearing operation is laborious, physically dangerous, and requires large forces.

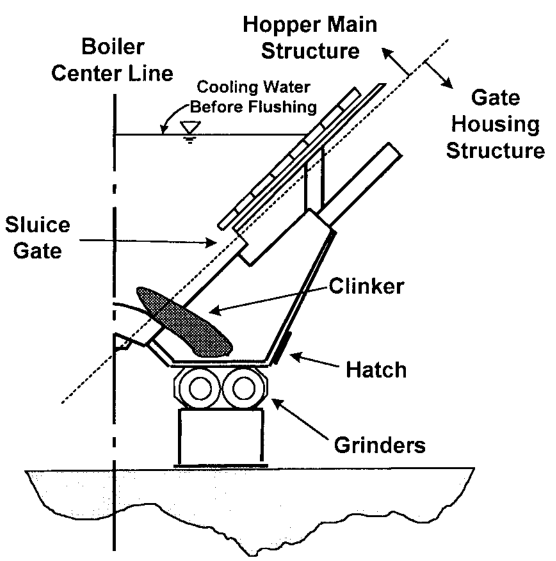

FIG. 3. Half of Bottom Hopper Structure of Power Plant Furnace

Teleoperated Clinker Clearing Robot

A teleoperated robot for the clinker clearing operation was developed by the University of Texas Field Systems and Construction Automation Group to automate the dangerous plant maintenance operation. Fig. 4 shows the geometry of the robot. Basically, the robot has three main components: (1) An arm with a pneumatic hammer attached at the front end; (2) an arm insertion mechanism and main cylinders; and (3) an attachment frame. The arm is inserted and retracted by six hydraulic cylinders installed inside the insertion mechanism. The two main cylinders extend and retract to rotate the insertion mechanism and the arm about a gimbal. After the pneumatic hammer attached at the front end of the arm is positioned near a clinker, the operator activates the hammer and breaks the clinker so that it can be handled by the grinder. The attachment frame is used to attach the robot to the gate housing structure for its working position. The robot is controlled from a distance using a control station. A CCTV camera is installed under the gimbal for remote control of the robot. Fig. 5 shows the robot installed on a hopper mock-up structure and the control station.

A graphical control interface of the robot was designed to improve the teleoperation with CCTV feedback that has an inherent depth perception problem. In addition, the visual feedback from a CCTV may be limited if the ash in the hopper obscures the vision. Unexpected collisions with the hopper structure during the robot operation are also a risk if the CCTV is the only source of visual feedback. The graphical control interface was also required for safe operator training without running the actual robot.

Architecture of Graphical Control Interface System

The robot has only three degrees of freedom. The motion planning of the robot is relatively simple, and predictive motion planning is not required if interferences with the hopper structure can be prevented with real-time control limits. Therefore, a passive graphical control interface was selected. A typical passive graphical interface system, as shown in Fig. 2, was designed for the clinker clearing robot. The graphical model of the clinker clearing robot is updated in real time only after the equipment state changes based on the sensor data from the robot's actuators. The clinker model is also updated and represented along with the static graphical models of the hopper environment. The operator gets the enhanced visual feedback by combining the live view and the real-time updated

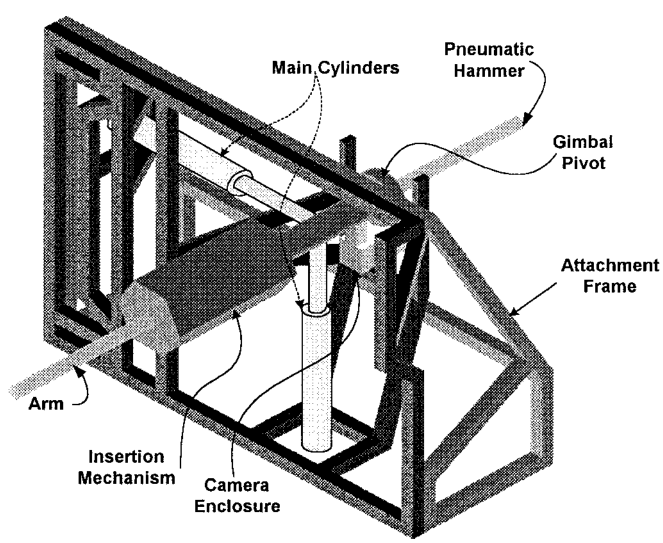

FIG. 4. Clinker Clearing Robot

J. Constr. Eng. Manage., 2000, 126(3): 210-218

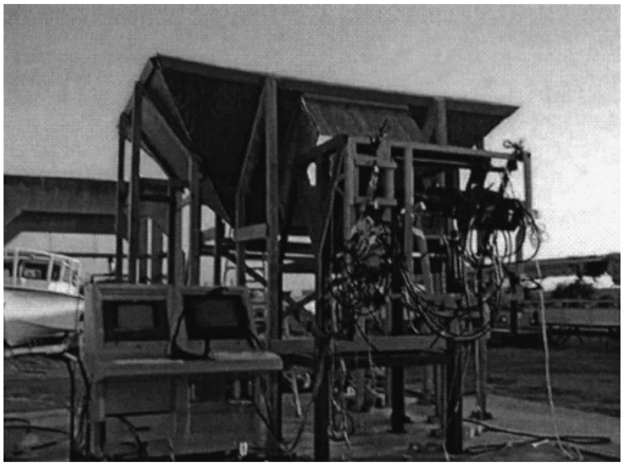

FIG. 5. Robot, Control Station, and Hopper Mock-Up

graphics, but the operator interacts directly with the robot for the motion control. Collisions between the robot and the work environment are avoided with real-time analysis of the graphical models.

Graphical Representation Design

Types of Graphics

The visualization of the hopper environment with 2D graphics was not sufficient to describe the geometric characteristics of the hopper. In addition, interference detection in 3D space was considered as one of the most important functionalities of the graphical control interface of the clinker clearing robot. Therefore, a solid model based 3D graphics design was selected for the graphics type.

Development Platform

A rack-mountable personal computer designed for industrial applications was selected as the hardware platform for the graphical control interface, considering the mobility requirement of the control station. For the software platform, a C++ based graphics library, OpenInventor (Wernecke 1994), and Microsoft Visual C++ compiler were used to develop a customized graphics program.

Abstraction, Graphical Primitives, and Rendering

Simplifications were required for the graphical control interface to provide a clear understanding of the robot operation to the operator. Fig. 6 shows the graphical interface screen with the selected graphical primitives. For the robot components, only the arm is shown to the operator, because the operator does not normally need visual feedback on the attachment frame and the insertion mechanism. For the hopper structure, only the inside surface was modeled, because the outside surface of the main hopper structure does not affect the robot's operations. Occupancy arrays that are composed of 152-mm (6-in.) cube cells were used to represent clinkers. The clinker model is explained in more detail in a later section. As shown in Fig. 6, a transparent rendering scheme was used for the walls of the main hopper structure and the gate housing structure so that the operator can see the robot arm through the hopper wall.

Viewing

As recommended by the viewing design principle, the two most needed views are initially provided as the reference views, as shown in Fig. 6. Since the CCTV camera provides a rear view, the combined CCTV view and two reference views (top and side) of the graphical interface provided the essential visual feedback to the operator. The operator can easily change the viewpoint and the zoom level from the reference views.

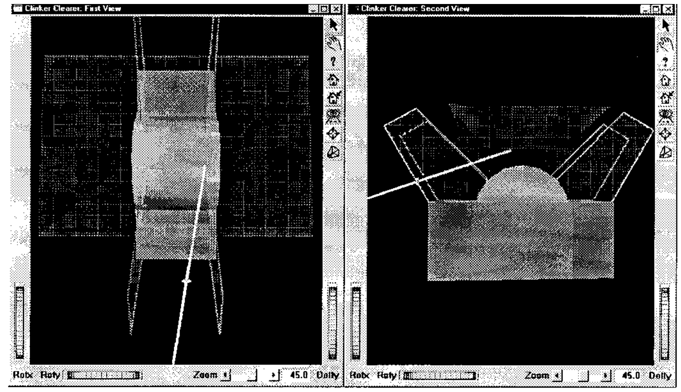

FIG. 6. Graphical Control Interface Screen

Color

Based on the principles on the usage of color for graphical control interfaces, the following color coding schemes were implemented:

- Work environment presentation. Graphics items for the left and right sides of the hopper structure were grouped together for color coding. The front, back, and side walls, and the round-shape hopper bottom portion are distinguished from each other with different colors.
- Localization of equipment and work target. Yellow was used for the arm to draw the operator's attention. Clinkers, the target of the equipment operation, are distinguished with a red color from the white side walls, the green front and back walls, and the blue bottom.
- Impending collision and motion status equipment. The color of the arm changes to red from yellow for warning when it gets into the prohibited zone to prevent collision with the hopper structure. The yellow color of the arm changes to brighter yellow and orange to indicate the insertion and extraction motions, respectively.

Graphics Update Scheme Design

Equipment Sensors and Kinematics

The main cylinders were equipped with linear transducers that report the cylinder length information in real time. A kinematic model was required to calculate the gimbal angles based on the cylinder lengths. The robot's arm inserted into the gimbal structure is rotated horizontally and vertically about the pivot point by two hydraulic cylinders, as shown in Fig. 4. A set of equations defining forward position kinematics was prepared to compute the robot's configuration based on the data obtained from the transducers. To detect the arm insertion length, two potentiometers were installed on the insertion and extraction cylinders. More details on the robot kinematics can be found in Saidi et al. (1998).

Work Environment Sensors

To update the graphical model of the clinkers, a laser triangulation method was used. This sensing scheme provides depth information from the CCTV camera to the clinker surface pointed by a laser beam. The range information from the camera image plane to the clinker surface is obtained from the

J. Constr. Eng. Manage., 2000, 126(3): 210-218

geometric relationship between the camera focal length, the physical laser offset, and the laser offset on the image plane (Seo 1998).

Clinker Model Update

To effectively update the clinker model by incorporating the sensor data, the occupancy array method was used. The 3D space of the inside of the hopper was divided into 152-mm (6-in.) cube cells that are not visible to the operator. If a point on the clinker surface is detected by the laser triangulation, the cube within which the point is located is considered occupied, and the cube becomes visible to the operator. Considering the 76-mm (3-in.) discrete movement of the insertion motion of the robot, a 152-mm (6-in.) cube cell to represent occupied space was used. Fig. 7 shows the graphical control interface screen with clinker models.

Tests and Evaluation

This section describes the tests performed with the developed graphical control interface system for the teleoperated clinker clearing robot. A mock-up structure, as shown in Fig. 5, was used for the accuracy measurement and the operator's performance test.

Accuracy Measurement

To check the accuracy of the graphical model of the robot, the end-effector position of the robot arm was measured. The average offset (distance between the measured data and the calculated data from kinematics) was 7 mm (0.28 in.), which is sufficient for the clinker clearing operation. The collision avoidance functionality tested with the mock-up structure was successful. The robot arm was stopped before actual collisions occurred and then allowed to move only in the safe direction. The accuracy of the laser triangulation sensing was also tested. The average error was 55 mm (2.16 in.) with decreasing accuracy as the distance to the target increases.

Operator's Performance Tests

The operator's performance with the developed graphical control interface system was tested by comparing the operator's performance of the CCTV based operation with that of the graphical control interface and CCTV combined operation. Fig. 8 shows one of the target setups prepared on the mock-up structure for the test, and its corresponding graphical control interface screen is shown in Fig. 7. Two different target

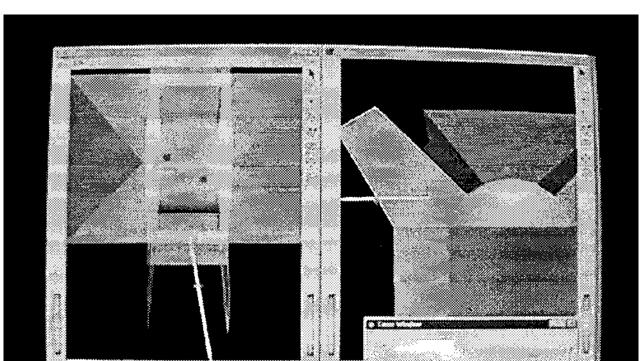

FIG. 7. Graphical Interface Screen of Target Setup

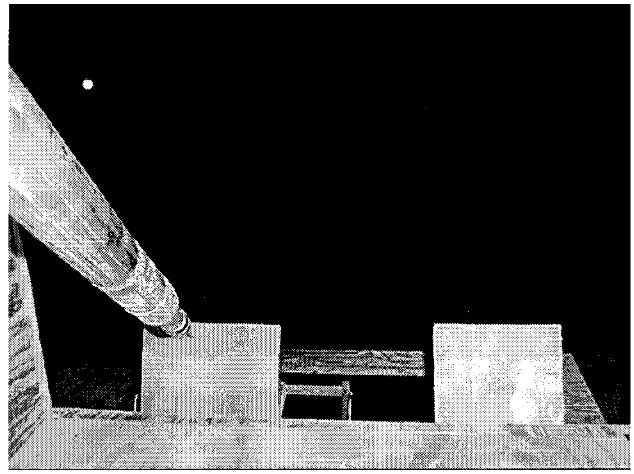

FIG. 8. Target Setup

setups with similar difficulties were prepared for the test. Two targets were placed with different depths for each target setup.

The subjects' task was to hit the targets with the end-effector of the robot's arm. The test subjects were asked to hit the front face of the targets with the end-effector and not to hit the targets from the side with another part of the arm. The side hits with other parts of the arm were considered as errors, because they mean the subjects misinterpreted the depth information. The subjects were also instructed to hit the closer target first to reduce the operation time. Therefore, the following three operational performances were adopted to measure the speed and the quality of the robot operation: (1) Job completion time; (2) side hit; and (3) order of hit (closer target or farther target).

Eleven subjects participated in the test. Each subject operated the robot based on the CCTV feedback and the combined feedback for the two different target setups. The subjects finished the operation 5 s faster on average when they used the combined system. The average finishing time of the CCTV based operation and the combined feedback based operation were 2 min 15 s and 2 min 10 s, respectively. The speed of the operation with the graphical control interface could be improved by reducing the time required for the laser triangulation to model the clinkers. Further investigations on the clinker sensing system will be valuable.

The subjects showed significant improvements in the quality of the work when they used the graphical control interface combined with the CCTV. Nine out of 11 subjects made mistakes, at least once, in detecting the closer target in the CCTV based operation. More importantly, five subjects hit the targets from the side when they used only the CCTV. This is clear indication of the depth perception problem that could induce damage or undesirable results during the robot operation. This test result, along with the collision avoidance functionality, shows the usefulness of the graphical interface for controlling the clinker clearing robot. Obscured vision caused by the smoke in the real hopper structure would make the graphical interface more valuable.

The robot's ability to break clinkers with the pneumatic hammer was also tested with actual clinkers (Saidi et al. 1998). The traditional clinker clearing process is a very dangerous operation that requires the presence of human workers beside the furnace hopper structure. The experimental results showed that the developed robot is fully functional and able to remove human workers from the dangerous conditions of the manual clinker clearing process.

CONCLUSIONS

This paper discussed graphical control interfaces for construction and facility/infrastructure maintenance equipment.

J. Constr. Eng. Manage., 2000, 126(3): 210-218

Design issues and principles based on comprehensive reviews of existing graphical control systems were presented. Designing a graphical control interface based on the suggested design principles is an effective approach for producing a graphical interface to improve equipment operation. A study on the development and the performance test of a graphical control interface for a teleoperated clinker clearing robot showed that the identified design issues should be rigorously addressed for the design of graphical interfaces for equipment control in construction and maintenance environments. The study also demonstrated the usefulness of graphical control interfaces. The use of graphical control interfaces that utilize real-time updated graphical models of equipment and work environments will continue to increase to improve the control of construction and maintenance equipment.

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J. Constr. Eng. Manage., 2000, 126(3): 210-218