CAD-Integrated Real-Time Control for Robotic Excavation and Pipe-Laying: Development and Testing

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FOREWORD

This report, *CAD-Integrated Real-Time Control for Robotic Excavation and Pipe-Laying: Development and Testing*, presents the results of research conducted for the Federal Highway Administration under a grant agreement with North Carolina State University, Raleigh, NC.

This research was initiated to develop and evaluate the concept of spatially integrated excavation. The research team had available three important hardware components: (1) in the laboratory, a robotic excavator that is fully automated and computer controlled with different force and position sensors, (2) a backhoe excavator that is equipped with electronic transducers for measuring angles on the boom, and (3) a laser-based spatial positioning system (SPS) that was integrated with the excavator. The overall goal of this project was to prove the technical feasibility and effectiveness of laser-based spatial position control under real-world conditions. In addition, innovative technologies for the detection of buried metallic obstacles and the laying of large pipes without the need for humans in the trench were successfully tested.

This work represents part of an effort on the part of FHWA to encourage the development of advanced and economical technologies that will drastically reduce the number of casualties caused by collapsing trenches, ruptured gas pipes, and so forth while increasing the productivity and economy of the trench operations.

Copies of this report are being distributed to the Federal Highway Adminstration regional offices and to each State highway agency. Additional copies of the report are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

Charles J. Nemmers, P.E.
Director
Office of Engineering
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16. Abstract

Trenching excavation and pipe-laying are, without a doubt, some of the most dangerous operations in construction. More than 200 people a year, in the United States alone, are killed during these operations. Machines that can reduce or eliminate the exposure of humans to these risks have the highest potentials to change the present situation. This research project was initiated under the contract between the Federal Highway Administration and North Carolina State University in order to develop and evaluate the concept of spatially integrated excavation. The research team had access to three important hardware components: 1) a robotic excavator in the laboratory; 2) a John Deere 690C backhoe excavator equipped with electronic transducers for measuring joint angles, and 3) the ODYSSEY, a laser based spatial positioning system that was integrated with the excavator. The overall goal of this project was to prove the technical feasibility and effectiveness of laser-based spatial position control under real-world conditions. In addition, innovative technologies for the detection of buried metal obstacles and the laying of large pipes without the need for humans in the trench were successfully tested. It is believed that the results of this research project lay the foundation for a dramatic reduction in the number of casualties caused by collapsing trenches, ruptured gas pipes, etc. Additionally, a variety of other benefits can be gained. For example, the automatic establishment of as built drawings, reduction of damaged utilities, increase of productivity due to the quantity of materials to be excavated (to meet OSHA requirements), and finally, the reduction of errors.

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Excavation, Pipe-Laying, Robotics
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 l shall be shown in m^3.

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C

ILLUMINATION

Symbol	When You Know	Multiply By	To Find	Symbol
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2

FORCE and PRESSURE or STRESS

Symbol	When You Know	Multiply By	To Find	Symbol
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F

ILLUMINATION

Symbol	When You Know	Multiply By	To Find	Symbol
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl

FORCE and PRESSURE or STRESS

Symbol	When You Know	Multiply By	To Find	Symbol
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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1. 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 1000 per year. In a recent report prepared by NIOSH, based on OSHA's inspection data, it was estimated that at least another 97 persons were killed as a result of all excavation-related accidents. 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 (Department of Labor)).

Excavation of soil and rock is a high volume and repetitive construction operation. Some 30 percent of the earth's crust is shale or mudstone, much of which can be excavated using a backhoe, front-end loader, or other heavy mechanical excavator. Because of their versatility, backhoe excavators are especially popular on construction sites. It is estimated that a fully automated excavating machine performing at 25 percent the efficiency of an expert human operator would be commercially feasible (Sing and Simmons).

Studies of the applications of robotic excavators and excavations have been undertaken by several researchers. Previous research results can be classified into three categories. The first category consists of work on geometric planning for robotic excavation. A few researchers have planned gross specifications for digging. This type of planning abstracts the world into a geometric basis and does not take into account considerations of mass, force or soil properties. The entire excavation task is segmented into a sequence of geometrical shapes before excavation begins. Researchers at Carnegie Mellon University have been working on problems of strategic planning and simulation of excavation in order to establish an optimal plan prior to the execution of the operation.

The second category consists of work on controlling the robotic excavator along a planned trajectory. Here different control principles and sensing technologies are presented. Vaha studied and established a kinematic and dynamic control model for a robotic excavator (Vaha). Bullock and Oppenheim in 1992 developed an approach for force-cognitive robotic excavation. Tochizawa reported about an automated excavator for excavating a trench for drainage using laser guidance. The authors showed that the laser guidance helped to decrease the labor hours and increase the digging accuracy. Path planning, which is responsible for identifying the most efficient means to fill the bucket with soil, requires data and information from the ongoing operation for intelligent and rapid updating and modification of planned paths. Bernold reported on his experimental work using small and real-scale excavation devices to collect data during the digging operation. He discussed the concept of pattern recognition as a means to develop a "grammar" to describe excavation using position and force measurements. The analysis of actual data provided the basis for describing the mechanics of an automatic path optimization system which would be able to adapt automatically to different bucket configurations, task objectives, and soil characteristics (Huang and Bernold).

Finally, there has also been interest in remote controlled excavators (or teleoperated excavators) for construction and hazardous waste handling. The aim of this work is to remove the human operator from the immediate work site. Langreth in 1992 reported about an advanced teleoperated hydraulic excavator. This excavator operates with a master-slave control and incorporates the force-feedback control so that the human operator can not only control the mechanical arm very easily, but also "feel" the obstacles that the bucket hits. Provided with video images from three cameras, the operator sits remotely inside a building or a vehicle, manipulating and observing the operations.

Trenching and pipe-laying are, without a doubt, some of the most dangerous operations in construction. Robotic manipulators that can reduce or eliminate the exposure of humans to these risks have the highest potentials to change the present situation. The main benefits from using cutting edge technologies for trenching and pipe-laying can be summarized in the following manner:

1) Drastic reduction of fatal accidents and lost workdays due to injuries.
2) Elimination of accidental damage to buried utilities such as water mains and power lines.
3) Augmentation of operator efficiency through intelligent control methods.
4) Reduction of wasted production time due to surveying or other related measuring errors.
5) Minimization of soil to be excavated since OSHA requirements for sloping do not apply.
6) Increase of the versatility of key machinery (e.g., backhoe excavator) by allowing the control of "smart" attachments. This hardware versatility combined with the new sensory controls should greatly increase the productivity of the work crew as a whole.
7) Automatic creation of updated as-built underground utility maps.
8) The technologies can be applied in a retrofit mode. Thus, existing machines could be easily equipped with the necessary technologies while new equipment could be redesigned for better integration of the necessary additional hardware.

This research project was initiated under the contract with the Federal Highway Administration (FHWA) in order to develop and evaluate the concept of spatially integrated excavation. The research team had available three important hardware components: 1) a robotic excavator in the laboratory that is fully automated and computer controlled with different force and position sensors; 2) a John Deere 690C backhoe excavator that is equipped with electronic transducers for measuring angles on the boom, and 3) the ODYSSEY^{TM}, a laser based spatial positioning system (SPS) that was integrated with the excavator. The overall goal of this project was to prove the technical feasibility and effectiveness of laser-based spatial position control under real-world conditions. In addition, innovative technologies for the detection of buried metal obstacles and the laying of large pipes were also field tested. All of these technologies are key components of a completely autonomous robotic excavation system of the future. However, this research project was also able to demonstrate how the individual systems can be independently attached to any existing excavator found on today's and tomorrow's construction sites. It is felt that the safety of trench excavation could be drastically increased by adopting the concepts developed and tested during the project.

The report will first introduce the conceptual designs for safe excavations and pipelayings. The following chapter discusses the basic problems of controlling large manipulators electronically. Chapter 3 presents the developed systems in the laboratory environment. In chapter 4, basic system components are developed, and chapter 5 introduces the activities and results of field tests.

2. CONCEPTUAL DESIGNS OF OPERATION

The key problem of a CAD-integrated system is the establishment of two spatial frameworks, global and local, and the automated transformation from one into the other. Global framework is used to display the entire picture, while local framework is used in calculating the relative positions of the different parts. A point as a vector in a local framework has to be represented in the global. Moreover, measurement technologies are necessary to provide the means to monitor compliance in the millimeter range. The later 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 3-D positioning system, 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). Secondly, position and force data from the robotic system can be established. Thirdly, since the relevant spatial position data is available (such as the final location of a pipe in the trench), an as-built data base 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 is not sufficient. The use of angle encoders mounted on the backhoe boom bridges this gap. Figure 1 depicts an overview of the trench digging operation using laser guidance with a backhoe excavator.

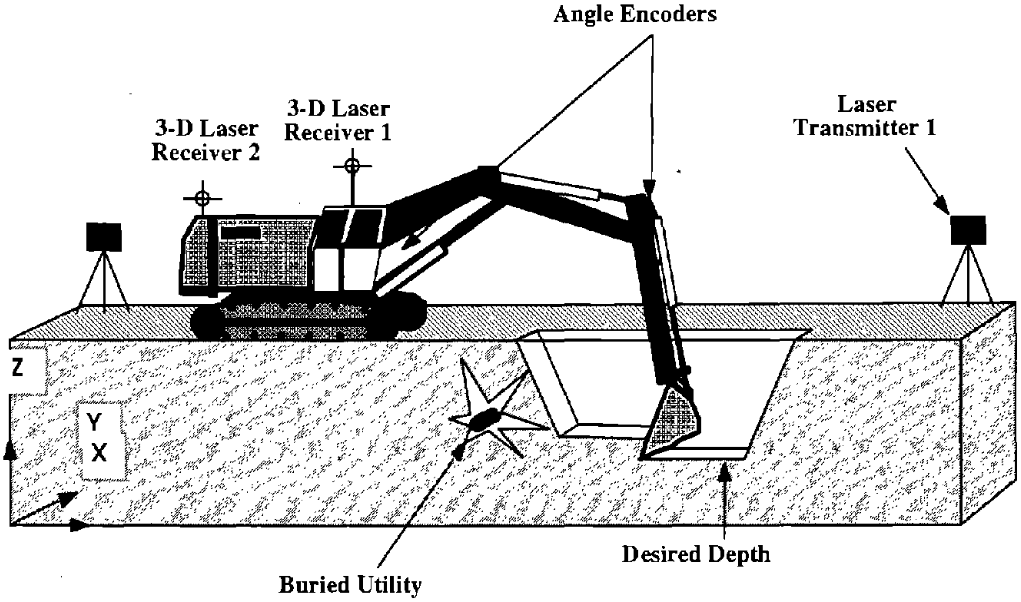


Figure 1. Concept of trench excavation using laser guidance

A conceptual layout of the envisioned future of laser guided pipe-laying is shown in figure 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 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 SPS together with the beam laser will provide the opportunity to measure the slope and alignment of the pipe very accurately.

Figure 3 depicts the conceptual design of the Buried Utility Detection System (BUDS). It is envisioned that an active metal detector search coil can be retrofitted onto a backhoe excavator to search for underground metal objects. As soon as the object is detected, the operator is warned to exercise caution. Research was undertaken to study the signals and provide the information about the location and orientation of the object.

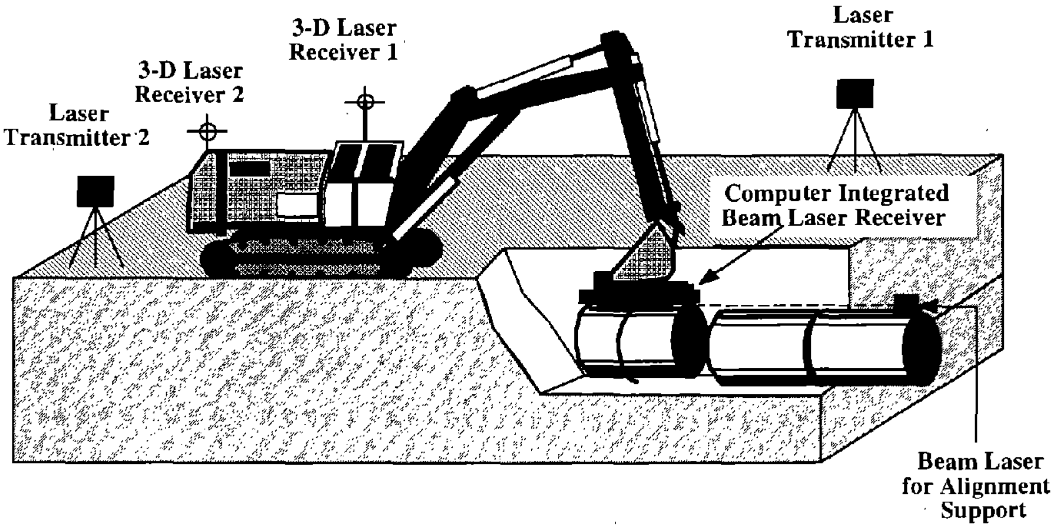


Figure 2. Concept of remotely controlled pipe-laying with laser guidance

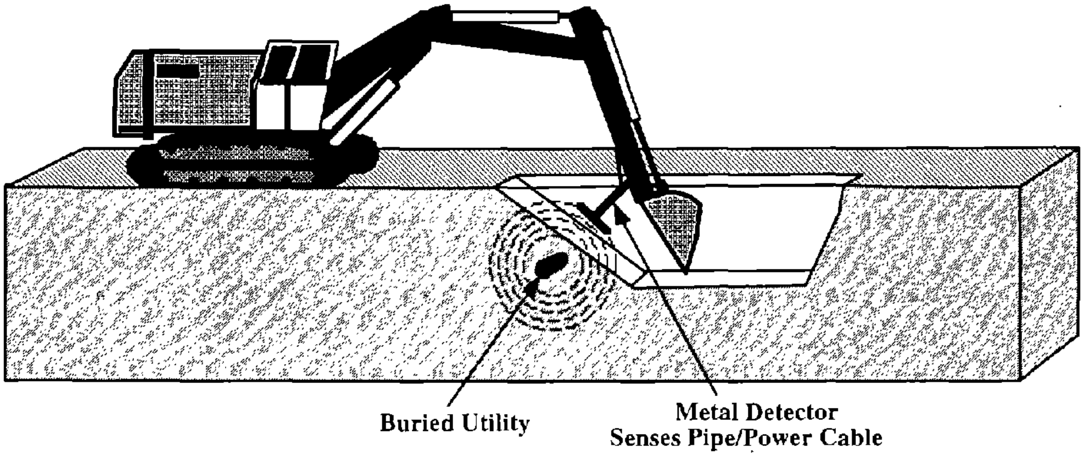


Figure 3. Concept of excavator mounted metal detection

3. CONTROL OF LARGE MULTI-LINK MANIPULATORS

SYSTEM COMPONENTS

Most robots can be regarded as multi-link manipulators which are composed of cantilevered beams, forming a sequence of arm links connected by hinged joints. The robotic arm is then driven by several electric motors or hydraulic/pneumatic cylinders. This determines that such a multi-link structure is inherently a complex nonlinear system. Effective analytical tools such as modern nonlinear control theories are necessary to understand the geometric, kinematic, and dynamic behaviors of the manipulator.

The basic components of a robotic manipulator include 1) mechanical links and actuators, 2) electronics, 3) power source, and 4) control devices. Sensors are the major components of the electronics. The most useful sensors include the position sensor (encoder), force sensor (load cell), pressure transducer, etc. Many industrial robots use electric motors to drive their links. Others use hydraulic cylinders to manipulate. Control devices of a robotic manipulator include devices to collect data from its sensors and a controller which generates the adequate control commands to achieve the control objectives.

The control of robotic manipulators is a challenging task, especially when the controlled robots are highly non-linear and complex. The difficulties that arise in the control of robotic systems can be classified into three categories. The first is the system complexity. A dynamic equation of a multi-link robot can consist of hundreds of terms. The second is the presence of nonlinearities such as Coulomb friction, saturation, dead-zones, and backlash which have to be taken into account. Coriolis and centrifugal effects are prominent when the manipulator arm moves at high speed. The third difficulty which may arise is the model uncertainties, which include structured (or parametric) uncertainties and unstructured uncertainties (unmodeled dynamics). The task becomes even more difficult when the robotic manipulators are interacting with the environment.

Traditionally, non-linear control design such as computed torque and sliding mode control is based upon a comprehensive mathematical model of the robotic system to be controlled. The model embodies detailed dynamics of the robotic system. The controller itself is also written in an intricate mathematical representation that is closely related with the system model. If the robot arm interacts with the external environment, an extra dynamic relationship between them must also be illustrated. The dilemma is that both of these dynamic models may be difficult to derive; further, even if a mathematical model could be constructed accurately, its applicability to control may be somewhat constrained due to its complexity; computation of the controls is also much more demanding.

EXPERIMENTAL RESEARCH FACILITY

An experimental multi-purpose robotic manipulator has been built at the Construction Automation and Robotics Laboratory (CARL) of North Carolina State University. This robotic manipulator is designed to serve as a platform for many different applications such as soil excavation, pipe-laying, rock breaking, etc. Figure 4 gives an overview of the newly upgraded experimental robotic excavator. Many different end-effectors (i.e., bucket, gripper) can be mounted to the end of the arm to reassemble this device into different experimental configurations. In this figure, the manipulator is equipped with a bucket to operate as a computer controlled backhoe excavator. This robotic manipulator has a reach of 6 m (16 ft) with heavy lifting capacity. It is driven by one hydraulic motor and three hydraulic actuators (cylinders) which provide a total of four-degrees-of-freedom (DOF). Two joy stick controllers have been installed to allow for shared, traded, and distributed controls. Each hydraulic line is equipped with an electronic pressure transducer.

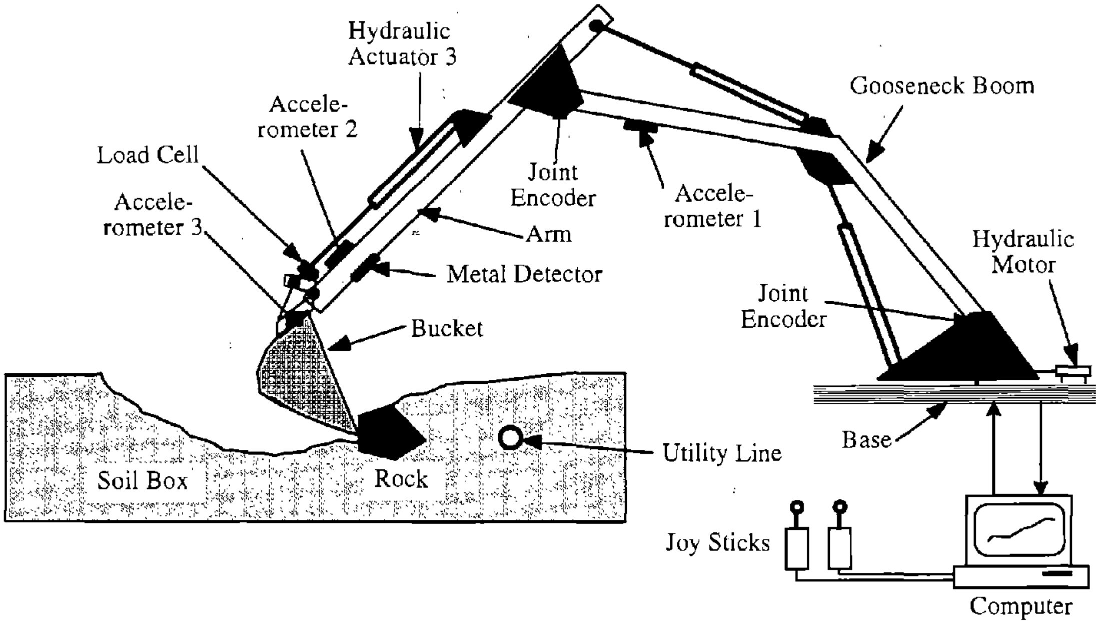


Figure 4. An experimental facility for robotic backhoe excavation

One PC computer is used to control the entire robotic manipulator and to collect data from the sensors in real-time. A/D data collection boards and a D/A control board act as interfaces with the electric transducers and hydraulic actuators. Several sensors have been mounted for assorted tasks. The joint encoder is used to measure the individual joint displacements during excavation. In order to establish an experimental system, one load cell mounted between the rod and the clevis of the actuator driving the bucket is used as a backup to confirm data from the pressure transducers. To detect metallic objects, such as pipes, one metal detector search coil has been designed and installed on the excavator arm. Figure 5 shows a picture of the experimental robotic excavator in the laboratory.

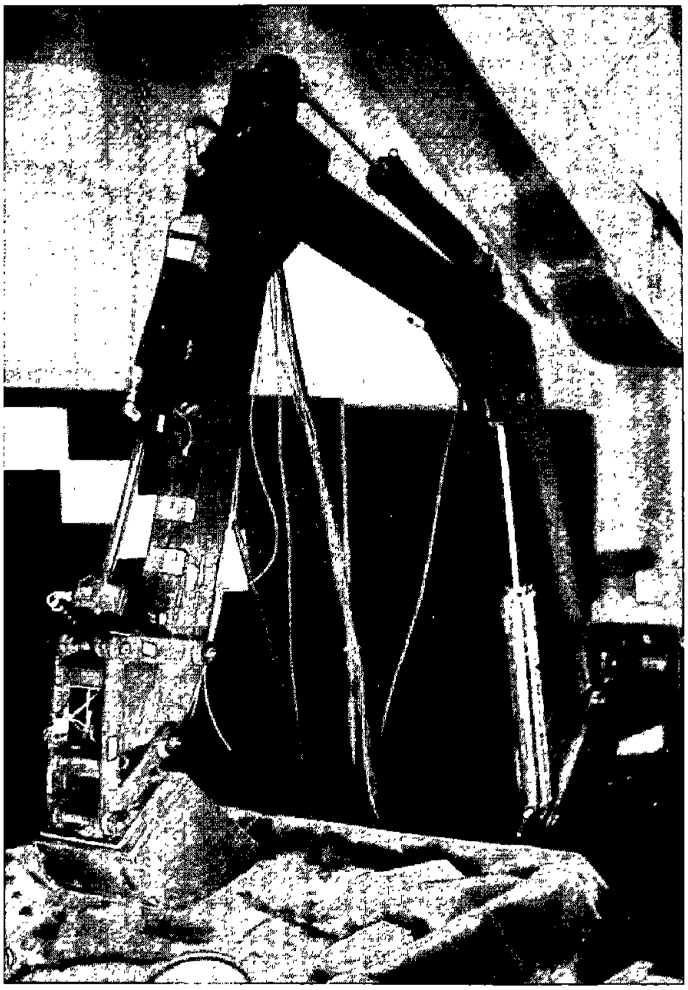


Figure 5. The experimental robotic excavator setup

THE UPGRADED JOHN DEERE 690C EXCAVATOR

A John Deere 690C multipurpose excavator has been used to implement the control algorithms developed in the laboratory. Figure 6 pictures the large-scale excavator in the field. This upgraded excavator has all the electronic sensors and control hardware built-in to perform sophisticated computer controls and manipulations. Each joint on the excavator is equipped with a high resolution resolver. Hydraulic pressure transducers have also been installed in all of the hydraulic lines in order to monitor the hydraulic pressures. The hydraulic cylinders installed on the excavator are driven by electro-proportional valves to allow easy computer controls.

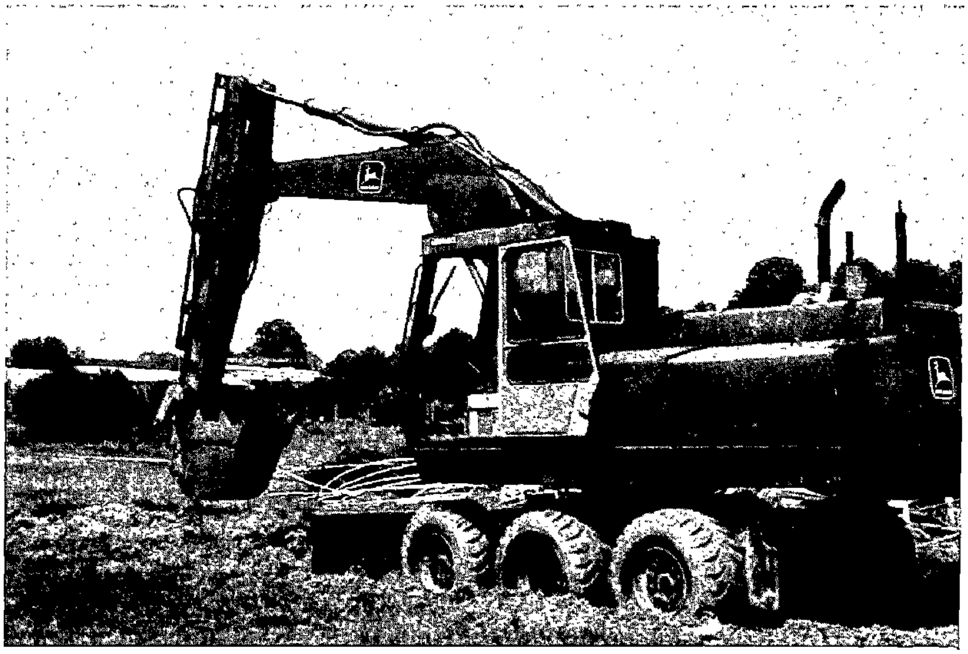


Figure 6. The John Deere 690C excavator in the field

Complete computer control as well as remote joystick control capabilities have been installed. The computer control enables the operator to run the excavator from a computer keyboard. At the same time, the hydraulic pressures can be monitored and the configuration of the excavator can be calculated based on the resolvers' outputs. This is critical for the later integration of the SPS and also the robotization of the complete system. Remote joystick control allows the operator to control each movement of the excavator from a remote place without sitting in the driver's cabin. Figure 7 depicts the excavator controlled through a laptop computer.

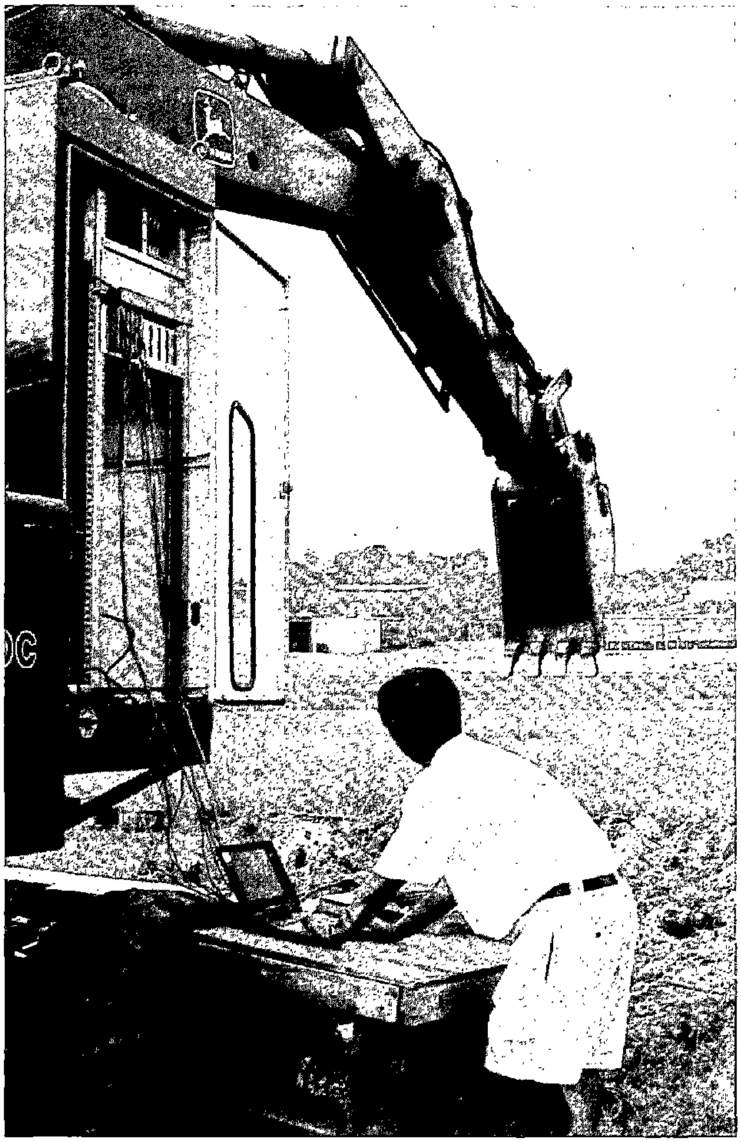


Figure 7. Computer controlled excavation

4. SYSTEM DEVELOPMENT

THE CAD-INTEGRATED SPATIAL CONTROL MODULE

When a tele-robotic excavator is used, the human operator must depend on the sensory feedback data to operate the machine. This feedback commonly includes force data and video images from the cameras mounted on the excavator. Thus, the human operator can remotely control the unmanned excavator based on what he/she sees on TV screens. Most modern systems also provide some sensitive joysticks. However, this paper introduces a supplementary and innovative visualization aid, the AutoCAD virtual display system. By integrating the SPS and other position sensors on the excavator, the AutoCAD system updates at real-time the excavator position in global coordinates. The operator can choose any viewing angle zoom to identify for example the distance between the cutting edge of the bucket and the bottom of the trench in 3-D. The following sections will describe its key components.

The ODYSSEY™ Spatial Position Measurement Technology

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. Each transmitter generates two inclined fan-shaped laser beams (planes) which are rotated about an axis at a constant angular velocity. When the rotation of a laser beam is such that it strikes the receiver, a photosensitive detector generates a signal to be used to calibrate its current position. The system consists of a CPU (Central Processing Unit) and an RPU (Receiver Processing Unit) for connecting with a computer. The transmitters can cover a distance of about 100 m. Figure 8 depicts an overview of the system setup.

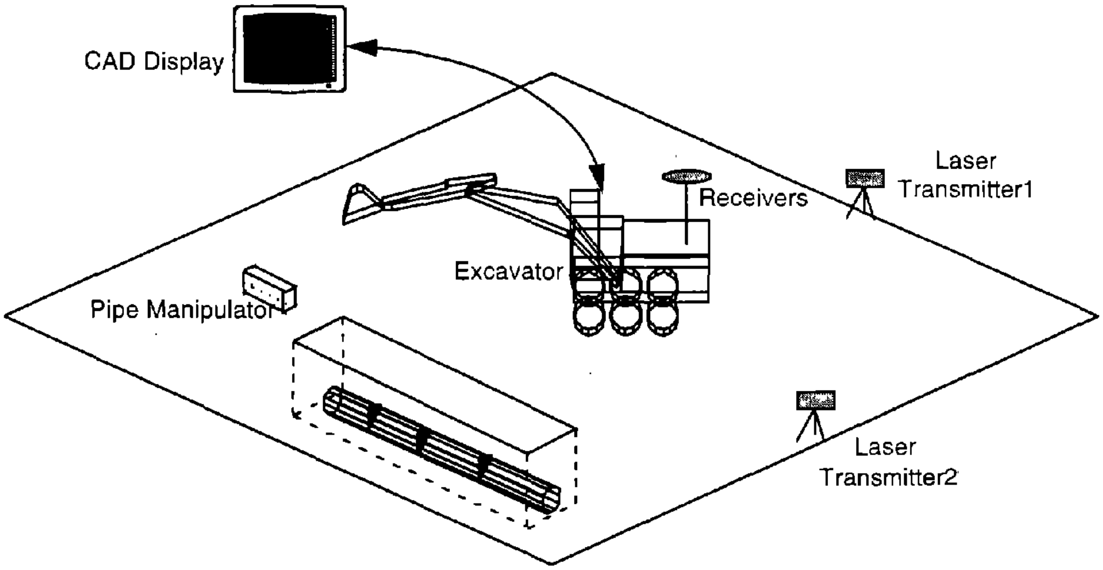
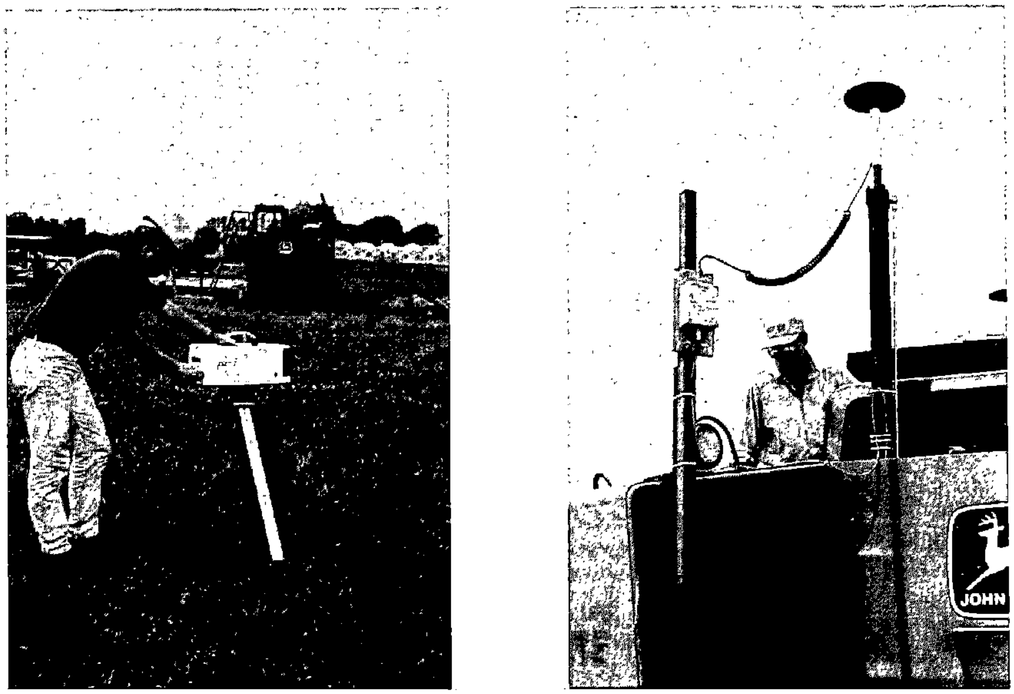


Figure 8. A schematic of the spatially integrated excavation

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 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. Secondly, through data fusion with force data from the hydraulic system, a robotic control system can be established. Thirdly, because it is able to capture and electronically store the relevant position data in space, such as the final location of a pipe in the trench, an as-built data base can be automatically established. Figure 9 shows pictures of the excavator mounted SPS. The two receivers provide 3-D position data 5 times per second. This data is automatically transferred to the main computer.



Laser transmitter **Laser receivers**

Figure 9. The spatial positioning system (SPS) for excavator

The Real-time AutoCAD Display Component

In order to assist the human operator to visualize different states of the operation of a field excavator, an AutoCAD display system has been developed to take advantage of the existing position sensors (resolvers) as well as the SPS. AutoCAD is just a display tool. In order to acquire the outputs from the SPS and other sensors, an interface program is written in QuickBasic to handle 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 SPS.
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.
5) The transfer of the local coordinates into the global coordinates.

Therefore, the QuickBasic interface program keeps gathering external data and providing them to AutoCAD for virtual displaying. At the same time, the AutoCAD updates position information and shows the real-time operations of the excavator. To coordinate the above two different actions, the latest OS/2 Warp operating system is used. The OS/2 Warp operating system provides a true multitasking environment to run a DOS program and the AutoCAD for Windows R12 at the same time. Figure 10 portrays the scheme of this multitasking under OS/2 Warp.

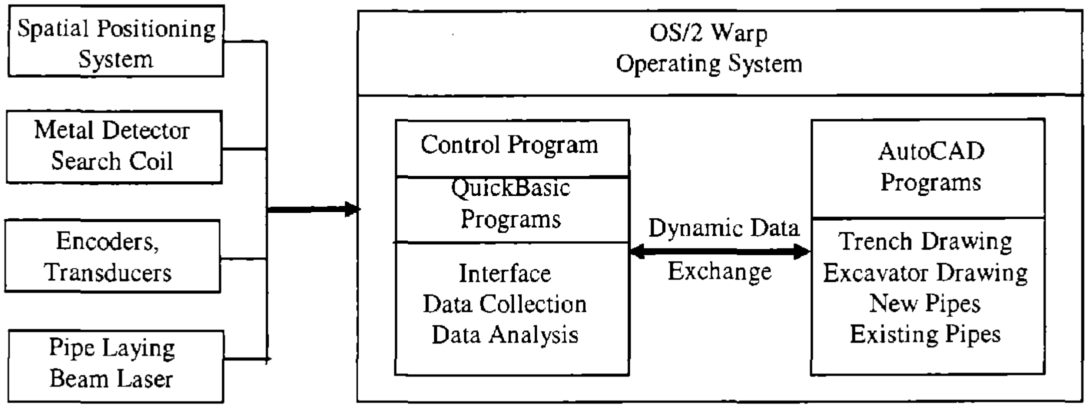


Figure 10. Structure of interface programs and sensors for spatial integration

Under the AutoCAD for Windows R12 environment, an AutoLISP program updates the position/orientation of the excavator and its trenching operations at real-time. Every 3-D perspective view will be based upon a fixed world coordinate system (global coordinate system) that is set up by the SPS. 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, the operator is able to see the 3-D field with the excavator operations, the trench under excavation, and other objects such as pipes under the SPS coordinate schemes. At the same time, he/she can also view the digging motion under the plan view and side view. It is believed that the above combination technique provides an excellent interface to enable the operator to manipulate the viewpoints in AutoCAD to his/her preferences.

The DOS 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) to enable fast access. This data file is then to be used with the AutoLISP program.

When both programs have to run at the same time sharing the same set of data, our first concern was how to coordinate the two applications. The data file which mainly consists of the position information of the excavator is only accessible to one of the programs at any one time. To solve the problem, error trapping technique has been applied in the coding of the programs. For example, the DOS program, which is compiled from the QuickBasic, stays in an error trap when the data file is called upon by the AutoLISP program. As soon as the AutoLISP program releases it, the DOS application will then take over the file. The next position data collected from different sensors are to be saved into this file again. The implementation is simple and direct. Figure 11 illustrates the execution procedures of the two programs.

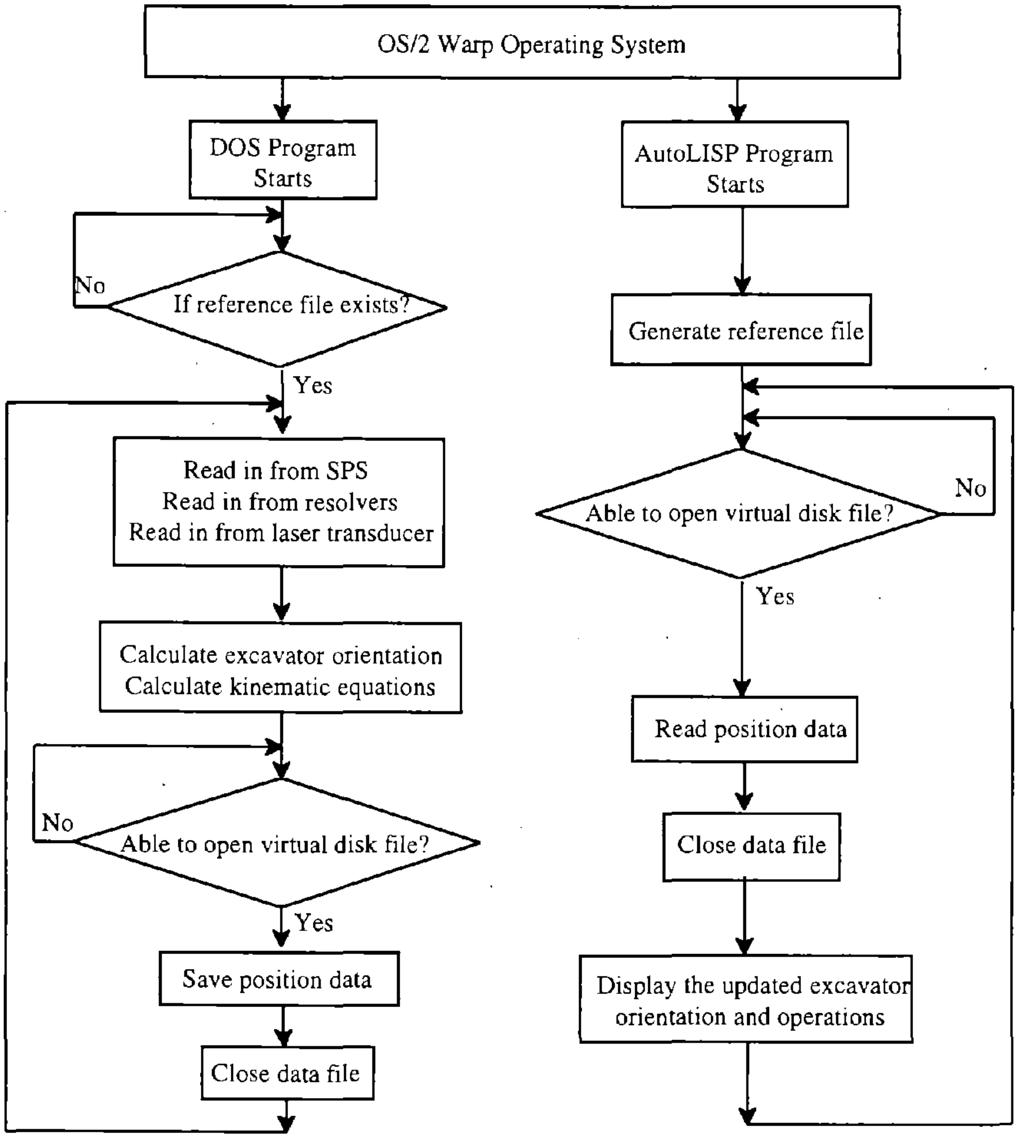
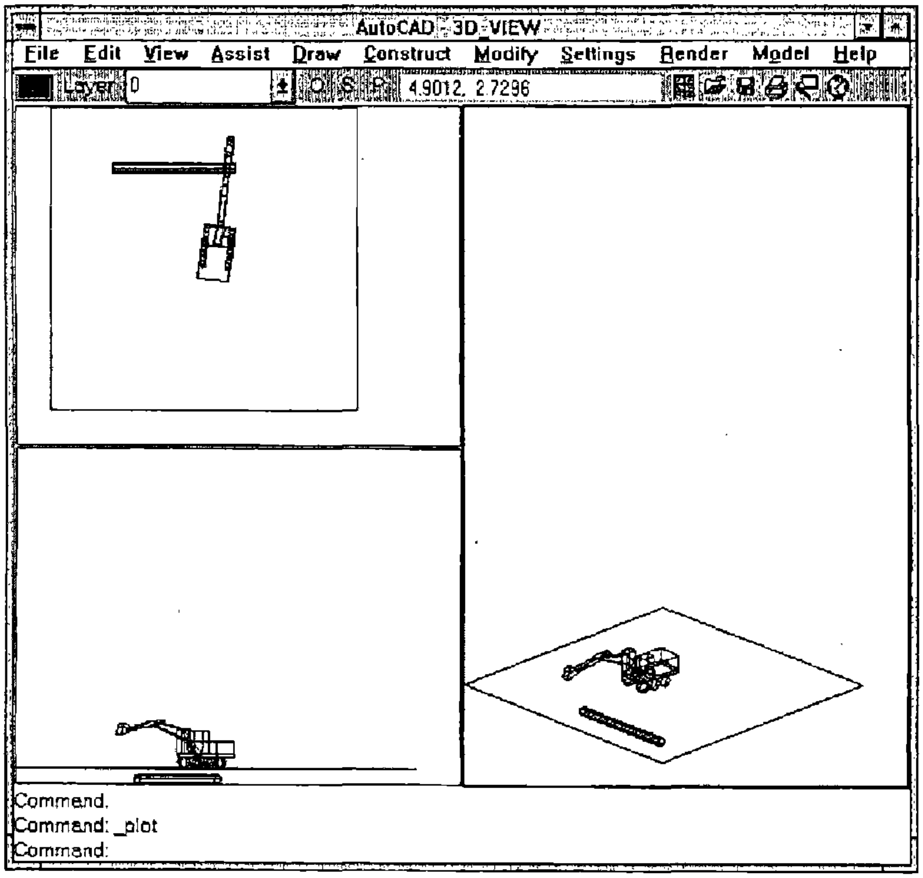


Figure 11. Schematic of the coordination of multiple programs

The real-time AutoCAD display component also supports easy switches for different view-points to visualize the drawing. For instance, a 3-dimensional drawing can be changed into a 2-dimensional one only showing the side view of the excavator. This is extremely helpful when the operator is performing a trench digging operation. The operator is also able to get a top view of the whole site to assist him in locating himself. Furthermore, several different views can be displayed and updated at a time on the same screen. Figure 12 shows an AutoCAD display with a 3-D view, top view, and side view together. The current display system is equipped with a touch screen. Because of the user friendly interface, most of the commands can be executed using the touch screen.



```
Commend.
Command: _plot
Command:
```

Figure 12. A real-time AutoCAD display of three views

BURIED UTILITY DETECTION MODULE

A new technology has been developed that is capable of locating underground utilities and any other ferrous or non-ferrous objects. Differing from traditional metal detection techniques, the selected sensing device developed in CARL is considered an active search system. It consists of: 1) a metal detector search coil, 2) a signal processing (control) unit, and 3) a PC computer equipped with an analog-to-digital (A/D) converter interface. Figure 13 presents schematically the relationship among these three core components of the system.

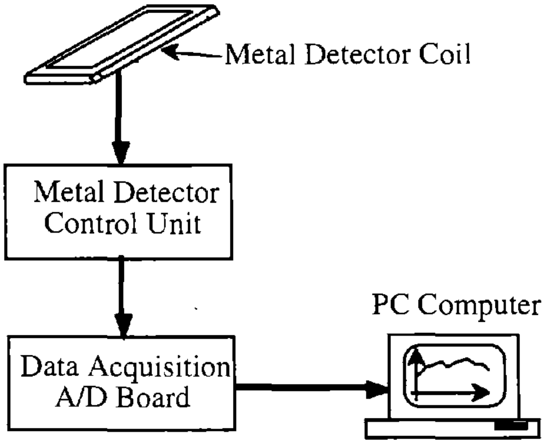


Figure 13. The computer integrated metal detection

In contrast to the traditional metal location technologies, active metal detectors generate their own magnetic field through the transmitter module and search coil. Its impact on any metal object in its detection range will be coupled and then picked up by the receiver module of the detector. The signals from the search coil are processed by the control unit. It also supplies the necessary DC power. As shown in figure 13, a data acquisition board is connected to an analog output port of the control unit. It performs an analog-to-digital conversion at a high sampling rate. A QUICK-BASIC program imports the data from the control unit. Thus, the computer is able to receive real-time data about the magnetic changes in its vicinity, to graph them on the screen, to sound a signal, and/or to store it in a file for analysis. The programming capability of the microprocessor provides an excellent platform for the future development of algorithms that engage in real-time pattern recognition to infer from the data stream detailed information about the depth, location, orientation, and even the size of the metal object.

Figure 14 illustrates an excavator buried utility detection system (BUDS). It is retrofitted onto a backhoe excavator. The lap top computer which is mounted in the driver's cab provides updated readings from the BUDS and sends out warning signals in case a metal object is detected.

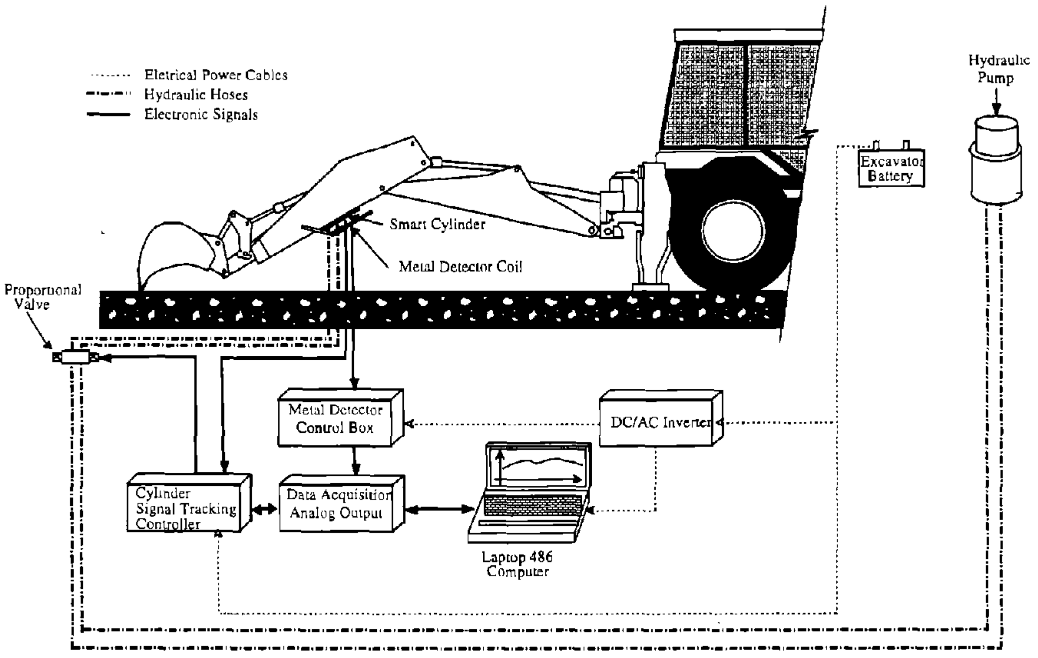


Figure 14. A schematic of the BUDS mounted on a backhoe excavator

PIPE-MANIPULATOR ATTACHMENT

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.

Hardware Design

As indicated in figure 15, the hardware consists of 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 with four wheels and a hydraulic cylinder that provides a linear motion capability. Each pipe segment is being held by one cable which is operated via an electric winch mounted on the carriage. A hydraulic motor and a chain allow the attachment to be rotated 360 degrees while the C-shaped connector base was designed so that the excavator operator is able to insert the bottom of the bucket into the cantilevered "hook." Provisions are made for introducing a clamp mechanism at the rear of the bucket that would secure the connector base from slipping off the bucket.

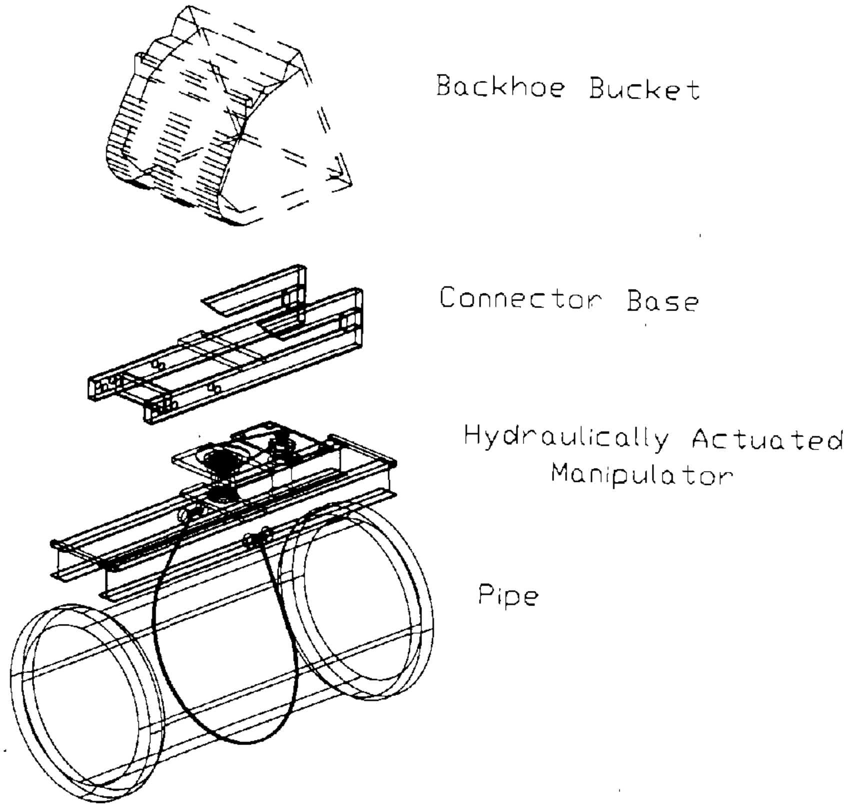


Figure 15. Hardware components of the pipe manipulator

Not visible in figure 14 are the hydraulic lines and the electronic cables which provide the operator with the data from the laser receiver. The laser receiver is mounted on the linear track and is capable of sensing the position of a laser that hits its plane surface. Figure 16 presents the laser system utilized for this project.

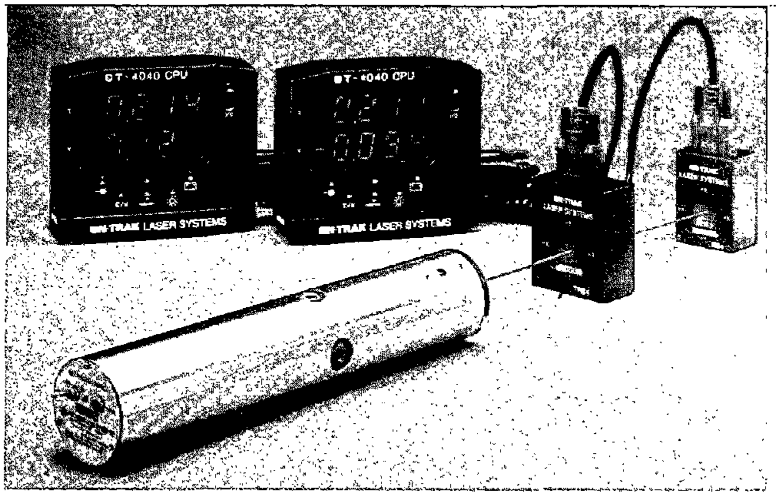


Figure 16. ON-TRAK alignment laser with CPU and X-Y remote sensors (On-Trak Laser Systems, 94)

The beam laser establishes a stable reference laser line for aligning the pipe section with precision while the SPS guides the operator to the approximate position of the beam in space. The selected system is composed of three units: a) Laser Diode Unit, b) X-Y remote laser sensor, and c) a central processing unit. The laser diode unit: transmits a laser beam 8 mm in diameter for a distance of 100 ft while the X-Y remote sensor uses the pulsed beam of laser light as a reference. It has a 0.788" by 0.788" (20 mm by 20 mm) capture area with an accuracy of 0.001". Integration is achieved with the battery operated laser position signal processing unit; which contains an RS-232 communication port. With a host computer, the CPU has the ability of addressing the remote sensor, collecting data, and changing/accessing target settings via the RS-232 serial port. The CPU displays the absolute X-Y position on 2 large digital read-out with a resolution of 0.001". With the capability of averaging the laser pulses, the CPU can account for vibrations and air turbulence that may be encountered in different applications.

5. FIELD TESTING

CONTROL MODES FOR JOHN DEERE EXCAVATOR

Two new control methods have been implemented with the John Deere 690C excavator. The first is the use of remote joystick control. Remote joystick control will let the operator manipulate the excavator from a site away from the driver's cabin. This has important applications for 1) hazardous and dangerous field operations, and 2) close-up operations, since the operator can stand next to the bucket to control the excavator. Figure 17 shows how the joystick control was demonstrated and tested.

Figure 17. Joystick control of the John Deere excavator

Direct computer control of this John Deere robotic excavator has also been implemented. This method establishes the platform for the implementation of a fully robotic control, integrated with a SPS and CAD (see figure 7). Figure 18 shows another picture of the computer integrated control mode for this John Deere excavator. A laptop computer is installed in the operator's cabin to provide updated information from the SPS and other sensory devices. These information data also can be used to evaluate the operator's skills.

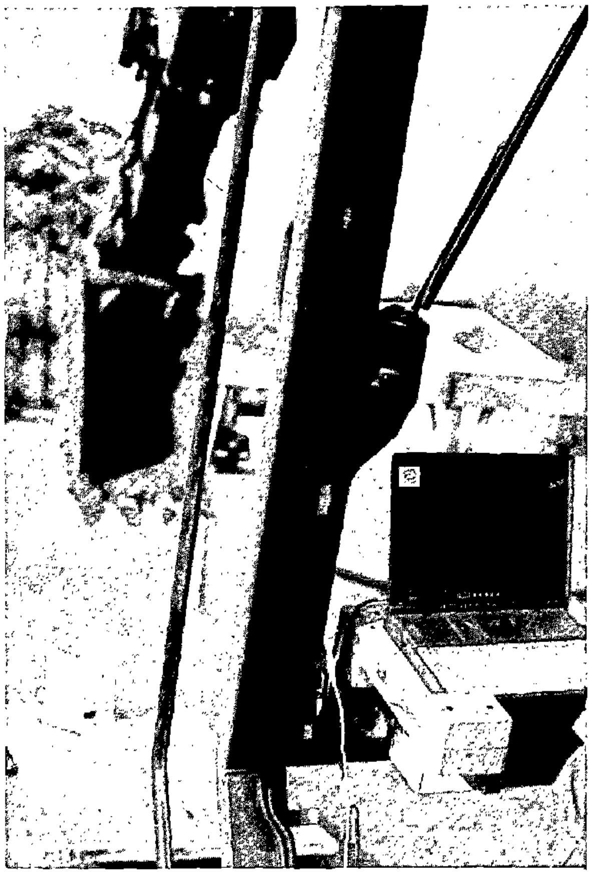


Figure 18. John Deere excavator equipped with computer

ASSESSMENT OF PATH ACCURACY

In order to accurately display the field excavator within the global coordinates of AutoCAD, accuracy of the two position feedback systems has to be reliable. The X-Y-Z coordinate of the excavator bucket in the global coordinate frame is determined by the following elements:

1) The X-Y-Z coordinates of the two laser receivers of the SPS.
2) The measurements of the John Deere 690C excavator.
3) The resolution of the joint resolvers on the excavator.
4) The algorithms which are used to calculate the X-Y-Z coordinate, (e.g. inverse kinematics).

Field tests to determine the path accuracy included the following five phases:

1) Surveying of fixed calibration points using SPS.
2) Calibration of excavator using different bucket angles at fixed calibration points.
3) Digging of a trench with position feedback implemented.
4) Surveying of the finished trench using SPS.
5) Comparing the results from phase 4 with phase 3.

Figure19 shows the first phase in which the SPS is used to establish the X-Y-Z coordinate of a fixed point at the top of a ground-anchored pole. In the next step, the excavator bucket was brought in a position where the cutting edge touched the calibration poles.

Figure 19. Surveying of fixed calibration pole using the SPS

Figure 20 exhibits three bucket configurations used to calibrate the position feedback system. The purpose of conducting these experiments is to evaluate the sensitivity of the system to minor changes in the mechanical system. Under an ideal situation, they should have little effect. However, in reality, errors stemming from different sources which have not been investigated at this point cause differences between the surveyed coordinates and the coordinates fed back by the excavator mounted sensors. Therefore, it is necessary to compensate for the errors according to the different cutting angles that the bucket poses. Those compensations are given in table 1 to be used to correct the excavator feedback readings in figure 22.

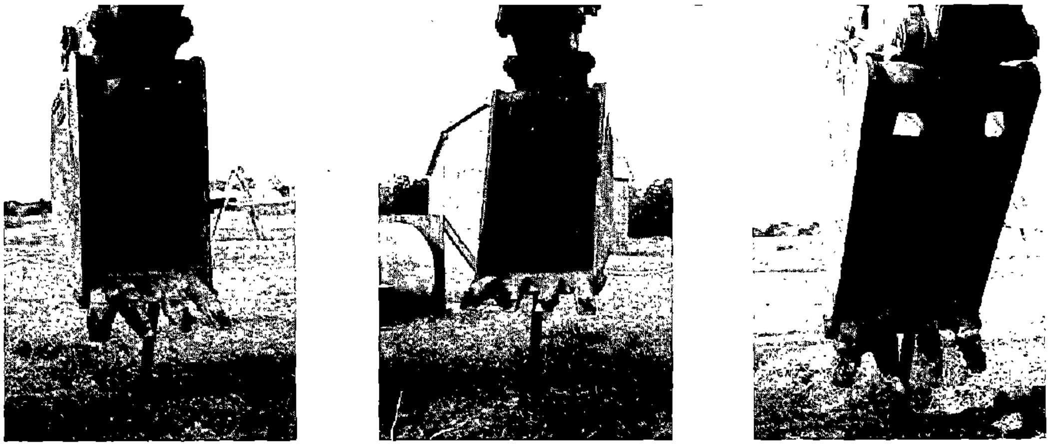


Figure 20. Calibration of bucket with three different bucket angles

Table 1. Errors between the actual and SPS points (Unit: cm)

	Point 1	Point 2	Point 3	Point 4
Δx	12	18	8	10
Δz	3.7	6.2	11.1	8.9
Δy	0	0	0	0

In the above table, the error discrepancy in the Y direction is so minimal compared with the discrepancies in the other two directions that $\Delta\ y$ is regarded as to be zero.

In phase 3 (figure 21a), an actual trench excavation is being performed. During the trench digging process, position is "called" by the computer as an input to an algorithm that calculates the bucket edge location in Cartesian coordinates. The purpose is to assess the X-Y-Z coordinates of several intermediate points. After the dig is complete, the SPS was used again to survey the coordinates of the intermediate points established in Phase 4 (figure 21b).

The results from the SPS are considered the correct, or actual points, while the calculated results from the algorithm in the computer are regarded as the feedback points. The smaller the discrepancy is, the more accurate the AutoCAD display system will be.

a) Digging with position feedback **b) Surveying of intermediate digging path**

Figure 21. Testing of System Accuracy

The result of the five phases used for assessing the accuracy of the system is presented in figure 22. The point coordinates given by the excavator position feedback, calculated using kinematic equations, are consistently lower than the 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 in order to reduce any error.

$$
\begin{aligned}
x_C &= x_{FB} + \Delta x \\
z_C &= z_{FB} + \Delta z
\end{aligned}
\tag{1}
$$

where x_C, z_C are the corrected X and Z coordinates, x_{FB}, z_{FB} are the feedback X and Z coordinates, and Δx, Δz are the correcting factors in the X axis and Z axis respectively, which are obtained from the test phase 2. In the above representation, X reflects the length direction; Z is the depth; and Y is in the width direction. Because there is little discrepancy in the Y direction, no correction is necessary for Y coordinates. In figure 22, the average of $\Delta x = 12$ (cm) and the average of $\Delta z = 7.4$ (cm). The objective of the correction is to compensate the error between the excavator feedback (FB) and the SPS reading.

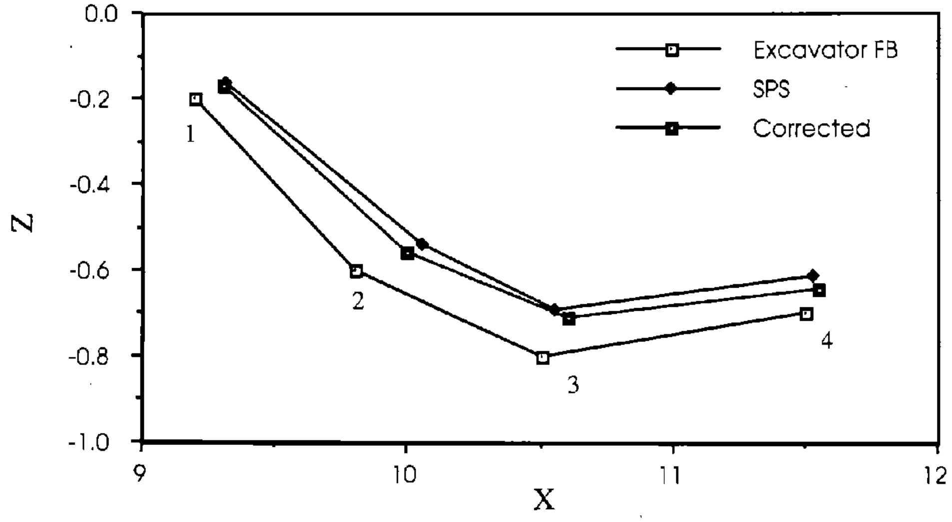


Figure 22. Comparison between the excavator feedback (FB) and SPS positions

Table 2. Errors between the corrected path and the actual path (Unit: cm)

	Point 1	Point 2	Point 3	Point 4
Δx	0	5	4	2
Δz	0	4	2	2

However, limitations exist with the current system. Based on the field tests, it was concluded that the measurements of physical dimensions of the excavator components (e.g., bucket) have the greatest effect on the overall system accuracy. From the SPS's manufacture's specifications, its accuracy is within 5 mm. The joint resolver installed at each joint of the excavator has a resolution of more than 10,000 readings per revolution. Because of the complexity of the excavator, its physical dimensions, which were measured manually for the project, have unavoidable measuring errors. It is apparent that they contribute to erroneous position calculation by the computer algorithm. Therefore, more work is needed to find simple methods for accurate spatial modeling of large construction equipment as well as simple calibration procedures that will help to increase the reliability and accuracy of the overall system.

BURIED UTILITY DETECTION

Excavation accidents involving cutting utility lines often happen during the backhoe's first dig. Therefore, a pre-dig detection of any metal object is considered important. Pre-dig detection focuses on scanning the ground, which basically repeats the traditional locating operation from the surface. For the pre-dig experiment, a 6.03-cm diameter metal pipe was first buried approximately 33-cm below the surface. For this test, the backhoe operator rotated only the boom of the backhoe which ensured that the detector coil was kept parallel to the surface of the ground while scanning the area beneath. Figures 23 and 24 illustrate sequences of metal detection procedure conducted in the field.

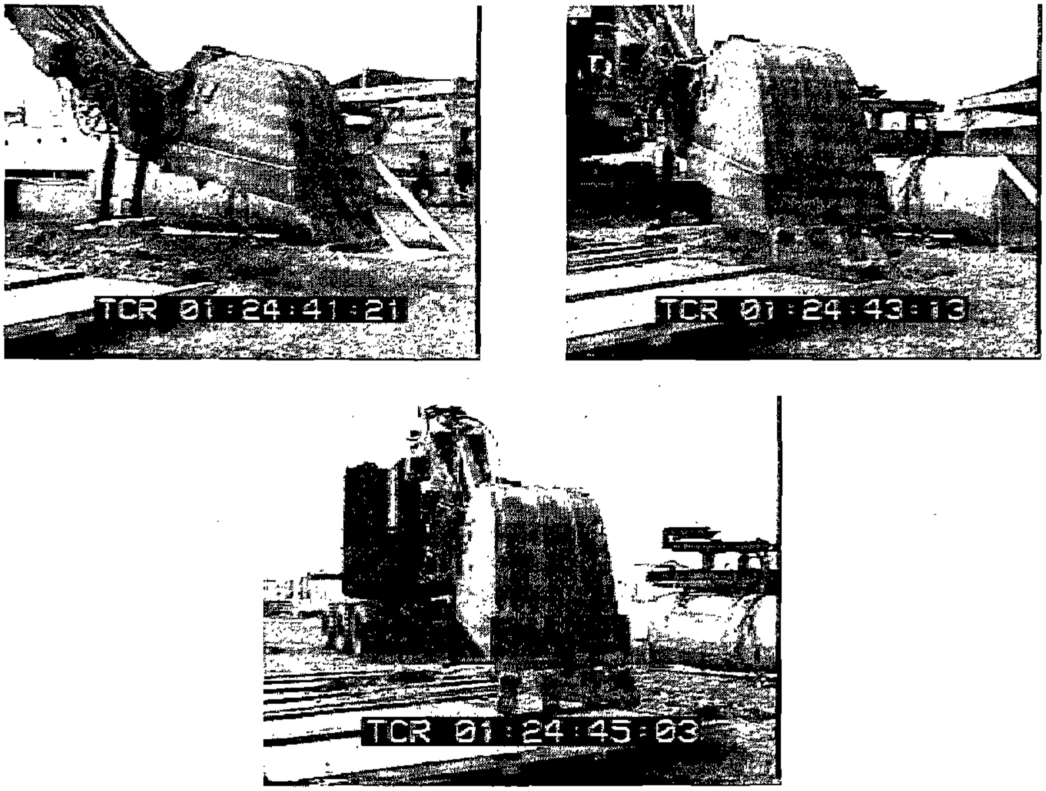


Figure 23. Horizontal pre-dig canning of the metal detector search coil

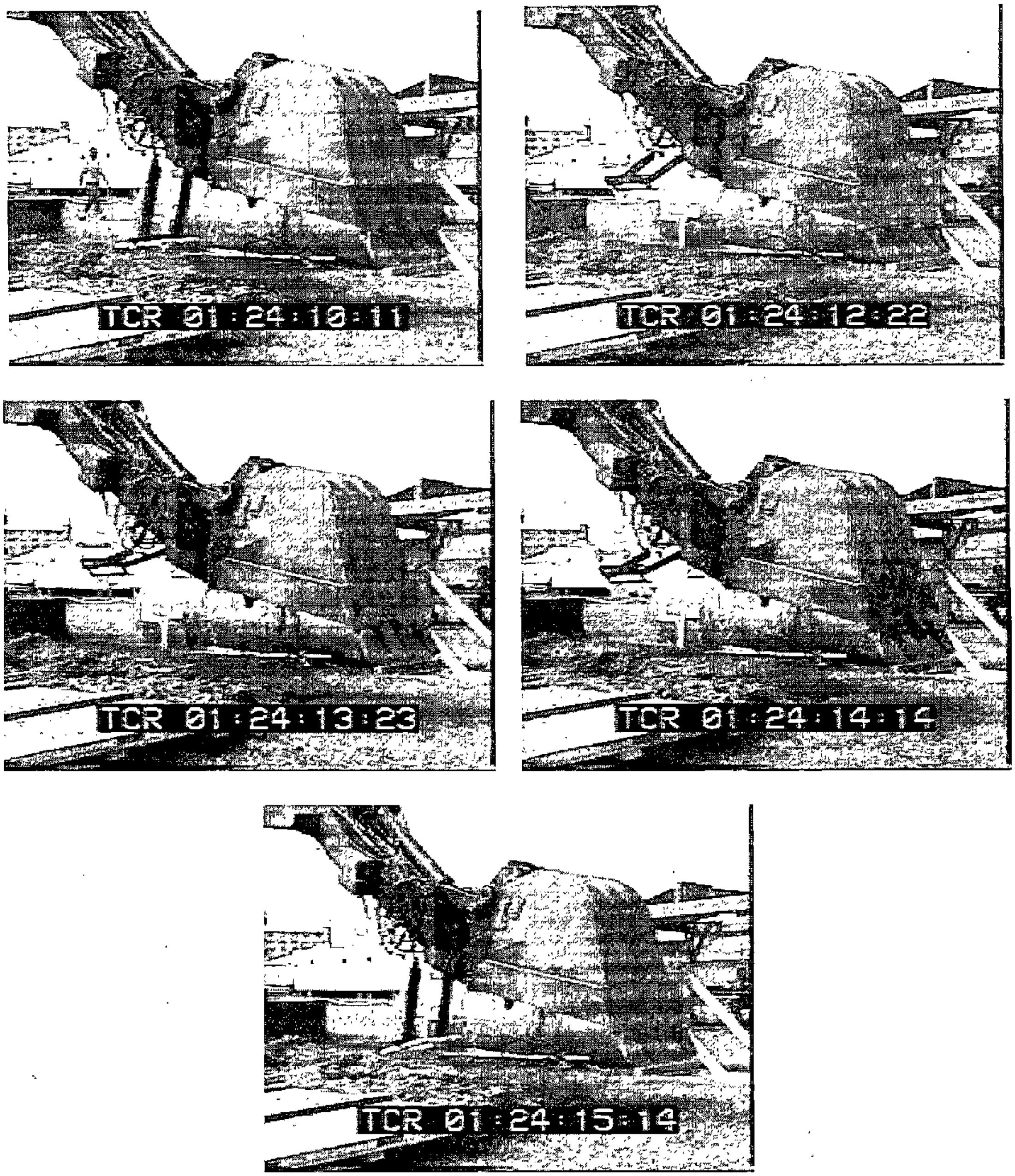


Figure 24. One scan of the search coil driven by a smart cylinder

Figure 25 depicts the collected data during the above pre-dig scanning. The vertical axis represents the metal detector output in volts, which is proportional to the size of the metal in combination with its distance from the coil. The horizontal axis corresponds to the sample number associated with the sequence of digitized analog signals acquired from the control box during the scanning process. The sample number is related to the positions of the boom in polar coordinates (angle). As shown in figure 25, the two curves, representing two pipe sizes, reach their peak at sample # 40. The maximum output value of 1.4 v resulted from a 6.03-cm metal pipe buried at approximately 33-cm depth. In order to test the influence of pipe size, a second test was conducted with two pipes, 6.03-cm diameter each, buried 33 cm deep. As indicated by the second curve, metal influence reaches the peak at the same place with a value of 2.8 v. This value is double that of a single pipe. Thus, the doubling of the sensor output amplitude is clearly related to adding a second pipe. The sensor outputs from the pre-dig scanning tests showed again, distinct patterns that may be used not only to detect metal, but also to distinguish between large and small metal pipes at different depths.

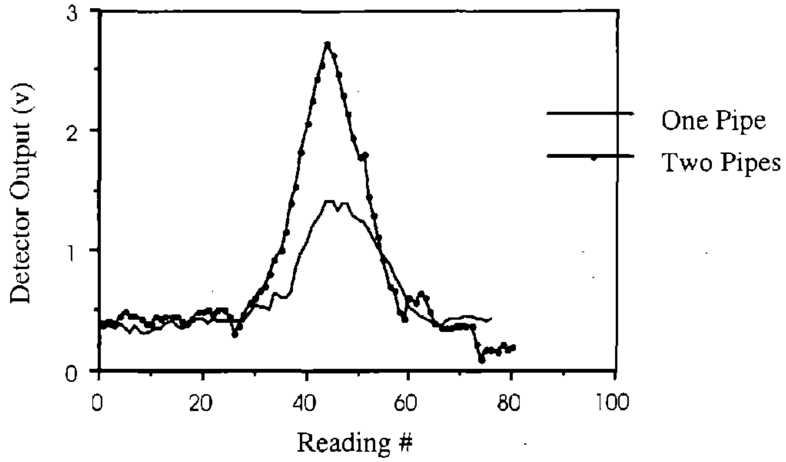


Figure 25. Data from horizontal pre-dig scans with buried metal pipe(s)

Metal detection during digging was the second configuration that was tested. In this scenario, the operator initiates a rotational motion of the coil before the bucket cuts through the soil. Figure 26 displays the data collected during three scanning actions. In this figure, the vertical axis represents the amplitude of the output signal in volts, while the horizontal axis indicates the extension of the "smart" cylinder in centimeters. The three curves represent the output signals of tests with 1) no buried pipe, 2) one 6.03-cm diameter metal pipe buried 30 cm deep, and 3) two 6.03-cm metal pipes buried 30 cm deep. Since the scanning movement starts with the metal detection coil very close to the backhoe stick, a saturated output signal caused by the metallic stick itself is expected. The influence of the stick results in the initial horizontal line between cylinder position 0 and 12.7 cm. for all three curves shown in figure 26. After this range, the effect of the stick is drastically reduced and the metal detector becomes sensitive enough to pick up any additional metal influences. This phenomena had already been observed during the laboratory tests, discussed earlier in this report.

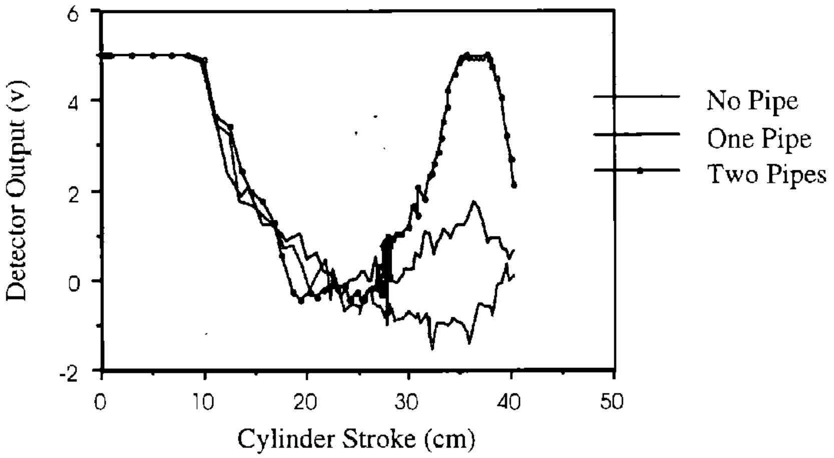


Figure 26. Data from horizontal pre-dig scans

The peak influence of the pipes can be noticed at a cylinder extension of 36 cm. At this point, an output of 1.8 v is measured. As figure 26 indicates, when no pipe was buried, an output of approximately zero has been measured. With two identical 6.03-cm diameter metal pipes buried 30 cm deep, a peak with a saturated output of 5 v resulted. Again, doubling the size of the metal showed a drastic change in the output signals.

REMOTELY CONTROLLED PIPE-LAYING

The following sequence of figures presents the pipe-laying process. Initially, a trench must be dug in order to lay the pipe into the ground. Figure 27 shows the trench digging procedure.

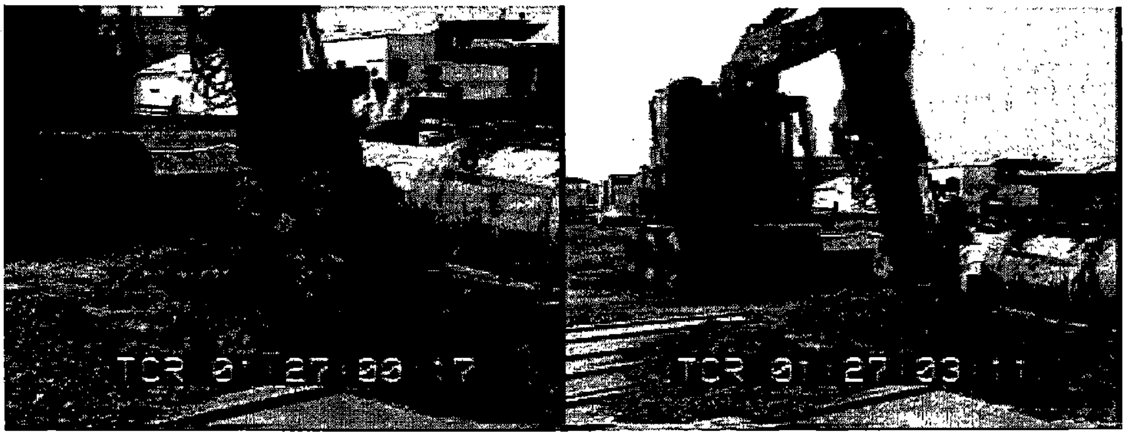


Figure 27. Trenching digging process for pipe-laying

The pipe manipulator has two degrees of freedom which are shown in figures 28 and 29. Figure 28 demonstrates the rotational capabilities of the pipe manipulator while figure 29 shows the translational motion driven by a hydraulic cylinder.

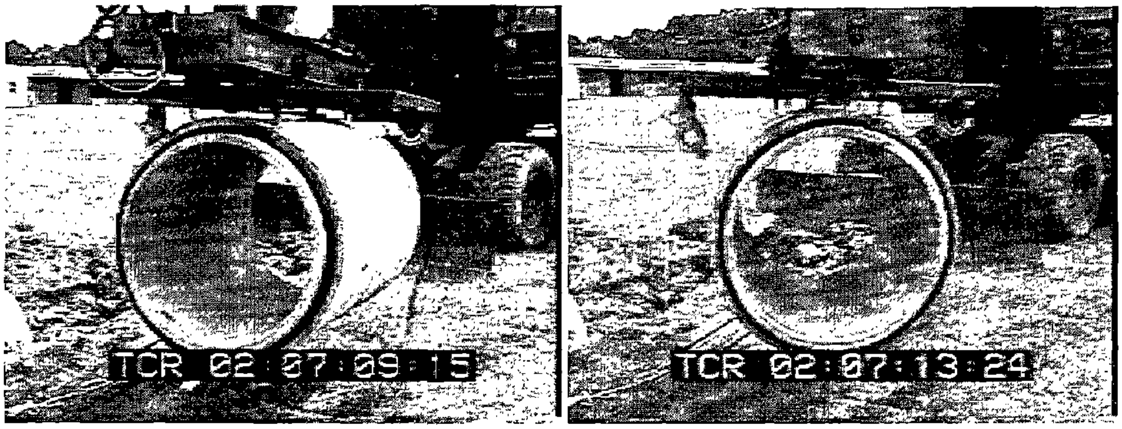


Figure 28. Rotational motion of the pipe manipulator driven by a hydraulic motor

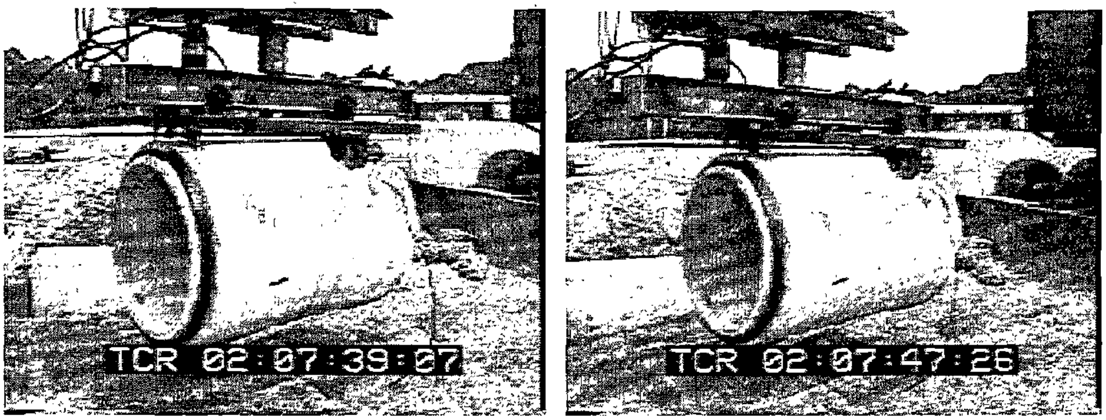


Figure 29. Translational motion of the pipe manipulator driven by a hydraulic cylinder

For the final alignment of the pipe, a beam laser and remote laser sensors are used. Figure 30 shows the laser sensor mounted on the pipe manipulator which is capable of capturing the position of the beam laser with an accuracy of 0.001". Integration is achieved with the battery operated signal processing unit linked to the central computer via an RS-232 cable.

Figure 30. A laser receiver used to align the pipe section in the trench.

Figure 31 shows 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 handle is used to release the cable attachment to remove the pipe manipulator from the pipe section finishing the procedure.

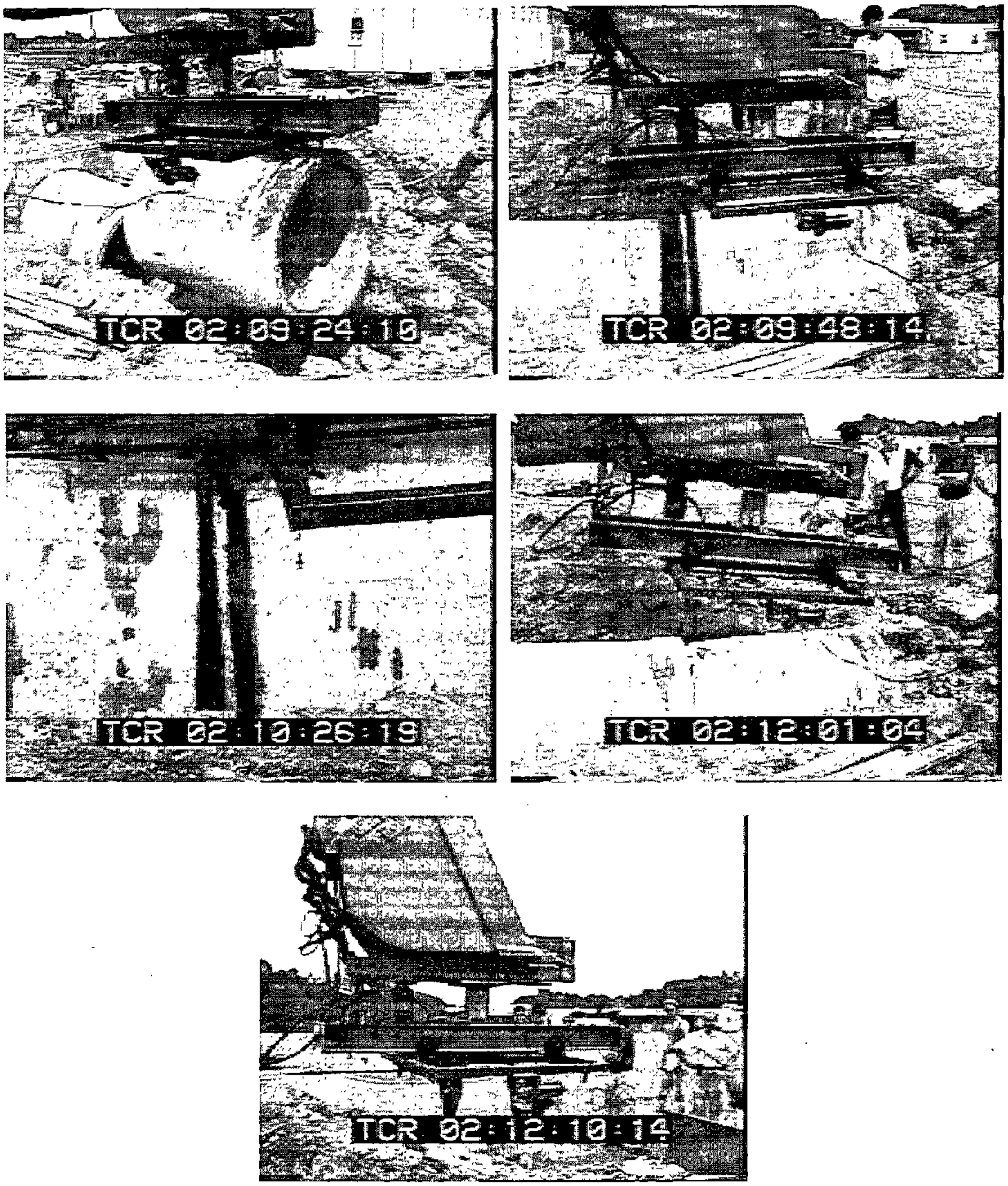


Figure 31. The sequence of the pipe-laying procedure

6. 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 research project investigated the possibility of eliminating the need for a human labor 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 a laser-based real-time spatial positioning system (SPS) developed and field tested to provide updated continuous spatial positioning information about the excavator within the 3-D CAD model of a construction site. Fused with data from encoders mounted on the excavator, the system provides the human operator real-time virtual images on an AutoCAD display system about the current position of the machine he/she is operating. The accuracy of this multi-sensor system has also been investigated. It has been found that 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 which drastically reduced the error. Other control modes such as remote joystick and computer controls have been demonstrated as well. All these methods combined lay the foundation for developing a complete robotic control system for an intelligent backhoe excavator of the future.

Innovative technologies for the detection of buried metal objects and the laying of large pipes without the need for humans in the trench were successfully tested. Experiments with different metal pipes were conducted that let to sensor patterns which can be used to detect and locate the presence of buried metallic utilities. The implemented BUDS (Buried Utility Detection System) can be retrofitted to any existing excavator.

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, electronics, etc., while increasing the productivity and economy of the trench operations.