Tracking and Steering Systems in Trenchless Construction

By R. Tanwani,[1] Associate Member, ASCE, and D. T. Iseley,[2] Member, ASCE

Abstract: Trenchless technology is a rapidly growing sector of the construction market in the United States. Trenchless technology includes all methods of installing, rehabilitating, and repairing underground utilities without utilizing an open-cut trench. Trenchless applications require proper equipment, materials, and experience to achieve the desired results. The desired results mean a usable hole, on target, with a minimum of effort. This necessitates the use of effective instrumentation to monitor the progress of the installation at various stages. This paper describes in brief the most common methods to track and steer a pipe as it is being installed in the ground using trenchless methods. It also identifies the applicability of the methods to be used in conjunction with the different trenchless techniques.

Introduction

Trenchless excavation construction includes all methods of installing utility systems below grade without utilizing an open-cut trench. Fig. 1 classifies the various trenchless excavation construction methods currently utilized in the United States. This classification system segments the industry into three major categories:

1. Horizontal earth boring
2. Pipe jacking
3. Utility tunneling.

Horizontal earth boring includes methods in which the borehole excavation is accomplished through mechanical means without workers being inside the borehole. Both pipe-jacking and utility tunneling techniques require workers inside the borehole during excavation and pipe or liner installation process. Pipe jacking is differentiated from utility tunneling by the support structure. Pipe-jacking methods use prefabricated pipe sections. New pipe sections are installed in the pit when the jacks are in a retracted position so that the complete string of pipe can be jacked forward. While utility tunneling techniques may require the same excavation equipment, the support structure is constructed at the face. The support structure is traditional tunnel liner plates or steel ribs with wooden lagging.

With the increasing underground congestion of utilities and the increasing complexities of installations, it is important that the installations be on the planned line and grade regardless of the type of construction method employed. The growing demand of trenchless methods for environmental char-

[1]Res. Engr., LAG Steering Systems, Inc., P.O. Box 2513, Southern Pines, NC 28388.

[2]Dir., Trenchless Tech. Ctr., Dept. of Civ. Engrg., Louisiana Tech Univ., Ruston, LA 71270.

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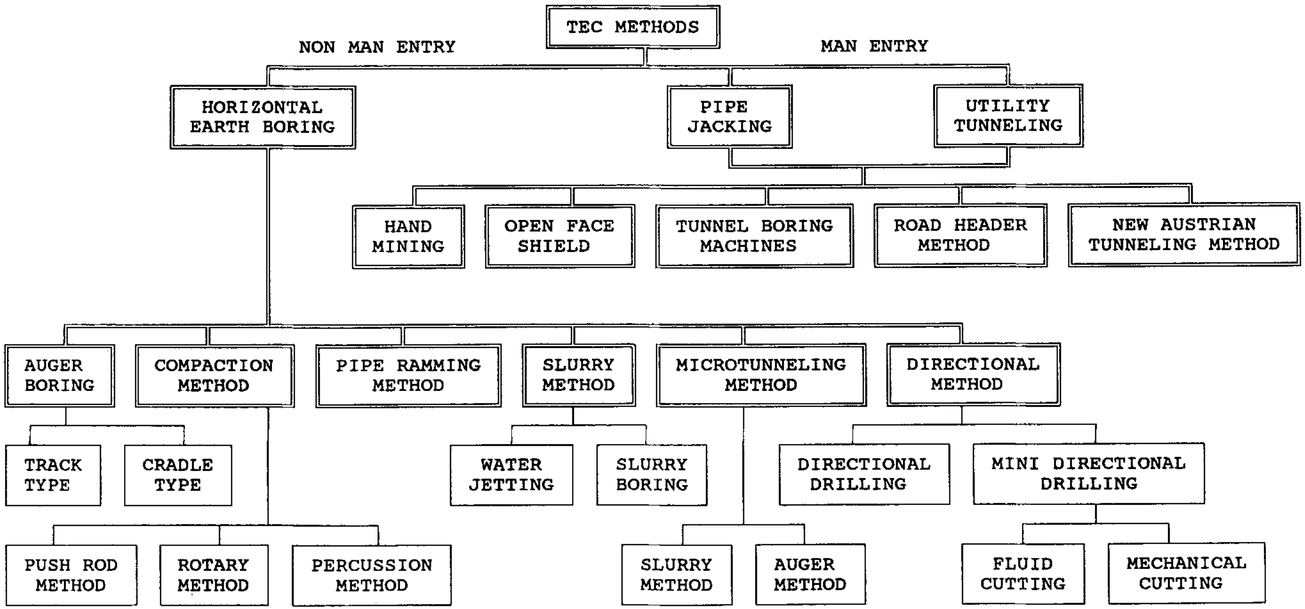

FIG. 1. Trenchless Excavation Construction (TEC) Classification System (Iseley et al. 1992)

acterization and/or remediation require instrumentation to carefully monitor the control line and path.

Traditionally, most systems for installing underground utilities have been unguided, i.e., the systems have not had the capability to have their projected paths adjusted or altered after the installation was begun. Thus, a very careful setup of equipment has been required to bore along the proposed line and grade. The final installation in most cases is a function of the initial setup.

Small installations for short distances of less than 30 m (100 ft) for electrical, gas, or water mains generally have relatively loose specifications compared with sewers, which often must maintain a precise grade. Traditional boring systems commonly use simple levels and sighting devices to align the equipment with the intended target. In most cases, the crew uses its experience to compensate for tendencies of the installation to deviate in various types of soils. Large-diameter installations are less susceptible to drift compared to smaller diameters because of greater stiffness.

TRACKING SYSTEMS

Several types of tracking systems are currently available. The instrumentation may vary from simple water levels to complicated inertial systems. Most of the systems consist of a sensor mounted on the drill head from where the information is transmitted to the operator. The type of tracking instrumentation required for a particular project is dependent on a number of factors including the type of installation, accuracy desired, ground conditions, and availability of funds. The selection of a method depends on the following parameters, which should be considered to achieve the desired accuracy of installation.

- Measurements: The various parameters that can be measured during the pipe installation process include vertical deviation, horizontal deviation, roll, vertical inclination, horizontal inclination, and length installed.
- Sampling method and rate: This category includes the following:
  - Method of transmitting information from the drill head to the operator
  - Time required to take a reading
  - Frequency at which the operator needs the information to make decisions on course corrections
  - Is the information transmitted real time (i.e., measurements are taken while drilling) or does drilling have to be suspended to take a reading?
- Operating range: This category includes the following:
  - Distance to which the system is accurate
  - Depth to which the system is accurate
  - Maximum angular response of the system both in horizontal and vertical directions
- Reliability: The tracking system must be able to operate in different soil conditions and be reliable under changing soil conditions. Some systems may not be reliable under wet or corrosive environments, or in case of significant temperature changes between the atmosphere and inside of pipe.

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- Size and other constraints: Some of the tracking systems are relatively small and can be designed to fit into smaller-diameter pipes but others are comparatively large and can only be used for larger installations. Some systems are sensitive to the material of the pipe being installed while others may be sensitive to the type of soil in which the installation is taking place. Magnetic fields may also impact the performance of certain tracking systems.
- Ease of use: Some tracking systems are relatively easy to operate with minimal operator training while other systems require specially trained personnel. Some systems create complications due to additional wiring or piping requirements or waterproofing of the entire system.
- Cost: The cost of the tracking system or the rental cost compared to the total cost of installing the pipe is an important factor. The direct and indirect operating and maintenance costs associated with the system should also be considered.

Based on their modes of operation, the tracking systems presently available can be classified into the following categories:

1. Laser/optical systems
2. Pipe locators/walkover systems
3. Electromagnetic systems
4. Inertial systems
5. Other methods

Laser/Optical Systems

These systems utilize a target board positioned near the head of the tunneling machine. The laser beam is set up in the starting pit on line and grade and strikes the target board inside the tunneling machine. A theodolite may also be used instead of a laser beam. In that case, the target is usually a light-emitting diode (LED) that is sighted using the theodolite set up in the starting pit. The laser/optical method is very accurate but requires a clear space, i.e., an optical passage throughout the length of the pipe run. A simple laser or optical system measures only the horizontal and vertical deviations from the design path. This method is most commonly used for straight pipe runs but methods exist that make it possible to monitor pipe jacking along curves using lasers.

When using a laser, the information can be transmitted to the control station with the use of either a passive target board or an active target board. With a passive target board, the information is transmitted from a TV camera inside the pipe. An active target board is equipped with photo diodes. The laser beam is converted into an electric signal, allowing the position and number of activated diodes to be reproduced on a monitor. The active target board combined with digital processing is used for generating automatic steering commands in a tunneling machine. The use of a theodolite requires an illuminated or luminous target board. In this case, the target is always passive as it is observed visually from the starting pit. Since the observation is visual, automatic steering is not possible in this case.

When using any optical method on a pipe-jacking job, the light beam must pass through air that may have a temperature gradient. Light beams are subject to diffraction at the transition from a dense to a thin medium.

This can be a limiting factor with all optical measuring methods. Fig. 2 illustrates the laser-beam deviation as a function of distance due to temperature difference between the pipe wall and the air inside the pipe. In addition to diffraction, laser beams are also subject to drift due to oscillations of the optical resonator depending on the temperature. The use of a theodolite has the advantage over the use of a laser in that the optical ray is not subject to drifting.

In addition to drifting and diffraction, laser beams also have a tendency to spread with the distance. After a certain distance, the beam is no longer coherent but starts spreading so that the beam size increases with distance making it difficult to ascertain the center of the beam. Hence, for long-distance pipe-jacking operations, a slight temperature gradient can make an automated steering system become erratic because of an oversized laser beam moving around on the target board.

The base required for the measuring instrumentation should be isolated from the jacking pit floor, walls, and the backstop as these may experience movement during the installation process.

Pipe Locators/Walkover Systems

This is one of the simplest and the least expensive methods for tracking installations if the area above the installation is accessible and a high degree of location accuracy is not required. It consists of a transmitter placed in or near the boring tool. The transmitter can be battery-operated or it may be hard-wired. The transmitter continuously emits signals that can be picked up by a handheld receiver at ground level above the boring tool. This handheld receiver gives information on position, depth, orientation, and roll of the boring tool. Thus, one crew member must walk along the path of the borehole above the transmitter as it progresses and transmit the data to the operator. These data are compared to the design bore, and correc-

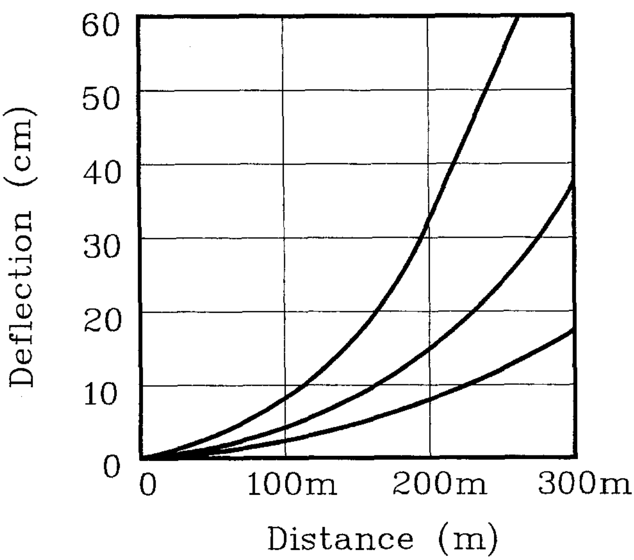

FIG. 2. Laser-Beam Deflection as Function of Distance due to Temperature Gradient (Devery 1984)

tions, if required, are made to bring the tool back to its design path. Different manufacturers use different techniques of transmitting the signal from the boring tool. These include the following.

- Use of a battery-powered sonde transmitter to transmit the signal that is picked up by a handheld receiver.
- Microprocessor-based walkover location system with a unique orthogonal configuration of antennae. These antennae allow tracking the boring tool from either side of the path.
- Two permanent magnets in the head of the boring tool and a receiver cart having three magnetometers to compute the head location by triangulation.

Some methods have the additional advantage of generation of automatic steering commands that can be directly displayed to the operator. The normal working depth for most walkover methods is less than 4.5 m (15 ft). The drill tool can be located to a precision of ±0.15 m (6 in.). Some manufacturers claim to have systems capable of reading depths of up to 9 m (30 ft). These systems are used for small-diameter pressure lines and cables, mainly electric, gas, and water lines where a high degree of accuracy is not required. The main drawbacks of these systems include depth range limitation, surface access, and in some cases, errors that are induced in areas with electromagnetic interference due to the presence of local metallic objects.

Electromagnetic Systems

These systems use the principle of generation of an electromagnetic field and locating the drill tool within that field. One technique uses ground-laid antenna placed above the boring path to generate an electromagnetic field. The field is detected by using either a magnetometer or a receiving coil close to the drill tool. This method consists of a series of parallel electric cables that are positioned above the desired tunnel path and secured in place. The cables may be weighted down to the bottom of a stream or canal or placed directly on top of a street or highway. The cables transmit an electromagnetic signal into the earth that is received by the navigational instruments located in the drill head. These instruments locate the position of the drill head in the ground with respect to the center of the cables to a precision of ±25 mm (1 in.) and continuously relay this information back to the computer on the operator's control console. The operator then uses this information to bring the tool back on the desired line and grade.

Another technique uses the earth's magnetic field as the base for location of the drill tool. The problem with such systems is that since the field strength changes with location, compensation has to be made for that. Because of lack of accuracy, this method is used mainly for the installation of cables and pressure lines that do not require a high degree of placement accuracy. Another version of the electromagnetic system uses a transmitter coil in the drill head and a receiving antenna in the receiving pit or vice versa. The signal from the transmitter is received by the antennae and the position of the drill head is calculated. The distance to which the signal can be transmitted is very limited in this case and is seldom over 30 m (100 ft). It also depends on the type of the soil through which the signal is being transmitted and the presence of any magnetic materials in the soil.

Inertial Systems

Inertial systems consist of a gyroscope whose reading is transmitted electrically to the surface using a wire line. These are not commonly used for pipe-jacking jobs because of the high vibrations and impact loads produced during the drilling process. Inertial systems are also subject to drift, and it is important to study the drift characteristics of the particular system before using it. Inertial systems have great potential in the trenchless market since these methods are not affected by magnetic interference. Another advantage is that inertial systems can be very accurate, regardless of the route or the jacking distance. It has been observed that the azimuth-stabilized gyro is suitable for measuring horizontal deviations (Stein et al. 1989). To date, gyros have been used only on big tunnel-boring machines. The biggest disadvantage of inertial systems lies in its size. For the system to become more useful and acceptable for the more common trenchless applications, it is important that the size of the gyros be reduced. Several tests were conducted on the use of small-size rate gyros for tracking the installations of steel pipe. However, these did not prove to be very successful due to problems with inconsistencies of the smaller-size gyros ("Comprehensive" 1992). However, investigation is continuing into the possible use of small-size inertial systems for tracking applications.

OTHER METHODS

Water Level

The water level is a device to measure the grade of pipe as it is being installed. It permits the monitoring of grade by using a water-level sensing head attached to the leading edge of the pipe. Fig. 3 illustrates the principle of a water level. It operates in the same way as the sight tube on a boiler. Both ends of the system are vented to ambient pressure. A pit-mounted control and indicator board is located at some convenient point in the pit near the operator. A hose connects the bottom of the indicator tube to a water pipe running along the top or inside of the pipe. Water is used to fill the system. The level of water in the indicator will then show the level of the trap at the end of the pipe as it is pushed into the ground. One should be careful when using this system to ensure that the system is full so that an incorrect reading is not obtained. Modern electronic levels are able to

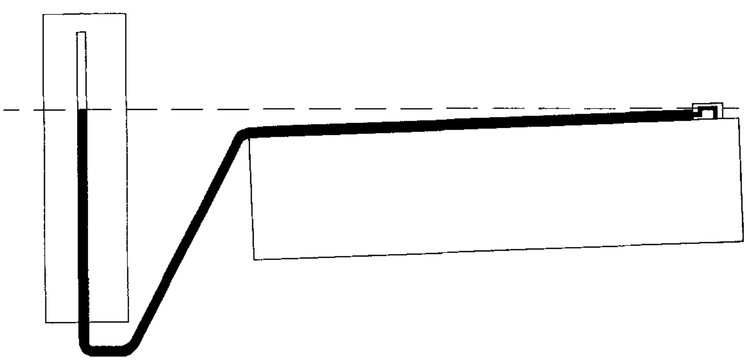

FIG. 3. System Full of Water Indicating Correct Level of Head in Water Level (*Dutch* 1987)

measure the fluid levels more precisely and print or display the data electronically or graphically on a monitor.

Inclinometer Method

In this system, electronic inclinometers or mechanical pendulums are used to measure the inclination of the machine in the direction of jacking. They can also measure the roll of the machine. For this, two inclinometers are set up at right angles. In addition to the angles, the distance jacked is also measured and these are integrated to calculate the tunnel position. Based on this, corrections are made to bring the machine to its design path.

STEERING METHODS

Once the exact location of the drill head has been determined, the next challenge is to steer the installation to its designed location. This is accomplished by a number of different methods. Based on their modes of operation, the steering methods can be classified into the following categories:

1. Slanted-nose (deflection plate) method
2. Hydraulic jetting method
3. Differential excavation method
4. Articulated-head method

Slanted-Nose Method

The slanted-nose method is usually a displacement-type method employed for the jacking of pilot pipes or small-diameter pipes through the ground. The nose of the drill head consists of a slant-shaped anvil that creates a bias to assist in mechanically steering the system. Fig. 4 illustrates a ground displacement-type slanted-nose pilot bit. When drilling along a straight path, the drill head is either rotated continuously or withdrawn inside the sleeve. When the bore is required to follow a curved path or to change the direction of the drill head, the nose is pointed in the appropriate direction while the pipe is advanced. This permits the drill head to move along the curved path in the required direction.

Once the pilot hole is in place on line and grade, a reamer is attached to enlarge the hole to the required size and the required pipe is pulled back through the enlarged hole.

Hydraulic Jetting Method

The hydraulic fluid jetting method is generally used for the installation of small-diameter lines or for the installation of pilots for larger-diameter

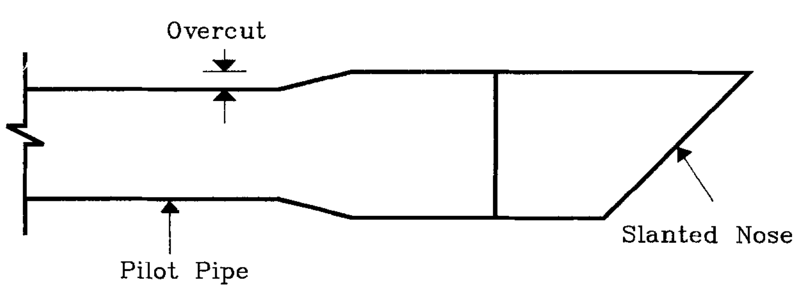

FIG. 4. Ground Displacement-Type Slanted-Nose Pilot Bit (Soltau 1991)

pipes. This process is characterized by a high-pressure fluid cutting system. The soil is cut by high-pressure jets using a mixture of water and bentonite clay. The number of jets used depends on the soil conditions. These jets cut the soil in advance of the boring tool and impregnate and line the bore wall with the bentonite clay. The clay lining maintains a stable opening even in some unstable soils such as fine sand. In addition, the clay lining lubricates the tunnel wall, greatly reducing frictional drag on the new line as it is being installed. The drill head can be remotely steered by changing or biasing the direction of the cutting jets at the nose of the boring tool as it is pushed through the soil. If the drill head begins to deviate from its designed path, it can be steered back on course, or, if required, it can be backed up 1–2 m (3–6 ft) and a new borehole created.

Differential Excavation Method

The differential excavation method is generally used for large-diameter pipes. This method is based on the principle that the pipe follows the hole cut by the cutting head. In this method, the position of the cutting head can be changed with respect to the pipe. In the case of large-diameter pipes with manual excavation, excavation is carried out in the direction where the pipe is designed to be deflected. In the case of remote-controlled machines, there are hydraulic or pneumatic arrangements to move the cutting head in the required direction. This method is effective only in stiff soils. For soft soil conditions, this method is not recommended.

Articulated-Head Method

In this case, the drill head is made up of two articulated units, the steering head and the follower. These two units can be deflected in relation to each other and in all directions by hydraulic steering cylinders or by steering screws. These are remotely controlled for nonman-entry-size pipes. For larger pipes the controls can either be inside the pipe or remotely controlled. In this, if a change in direction of pipe jacking is required, the steering head is deflected in the desired direction and the pipe is jacked forward. This results in the pipe moving in the direction of the deflection of the steering head. This is the most common method currently being used for jacking pipes.

APPLICABILITY AND COMPATIBILITY OF VARIOUS METHODS

Every tracking system cannot be used with all of the steering systems. The selection of a tracking system will depend to a great extent on the method of installation of the pipeline.

Table 1 summarizes the applicability of tracking systems to various trenchless techniques. The tracking systems are limited by various factors such as the size of the pipe, access into the pipe, optical passage through the pipe, magnetic interference, space available, accuracy desired, and availability of funds.

The laser/optical system can be used in conjunction with the slanted-nose method, differential excavation method, or the articulated-head method. It cannot be used in conjunction with the hydraulic jetting method, which is generally used for directional drilling projects. The directional drilling method is generally not used for the installation of gravity sewer lines to a precise line and grade but is used for the installation of pressure lines that generally do not require precise placements. When using the laser method, care must

TABLE 1. Summary and Applicability of Tracking Systems

Tracking-system type (1)	Applications (2)	Measurements (3)	Cost (4)	Comments (5)
Laser/optical system	pipe jacking, utility tunneling, microtunneling	horizontal deviation, vertical deviation	medium	high degree of precision
Pipe locators/walkover systems	compaction method, slurry boring minidirectional drilling, auger boring	horizontal deviation, vertical deviation, roll, orientation of tool	low	surface access required, limited in depth, not very precise
Electromagnetic systems	directional drilling, minidirectional drilling	horizontal deviation, vertical deviation, horizontal orientation, vertical orientation, roll	medium to high	performance of systems may be affected by magnetic fields
Inertial systems	pipe jacking, microtunneling	horizontal deviation, vertical deviation, horizontal orientation, vertical orientation, length installed, roll	high	limited applicability due to size constraints and inability to withstand excessive vibration and impact loads
Water level	auger boring	vertical deviation only	low	limited to auger boring technique only
Inclinometer	pipe jacking	vertical inclination, roll	low	not very precise

be taken to ensure that the pipe being installed does not deviate too much from its straight line path or the laser might move off target. If that happens, it is very difficult to continue the jacking process without tracking information.

The pipe locator/walkover system can be used with most types of trenchless installations. The disadvantages of the system include low accuracy, depth limitation, and required accessibility of the area above the installation to take measurements. Even though this method has been successfully used with pipe-jacking operations for the installation of sewer lines, it is not recommended due to its accuracy limitations. The transmitter signal cannot penetrate steel obstructions and has been found to give erroneous readings in areas of magnetic influence.

Electromagnetic systems can be used with any kind of trenchless system. The biggest drawback of electromagnetic systems is their limitation in areas with magnetic influence and the fact that these cannot be used with steel pipe. Also, it has been observed that the system induces an error due to the movement of construction traffic above the installation ("Comprehensive" 1992). These methods are not used for the installation of sewer lines because of the high degree of accuracy required.

Inertial systems have been used successfully on a number of pipe-jacking projects around the world. These are used when a very high degree of accuracy is desired. These methods have great potential in the trenchless market since they are not affected by magnetic influence. These methods can be accurately used for pipe-jacking operations even along curves. Due to the size of the gyro, these methods have been limited to large-diameter pipe-jacking projects. Experiments have been conducted on the use of smaller-sized gyros, but these have not been very successful ("Comprehensive" 1992).

The water level has been used for many years to determine the grade on pipe-jacking jobs using auger boring. It is limited by the fact that it measures only the grade, and hence is used on projects where the line is not very important. This method has been used only with an articulated-head-type jacking operation. It cannot be used for the installation of small-diameter pipelines. Its advantage lies in the fact that it is a time-tested method that is very simple to operate and is not affected by any type of magnetic interference.

Electronic inclinometers also have been commonly used on directional drilling jobs for a long time. These methods lack the high degree of accuracy needed for sewer installations and so are used only for the installation of pressure lines.

TRENDS AND FUTURE DEVELOPMENTS

There has been growing interest in research and development in the area of trenchless technology. With increasingly stringent safety and environmental regulations, the demand for non-man-entry installations is increasing and is bringing with it an increase in the development of new techniques for tracking, installation, and control. In the past few years, there has been a significant development in the area of electromagnetic systems. In the future it is expected that there will be considerable research into the areas of application of lasers to long pipe-jacking projects and in the area of inertial tracking systems. There also seems to be considerable interest in the development of steering systems for use in rock formations.

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