A TELE-ROBOTIC SYSTEM WITH DYNAMIC GRAPHICAL INTERFACING FOR ELECTRICAL POWER PLANT MAINTENANCE

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ABSTRACT

A tele-operated robotic device for maintenance of lignite coal fired power plant is presented in this paper. The robot was developed to clear hardened lignite ash build-up (known as "clinkers") from the bottom hoppers of the power plant furnaces. The robot is a specially designed 3 D.O.F. manipulator to cope with the challenging hopper environment. A graphical operator interface with real-time updated graphical feedback of the robot and the work environment was developed for the robot control system to improve the tele-operation of the robot. A discussion of the experimental results on the performance of the robot is also included.

1. INTRODUCTION

Maintenance of electrical power facilities can be dangerous and costly. An environment of tremendous potential energy sources, enclosed spaces, and hazardous working conditions causes threats to health and safety. In the case of lignite fired power plants, clinkers which are hardened lignite ash in the bottom hopper must be cleared when they block or plug the flushing apparatus. Clearing clinkers by conventional methods is laborious, physically dangerous, unpleasant and dirty, and requires large forces.

A tele-operated robot for the clinker clearing operation was developed by the University of Texas Field Systems and Construction Automation Group. The developed robot, hydraulically actuated 3 D.O.F. manipulator, is remotely controlled with the aid of a graphical operator interface with real-time updated graphical feedback of the robot and the work environment. The robot was delivered to a station of the Houston Lighting & Power (HL&P) that has two 780 MW units. This paper discusses the design of the mechanical systems and the control system with a graphical operator interface as well as the experimental results on the performance of the robot.

2. CLINKER CLEARING OPERATION

Lignite-fired electric power facilities produce a byproduct of the combustion process referred to as "clinkers". The clinkers accumulate along the furnace hopper walls and continuously drop to the bottom into a cooling pool of water. The cooling pool serves to fragment the clinkers and to flush them out of the hopper [Carter 92, Haas 95]. As shown in Fig. 1, the hopper is composed of a hopper main structure that contains cooling water and a gate housing structure with a grinder and a hatch opening. A sluice gate separates the hopper main structure from the gate housing structure. This gate is opened to allow the flushing of the hopper contents. However, 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. The gate housing structure and the grinder are also shown in Fig. 2.

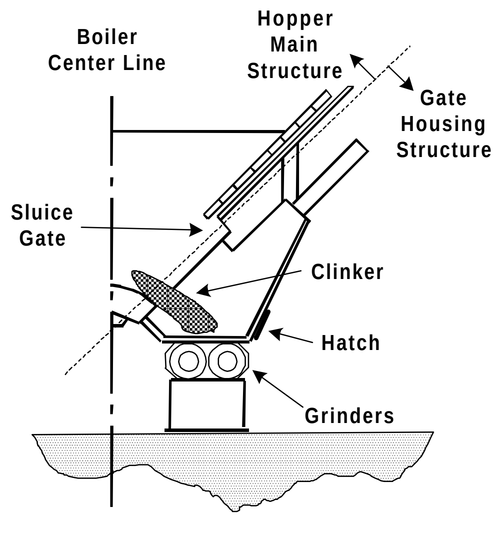

Fig. 1 Half of the Bottom Hopper Structure

Clearing clinkers is a dangerous operation. Workers are required to wear cumbersome, hot suits and to manipulate a long and heavy steel rod connected to a jack hammer. One worker should position the front end of the steel rod to a clinker through the hatch opening standing on a platform (the height of the hatch opening from the floor is about 8 ft). Normally two workers are required to manipulate the jack hammer connected to the back end of the rod. Another worker should support the middle portion of the rod. The workers should also push forward the rod and the jack hammer to break clinkers. Controlling the jack hammer and steel rod combination with their hands while in heavy protection suits exposes the workers to several safety hazards. The vibrations from the jack hammer can cause severe fatigue and internal injuries. The hot and humid environment easily 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. 2 Gate Housing Structure, Grinder, and Outer Environment

3. ROBOT DESIGN

3.1 Robot Specifications and Conceptual Design

To improve the dangerous and labor intensive clinker clearing process, a tele-operated clinker clearing robot was developed by the University of Texas at Austin. The UT-Austin and the plant workers at HL&P who have performed the manual clinker clearing operation identified the following robot specifications:

1) Tele-operation from a distance of eighty feet from the hoppe
2) Limitation on the set-up time (twenty minutes) and the working time (thirty minutes)
3) Ability to break clinkers into small pieces
4) Operating temperature (140 F to as high as 1200 F for short periods of time)
5) Ability to handle the flushing operation
6) Stable platform
7) Satisfactory reachabilit
8) Low-cost components inside the hopper to be sacrificed in possible impacts
9) Visual feedback and sensing

Considering above robot specifications, a customized 3 D.O.F. manipulator with an air hammer at the front end of the robot arm was designed. As shown in Fig. 3, the Degree of Freedom (DOF) of the robot includes two rotational degrees of freedom and one translational degree of freedom. To minimize of the loss due to the damage by falling clinkers, a simple pole was selected for the robot arm. Other design alternatives considered can be found in [Haas 1995].

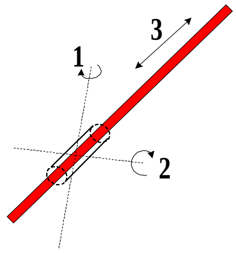

Fig. 3 Three DOF Spherical Robot

For the platform of the robot, the following two options were considered: 1) Forklift and 2) Attachment Frame. The attachment frame option was selected because the forklift-mounted system had problems associated with exact positioning of the forklift relative to the hopper. Access difficulties for the forklift after the flushing operation also discouraged the option. Therefore, the robot was designed to be anchored to the hopper structure so that it can perform the clearing operation through the hatch opening of the hopper.

Fig. 4 shows the geometry model of the robot. Basically, the robot has three main components: 1) a pole with a pneumatic hammer attached at the front end, 2) a pole insertion mechanism and main cylinders, and 3) an attachment frame. As represented in Fig. 4, the pole is inserted into the insertion mechanism. The pole is then inserted and retracted by six hydraulic cylinders installed inside of the insertion mechanism for the prismatic motion specified in the conceptual design.

For the two rotational degree-of-freedom of the robot, two main hydraulic cylinders and the gimbal structure are used. The two main cylinders extend and retract to rotate the insertion mechanism that contains the pole about the gimbal pivot point. After the pneumatic hammer attached at the end of the pole is positioned near clinkers, the hammer is activated and breaks clinkers so that they can be handled by the grinder.

The robot is anchored to the hopper using the attachment frame. As explained, the hopper main structure is filled with cooling water, and it needs to be flushed before the clinker clearing operation. This flushing situation produced a unique installation sequence for the robot. During flushing, it was desirable to keep the critical components of the robot out of the way of hot water flushing from the hopper. Therefore, the robot was designed to swing open with a hinge mechanism. As shown in Fig. 5, the attachment frame is composed of the actuator frame and the mating frame. The actuator frame swings open during flushing to keep the insertion mechanism and the main cylinders out of the way of flushing water. The other part of the attachment frame, the mating frame, remains to be attached to the hopper structure. After flushing, the actuator frame is closed to its working position as shown in Fig. 4.

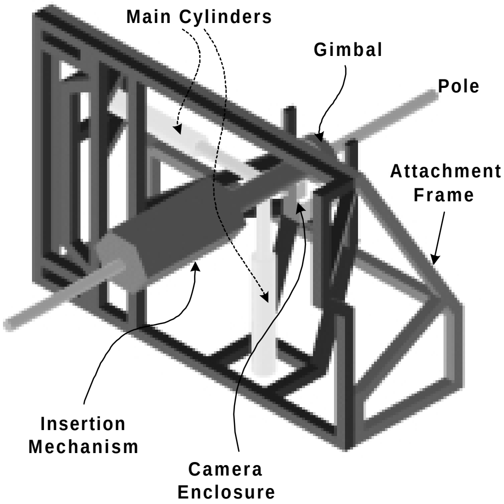

Fig. 4 Clinker Clearing Robot

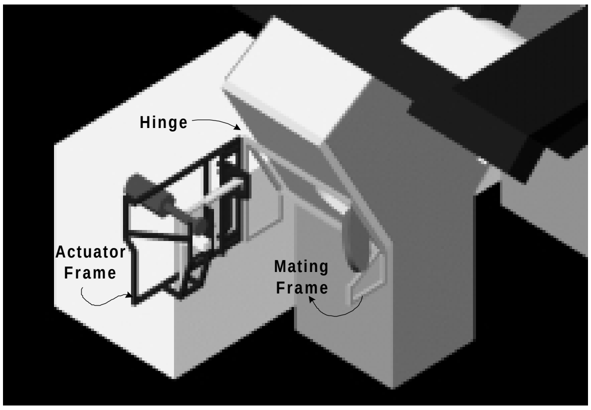

Fig. 5 Actuator Frame Open for Flushing

With the developed robot design, the following steps are required for the robot installation:

1) Winch and clamp the robot to the hopper
2) Open the actuator frame
3) Open the hatch door
4) Flush cooling water by opening the sluice gate
5) Close the actuator frame
6) Insert the pole
7) Start operation

Any modification of the existing structure was not desirable, so the interferences between the robot and the work environment were carefully checked for the geometric design of the robot. The workspace of the robot was also assessed to select proper pole lengths. Two poles with different lengths were required for satisfactory reachability because of the outer interferences [Seo et al. 1997].

3.2 GIMBAL AND INSERTION MECHANISM

The two rotational degrees-of-freedom of the robots are achieved by the two main hydraulic cylinders and the gimbal. The gimbal is composed of two rings to achieve the two rotational degrees of freedom as shown in Fig. 6. The inner ring is a part of the outer ring, and the Axis 1 is fixed to the actuator frame. So when the outer ring rotates about Axis 1, the inner ring also rotates about Axis 1. However, the rotation of the inner ring about Axis 2 does not affect the rotation of the outer ring.

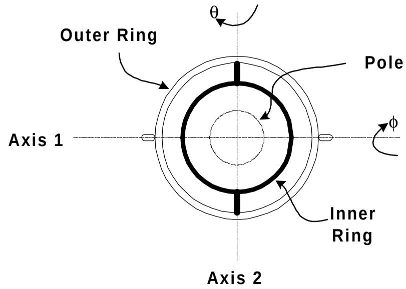

Fig. 6 Gimbal

The pole insertion mechanism as shown in Fig. 7, has six insertion-extraction actuators and two clamping actuators. A clamping plate can be moved by a set of three insertion-extraction cylinders. The pole can be inserted or extracted by extending and retracting the insertion and extraction cylinders with proper clamping sequences. The incremental travel of the insertion mechanism can be adjusted to 6 in. or 3 in. for the course positioning, and the fine positioning, respectively. Finally, Fig. 8 shows the robot installed on a hopper structure at HL&P.

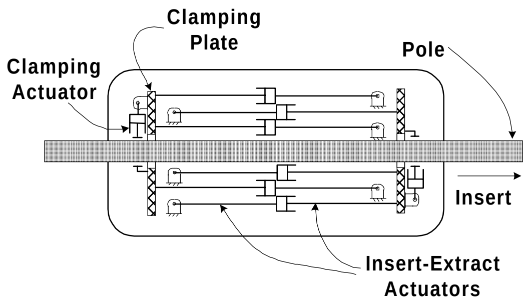

Fig. 7. A Schematic of the Pole Insertion Mech.

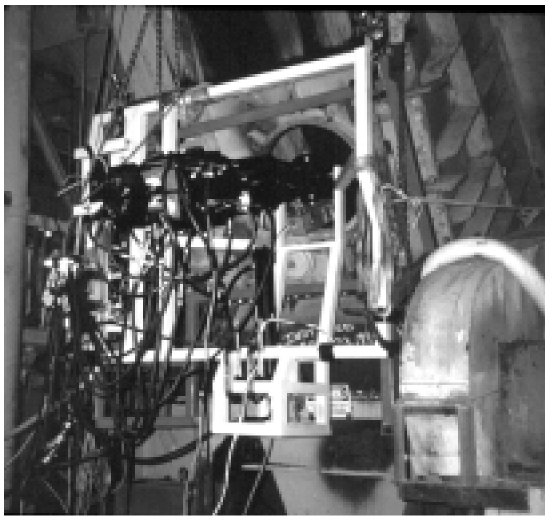

Fig 8. Clinker Clearing Robot on the Hopper

4. GRAPHICAL CONTROL INTERFACE

A CCTV camera is installed underneath the gimbal as shown in Fig. 4 for tele-operation of the robot. However, tele-operation with CCTV feedback has an inherent depth perception problem. In addition, it was anticipated that the visual feedback from CCTV may be limited if the ash obscures the vision. Unexpected collisions during the robot operation were also a risk if the CCTV were the only source of the visual feedback. A graphical interface was required to overcome the problems in the remote control of the robot as explained above.

4.1 Overall Control System Architecture

Fig. 9 shows the control architecture of the clinker clearing robot. The graphical model of the clinker clearing robot is updated based on the real motion of the robot. The sensor data from the robot's actuators give the configuration of the robot in real-time. The clinker model is also updated and represented along with the static CAD models of the hopper environment. The operator gets enhanced visual feedback by combining the live view from the CCTV camera and the real-time updated graphics, but she directly interacts with the robot for the motion control with a joystick. During the motion control, collisions between the robot and the work environment are avoided with the real-time analysis of the graphical models. Fig. 10 shows the control station with two monitors (CCTV monitor and Graphics Monitor). The robot is a new device, so the operator should be trained before actual execution of the robot operation. The graphical interface was also used for safe operator training. The operator could be trained by running the graphical model of the robot instead of running the actual robot.

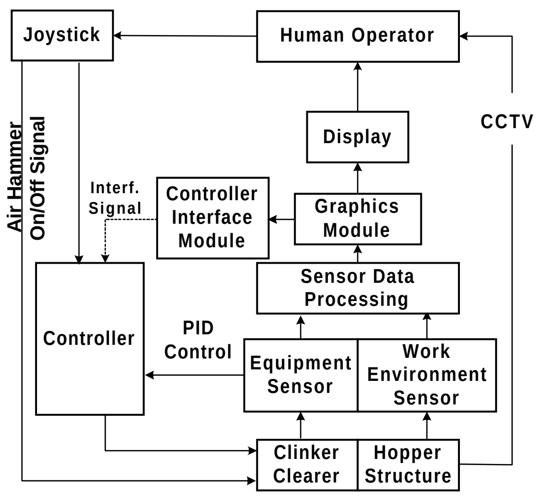

Fig. 9 Control System architecture

4.2 Graphics Module

A C++ based graphics library, OpenInventor ™, and Microsoft Visual C++™ compiler were used to develop a customized graphics program. Fig. 11 shows a view of the graphical control interface screen. For the robot components, only the pole is shown to the operator because the operator does not normally need visual feedback on the attachment frame and the insertion mechanism. A transparent rendering scheme was used for the walls of the main hopper structure and the gate housing structure. With the transparent rendering scheme, the operator can see the pole through the hopper wall, yet the hopper structure is still identifiable. Multiple windows can provide different views simultaneously. Two windows with reference views are initially provided as shown in Fig. 14. The operator can change the viewpoint from the reference views easily. The operator can also return to the reference views quickly after viewpoint changes. The details on the graphical representation and viewing schemes can be found in [Seo 98].

Fig. 10 Robot Control Station

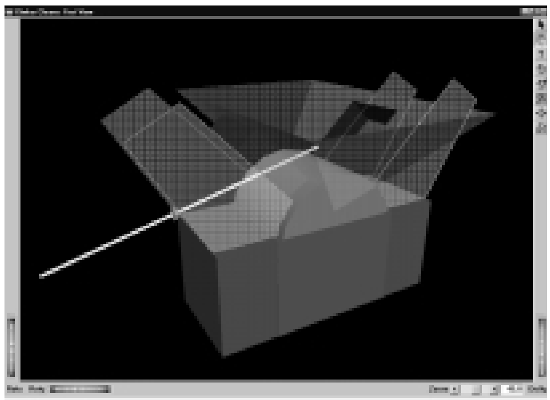

Fig. 11 Graphical Interface Screen

4.3 Sensing and Position Kinematics

Sensing is required to update the graphical models in real time. The main cylinders are equipped with linear transducers which report the cylinder length information in real time. A kinematic model was required to calculate the gimbal angles based on the cylinder lengths. Fig. 12 shows the kinematic structure of the robot. **A** and **B** are ball joints that connect the gimbal extension and the cylinders.

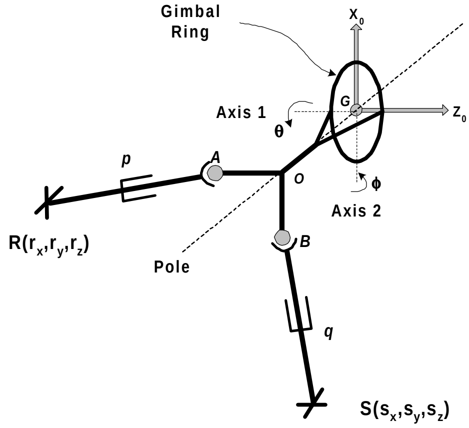

Fig. 12 Kinematic Structure of the Robot

A set of equations defining forward position kinematics was prepared to compute the robot's configuration (gimbal angl θ and ϕ) based on the data obtained from the transducers (p and q):

$$p^2=c^2+a^2+r_x^2+r_y^2+r_z^2-2r_x s\theta(c\phi c+as\phi)+2r_y c\theta(c\phi c+as\phi) - 2r_z(ac\phi-cs\phi) \quad \textbf{(Eq. 1)}$$

$$q^2=c^2+b^2+s_x^2+s_y^2+s_z^2-2c\phi c(s_x s\theta-s_y c\theta)+2b(s_x c\theta+s_y s\theta) + 2c(s_z s\phi) \quad \textbf{(Eq. 2)}$$

The equations can have up to sixteen distinct solutions, and reasonably accurate solutions of the above high degree polynomials in real-time are difficult to obtain. Instead, a look-up table with pre-calculated θ and ϕ values for 625 sets of p and q values was prepared and incorporated into the graphical interface program. To detect the pole insertion length, two potentiometer were installed on the insertion and extraction cylinders.

A laser triangulation method was used to update the graphical model of the clinkers. 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 geometric relationship between the camera focal length, and the physical laser off-set, and the laser off-set on the image plane [Seo 1998]. To effectively update the clinker model by incorporating the sensor data, the occupancy array method was used. The 3-D space of the inside of the hopper was divided into six-inch cube cells which 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 three-inch discrete movement of the insertion motion of the robot, a six-inch cube cell to represent occupied space was used. Fig. 14 (bottom) shows the graphical control interface screen with clinker models.

5. TESTS AND EVALUATION

This section describes the tests performed with the developed tele-operated clinker clearing robot. Th robot installation features (as explained in Section 3.1) and its reachability were tested at HL&P. Fig. 8 shows the robot installed on the hopper during the field test. Since the filed test was allowed for a short period of time while the plant was shutdown for annual maintenance, a mock-up structure that was identical in geometry to the hopper structure at HL&P was used for the accuracy measurement, the collision avoidance test, and the operator's performance test.

5.1 Accuracy Tests

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

5.2 Clinker Breaking Tests

The robot's ability to break limestone rocks and clinkers (obtained from the HL&P hoppers) was evaluated. The limestone rocks and clinkers were placed within a steel frame which was rigidly attached to the hopper mockup inside the laboratory (see Fig. 13). This experiment closely resembles the conditions in the actual hopper since the clinkers are not restrained in all directions. Once the clinker was in contact with the back of the steel frame it could no longer move away from the pole as if a clinker had been pushed against the hopper wall by the robot in real situation. The air hammer was switched on once the clinker appears to be close to the target. The pole was then inserted through a distance of one insertion length (3 in.) until the air hammer made contact with the target. Limestone rocks and clinkers were easily fractured at the moment of contact or when the pole is inserted b one more insertion length after the contact.

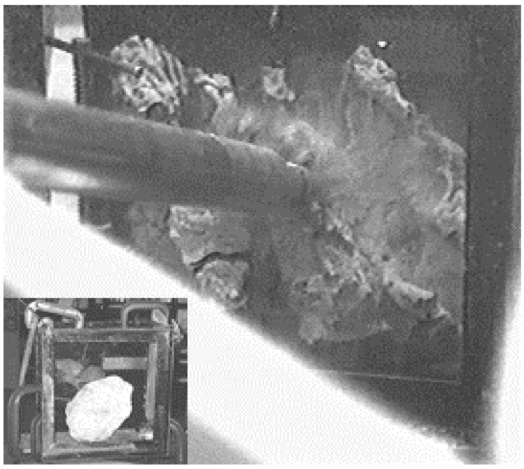

Fig. 13 Clinker Breaking Test

5.3 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. 14

shows one of the target set-ups prepared on the mock-up structure for the test and its corresponding graphical control interface screen. Two targets were placed with different depths for each target set-up. The subjects' task was to hit the targets with the end point of the pole. The test subjects were asked to hit the front face of the targets with the end point of the pole, and not to hit the targets from the side with another part of the pole. The side hits with other parts of the pole 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 three operational performances observed to measure the speed and the quality of the robot operation are: 1) Job completion time, 2) Side hit, and 3) Order of hit (Closer target or Farther target).

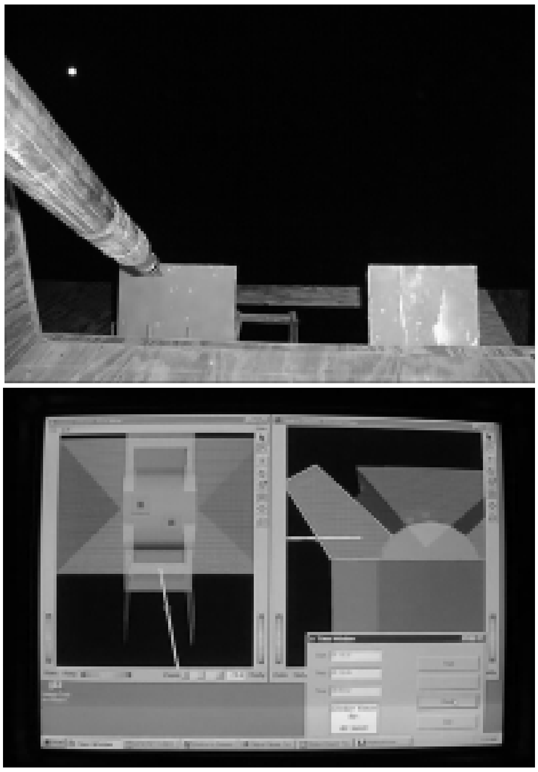

Fig. 14 Performance Test Set-up(top) and Corresponding Graphical Interface Screen(bottom)

The subjects finished the operation 5 seconds faster on average when they used the combined system (Graphics & CCTV). The average finishing time of the CCTV-based operation and the combined system were 2 min. 15 sec. and 2 min 10 sec., 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 investigation 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 and CCTV together. Nine out of eleven 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 CCTV only. This is clear indication of the depth perception problem which could induce damage or undesirable results during the robot operation. Obscured vision caused by the smoke in the real furnace hopper structure would make the graphical interface more valuable.

The operator training was necessary before the delivery of the robot. A selected HL&P plant maintenance worker without previous experience on the robot control could successfully finish a clearing operation with a test setup after a three-hour training session.

6. CONCLUSIONS

This paper presented a tele-operated robotic device for clearing bottom ash clinkers from lignite-fired power plant furnaces. The mechanical and control system of the robot and the experimental results were summarized. 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. The robot was delivered to a station of HL&P in Jewett, TX in January 1999.

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