Automatic As-Built Generation with Utility Trenchers

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Abstract: The proper functioning of the subsurface infrastructure is vital for the public, industry, and government. As is demonstrated almost daily, small disruptions or malfunctions of public utilities, such as power, gas, or phone, can result in catastrophic events on local, regional, or national levels. This paper addresses a known weak point in protecting buried utilities from damage, the lack of accurate as-builts. It is suggested to take advantage of enabling technologies to automatically create as-built drawings relying on electronic sensory data collected real-time from operating machinery. A significant portion of the paper discusses the development of a spatially integrated trencher, a prototype that was subsequently used to execute field experiments. The encouraging outcome of those tests, which are supported with actual data, demonstrated the soundness of the concept and the level of accuracy that can be expected. The relevance to the industry lies in that it addresses a real and complex problem, proposing and demonstrating a workable technology to close a large gap in the way we track our subsurface infrastructure. It is hoped that researchers will be encouraged to extend the concept to other relevant applications while applying a similar rigorous method of experimental field testing.

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Introduction and Background

On September 12, 2002, a public works crew in Hornell, N.Y. struck a 2.54 cm gas line while repairing a fire hydrant. One witness told news media that the gas company had put yellow paint marks on the ground to indicate the line's location, but the marks were about 1.52 m from where the line was hit. On November 11, 2002, in Exeter, N.H., a construction crew damaged a gas line with a backhoe. The backhoe bucket had caught a 2.54 cm gas line that was known to be there. However the crew thought it was much deeper. Firefighters had to evacuate a nearby hospital building while police closed off streets while the break was repaired. On September 18, 2002 a construction crew was observed trying to make visual "contact" with a buried plastic gas line in order not to damage it while connecting a new house to the water main running along the street. As shown in Fig. 1, the two men crew spent 2 h searching only using small shovels so as not to accidentally damage the pipe. 22.52 million km

These three simple cases, two of which could have ended up in a disaster, had one phenomenon in common: lack of precise geographical/spatial information about the location of the underground utility lines. It is no secret that the United States, similar to other countries, has a vast subsurface infrastructure of pipes, wires, and cables which are critical to its economy and security. A multitude of "buried highways" distribute crude oil, refined petroleum products, natural gas, information, electricity, water, sewage, and other vital products and services. In 2002, the United States had approximately 22.52 million km of subsurface utilities ⟨*www.GeoSpec, 2003*⟩. Disruption of any of these underground facilities effects, directly or indirectly, many entities in the public, business, or governmental areas. As a prevention mechanism many states have implemented "Call Before You Dig" laws requiring everyone who digs into the ground to call centers (commonly referred to as a One-Call center) that "receive notification of proposed excavations, identify possible conflicts with nearby facilities, process the information, and notify affected facility owners/operators." The identified buried facility owner must have their lines located and marked using colors which identify their identity. According to the uniform color code, red is used for electric lines, yellow for gas and oil, orange for communications, and blue for water. After the lines are marked on the surface, the construction crew may begin its digging operation, but has to follow specific restrictions about how far away from the line they may dig.

Utility companies, locator services, and contractors are searching for new locating equipment, methods, and ways to overcome unreliable utility locates. But they face huge obstacles. For instance, the conduits for these utilities range from steel, cast iron, and ductile iron pipes to clay, polyethylene, polyvinyl chloride, and fiberglass reinforced plastic pipes. Cables may be copper or fiber optic. The conduits have different shapes, compositions, densities, and diameters, and their depths range from 0 to 10 m. Some lines (usually local telephone, electric, and gas) may be stacked vertically in a common trench. Multiple lines may be grouped in a single conduit or duct.

The reason for having to locate pipes before digging is that there are poor records with inaccurate utility positions. Some live (e.g., operating) services do not even appear on the utility plans. This means it is critical to physically determine the location, nature, and depth of underground utility services on site in order not to damage them during construction. As the few examples men-

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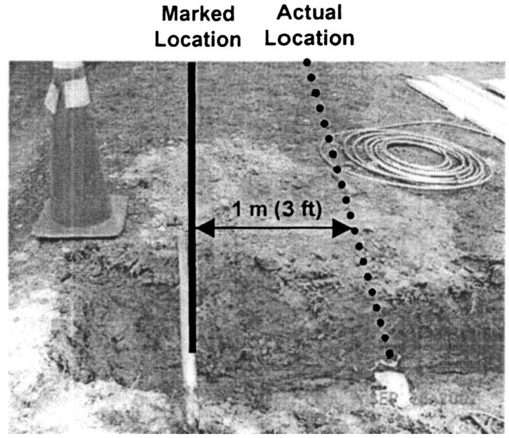

Fig. 1. Hand digging because markings of new gas pipes are unreliable

tioned earlier indicate, locating buried utilities is indeed extremely difficult.

Subsurface Utility Engineering and Design Locates

One response to the inherent problems with damaged buried facilities was the emergence of the subsurface utility engineering (SUE) as a civil engineering specialty. One early product of its proponent is the CI/ASCE *Standard 38-02* (ASCE 2002), *Standard guideline for the collection and depiction of existing subsurface utility data*, published by the Construction Institute of the ASCE. It addresses issues such as how utility information can be obtained, what technologies are available to obtain that information, etc. It is clearly designed to streamline the process of "seeing into the earth" but also to caution about the fallacy of trusting available information. The problem was highlighted in a report by the Federal Highway Administration (FHWA 1999) who indicated that: "existing records of underground site conditions are usually incorrect, incomplete, or otherwise inadequate because (1) they were not accurate in the first place: design drawings are not as-built, or installations were field run and no record was ever made of actual locations; (2) on old sites, there have usually been several utility owners, architects/engineers, and contractors installing facilities and burying objects for decades in the area. Seldom are the records placed in a single file, and often they are lost. There is almost never a composite; (3) references are frequently lost: records show that an object is a certain distance from a building that is no longer there, or an object is a certain distance from the edge of a two-lane road that is now four lanes or is part of a parking lot."

The FHWA report (1999) states that the North Carolina Department of Transportation (NCDOT) spends approximately \$3 million/year on SUE. Apparently, the computed cost savings is \$6.63 for every dollar spent for work done in-house. The Virginia Department of Transportation estimates an annual expenditure of approximately \$10 million on SUE in a variety of contracting methods.

One of the goals of SUE is to foster design locates. The purpose of this approach is to identify trouble spots early on and design the route of a new utility around trouble spots or, at least, with a good understanding of it. Presently, this concept is being heavily relied on in areas where many utilities exist. Most recently, vacuum excavation is being required to visually confirm the location and depth of utilities at predefined locations.

Prevention Begins with Accurate As-Builts

Valid as-built information about the location of all buried facilities in absolute coordinates is essential to avoid hitting them during digging or drilling. The establishment of such data would most effectively start during utility construction. In fact, the Best Practices report by the Common Ground Alliance (1999) (USDOT 2003) suggests that: "contractors installing underground facilities notify the facility owner/operator if the actual placement is different from expected placement.…" The Alliance adds that keeping and updating the data is best done by the utility owners.

Fig. 2 schematically models the Best Practices' recommendation and the approach considered critical for SUE together with a concept that integrates all the shareholders through electronic data communication. Indicated by the double lines, the "cradle" of the data is the construction crew installing a new utility line which feeds into a project-oriented as-built data bank to store old and new utility data in geographical information system/computer aided design (GIS/CAD) format. According to this simplified model, the GIS/CAD bank contains project specific data on topography, physical objects above, and below ground. Operating on a wireless and web-based platform until the end of the project it would feed the updates back to the utility owners.

The relevance of the electronic communication concept, modeled in Fig. 2, is in highlighting the link that is missing today, namely the automatic data generation and communication from the site to the as-built data bank. While the Best Practice report recommends that as-built information should flow from the construction site to the utilities, the FHWA report mentioned above points to some of the problematic results that go with this common approach. The findings of the report don't seem to be too surprising considering the fact that no common standards for reporting, verifying, and updating exist.

Reliably error-free excavation will only become possible when the positions of all utilities in a given area are accurately mapped. This is impossible today, but could be accomplished over time if we begin with the new utility construction today. The one approach that has great promise to make it possible uses electronics to measure, collect, and communicate data from remote locations and is referred to as telemetry. The following section will present a brief description of this technology before the paper will describe how it was employed to create as-builts for buried cables.

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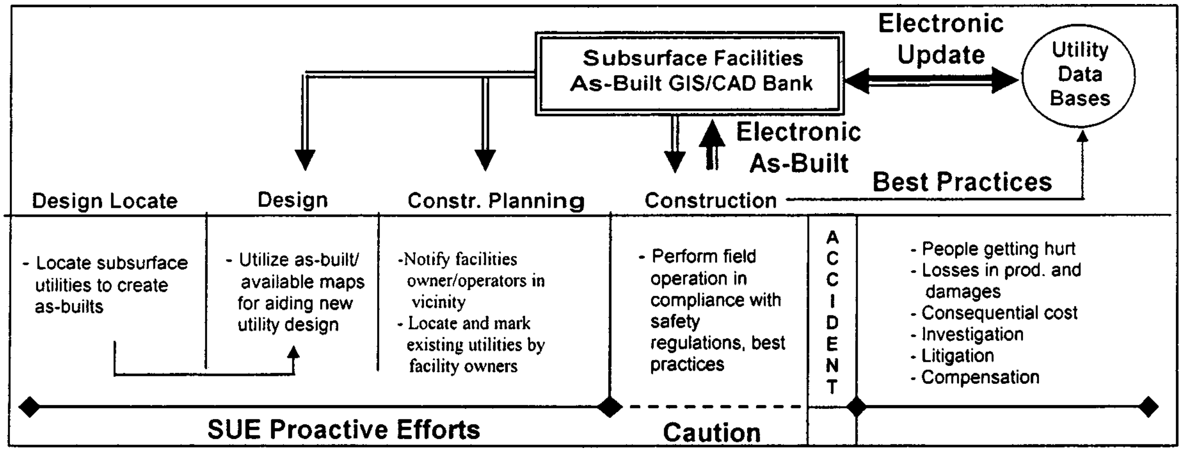

Fig. 2. Data and information flow for different damage prevention efforts

Telemetry for Utility Construction

In broad terms, telemetry is the science and technology of collecting, communicating, and receiving electronic data. *Encyclopedia Britannica* (Encyclopedia Britannica Inc. 2003) defines telemetry as the: "highly automated communications process by which measurements are made and other data collected at remote or inaccessible points and transmitted to receiving equipment for monitoring, display,…" Since as-builts for utilities rely heavily on three-dimensional point coordinates along a buried pipe, etc., the data that a telemetric system would have to collect are spatial coordinates of their final position underground. Telemetry would be well suited to serve as an enabling technology if "married" with other technologies, including GIS, Internet, wireless communications, and portable location devices that have given rise to exciting new types of information utilities. For example, personnel in the field, away from their office desks, are now using wireless devices to retrieve information that is in any way relevant to their current location.

Signaling an even larger boost to location measurement was a mandate of the United States Federal Communications Commission that the geographic position of all cellular phone devices must be detected so that emergency services can be dispatched to the caller's location. It is estimated that more than 100,000 calls per day to 911 come from wireless phones. Most of these wireless calls are from highways where it is difficult for callers to identify their precise location.

Very exciting, albeit still in its infancy, is machine-to-machine communication. Bypassing any delay causing interferences, one unit automatically notifies another about its location and state. Machines that are considered potential candidates for building telemetric nets include vending machines, heating–ventilation–air conditioner, power lines, etc., but more importantly for construction mobile equipment such as trucks and cranes. Thus, power lines that warn and possibly disable encroaching cranes may become a common accident-prevention technology in the future.

Equipment Instrumentation for Real-Time Position Control

The state of the art in the field of equipment instrumentation to determine its position in real-time is moving rapidly ahead while the state of practice has focused on using surveying systems in tracking position equipment of heavy earthwork equipment such as dozers and backhoes (Bernold 2002). The inherent problem of measuring position over long distances and during operation is achieving the accuracy needed for finish work, such as grading or

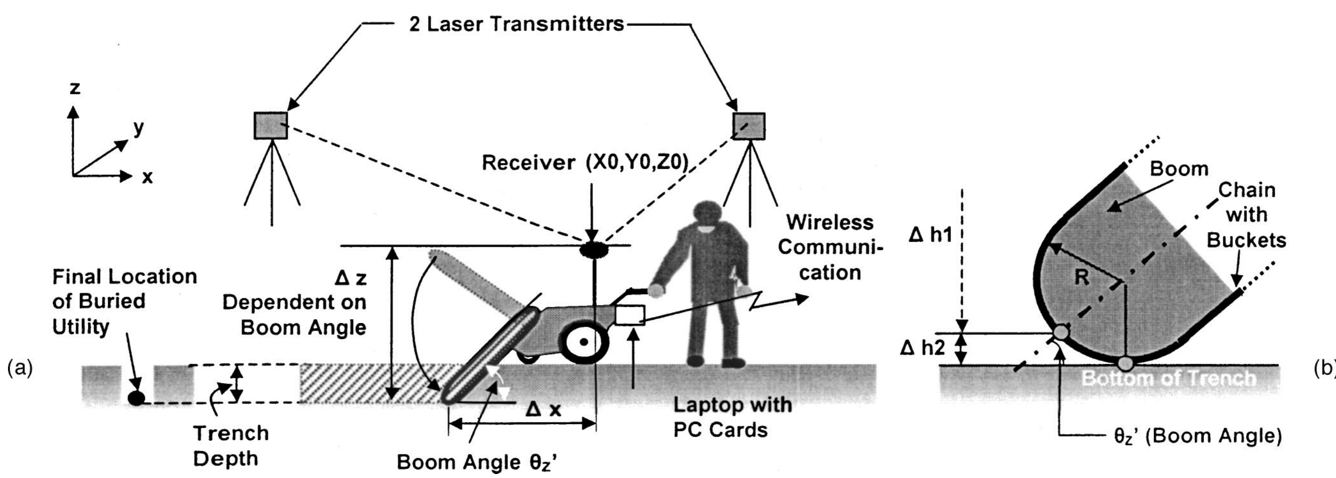

Fig. 3. Schematic of spatially integrated trencher

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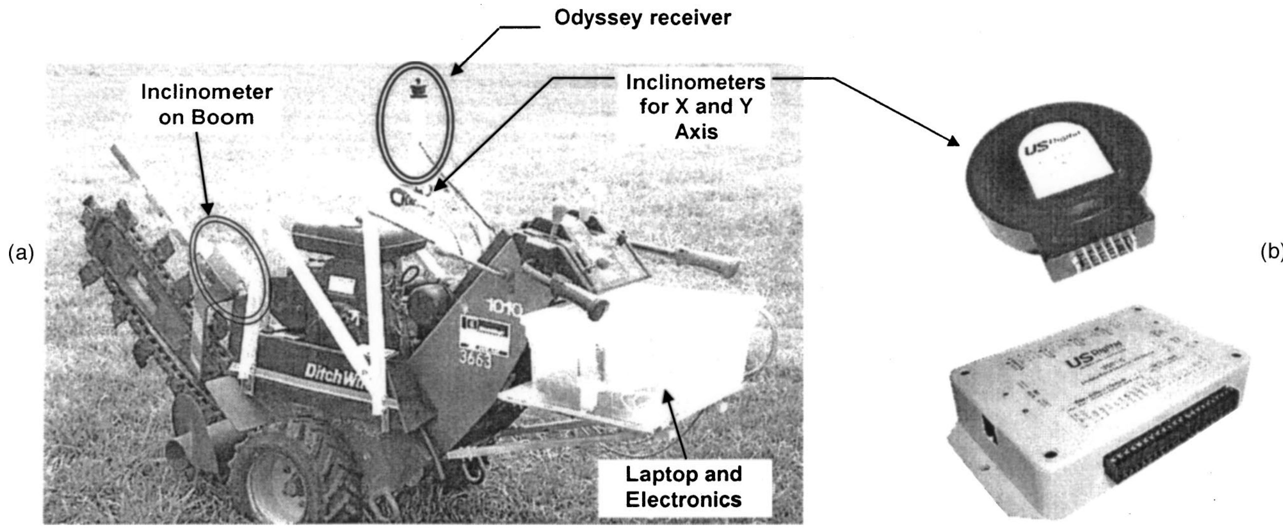

Fig. 4. Prototype hardware configuration

asphalt placement. The finish researchers Heikkil and Jaakkola reported on their effort to assess errors and to improve accuracy and reliability using new measuring algorithms to correct for inaccuracies in the hardware. After an initial field test with Trimble ATS tachymeters they assert that (Heikkil and Jaokola 2004 ; "… the developed stochastic models can be used to estimate in real-time the three-dimensional (3D) positioning accuracy of mobile work machines." However, random errors and many other uncertainties require a series of calibration tests with every machine.

A team from Japan also recently reported progress in field testing a road grader equipped with a Topcon 3D motor control (MC) system on an expressway job (Fukukawa and Yamaguchi 2004). The blade was controlled automatically with data fed from an on-board controller that received information from a tilt sensor on the blade and the autotracking total station which monitored the position of the laser–receiver mounted to the blade. By comparing the x,y,z and the tilt angle with the CAD drawing of the road surface, the blade was adjusted to close the difference. Common stakes were used to compare the accuracy of a grader steered by an operator with the accuracy achieved with the 3D MC. To the satisfaction of the team it was found that the errors in the vertical axis were equally acceptable. However, the measured productivity of one machine went from 2,500 to 3,000 and 4,000 $\mathrm{m}^2/\mathrm{day}$. Other benefits included less surveying work for the stakes, thus reducing labor time and risks of accidents. Another finding of the field test was the confirmation of the hypothesis that the 3D MC technology and data interface could be easily transferred to asphalt pavers as well. One can expect that the efforts to improve the accuracy and reliability of position measurement instruments mounted construction equipment will further increase over the short and long term.

Development of Spatially Integrated Trencher

The basic premise of collecting as-built data directly from an operating trencher builds on the observation that the final location of a buried utility is determined by the narrow gap/opening created by its boom and chain tool. If it is possible to collect data about the position of the running boom electronically, as-built data of the installed facility could be created automatically in real-time. In order to test such a concept, the Construction Automation and Robotics Laboratory (CARL) ⟨*ce.ncsu.edu*⟩ at NC State Univ. reconfigured a borrowed Ditch Witch trencher with the necessary electronic data collection and storage devices. The following section describes the concept as well as the hardware configuration of the spatially integrated trencher.

Ascertain Trencher Position Coordinates in Real-Time

Fig. 3 presents a schematic overview of the two main measures required to establish the position of the trencher boom tip inside a trench: (a) the position of a fixed point on the trencher within the construction site and (b) its spatial relationship to the boom tip. The first requirement was fulfilled through the use of the laser-based Odyssey™, a real-time positioning system that provides accurate 3D position measurements five times/s (5 Hz). Odyssey was fabricated and sold by Arc 2nd Inc., Blacksburg, Va. and received the 1995 NOVA award from the Construction Innovation Forum. As depicted in Fig. 3(a), two fixed transmitters allow receivers within its power/laser range to establish its 3D position. The receiver includes an optical lens and a data retrieval system. Similar its use for CAD-integrated excavation (Huang and Bernold 1997) one receiver unit was mounted directly onto the trencher providing X_0, Y_0, and Z_0 coordinates of its position at all times.

The second requirement was fulfilled by defining the spatial relationships Δx and Δz between the tip of the boom and X_0, Y_0, Z_0. Because of the boom mechanism of a trencher stays within the $X-Z$ plane only Δx and Δz vary with the changing boom angle θ_z', which the operator selects based on the desired trench depth. As indicated in Fig. 3(b) Δz has two components: $\Delta h1$ and $\Delta h2$ where

$$\Delta h2 = \left(\frac{R}{\sin\theta_z'} - R\right) * \sin\theta_z' \qquad (1)$$

where Δx can be calculated accordingly. These calculations are only valid as long as the trencher operates on a horizontal surface something that rarely happens over long distances. Thus, while X_0, Y_0, and Z_0 is established independently from the trencher's orientation in space, Δx, Δy, and Δz have to consider the inclinations of the equipment in x and y. Because of space limitations, the calculations of those values will not be presented here. Hence-

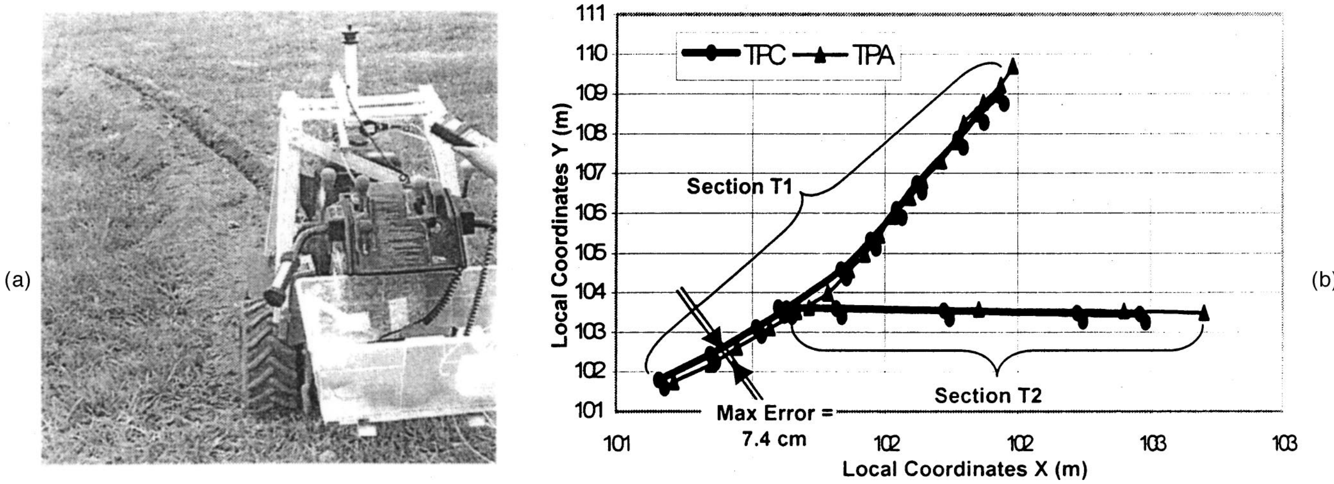

Fig. 5. Performance results from first field test

forth, two kinds of trench bottom coordinates will be used; the points that are defined through calculations based on the position sensors will be referred to as trench points calculated (TPC) while the surveyed points will be labeled trench points actual (TPA).

Configuration of Telemetry Hardware

As shown in Fig. 4, a Ditch Witch 1010 trencher, on loan from the City of Raleigh's Dept. of Public Utilities, constituted the base vehicle. Because the focus of the field test was assessing accuracy, no wireless communication was installed. However, an equipment mounted laptop was configured to collect and save data from the four sensors while calculating autonomously as-built data.

System Calibration

As Fig. 4 indicates, special care was given to fabricating a rugged framework for the machine mounted sensors. In order to establish true "zero" values, the entire system had to be calibrated by measuring actual dimensions on the prototype version (e.g., distances between fixed points) as well as inclinations and angles for given setups (e.g., boom at horizontal position). Using the sensor data, the boom tip position was calculated and compared with actual measurements until the system inaccuracies in x, y, and z directions were established as 10 mm, −5 mm, and −16 mm, respectively. One has to keep in mind that these correction values are only valid while the trencher is not in operation since the forces that act on the boom will create deflections of the system due to loose joints or the elastic deformation of the steel. These errors, however, can only be established through actual field tests.

Software Architecture

Two interfaced programs *TRAC.EXE* and *DRAW.LISP* (see Fig. 8) constitute the processing software. The first collects data from the electronic sensors at given intervals, calculates the trench point at

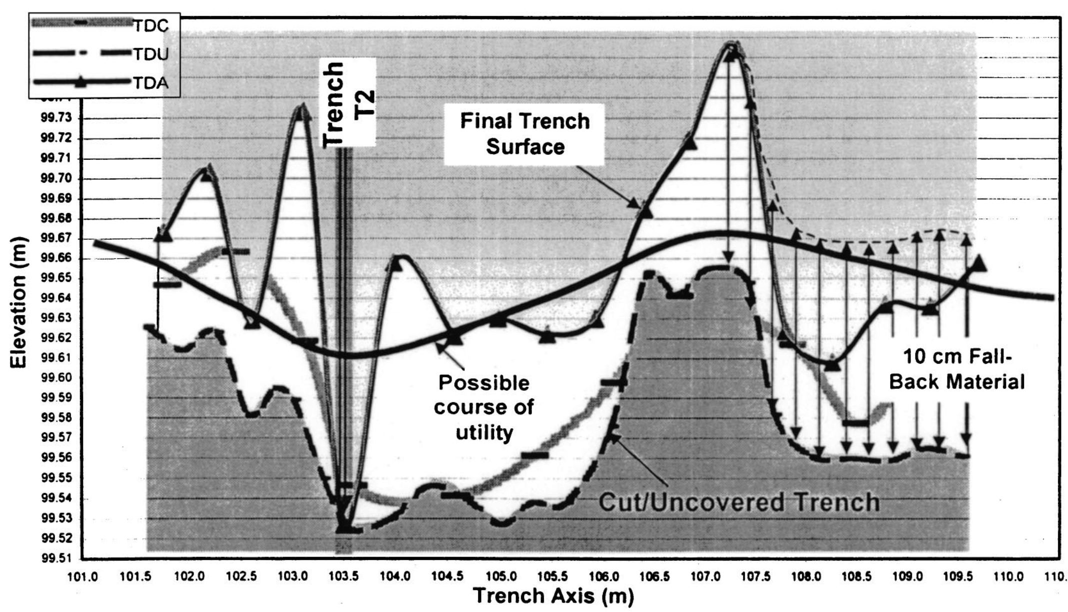

Fig. 6. Comparison of trench profiles

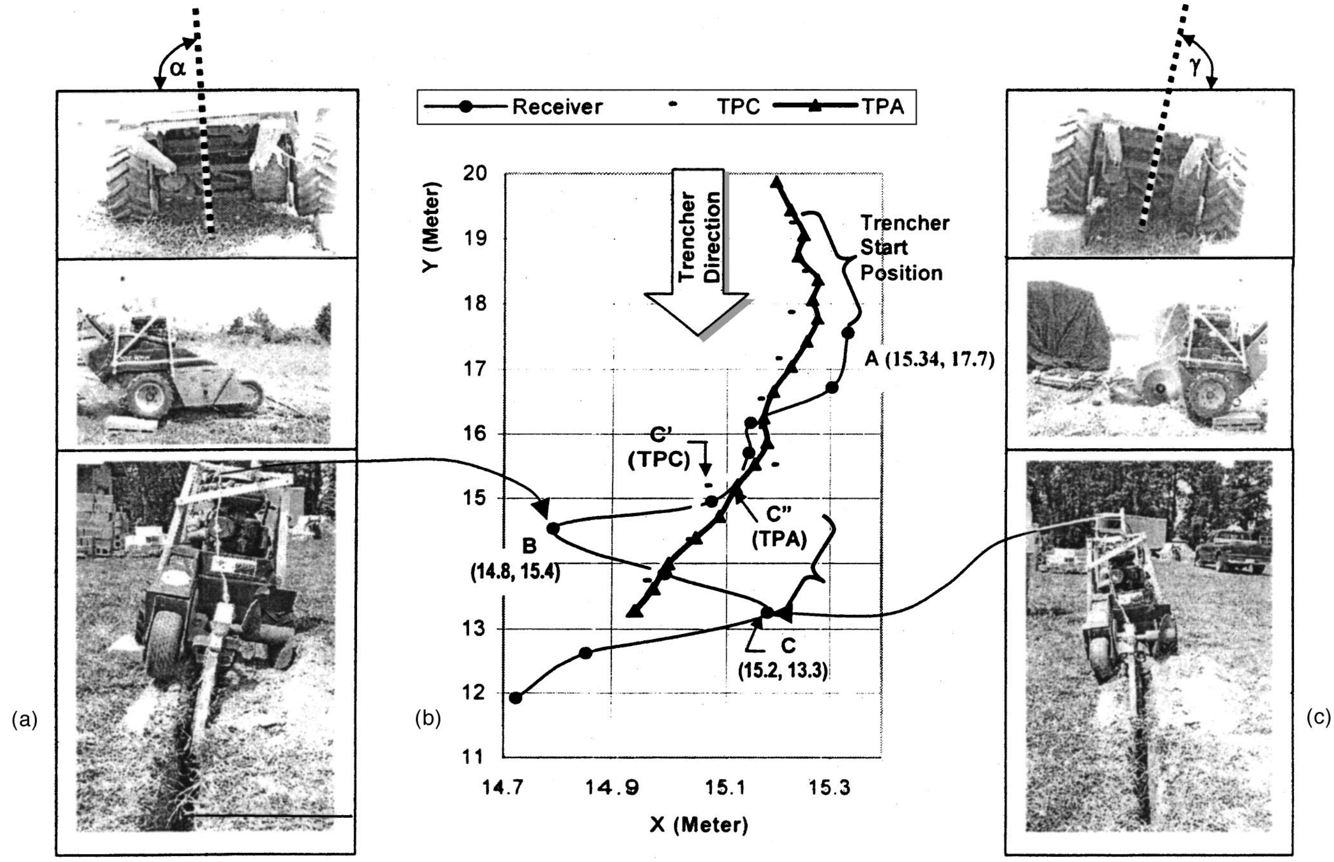

Fig. 7. Setup and results of second field test

that instant, and stores it in virtual memory or in a data file. The *DRAW* program uses the *TRAC* data to update a drawing of the trencher/boom position and to append the as-built file with new points along the trench bottom.

Results of Field Experiments

Two sets of field experiments were designed to assess the performance of the prototype system under common site conditions: (1) flat and (2) rough terrain. The following sections will present the key findings of those tests.

Operation on Flat Terrain

The most common use of "walk-behind" trenchers is along streets with sandy–clayey soil with a boom set for a 50 cm deep trench. Thus the first experiment was set up on a flat field with a shallow dip and clay as its soil material. As indicated in Fig. 5(a) the trencher was first led along a slight curve (section T1) before repositioning it to cut a "feeder" trench, section T2.

Fig. 5(b) depicts one important result of the first field test plotting the TPC against the TPA. As indicated, the errors correlate with the curvature with the maximum error being 7.4 cm. This phenomenon could be expected because of the horizontal reaction forces acting on the boom will deflect it towards the "inside" of the curve. On the other hand, on straight segments, the errors are minimal and can be attributed to measuring errors.

Fig. 6 presents three profiles, trench depth calculated (TDC), trench depth uncovered, and trench depth actual along T1 intersected by trench T2 at 103.5 m and highlights both the cut/uncovered and the final trench profiles, both surveyed after the trenches were completed. What constitutes the difference between those two is the soil material that fell back into the trench despite the auger that pushes the soil away from the rim of the trench. The vertical arrows on the right side of the graph create an imaginary final trench 10 cm above the cut trench. At the location where trench T2 joins, the bottom has been "cleaned" by the chain pushing it to the open sides to create a slightly larger accumulation on both sides, resulting in 13 cm high peaks. Overall, however, we can approximate that this type of trencher working in clay allows between 8 and 10 cm of the loose soil to fall back. The third curve, labeled TDC, represents the profile resulting from the sensory data. As in the x,y plane, the errors are between −2 and +4 cm. Overall, however, TDC mirrors the contour of the measured trench generally located between the cut and the final profiles. By accounting for the fallback material, adding an average of 7 cm, and the subsequent smoothening by the utility placement operation, we can estimate that the final depth of the buried utility will be between ±3 cm of the calculated values.

Although the error estimates in both horizontal and vertical direction should be verified, the outcome of the first field experiments turned out to be very encouraging. The results were within acceptable ranges and some of the observed discrepancies could be easily included in a final machine dependent data processor. Subsequently, a second field test was designed to assess the performance of the system when exposed to a more rugged environment such as a rocks or large bumps.

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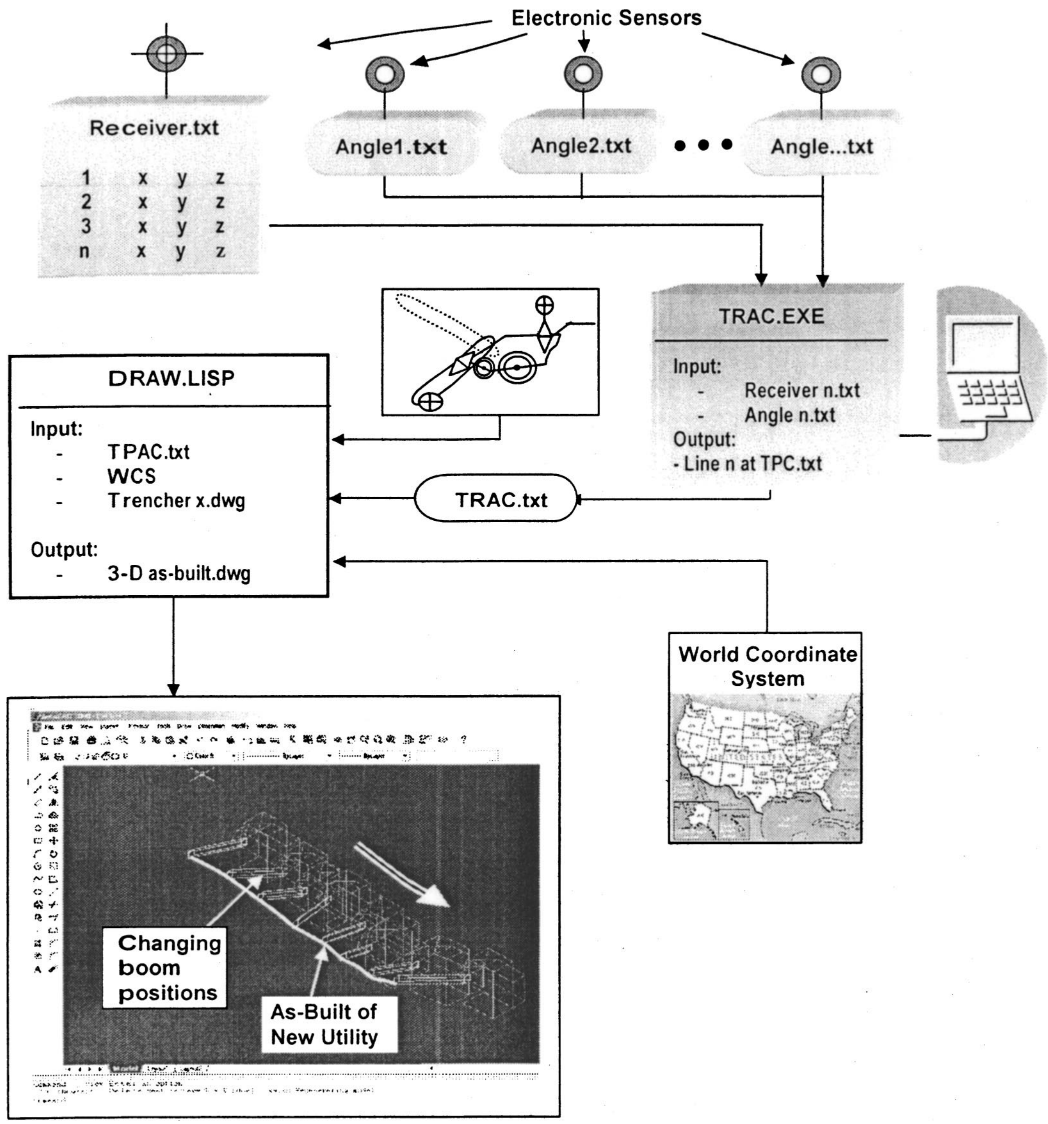

Fig. 8. Software architecture generating automatic as-built data

Operation in Rough Terrain

In order to simulate an abrupt change of the surface, a concrete block was alternatively placed under the left and the right driving wheel of the trencher. As shown in Fig. 7, the trencher experienced drastic "torsional" deformations between the boom in the trench and the main axle and main body of the equipment.

At the selected starting position A, the right wheel of the machine was situated in a slight depression and the direction of the trencher had to be corrected to the left. As a consequence, the laser receiver located in front of the boom swung to the left after the start. The first concrete block forces the right wheel upwards, as indicated in Fig. 7(a), and as a result the vertical axis is being tilted to the angle α. As a consequence the receiver moves horizontally approximately 20 cm to point B on the left side of the trench axis. The second block, shown in Fig. 7(c), tilts the trencher until it reaches γ, positioning the receiver approximately 20 cm to point C at the right. Also identified in Fig. 7(b) are the corresponding points C' on the calculated path and C'' on the measured trench path. Not surprisingly, the calculations did not match the final situation, although the inclusion of the tilt angle in the calculations dampened the large oscillations of the laser receiver mounted on top of the trencher. The "physics" of the trenching operation provides a logical explanation for the distance between C' and C''. As shown in both Figs. 7(a and c), the boom is confined by the two sidewalls of the trench while the axle and with it the main engine block is being rotated by the concrete block. Naturally, the reaction forces acting on the boom initiate a torsional deflection, which is limited by the stiffness of the boom and its connection to the motor block. The resulting error, approximately 6 cm in our case, will be machine dependable and might even change over time as the parts wear. Nevertheless, calibration procedures could be established that would allow the inclusion of machine dependent parameters in the calculations.

Similar to the first experiment, the depth profiles were also established but revealed no new information. Thus, an analysis of depth calculations is not included in this paper.

Generation of As-Built Data

Fig. 7(b) indicates that data points were calculated approximately every 66 cm (2 ft) which was an arbitrarily selected distance. At those points, not only the laser receiver's location was stored but

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also the various reading from the angle encoders and inclinometers. Thus, a CAD representation of the boom tip coordinates could also show the position of the trencher at that point. Fig. 8 presents the software architecture and the view of a CAD window showing the motion of the trencher boom as it progresses from left to right during the rough terrain experiment. As indicated, the telemetric components of the system consist of: (1) electronic sensors, (2) laptop with PC communication cards, (3) various communication cables, and (4) signal/data processing software. The *TRAC.EXE* module processes the sensory outputs to calculate 3D points along the TPC profile and matches them with the boom and tilt angles to create an intermediate data list *TRAC.txt*.

As shown in Fig. 8, the Lisp program *DRAW* requires three sets of data: (1) a coordinate framework to map the local coordinates into, (2) the drawing of the trencher, and (3) the TRAC list. To close the loop of the experiment, a *DRAW* program was written in *AutoLisp* and integrated with *AutoCAD*. The result of the prototypical output with changing boom positions is shown as the final module of the software architecture. It goes without saying that the CAD representation could be in real-time, also showing the existing utilities and sent wireless to any Internet connection point in reach of the antenna.

Final Observations

Overall, the two experiments with a prototype spatially integrated trencher demonstrated the validity of applying a telemetric approach to the creation of as-built data for buried utilities using a trencher. It was shown that the system calculates positions that include errors because of the nature of the operation. One category of errors is caused by loosened soil that remains or falls back into the trench. A second category is related to the ruggedness of the environment, specifically the uneven ground surfaces. Both errors can be minimized, albeit not eliminated, to a level that should be acceptable. Key to creating proper adjustment algorithms are site observations/measurements and a good model of the machine deformations under various operational conditions. Storing the large amount of as-built data securely is made possible by a growing number of different communication channels which includes wireless technology.

Summary and Conclusion

Keeping a safe distance between ships or airplanes depends on knowing their locations at all times. While we are dedicating large amounts of resources to plan and track those parameters on water and in air, very little is being done for objects buried in the ground. In this, our habits resemble those of squirrels in my yard burying nuts in the ground but promptly forget where. Thus, a squirrel would find the following statement very familiar: “existing records of underground site conditions are usually incorrect, incomplete, or otherwise inadequate…” (FHWA 1999).

This paper discusses the effect that the lack of accurate asbuild data may have on new construction and presents a recent effort to create standards for subsurface utility engineering. It is well recognized, however, that the key to preventing accidents during the design, planning, and construction is accurate data about what is in the ground and where. Since creating such information through nondestructive methods is still more an art than a science, utility protection today relies on expensive hand or vacuum excavation. What is needed is accurate as-built data in world coordinates which should be established during construction, verified, and updated according to a common standard.

A major portion of the paper discusses the result of investigating the efficacy of using telemetry to create as-built information automatically while operating trenching equipment. Two field experiments were conducted to assess a prototype spatially integrated trencher that was developed in order to test the concept under real conditions. The test results not only proved its technical merit but provided operational insights that will allow the establishment of equipment-specific error correction and calibration routine. Based on the outcome of the experiments it is expected that the actual location of new utilities will be within ±3 cm of the as-built data provided by such a system.

The role of a working prototype, such as the modified trencher, is to demonstrate new ideas and to provide key information for the development of marketable products. Since all the components that constitute the developed system are available on the market today, the concept of creating as-builts automatically is ready to be turned into reality. Today, the construction industry is burying hundreds of miles of new utilities every day without keeping accurate spatial data, a lapse that will come to haunt the industry if we are not willing to abandon old ways.

Acknowledgments

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