CAD-Integrated Excavation and Pipe Laying

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Abstract: Excavation and, in particular, trenching using backhoes represents a hazardous working environment for workers. The hazards include trench walls that collapse, the accidental drop of heavy objects into the opening, excavators and other equipment that become unstable, and buried utilities that are damaged during the operation. The three main accident prevention efforts used today are the use of the trench box, inspection, and the training of the site personnel. The work discussed in this paper is the result of a search for a more revolutionary prevention method: one that does not require a worker to enter the open trench. This paper presents the development and testing of a computer-aided design (CAD) integrated trenching and pipe-laying system. The successful testing of the first prototype could lay the foundation for safer and more productive trenching operations in the future.

INTRODUCTION

The hazardous nature of construction work related to excavation is well documented. The fatality rate was estimated by the Occupational Safety and Health Administration (OSHA) to be 50.8 deaths per 100,000 workers per year from 1984–1988, whereas, for construction work in general, it was estimated to be 24.8 deaths per 100,000 employees. Similarly, trenching cave-in fatalities have been estimated by the National Institute of Occupational Safety and Health (NIOSH) to be 75 per year, and lost workday injuries due to cave-ins are estimated at 1,000 per year. The incidence rate for injury among construction workers, including those doing excavation work, is about two times the total industry average [i.e., 15.1 injuries per 100 workers in construction, compared with 7.7 injuries per 100 workers in all industries (''Occupational'' 1989)]. Considering these statistics, it is not surprising that trenching and pipe laying have been listed as two of the most important applications for advanced technologies in a recent report published by the Federal Highway Administration (''Robotics'' 1995). The report was the result of an extensive study that included two workshops, site visits of automation experts, and a life-cycle cost-benefit analysis.

Because of their versatility, excavators are especially popular in construction (Huang and Bernold 1993b) and mining (Lever et al. 1994). The control of these machines has received increased attention because of their importance to increase the safety and the productivity of excavation related work. Several authors also report on work that focuses on the implementation of robotic concepts on excavators. For example Singh (1994) studied automatic planning while Hoffman and Simmons (1994) worked on ways to simulate the process of excavation using physical parameters. Koivo and Nease (1996) as well as others (Huang and Bernold 1994; Lever et al. 1994) developed new insights into the issue of control. In the early 1990s, Bernold started an experimental approach, since the complexity of the soil-tool interactions at the excavator bucket made the accurate mathematical modeling impossible (Bernold 1991, 1993; Huang and Bernold 1993a). This work is still ongoing.

Trenching and pipe laying are some of the most dangerous operations in construction. The main benefits from using cutting edge technologies for trenching and pipe laying can be summarized as follows: (a) drastic reduction of fatal accidents and lost workdays due to injuries; (b) elimination of accidental damage to buried utilities such as water mains and power lines; (c) augmentation of operator efficiency through intelligent control methods; (d) reduction of wasted production time due to surveying or other related measuring errors; (e) minimization of soil to be excavated since OSHA requirements for sloping do not apply; (f) increase of the versatility of key machinery (e.g., backhoe excavator) by allowing the control of ''smart'' attachments; and (g) automatic creation of updated as-built drawings of underground utilities.

This paper presents the concept and development of a spatially integrated excavation and pipe-laying system. The research team, consisting of undergraduates and graduates from mechanical and civil engineering programs, had available four important hardware components: (1) a John Deere 690C backhoe excavator; (2) electronic transducers for measuring angles on the excavator arm; (3) a laptop computer with data-acquisition board and touch screen; and (4) the ODYSSEY, a laser based position measurement tool. All of these components were integrated into one system termed the Excavator Mounted Spatial Positioning System (EM-SPS). The overall goal of this project was to prove the technical feasibility and effectiveness of such a system under field conditions. In addition, innovative technology for the remotely controlled laying of large pipes was tested. All of these technologies are considered key components of a safe and economical robotic excavation system of the future. However, this research project was designed to find out how the individual system components may be independently installed by attaching them to any existing excavator found on today's construction sites. As a result of the work described in this paper it is felt that the safety of trench excavation could be drastically increased by adopting any of the technologies developed and tested for this research project.

DESIGN OF NEW TECHNOLOGIES

The key problem of a computer-aided design (CAD) integrated system is the establishment and integration of two spatial frameworks, the fixed global or world coordinate system, and that of the excavator, considered a local coordinate system (Huang and Bernold 1996). Commonly, the global framework is used to display the entire construction site, while the local framework is used in calculating the relative positions of the different parts to a chosen origin. One point in a local framework has to be represented in the global one. Moreover, measurement technologies are necessary to provide the means to monitor compliance in the millimeter range. The latter has been a stopping block for any serious development of such systems in construction due to the commonly large space of building sites. The long range three-dimensional (3D) laser-

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J. Constr. Eng. Manage., 1997, 123(3): 318-323

based position measurement tool, ODYSSEY, makes it possible to overcome this serious obstacle.

The availability of real-time spatial position information at the digging machine has three main implications. First, it allows the operator to acquire accurate data about the actual path and speed needed for the control and planning of future actions when in an autonomous mode. Also, discrepancies between desired paths and actual paths may provide information about the environment (e.g., type of soil). Second, position and force data from the robotic system can be established. Third, since the relevant spatial position data is available (such as the final location of a pipe in the trench), an as-built database can be established automatically. The laser-based technology for spatial positioning has some major drawbacks, however. It requires a line of sight between the receiver and the transmitter. Since the digging device, the bucket of a backhoe excavator, has to be operated in the narrow opening of a trench as well as in free space, the laser-based system will not work when the laser receiver ends up in the trench. The use of angle encoders mounted on the backhoe boom bridges this gap. Fig. 1 depicts an overview of the trench digging operation using a 3D laser guidance system for a backhoe excavator.

As shown, two laser receivers are mounted high up on the back of the excavator. They provide data about the orientation of the excavator within the global coordinate system of the construction site or "the world." A link of angle encoders mounted on the boom and stick of the arm allows the establishment of the two-dimensional (2D) coordinates of the bucket within the framework of the equipment. A conceptual layout of the envisioned future of laser guided pipe laying is shown in Fig. 2.

The availability of laser guidance, together with the mechanical means to manipulate and connect drainage pipes with O-ring joints, will eliminate the need for positioning workers in the trench. As shown, a beam laser that is already in use today has been applied to support the installation of pipes. Thus, the EM-SPS together with the beam laser will provide the opportunity to guide the pipe into the trench and to measure its slope and alignment very accurately.

To prove these two concepts, hardware and software were developed to be tested in a prototype system in an experimental testing facility. The next sections will discuss the different components that were integrated into a comprehensive system.

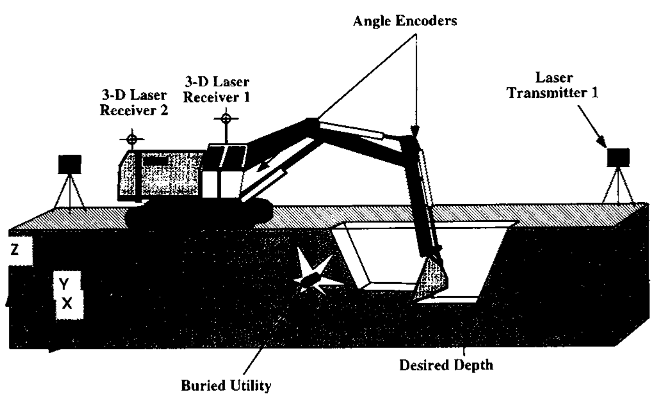


FIG. 1. Concept of Trench Excavation Using Laser Guidance

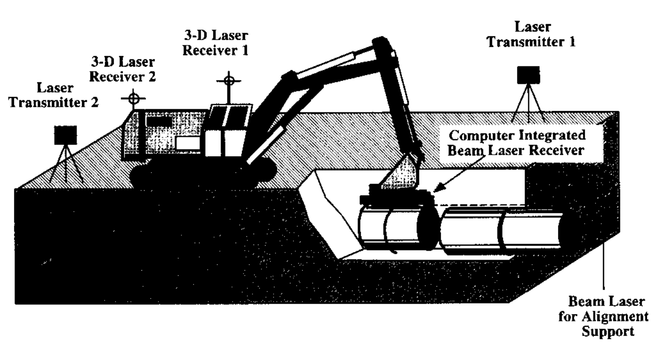


FIG. 2. Concept of Remotely Controlled Pipe Laying with Laser Guidance

JOHN DEERE 690C EXCAVATOR AS TEST PLATFORM

A John Deere 690C multipurpose excavator has been used to implement the aforementioned concepts. Fig. 3 pictures the large-scale excavator in the field. This excavator was equipped with a high resolution resolver at each joint. Hydraulic pressure transducers have also been installed in all of the hydraulic lines to monitor the hydraulic pressures. The hydraulic cylinders installed on the excavator are driven by electroproportional valves to allow easy computer interfaces of the controls.

The modified John Deere excavator provides opportunities to utilize several control interfaces sequentially or in parallel. For example, the machine can be operated: (1) completely autonomously; (2) via a remote joystick; (3) using pretaught digging and other actions; (4) utilizing the traditional levers; or (5) in a shared control mode.

Two critical hardware components had to be added further to the John Deere excavator: (1) two laser receivers and processors; and (2) the pipe manipulator with the capability of positioning and releasing large pipes without the need for workers entering the trench.

SPATIAL INTEGRATION

Positioning materials and equipment accurately at the construction site is a fundamental process throughout the industry. The ODYSSEY system is based on the position measurement technology originally developed by the Spatial Positioning System, Inc. (SPSI) for surveying and vehicle tracking applications. The system employs two or more laser transmitters and one or more laser receivers. The system consists of a central processing unit (CPU) and a receiver processing unit (RPU) for connecting with a computer. Fig. 4 depicts an overview of the system setup.

Real-time spatial position information in excavation has several main implications. First, it allows a moving object to acquire data about its actual excavation path and speed that are useful in planning future actions when in autonomous mode. Discrepancies between commanded paths and actual paths that might be caused by friction can provide information about the environment. Second, through data fusion with force data from the hydraulic system, a robotic control system can be established. Third, because it is able to capture and electronically store the relevant position data in space, such as the

FIG. 3. John Deere 690C

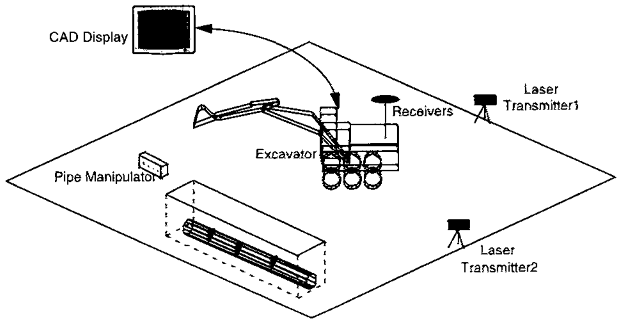


FIG. 4. Schematic View of Spatially Integrated Excavation

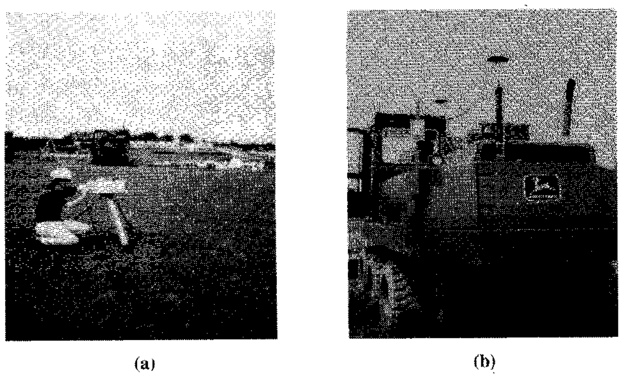


FIG. 5. Deployment of Spatial Positioning System (EM-SPS) Hardware: (a) ODYSSEY Laser Transmitter; (b) ODYSSEY Laser Receivers on Excavator

final location of a pipe in the trench, an as-built database can be automatically established. Fig. 5 shows pictures of the excavator mounted receivers. The two receivers provide 3D position data five times per second which is automatically transferred to the main computer (Huang and Bernold 1996).

To assist the operator in visualizing the location of the excavator within "the world" coordinates, a display system using AutoCAD software has been developed. It integrates the 3D data from the EM-SPS with the joint encoders mounted on the excavator itself. The needed interface program written in QuickBasic handles all the data collection and processing tasks. These tasks can be summarized as follows: (1) acquisition of the two x-y-z coordinates provided by the two receivers of the ODYSSEY; (2) calculation of the orientation of the excavator in the global coordinates; (3) collection of position data from the resolvers mounted on the excavator; (4) calculation of the kinematic equations to establish the position of the bucket in local coordinates; and (5) transfer of the local coordinates into the global (world) coordinates. The AutoCAD software is used to display the updated position while the latest OS/2 Warp operating system, allows efficient coordination between the DOS environment, Windows R12, and AutoCAD.

Under the AutoCAD for Windows R12 environment, an AutoLISP program updates the position/orientation of the excavator and its trenching operations. Every perspective view is based upon a fixed world coordinate system (global coordinate system) that is defined by the ODYSSEY. However, since the trenching operation takes place within one plane, and movements of different links of the excavator can be depicted relative to the excavator's base, it is convenient to implement the trenching operations under a local coordinate system (excavator coordinate system), with its origin at the center of the excavator's swing base. Therefore, operators are able to see the 3D field with the excavator operations, the trench under excavation, and other objects such as pipes under the EM-SPS coordinate schemes. At the same time, they can also view the digging motion under the plan view and side view. It is believed that the aforementioned combination technique provides an excellent interface to enable operators to manipulate the viewpoints in AutoCAD to their preferences.

The QuickBasic program saves the results, most of which are the x-y-z positions of the excavator joints, into a virtual disk drive data file, which is simply created in the random access memory (RAM). The same data file is also accessed by the AutoLISP program. The real-time spatial integration of the equipment with the CAD representation of the construction site provides many opportunities to assist the operator. For example, interference checks can be performed automatically to make sure that the backhoe does not accidentally damage buried utilities, or as-built drawings of trenches or the location of pipes can be created without the involvement of the operator. The innovative technology developed for the safe laying of pipes will be discussed in the next section of this paper.

REMOTE CONTROLLED PIPE MANIPULATION

The manipulation and final positioning of large concrete pipes in the trench requires several important capabilities. First, the hardware has to be very robust and heavy duty since such pipes are generally heavy. Second, the O-ring compression joints require a linear insertion of the new pipe element into the bell of the previously laid pipe. Third, proper laying of pipes to meet line and grade requirements make it necessary to utilize a beam laser. Fourth, the release mechanism for the pipe has to be remotely controllable.

As shown in Fig. 6, the hardware consists basically of two major components: (a) a connector base; and (b) a hydraulic actuated manipulator to which the pipe is attached. The hydraulically actuated manipulator is made up of a heavy duty bearing and a linear track supporting a carriage and a hydraulic

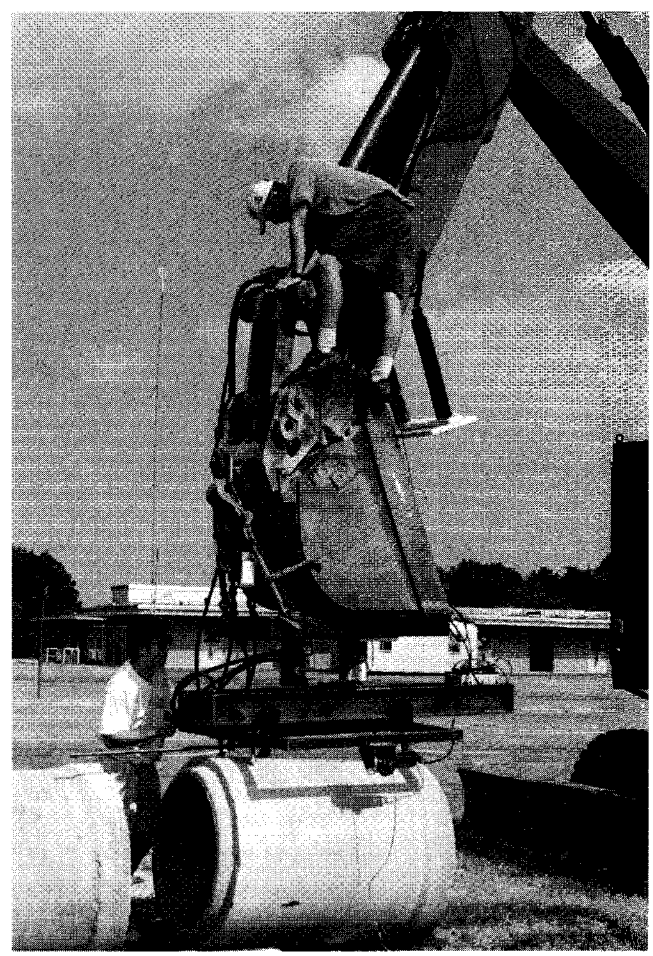


FIG. 6. Pipe-Manipulator Attachment during Development

J. Constr. Eng. Manage., 1997, 123(3): 318-323

cylinder that provides the linear motion capability. Each pipe segment is being held by one cable that is operated via an electric winch mounted on the carriage. A hydraulic motor and a chain allow the attachment to be rotated 360° while the C-shaped connector base is designed so that the excavator operator is able to insert the bottom of the bucket into the cantilevered "hook." A clamp mechanism at the rear of the bucket secures the connector base from slipping off the bucket. Quick connects allow the rapid hookup of the hydraulic lines and the electronic cables that provide the operator with the data from the beam laser receiver mounted on the actuator itself. This receiver is capable of sensing the position of the laser beam that hits its plane surface. The beam laser that is traditionally used for pipe installation establishes a stable reference laser line for aligning the pipe section with precision while the EM-SPS guides the operator to the approximate position of the beam in the trench. The selected beam laser system is composed of three units: (a) laser diode unit; (b) X-Y remote laser sensor; and (c) a CPU. The laser diode unit transmits a laser beam 2 mm in diameter for a distance of 100 ft (33 m), while the X-Y remote sensor uses the pulsed beam of laser light as a reference. It has a 0.788 × 0.788 in. (20 × 20 mm) capture area.

PROTOTYPE TESTING

To accurately display the backhoe excavator within the global or world coordinates of AutoCAD the information from the two position feedback systems has to be reliable. For this purpose a set of simple tests with the large-scale excavator were designed and executed. The *x-y-z* coordinates and inclination of the excavator bucket in the global coordinate frame is determined by integrating following spatial elements: (1) the location of the two EM-SPS laser receivers mounted on the backhoe; (2) the physical dimensions of John Deere 690C excavator; (3) the angles measured by the joint encoders mounted on the arm of the excavator; and (4) the inverse kinematic calculations that are used to establish the *x-y-z* coordinates of the bucket in the coordinate frame of the backhoe.

System Calibration

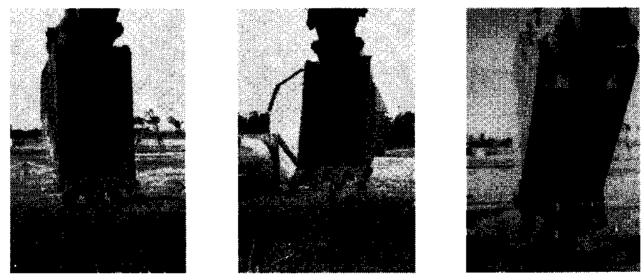
Field tests to determine the path accuracy included the following five phases: (1) survey of four fixed calibration points using the ODYSSEY; (2) calibration of the excavator using different bucket angles at the fixed calibration points; (3) excavation of a test trench while saving the position feedback from the system; (4) survey of the finished trench using ODYSSEY; and (5) comparison of the results from phase 4 with phase 3.

Fig. 7 shows how ODYSSEY was used during phase 1 to establish the *x-y-z* coordinates of a calibration point at the top of one of the four ground-anchored poles. For phase 2, the excavator bucket was brought in a position where the cutting edge touched the calibration poles. Fig. 8 exhibits three bucket configurations used to calibrate the position feedback system. The purpose of conducting this step is to evaluate the sensitivity of the system to minor changes in the mechanical system. Differences between the surveyed coordinates and the coordinates fed back by the EM-SPS were assessed and used as compensation factors that should account for all the small errors in the entire system.

The calculated errors, which represent averages from a series of measurements, are given in Table 1. They provided the basis for establishing the compensation values used for the next phases of the experiment. In Table 1, the differences in the *y*-direction were in the millimeter range, thus the Δy is regarded to be zero.

The results from the ODYSSEY are considered the correct,

FIG. 7. Surveying of Fixed Calibration Point Using ODYSSEY



(a) (b) (c)

FIG. 8. Calibration of EM-SPS with Three Bucket Angles

or actual, points while the coordinates fed back by the EM-SPS require error compensation. The smaller the discrepancy, the more accurate the AutoCAD display system will be.

The result of the five phases used for assessing the accuracy of the system is presented in Fig. 9. The point coordinates given by the excavator position feedback, calculated using kinematic equations, are consistently lower than the EM-SPS surveyed coordinates. By repeating the same test several times and taking into account of the test in phase 2, the relationship between the path discrepancy can be found and the compensation (correction factor) can then be calculated to reduce any error

$$x_C = x_{FB} + \Delta x \quad (1)$$

TABLE 1. Differences between *x-y-z* Coordinates of Four Calibration Points Measured with ODYSSEY and EM-SPS

Coordinate (1)	Point 1 (cm) (2)	Point 2 (cm) (3)	Point 3 (cm) (4)	Point 4 (cm) (5)
Δx	12	18	8	10
Δz	4	6	11	9
Δy	0	0	0	0

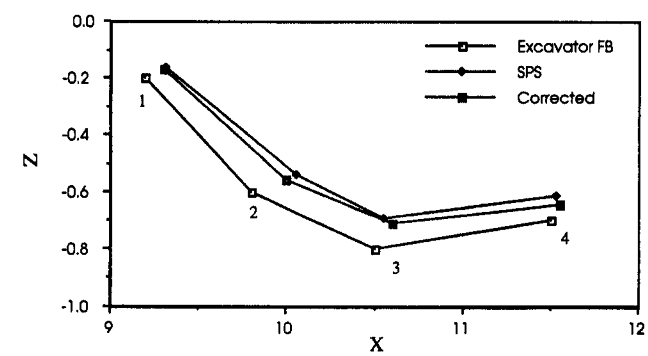


FIG. 9. Comparison between Excavator Feedback (FB) and EM-SPS Positions

J. Constr. Eng. Manage., 1997, 123(3): 318-323

TABLE 2. Errors between Corrected Path and Actual Path

Coordinate (1)	Point 1 (cm) (2)	Point 2 (cm) (3)	Point 3 (cm) (4)	Point 4 (cm) (5)
Δx	0	5	−4	−2
Δz	0	4	2	2

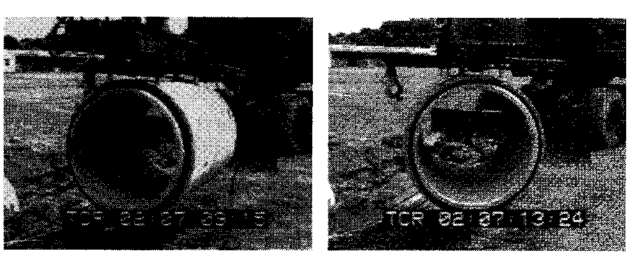
$$z_C = z_{FB} + \Delta z \qquad (2)$$

where x_C and z_C = corrected x and z coordinates; x_{FB} and z_{FB} = feedback x and z coordinates; and Δx and Δz = correcting factors in the x-axis and z-axis, respectively, which are obtained from the test phase 2. In the foregoing representation, x reflects the length direction, z is the depth, and y is the width direction. Because there is little discrepancy in the y direction, no correction is necessary for y coordinates. In Fig. 9, the average of Δx = 12 cm and the average of Δz = 7.4 cm. The objective of the correction is to compensate for the error between the excavator feedback (FB) and EM-SPS reading. As shown in Table 2, the utilization of the correction factor led to a significant reduction of the errors at each of the four points. Most drastic is the change in point 1, which is at the beginning of the digging path and became error free.

However, limitations exist with the current system. From the ODYSSEY specifications, its accuracy is within 5 mm of the range of the designed experiment. The joint resolver installed at each joint of the excavator has a resolution of more than 10,000 readings per revolution. Based on the tests, it was concluded that the lack of an accurate physical representation of the excavator components (e.g., bucket) has the greatest effect on the overall system accuracy. Because the physical dimensions of the excavator had to be measured manually and since no shop drawings were available, unavoidable measuring errors were introduced. It is apparent that they contribute to erroneous x-y-z positions calculated by the computer algorithm. Therefore, more work is needed to find simple methods for accurate modeling of existing large construction equipment as well as simple calibration procedures that will help to increase the reliability and accuracy of the overall system.

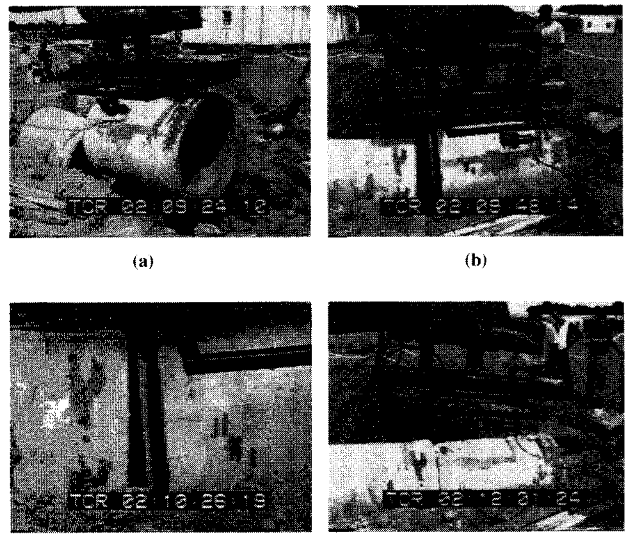
Remotely Controlled Pipe Laying

Fig. 10 demonstrates the rotational action of the pipe manipulator. Fig. 11 demonstrates the procedure of lowering and lining up the pipe section with the already placed pipe section. Once the pipe section is in place, a quick release is used to unhook the cable that allows the remote controlled winch to pull it from underneath the installed pipe. The tests of the prototype system demonstrated the feasibility of the developed hardware and software. It was learned that attachments, such as the one described in this paper, are providing excellent opportunities to economically upgrade existing equipment to become more versatile and to drastically increase the safety of pipe laying.



(a) (b)

FIG. 10. Rotational Motion of Pipe Driven by Hydraulic Motor: (a) Start of Rotation; (b) End of Rotation



(a) (b) (c) (d)

FIG. 11. Sequence of Remotely Controlled Pipe-Laying Process: (a) Pipe Being Lowered into Trench; (b) Horizontal Alignment; (c) Final Alignment and Pipe Jointing; (d) Pipe Installation and Remote Release Completed

CONCLUSION AND SUMMARY

Trenching and pipe laying represent two very common but hazardous operations. The key problem is the instability of soil that, if not properly supported, will result in a rapid collapse of the trench wall. This paper presented a research project that investigated the possibility of eliminating the need for a human worker to enter this dangerous zone. Based on the result of the study, one can conclude that modern technology is indeed capable and practical to achieve this goal.

The cornerstone of the innovative concept is the EM-SPS that was developed and tested for this project. It provides critical information about the position of the equipment within a fixed coordinate system in "real time" and linkages to a 3D CAD model of the excavator within the construction environment. Interfaced with data from electronic encoders mounted on the excavator itself, the system provides human operators real-time virtual images on a computer display about the current position of the machine they are operating. The accuracy of this multisensor system has also been investigated. The measured minimal discrepancy between the actual path and the calculated path is the result of several inaccuracies, mainly in modeling the backhoe excavator itself. It is felt that these discrepancies can be easily overcome. A simple calibration system was also tested that drastically reduced the error. Currently an effort is underway to demonstrate and test this system under actual job conditions.

In summary, it is believed that the results of this research project should encourage us to develop advanced and economical technologies that will drastically reduce the number of casualties caused by collapsing trenches, ruptured gas pipes, etc., while increasing the productivity and economy of the trench operations. The concept of SPS can be easily transferred to other large equipment commonly found on construction sites.

ACKNOWLEDGMENTS

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