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A comparison of two innovative technologies for safe pipe installation — "Pipeman" and the Stewart–Gough platform-based pipe manipulator

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Abstract

Excavating and installing utilities between the narrow walls of a trench are hazardous. The main causes of accidents are tools and materials that fall into the confined space and the instability of the trench walls if not properly supported. Two research teams from Korea and the US worked for several years on developing technological interventions capable of installing large concrete pipes tele-robotically. A serial mechanism with 2-Degrees of Freedom (DOF) was applied to the "Pipeman" (short for Pipe-manipulator), which was developed at the North Carolina State University (NCSU), and connected to the bucket of the backhoe excavator. The Stewart–Gough Platform, which provides 6-DOF, was adopted for the Stewart Platform-based Pipe Manipulator (SPPM) developed by the Korea Institute of Construction Technology (KICT) and it was directly connected to the boom instead of the bucket.

The paper compares how the two research teams solved some of the most unique technical problems and presents the lessons learned during the field tests.

Despite the differences between the two prototypes, both systems demonstrated their technical readiness to install pipes in trenches without the presence of laborers. Experiments with actual field personnel not only highlighted the value of involving future users in the evaluation of early prototypes, but also provided reassuring data that the innovative devices will be able to reduce cycle times and cost while increasing the productivity of pipe installation. The ongoing process of adding improvements gives rise to the hope that tele-robotic pipe installation will eventually lead to the elimination of deaths in trenches around the globe.
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1. Introduction

The labor-intensive construction industry has a high accident rate. According to the Bureau of Labor Statistic [1], there were 1126 fatal work injuries in 2003. This number represents 20.3% of the fatalities from all industries and indicates that the construction industry has the highest incidence rate. One reason for the extreme hazard is the exposure of workers to hazardous environments such as heights and confined spaces, as well as the handling of heavy materials. Working in a trench to lay concrete or any other type of pipe or cable poses an extremely hazardous environment for workers.

A trench is defined as a narrow, in relation to its length, excavation made below the surface of the ground [2]. While the use of trench-less technologies is increasing, trenching is still the most common approach for burying utilities underground. Since the installation of a utility in a trench requires hands-on aligning and jointing by one or several laborers inside a narrow and sometimes deep trench, the working environment for pipe installation is extremely hazardous. The main cause of deadly accidents in trench work is the rapid collapse of the trench wall

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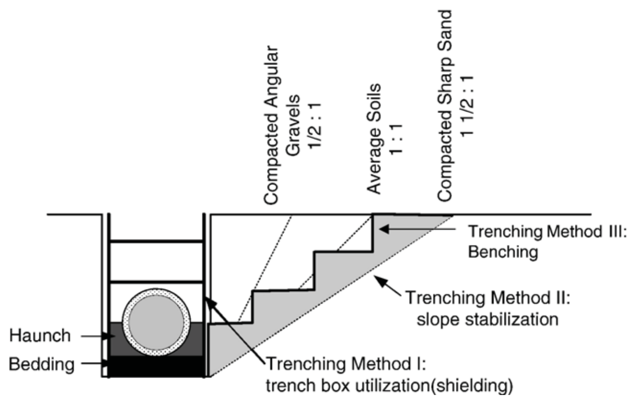

Fig. 1. Protection methods: shielding, sloping and benching (adapted from Ref. [14]).

if it is not properly supported. Other potential dangers include being crushed by heavy pipes or being hit by falling tools and materials [3].

The conventional pipe-laying method consists of a set of repetitive tasks geared towards assembling piece after piece along a pre-defined slope connecting two man-holes. The quality of the finished work is influenced by the experience and skill of the operator of the backhoe excavator, pipe installers and helpers. Recently, increasing labor costs have contributed to the increase in the cost of pipe installation [4]. On the other hand, the construction methods for pipe laying have not changed much since the time of the Romans.

The repetitiveness and the apparent hazard of operation make it a prime target for the application of robotic technology [5]. However, the requirements and conditions found on construction sites create several challenging problems: a) preparation of bedding so that the pipe will be on grade, b) lowering and aligning a new pipe segment, c) jointing the pipes with proper alignment (line and grade), and d) haunching to provide the necessary pipe support. Two independent research groups, one in Korea and one in the US, have been working for many years to solve some of the key problems on pipe installation, focusing on solving the problems arising from b) and c) through the handling and jointing of new pipe segments in tele-robotic mode. To perform the abovementioned tasks, b) handling and c) jointing, the research group in Korea adjudged the need for 5-DOF mechanism independent of the backhoe excavator. It pursued an approach that takes advantage of the Stewart–Gough Platform, a parallel mechanism, providing 6-DOF including the needed 5-DOF. Following a different solution path, the research group in the US adopted a concept where the backhoe excavator and the new equipment complemented each other. Taking advantage of the DOFs that the backhoe provides only 2-DOF had to be added. Finally, both equipment prototypes were deployed and tested under real site condition and both achieved their main mission, no people were needed in the trenches. In addition, even counting the connection and disconnection times the overall improvements in productivity compared extremely well with the traditional methods. As is the nature of building prototypes needs for improvements surface at every stage.

The objective of this paper is to compare the two approaches and technical solutions. It highlights some of the lessons learned during the field tests, which considered the different construction

Table 1
Cycle time of conventional pipe laying

Activity	Task	Time (s)	Ratio(%)
Pipe handling	Connecting	35	4.9
	Traveling	163	22.6
Positioning	Locating	198	27.5
Jointing	Jointing	171	23.7
Aligning	Aligning	141	19.6
	Releasing	12	1.7
Total cycle time		720	100.0

Fig. 2. Comparison of conventional pipe installation methods in the US and Korea.

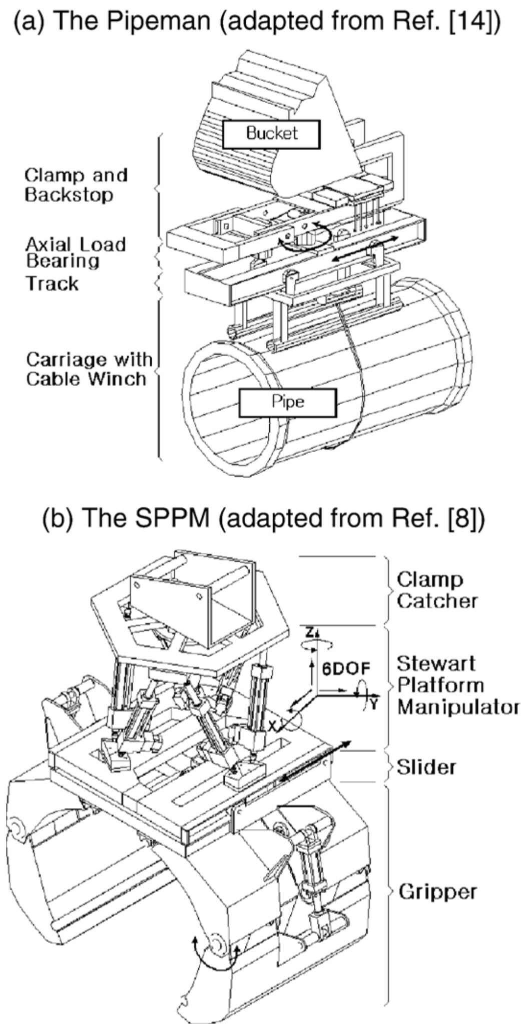

Fig. 3. Configuration of the systems.

methods commonly used in the two countries. Finally, the most recent efforts to improve the first prototypes are presented.

2. Conventional method of laying drainage pipes

To prevent the soil from caving into the open trench, three basic approaches are currently used: a) shielding, b) sloping, and c) benching. Fig. 1 presents the three methods most commonly found in the US and Korea.

In order to understand the different approaches in resolving the problems, the conventional pipe-laying operations of the countries need to be observed and analyzed. The findings from the site investigations are that the respective processes of pipe laying in the two countries are basically similar. It consists of excavating, pipe installation and backfilling. Then, the pipe installation process is composed of pipe handling, positioning, jointing and aligning the pipes [6,7].

In the case of installing concrete pipes with 800 mm in diameter, a backhoe excavator with a 0.8 m^3 bucket capacity is used in sites in both countries. A crew size of 5–8 workers are utilized to conduct the tasks. A concrete pipe is delivered into the trench with the help of the backhoe excavator and a steel cable. The laborers align and join the new pipe using surveying tools, levers, and others. The daily production rate in pipe installation is estimated to be 40 pipes based on 12 min of cycle time for installation, as shown in Table 1 [8].

One major difference between pipe-laying methods found in the two countries is the sequencing of pipe installation and excavation. As shown in Fig. 2 (a), contractors in the US most commonly excavate the trench for one pipe-length, immediately followed by the installation of the segment and initial backfill. Contractors in Korea, on the other hand, prefer to excavate the entire stretch between two man-holes first. As a consequence, during pipe installation, the excavator must position itself at a safe distance next to the trench (see Fig. 2 (b)). As will be shown in the next section, this operational discrepancy is one reason for the dissimilar design approach taken by the two research teams.

A diverse set of trenching machineries, including hydrostatic trenching units and trench compactors, can be found on today's sites. Missing is a technology that addresses the most unsafe tasks namely the handling and jointing of pipes at the floor of an open trench. Of course, trench-less technology eliminates the need for an open trench altogether and gained popularity due to its advantage in installing pipes in a traffic-congested city. Due to its higher cost, however, trench-less methods will not replace the open-cut approach in areas that provide easy access for equipment and space for storing soil material for backfill.

3. Comparison of remote manipulation schemes

The "Pipeman" (short for *Pipe-man*ipulator) developed at the North Carolina State University (NCSU) uses a serial mechanism with 2-Degrees of Freedom (DOF) [9,10], while the Stewart Platform-based Pipe Manipulator (SPPM) by the Korea Institute of Construction Technology (KICT) employs a parallel mechanism with six hydraulic cylinders (in parallel), thus providing 6-DOF. The main reason why the two research teams developed different designs was their differing approaches to actuating the motions needed in laying pipes. Overall, a remotely controlled mechanism has to provide 5-DOF consisting of three linear motions in x, y and z directions and two rotational motions around the z and x axes. NCSU simplified the equipment by letting the equipment perform only a linear along the x axis and on rotational motion around the z axis while the backhoe excavator provides the other three DOFs (see Fig. 3 (a)). Taking into account the fact that an operator faces a complex control task when required to simultaneously activate a backhoe and manipulator, the research team at KICT decided to create a system that moves independently from the backhoe. In other words, the excavator would only be used to move the pipes near the point of jointing from where the new mechanism could independently and accurately install pipes. For this reason, a 5-DOF manipulator was needed by the KICT group. The Stewart–Gough platform was a perfect match since it supports motions that are greater than 5-DOF while made of structural members that are light and solid (see Fig. 3 (b)).

The following section presents an overview on how the two systems solved problems related to installing pipes from a remote and safe location, emphasizing four main issues: a) use of the backhoe excavator as an attachment carrier, b) pipe-handling approach, c) alignment and jointing of sequential pipe segments, and d) operator interface. Presenting the corresponding components, the discussion will highlight the differences and commonalities in the way the two groups solved the related problems.

3.1. Systems overview

Both technologies are based on the flexible attachment concept rather than on a stand-alone machine. Fig. 3 puts both manipulator attachments side by side, labeling four main elements: a) mechanical connector to the backhoe excavator, b) system for aligning the pipes in the proper line and grade, c) mechanism for jointing two pipes, and d) means for handling one pipe segment. As shown in Fig. 3, the philosophies for attaching to the backhoe excavator differ in that the Pipeman sought a solution that did not require the bucket to be exchanged with the manipulator (see Fig. 3 (a)) [9,10]. As depicted, the Pipeman secures itself to the bucket while the SPPM utilizes a quick tool exchange interface consisting of a catch, hook and lock apparatus (see Fig. 3 (b)).

Another apparent difference is in the design of the device that allows the actual manipulation of a pipe. Clearly visible in Fig. 3 (b), the SPPM built a hydraulically powered Stewart–Gough platform, a 6-DOF parallel mechanism, between the connection and the pipe grappler. The Stewart–Gough platform [11,12,13], also referred to as an octahedral hexapod, was first used for flight simulators and universal testing machines for airplane tires. While the 6-DOF platform allows the SPPM to operate almost independently from the backhoe excavator, after a new pipe has been moved into the trench, the Pipeman depends heavily on the actuation of the bucket for alignment. The first prototype only allows a 360-degree rotation of the pipe, which is made possible with a heavy-duty axial load bearing actuated by a hydraulic motor with chain. As will be discussed later, the operational restrictions due to the lack of DOF have since been overcome. For the jointing of the pipe, however, both designs employ similar linear systems.

The final main difference between the first prototype versions is in the way the pipes are affixed to the actuator. In case of the Pipeman, each segment is held by a single cable fed underneath the pipe and tightened by an electric winch mounted on the opposite side of the carriage. As can be clearly seen in the

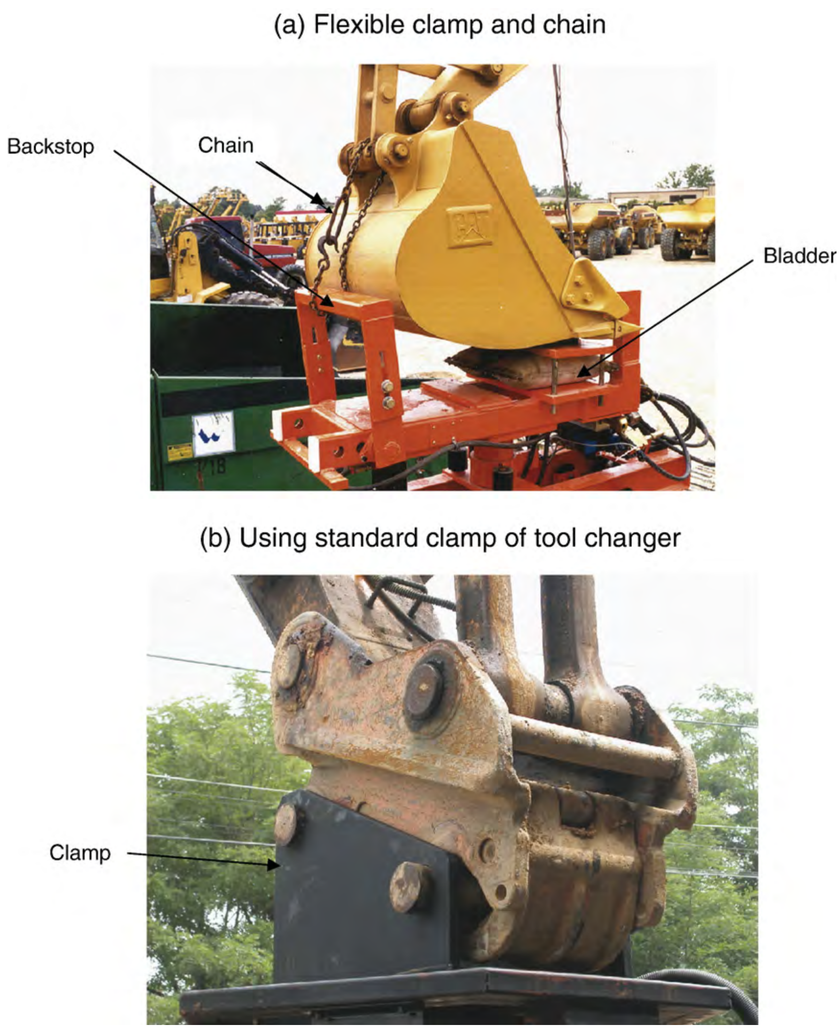

Fig. 4. Mechanical components to interface with the excavator.

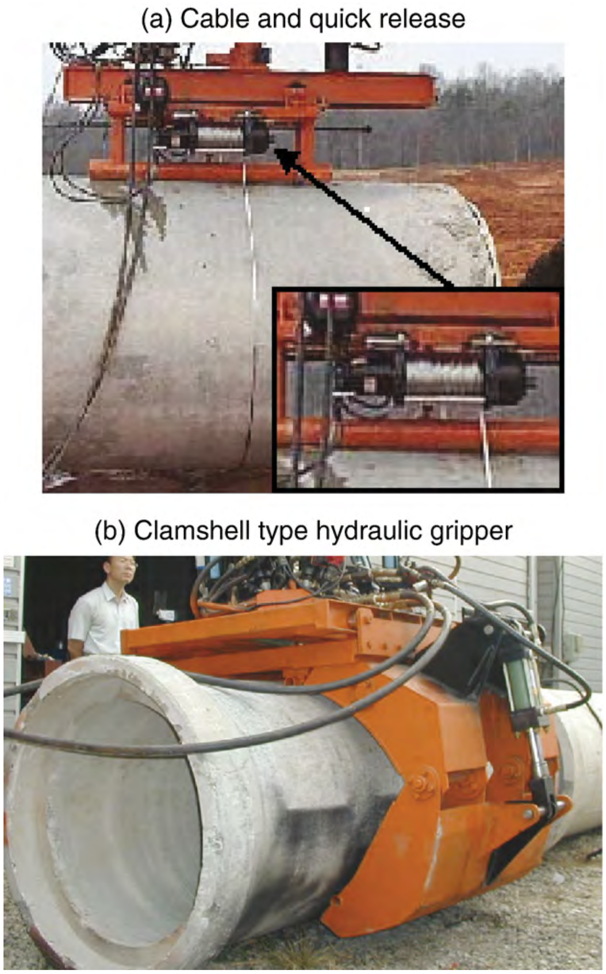

Fig. 5. Mechanical components for holding and releasing pipes.

3-D drawing, the SPPM employs a clamshell-type gripper to hold and release the pipe. The following section will provide a more detailed discussion of why and how the two systems solved the main mechanical problems.

3.2. Comparison of critical enabling mechanisms

3.2.1. Means of attachment

The Pipeman was designed to attach itself to the bucket of the backhoe excavator involved in trenching without the need for a special tool-changing mechanism, something that is not commonly found in the US. For this reason a C-clamp-type fastening approach was chosen. As shown in Fig. 4 (a), two solid-steel brackets provide an opening for the operator to insert the front edge of the bucket. A mechanical backstop, ready for operation after the hydraulic lines are connected to the actuator, prohibits the bucket from sliding off. The clamping force is provided by a heavy-duty hydraulic fluid bladder located underneath the bucket. By opening the hydraulic valve, hydraulic fluid fills the bladder until the maximum pressure is reached. Emptying the bladder after use depends on the backhoe forcing the fluid back into the return line. As discovered during the field experiments, this is not a very efficient method because this requires some time during which the excavator is not able to do productive work. As a consequence, the bladders as well as the backstops were later replaced with more conventional approaches of securing the actuator to the excavator.

As mentioned earlier and as shown in Fig. 4 (b), the SPPM employs a quick tool-changing scheme. Here, the bucket was replaced with the manipulator. As shown, the solid catch on the manipulator and the hook-clamp at the end of the excavator arm provide a strong interface. The requirement for exchanging the tools does not slow down the operation since the tool exchange happens only once in one continuous operation, at the beginning of pipe installation.

3.2.2. Pipe holding and release

A cable offers many advantages, such as strength, flexibility and small space requirement, when it comes to fastening heavy loads to a base frame. The first Pipeman prototype tried to benefit from its simplicity by attaching an electric winch on one side and a strong quick-release mechanism on the other side of the carriage (see Fig. 5 (a)) [14]. After the end of the cable is hooked to the closed quick-release, the electric winch is activated to tighten the cable underneath the pipe. After the pipe is installed, the quick-release is opened remotely by pulling a cable or electronically, and the winch is able to retrieve the cable. Again, the simplicity and flexibility of the cable to carry any type and size of pipe went along with some key disadvantages, one of which is the fact that a pipe, after being released, can never be picked up again. Although this need does not arise frequently the final product has to include this capability. Furthermore, having only one electric winch is not safe for carrying a pipe over 1000 kg.

The hydraulic clamp apparatus applied by the SPPM provides a simple method for collecting and handling a pipe segment. Because of the necessary forces that have to be generated in order to hold a heavy round object, the resulting mechanism has to be significantly larger than the simple cable and winch first used by the Pipeman. The clamping system shown in Fig. 5 (b) was driven by two hydraulic cylinders each with a 100-mm stroke and a 63-mm radius. The maximum open width of the system is 1200 mm and the minimum close width is 700 mm. It is apparent that the weight of the gripper with the strong hydraulic cylinders is significantly higher than the cable and winch used by the Pipeman to hold a pipe segment.

3.2.3. Pipe alignment

As mentioned earlier, the 6-DOF Stewart–Gough platform selected by the Korean research group offers excellent flexibility and utmost precision. Six hydraulic cylinders provide the motion and six potentiometers measure elongation in real time. With the help of visual clues from the direct view or a video screen, the operator is able to align the new pipe with the previous one. The SPPM deploys conventional surveying tools so that the alignment is as accurate as with traditional equipment.

The work envelop of the manipulator is of ±120 mm in linear actuation, ±16° rotation of x, y and z axes, respectively (see Fig. 6 (b)).

While the first Pipeman prototype relies heavily on the movement of the bucket to align the grade, it provides the operator several tools to achieve proper alignment line and grade. After the bedding has been properly established, using a laser beam as a guide, the two wireless video cameras and a laser target show the operator the orientation and position relative to the previous pipe and relative to a laser beam through the already installed pipes (see Fig. 6 (a)). Using the backhoe arm and the 360-degree rotation motion, the pipe can be easily aligned after the operator has had some practice.

3.2.4. Pipe jointing

Both systems make use of hydraulic cylinders to create linear motion to joint two pipes together. As illustrated in Fig. 6 (a), four wheels support the carriage, to which the pipe is attached via cable and winch. Not clearly visible, a hydraulic cylinder provides the necessary force to move the carriage forward or backwards. This arrangement allows the operator to push the lip of the pipe snuggly into the bell with the appropriate gasket. In the case of the SPPM, a track roller, also using a linear hydraulic actuator, slides the entire clamshell-type gripper to joint the pipes (see Fig. 6 (b)).

3.2.5. Man–machine interface

Controlling a manipulator remotely creates a need for bridging the gap between the actuators and the human controlling the machine. The hardware and software require two-way real-time communication, mostly electronic, and is commonly referred as the man–machine interface. Both the delivery and presentation of feedback information, as well as the commands to control the motion of the manipulator, have to be carefully worked out.

Both research teams realized the need for providing visual information during the delicate final alignment of the pipe joint. In the US, line-and-grade lasers together with hand held targets are commonly used for tracking the proper alignment of each piece. To substitute the laborer monitoring the laser light on the target, the Pipeman uses two wireless video cameras, one (#1) facing the front of the pipe to provide a view of jointing the new into the bell of the previous piece and the other (#2) focusing on a laser target to monitor the position of the laser beam relative to the target, as shown in Fig. 7 (a). In contrast, lasers are commonly not used during a pipe installation in Korea. Instead, a pipe layer uses his eyes to decide on line and grade of the pipe during installation. Surveying tools are used subsequently to check for accuracy. This simplification allowed, as Fig. 7 (b) indicates, that the SPPM's only camera aims at the area where the pipes are jointed in a 45-degree angle. Monitors were installed in the cabins of both excavators to prove the operator a close-up view of the connection area. For the purpose of interfacing with the electro-hydraulic valves, both systems selected joysticks that translate motion into

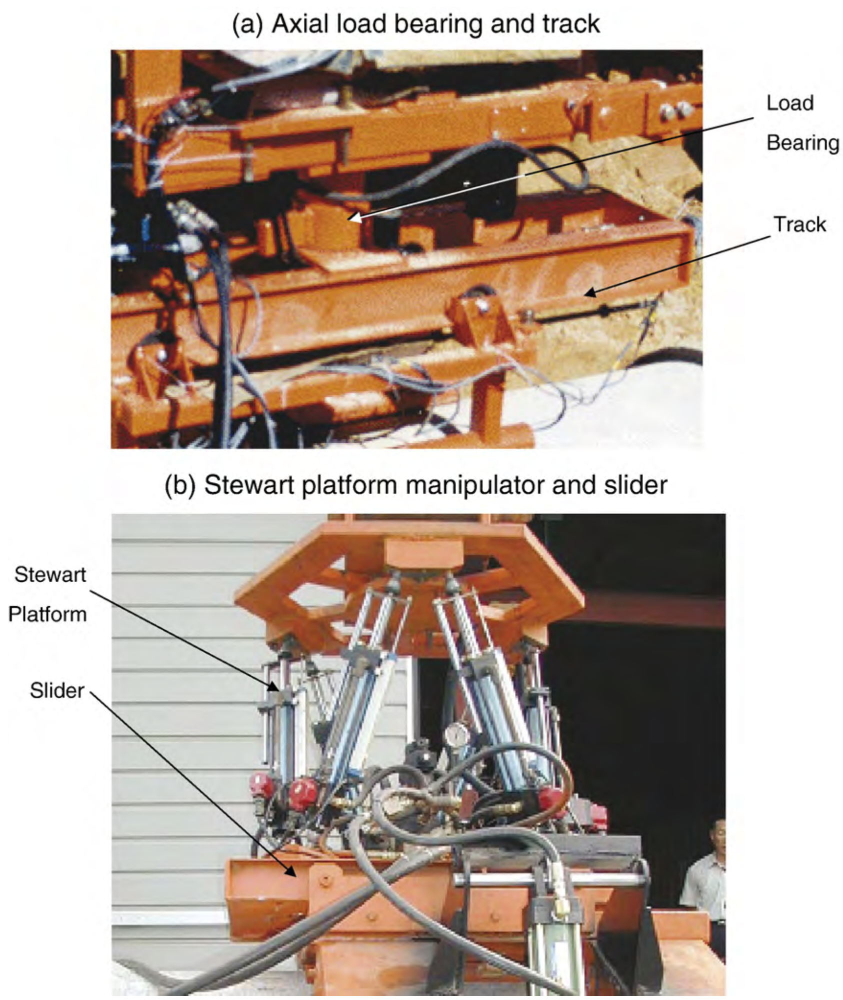

Fig. 6. Pipe alignment and jointing mechanism.

analogue electronic signals that are wirelessly communicated to the receiver on the manipulator. Having the many valves and the necessary power built into the manipulator requires only the quick connection of two hydraulic lines to make the manipulator operational.

4. Performance evaluations

Innovative new technology does not become an invention until it is used on a regular basis. Moving prototype systems into the field, which is referred to as technology transfer, is a long process and commonly starts with an assessment of its performance. This section offers a discussion on how the two research teams designed and implemented the field tests of their prototypes. Two main questions stood at the forefront: a) Is the prototype able to perform the necessary tasks? and b) What are the economic benefits [14]? For the purpose of providing transparency, the technical discussion is organized according to the three main performance tasks: a) transporting pipes into the trench, b) aligning the pipes, and c) jointing the pipes. Both tests were done by field personnel who were able to perform the pipe installation after only 15 min of training.

4.1. Transporting pipes into the trench

The Pipeman team readied for the field test faced an immediate surprise in that the contractor had ordered 8 ft (2.4 m) instead of the 4 ft (1.2 m)-long concrete that the team had used for tests. Doubling the size meant doubling the weight that the manipulator had to carry, which might challenge the weakest link in the system. The buckling of the winch-plate connection during the first pipe installation cycle made the cable unusable. This unexpected calamity was quickly overcome with a chain and tightener brought along by the contractor [14]. As Fig. 8 (a) illustrates, the chain solution worked while only requiring additional time to connect and tighten the chain by hand. However, the incident made clear that a different and more secure solution should be found for attaching a segment to the Pipeman. The SPPM, on the other hand, was able to easily grab a pipe as designed (see Fig. 8 (b)). After attaching a pipe, the backhoe operators for both systems transported each pipe into the trenches to be aligned with the previous element.

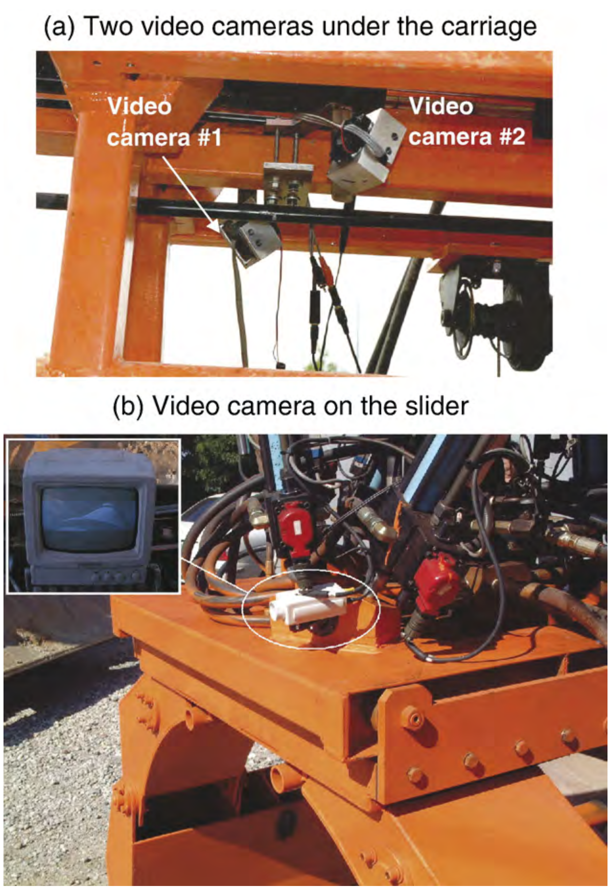

Fig. 7. Man–machine interface.

Fig. 8. Transporting pipes into the trench.

4.2. Aligning pipes

The skillful operator of Pipeman quickly learned how to control the manipulator using the additional joysticks and was enthusiastic about the video images and even the sound he received from inside the trench. However, he preferred to use his own laser target positioned at the bottom of the pipe and

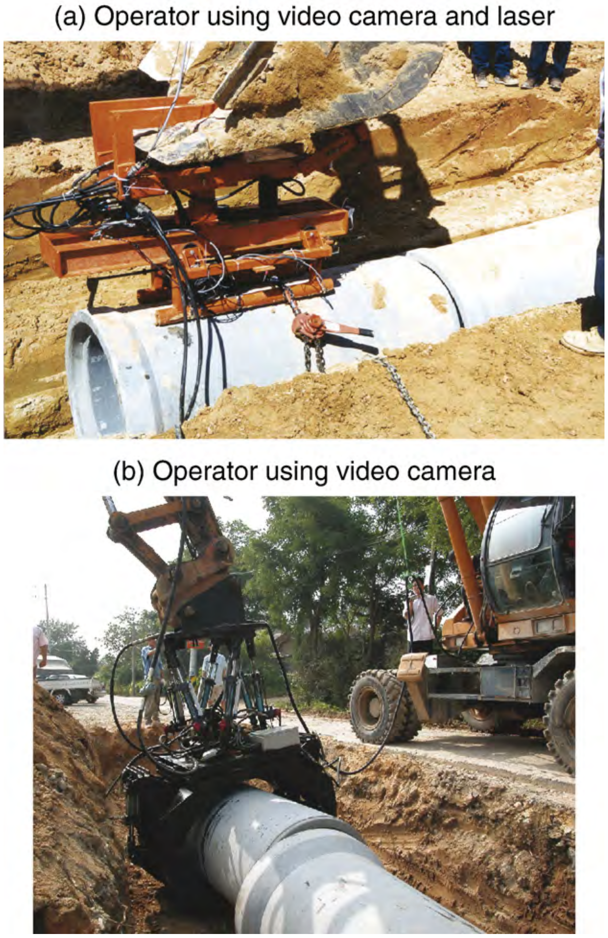

Fig. 9. Aligning pipes.

visible from his seat. His preference, understandable due to having no experience with Pipeman's targeting system, was easily accommodated. Eventually, the operator took advantage of the video image that showed him the position of the bell on the front of the pipe as well as his own laser target. After the installation of a segment, the target was removed using a long pole with a hook at the end. Fig. 9 (a) presents the operator preparing the pipe for jointing. As designed, the 6-DOF Stewart–Gough Platform aligned the pipe independent of the excavator after it was brought close enough to the preceding element (see Fig. 9 (b)).

4.3. Jointing pipes

The last key task in installing a pipe was made easy by the linear motion capabilities built into both systems. Jointing a pipe segment was accomplished by simply activating the hydraulic cylinders of Pipeman's 4-wheel carrier or SPPM's slider until the lip of one pipe sat snugly inside the bell of the other. The gaskets, necessary to prevent leaking, did not provide enough friction force to stop the jointing. Fig. 10 highlights the successful last step of both devices.

4.4. Productivity comparison

As mentioned above, it is important to demonstrate and prove the economic benefits of new technologies if one expects its adoption by the industry. The fact that only prototypes are first available makes a meaningful assessment extremely difficult. One method found to be useful is a comparative experiment that keeps all but one variable the same. In the case of the Pipeman, ABE Utilities, Inc. of Raleigh agreed to provide a crew and a field for an experiment where, on the first day, 8 pipes were installed in the traditional way, and on the second day, the same 8 pipes were installed using the Pipeman. Because the field and weather conditions were exactly the same, a true comparison was possible. The SPPM, on the other hand, was tested at a pipe-laying site at KICT by a backhoe operator and an experienced helper. During operation, cycle times for laying the pipes were analyzed to calculate the productivity and production rates. The measured tasks included time for connecting and disconnecting the device to and from the excavator, attaching/grabbing, transporting, aligning, jointing and releasing the pipes.

Table 2 summarizes the mean times of 8 and 21 installations, respectively [9]. The average cycle time spent for pipe laying with the Pipeman was 9.6 min (576 s), whereas it was 2.4 min (144 s) with the conventional method. As indicated above, the use of the chain instead of the cable added approximately 5 min, which is an unexpected amount of wasted time. As will be shown later, the use of a new fastening approach is expected to reduce the cycle time to 3.6 min or less. Moreover, a crew of 3

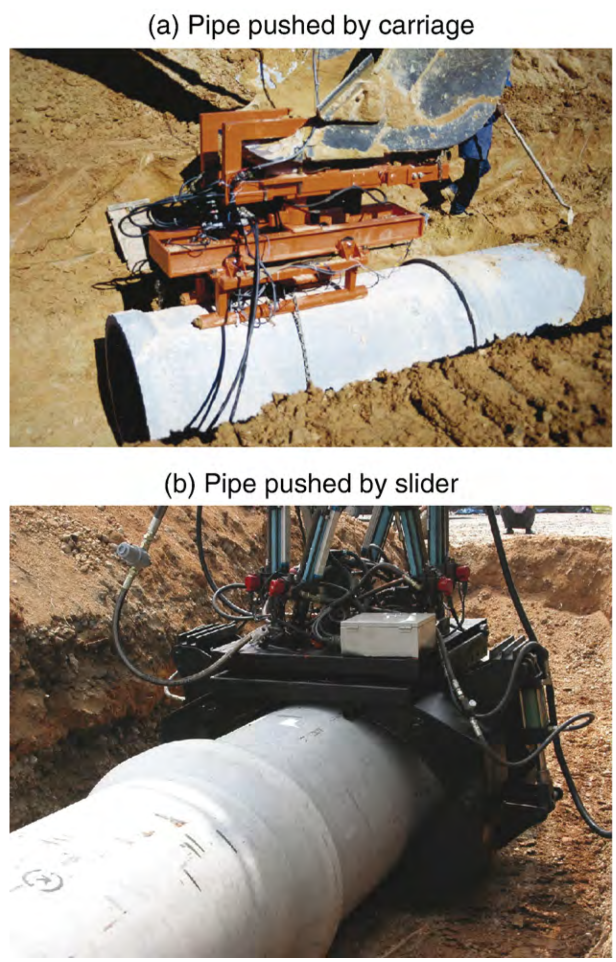

Fig. 10. Jointing pipes.

Table 2
Cycle time comparison

Activity	Task	Time (s)	
		Pipeman	SPPM
Pipe handling	Connecting	162	15
	Traveling	18	163
Positioning	Locating	42	23
Jointing	Jointing	18	33
Aligning and leveling	Aligning	–	141
	Releasing	72	11
Subtotal (time/each)		312	386
Preparing	Connecting equipment	102	1645
Finishing	Disconnecting	162	1645
Subtotal (time/each)		264	50
Productivity (time/each)		576	436

was able to perform the installation instead of the conventional 5, drastically increasing productivity, which can also take advantage of less time for excavation and compaction. The productivity, measured in meter of installed pipe per man-hour, with the traditional 5-member crew is 1.9 m/man-hour and 4.2 m/man-hour for the Pipeman with a 3-member crew. The production rate, including excavation and bedding, however, would drop from 50 to 42 pipes/day. It is estimated that the daily production of the Pipeman would be approximately 70 pieces of 8 ft (2.4 m) pipes if laid consecutively into an open trench. This option, of course, mirrors the way the SPPM test was performed. Here, the "stop-watched" cycle time was 7.3 min (436 s) with two crews working, which calculates into a daily production for the SPPM of 66 pipes/day, a 25% improvement over the traditional method used in Korea. As shown in Table 2, the average time to connect and disconnect Pipeman to and from the bucket was 102 s and 162 s, respectively. The time for attaching and removing the SPPM to the backhoe arm stood at 1645 s. Taking into account the fact that laying pipes in Korea is done consecutively on a stretch that previously been trenched, the average time per pipe is 50 s. It is believed that this time can be improved by simplifying the process.

Field-testing prototype technology for the first time is always a "nail-biting" experience. As with the two pipe manipulators, the question "Will it work?" was quickly replaced with "How well does it work?" One final qualitative measure, very critical to technology transfer, is its acceptance by the field crew. Even the best technology, hated by the people who are supposed to use it, is prone to fail. Fortunately, the operators, pipe layers and helpers accepted the new technology wholeheartedly, even participating in brainstorming for substitutions for the unusable winch, and took expert control of the hardware. They felt that the most important role of the manipulator was in protecting their lives by eliminating their hazardous stay in the trench.

5. Modifications for second-generation prototypes

As mentioned above, each field test revealed several weaknesses. The following explains the technical modifications that will further enhance the performances of each.

5.1. Fastening to the backhoe bucket

The clamping mechanism of the Pipeman, consisting of a backstop and a hydraulic bladder, needs to be replaced. The modification consisted of a hydraulic two-link clamp pressing against the underside of the bucket and a simple chain to replace the backstop.

5.2. New concepts for pipe handling

The Pipeman's designers decided that instead of adding a second cable and winch, the simple approach to holding the pipe should be abandoned altogether. An additional impetus for this step was the fact that a pipe, once released from the quick-

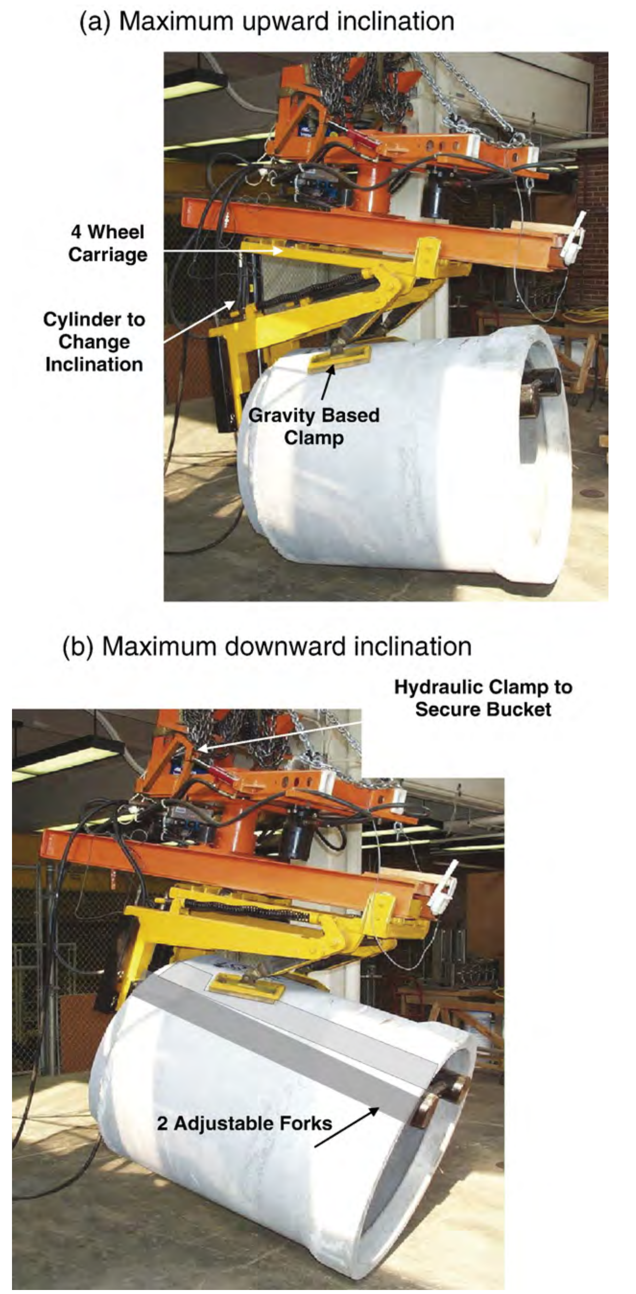

Fig. 11. New mechanisms bring flexibility to the Pipeman.

connect, could never be picked up again. This could create consternation in a situation where a misalignment is detected after the cable has been winched in. Fig. 11 portrays the result of the changes that were made.

The most apparent change is the two adjustable forks, replacing the winched cable, combined with the gravity-based clamp which activates as soon as the weight of the pipe acts on the forks. A modification of the carriage on the horizontal steel tracks allowed the inclination of the pipe to be changed without any actuation of the bucket. This change enables the Pipeman to install pipes when, similar to the SPPM, the backhoe excavator or any other carrier is operating from the side of the trench. Also visible is the clamp and steel bar that grip the backhoe bucket.

In the case of the SPPM, the extra space needed to open the clamp after the pipe has been released requires an over-excavation of the trench. In the modified version, the mechanism will be changed to reduce its space requirement while added adjustment capabilities should permit various pipe diameters to be handled. One possible solution is the use of exchangeable gripping tools. Another modification is the addition of a stand-alone frame for parking, transportation and maintenance.

5.3. Improved tele-op capability during alignment

Providing effective visual feedback during the alignment process will be critical in cases where pipes need to be installed in deep trenches. In the case of the SPPM, a second video camera is needed to provide the operator with a better view of the two segments to be jointed together. In addition, both systems need to improve the interface with the line-and-grade laser on top or inside the pipe. Eventually, the alignment process could be automated but requires more investments on electronic position measurement and control software.

5.4. Spatial integration and buried utility detection

In order to allow for a pipe installation with an acceptable line and grade, creating of the proper bedding is instrumental. While experienced operators are able to prepare a bedding for one segment at the time, less experienced novices and operators digging a continuous trench need the help of the laser. Both systems possess the electronic infrastructure to interface with 3-D CAD and spatial positioning (SPS) to complement the video systems. Integrating the backhoe and pipe manipulator spatially creates many other opportunities such as avoiding damaging buried utilities, marked in the 3-D CAD, or the creation of automatic as-built drawings or even as-it-was-built reports. Such reports would not only show the x,y,z of a pipe but also a capture of the soil conditions inside the trench and the situation during the installation of each pipe.

6. Summary and conclusions

This paper provides a unique comparison of two independent research projects that were undertaken to find a remedy to a worldwide problem in construction safety — collapsing trenches and falling objects killing laborers during pipe installation. Research teams at the NC State University and the Korean Institute of Construction Technology both selected the backhoe excavator as the carrier of a manipulator attachment but followed different strategies in interfacing with the backhoe and in the design of the pipe-handling tools. The 2-DOF serial mechanism adopted by Pipeman connects to the backhoe bucket while the 6-DOF Stewart–Gough Platform selected as a base for the SPPM connects to the stick of the excavator arm. Furthermore, the electric winch and cable method used to hold a pipe segment in the early prototype of the Pipeman SPPM utilizes a heavy-duty hydraulic clamping mechanism. Owing to such design differences, the Pipeman became a simple, solid and easy system to operate, but depended on the backhoe to provide 3-DOF needed in laying pipes. In contrast, the SPPM was built with sufficient DOF to manipulate a pipe accurately but its motion control interface is hard for operators to learn. As demonstrated, some of the differences between the first prototypes can be attributed to discrepancies in the way contractors in the two countries prefer to install pipes. This is not surprising since a key objective in innovating new systems is to design for easy acceptance in the industry. However, it is remarkable that both projects included similar field tests with the first prototypes executed by crews from the construction industry. It is felt that such experiments, which also assess the acceptance of the innovation by field personnel, are critical in laying the foundation for the successful transfer of the technology into the industry. The result of the comparative field studies, accomplished by having field crews lay 8 and 21 pipes, respectively, reported improvements in both productivity and unit cost. Since it is the nature of scientific research to pose new questions at the end of a project, the two field tests brought to light weaknesses that had not been foreseen during the building of the first prototypes. Presently, the two research teams are designing and testing the second-generation prototypes that remedied the weaknesses that surfaced during the initial tests.

A well-known aphorism states that: “Every problem presents an opportunity.” The two authors hope that this attitude will move the two technological innovations to further improvements in the future, and as an example of technological progress, lead to the elimination of deaths in the trenches.

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References

[1] U.S. Department of Labor, Bureau of Labor Statistics, website accessed on Dec 15, 2004. http://stats.bls.gov/iif/home.htm#News.
[2] Federal Register, Occupational Safety and Health Administration, 29 CFR Part 1926, Occupational Safety and Health Standards — Excavation; Final Rule, 1989.
[3] K.T. Kim, J. Lee, C.H. Han, S.K. Kim, A Feasibility Study for Introducing Teleoperated Pipe Manipulator, Korea Institute of Architects, vol. 175, 2003, pp. 105–112.
[4] J.G. Han, K.T. Kim, Y.S. Kim, J. Lee, J.T. Kim, A development of Stewart platform based pipe manipulator, Proceedings of the 21st International Symposium on Automation and Robotics in Construction, Jeju, Korea, 2004, pp. 352–357.
[5] Y.S. Kim, J.B. Lee, A Study on the Research and Development Process Model for Construction Robots, Korea Institute of Architects, vol. 19, No.6, 2003.
[6] Dong Yang Concrete Industry Co., LTD., website accessed on Nov 8, 2004, URL: http://www.dy-humepipe.co.kr.
[7] Korea Centrifugal Reinforced Concrete Industry Cooperative, website accessed on Dec 10, 2004, URL: http://www.kcrcic.or.kr/.
[8] Korea Institute of Construction Technology, Development of teleoperated concrete pipe laying manipulator in the trenches, in: H.G. Park (Ed.), Research Report 2004, Korea Ministry of Construction and Transportation, Gyeonggi, Korea, 2004.
[9] J. Lee, S.J. Lorenc, L.E. Bernold, A comparative performance evaluation of tele-operated pipe laying, J. Constr. Engrg. and Mgmt., ASCE 129 (1) (January/February 2003).
[10] J. Lee, S.J. Lorenc, L.E. Bernold, Saving lives and money with robotic trenching and pipe installation, J. Aerospace Engineering, ASCE 12 (2) (April 1999) 43–49.
[11] V.E. Gough, S.G. Whitehall, Universal tyre test machine, Proceedings of the FISITA Ninth International Technical Congress, May, 1962, pp. 117–137.
[12] D. Stewart, A platform with six degrees of freedom, Proceedings of the Institution of Mechanical Engineers, 180, 15, 1965, pp. 371–378.
[13] K.L. Cappel, Motion simulator, US Patent No. 3, January 3, 1967, 295, 224.
[14] J. Lee, Comparative performance evaluation of teleoperated pipe laying, Ph.D. Thesis, Department of Civil Engineering, NCSU, Raleigh, NC, 1999.