3차원 그래픽 모델에 근거한 자동화 장비의 설계 및 조종

3-D Graphical Model-Based Design and Control of Automated Equipment

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Abstract

This paper concerns 3-D graphical modeling and simulation techniques for design and control of automated equipment for construction and facility maintenance. A case study on the use of 3-D graphics techniques for developing a power plant maintenance robot is presented. By simulating equipment operation within the 3-D geometry models of the work environment the equipment design was improved. The 3-D graphical models of the equipment and the work environment were further utilized for the control of the robot from a remote distance. By presenting the real-time updated equipment configuration and the work environment to the operator, the graphical model-based equipment control system helped the operator overcome the problems associated with spatial perception. The collision between the robot and the plant structures was also avoided based the real-time analysis of the dynamically updated graphical models.

Keywords: Construction Automation, Computer Graphics, Graphical Control, Tele-operation

1. Introduction

This paper presents an exemplary practice on using 3-D graphical modeling and simulation techniques for design and control of equipment in unstructured and large-scale environment such as construction and facility maintenance. The case study presented in this paper can be employed for developing many other types of automated equipment.

The equipment discussed in this paper is a robot developed to break and clear "clinkers" in fossil power plants as an automated maintenance effort. As other construction and maintenance operation, clinker clearing is very labor intensive, dirty, requiring heavy forces and, most of all, very dangerous. This paper describes the development process of this robot, which was based on graphical modeling and simulation techniques.

2. Power Plant Maintenance Operation

Lignite-fired electric power facilities produce clinkers. The clinkers accumulate along the boiler hopper walls and continuously drop to the bottom into a cooling pool of water. As shown in Figure 1, the hopper is composed of a main structure with a grinder and a hatch opening. A sluice gate is used to allow the flushing of the hopper contents along with the cooling water. Some clinkers could 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 conventional clinker clearing operation is laborious, physically dangerous and requires large forces. Workers are required to wear cumbersome hot suites and manipulate a long heavy steel rod connected to a jack hammer to break clinkers through the hatch opening [Carter et al. 1992 and Seo et al. 2000]. A tele-operated robot to automate the manual clinker clearing operation was developed by the Univ. of Texas Field Systems and Construction Automation Group.

3. Graphical Modeling and Simulation for Robot Geometry Design

This section describes the three-dimensional modeling and graphical simulation techniques for the geometric design of the clinker clearing robot. The robot must work in a constrained space, and many possible interferences with the existing structure exist. The robot design was improved and verified

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through three-dimensional graphical simulation. The robot behaviors could be simulated within the graphical work environment, and every step of the operating sequence could be verified with graphical models. The models developed at this stage naturally migrated to those used for graphical control.

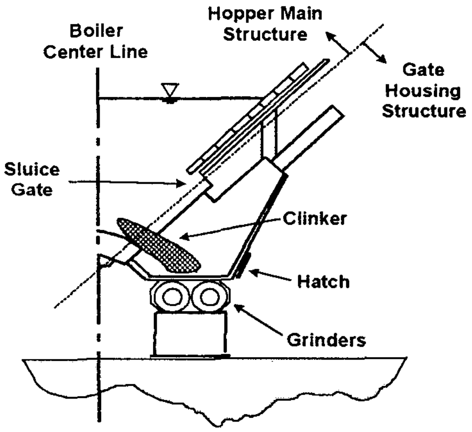

Figure 1. Hopper Structure of Power Plant Furnace

3.1 Geometric Modeling

The hopper structure and the outer environment that could affect the robot manipulation were modeled. Figure 2 shows an isometric view of the work environment model. Complex pipelines and other outer structures were simplified with virtual ceilings and walls that are not visible in the Figure 2. Once the work environment model was completed, various ideas of the robot geometry could be experimented within the graphical work environment to embody the initial design concepts.

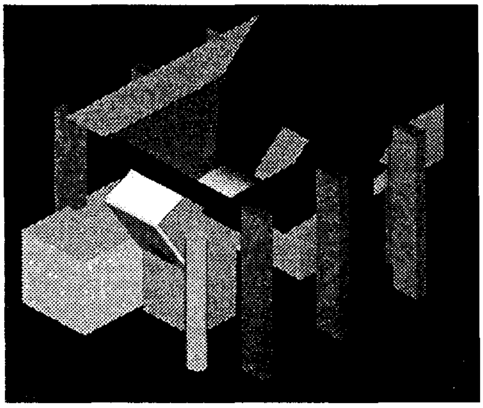

Figure 2. Work Environment Model

3.2 Robot Geometry Model

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 access door of the hopper. The attachment frame and other geometry of the robot was designed with the aid of three-dimensional graphical simulation. Figure 3 shows the completed geometry model 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. As represented in Figure 3, the arm is inserted into the insertion mechanism. The arm is inserted and retracted by six hydraulic cylinders installed inside of the insertion mechanism for the prismatic motion. 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 arm about the gimbal pivot point. After the pneumatic hammer attached at the front end of the arm is positioned near clinkers, the hammer is activated and breaks clinkers so that they can be handled by the grinder.

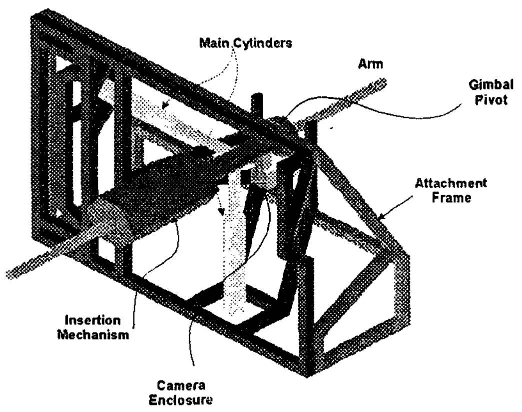

Figure 3. Robot Model

3.3 Operating Sequence and Interference Analysis

As explained in Section 2, 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 operation 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 installed on the left side of the robot. Figure 4 shows the configuration of the robot when the actuator frame is open. An actuator frame that is a portion of the attachment 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 positioned to its working location as shown in Figure 3.

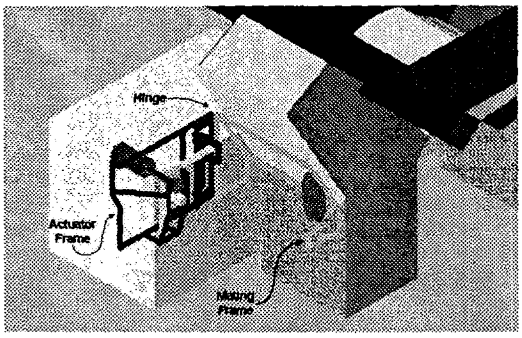

Figure 4. Robot Configuration for Flushing

3.4 Workspace analysis

It was important to analyze the workspace of the robot arm and to determine the proper length of the arm. The inner and outer interferences limit the workspace of the robot, so the workspace was determined considering the interferences. As explained in Section 3.2, the whole arm has to move back and forth for insertion and extraction, so the determination of the arm length was important. The arm should be long enough to be able to reach far away from the access door. However, a long arm cannot operate in the area closer to the access door because of interference with outer structures. The work space analysis has been done with an AUTOLISP routine. AUTOLISP is an interface language for AutoCAD^{TM}. The routine iterates interference checking between the arm and the existing structures by changing the insertion length and the rotation angles of the arm incrementally. The result of the routine is a representation of the reachable volume with a given length of the robot arm. [Seo 1998]

3.5 Animation

The robot was intended to replace the workers in hazardous areas. The communication between robot designer and the field workers who have been doing the clearing operation manually was critical to check the design of the robot. The robot design and its operation was presented to the field workers with animated graphics for better communication. It helped the design process with the feedback from the field workers.

4. Graphical Modeling and Simulation for Robot control

The robot has a CCTV camera for tele-operation. However, it is anticipated that the visual feedback from CCTV may be limited for the tele-operation if the ash obscures the vision. In addition, tele-operation with CCTV feedback has an inherent depth perception problem. 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. The robot is a new device, so the operator should be trained before actual execution of the robot operation. The graphical interface was also required for safe operator training because the operator can be trained by running the graphical model of the robot instead of running the actual robot.

4.1 Overall Control System Architecture

Figure 5 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. Figure 6 shows the robot and the control station with two monitors (CCTV monitor and Graphics Monitor).

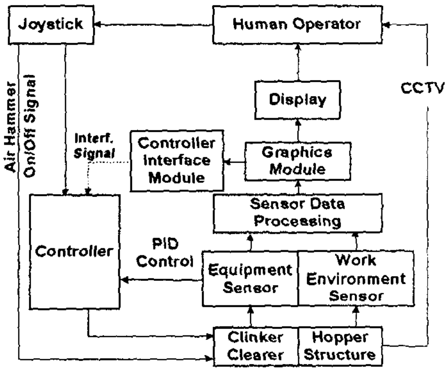

Figure 5 Control System architecture

4.2 Graphics Module

A C++ based graphics library, OpenInventor^{TM}, and Microsoft Visual C++^{TM} compiler were used to develop a customized graphics program. Figure 6 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 so that the operator can see the pole through the hopper wall, yet the hopper structure is still identifiable. The details on the graphical representation and viewing schemes can be found in [Seo 98].

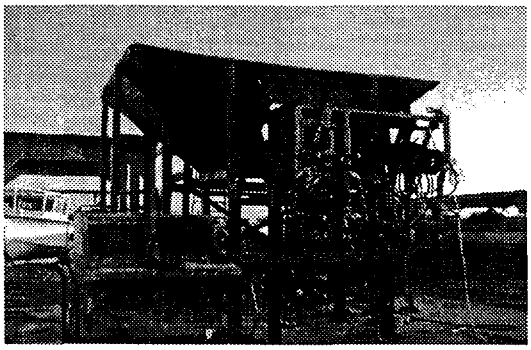

Figure 6. Robot and Control Station

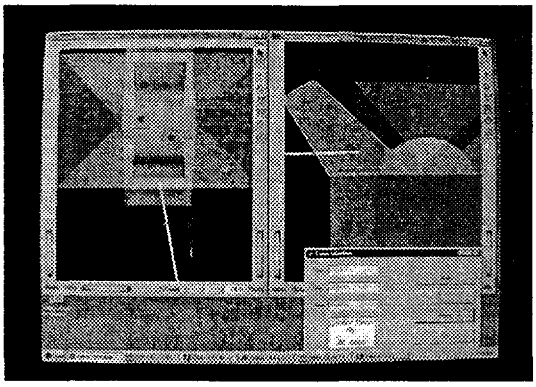

Figure 7. Graphical Interface Screen

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. 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 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 as shown in Figure 7.

5. Tests and evaluation

The following tests were successfully performed with the developed tele-operated clinker clearing robot.

1) Graphical Model Accuracy Test.
2) Clinker Breaking Tests
3) Operator's Performance Tests

A mock-up structure that was identical in geometry to the hopper structure was used for the accuracy measurement, the collision avoidance test, and the operator's performance test. It was found that the collision between the robot arm and the hopper structure was avoided by the real-time analysis of the accurate graphical models. The mechanical system was fully functional based on the clinker breaking test. The result of the operator performance tests proved that the robot operation could be improved when the real-time updated graphical models were utilized for the control purposes. Details on the test results can be found in [Said et al. 1998 and Seo et al., 2000].

6. Conclusions

This paper presented a tele-operated robotic device for clearing bottom ash clinkers from lignite-fired power plant furnaces. The graphical modeling and simulation techniques for the design and the control of the robot 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. It is expected that the presented graphics techniques for design and control of automated equipment can be further extended to other types of equipment.

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