Autonomous Robot for Pavement Construction in Challenging Environments

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Abstract

Conventional concrete paving construction machinery has insufficient automation in design, standardized process, and controls for paving construction in hazardous environments on earth as well as other planets. Although the state-of-the-art paving process includes a high level of automation, the process is still labor intensive which hinders its use due to operation cost and safety in hazardous environments. Researchers at Ohio University are developing an autonomous robot to perform the rebar placement, vibration, screed, and curing tasks associated with a concrete paving process. These single tasks can be automated and integrated into a novel single paving robot called RoboPaver. This single robot is capable of operating in challenging environments on Earth and on other planetary bodies such as the Moon and Mars with minimal assistance. This paper presents the mechanical and controller design of a fully autonomous robot that will be used for concrete pavement construction. It is envisioned that with the aid of an autonomous paving robot, pavement construction can be safely conducted in hazardous environments, for which conventional paving equipment and operations are not suited.

Introduction

Robotics and automation technology will continue to change the construction field. With an autonomous paving robot, pavement construction can be safely conducted in hazardous environments, for which conventional paving equipment and operations are not suited.

Several Japanese construction companies known as the “big five” have already developed their own fleet of single task construction robots (Obayashi, Takenaka, Kajima, Shimizu, and Taisei). Today there are robots helping to build structures, renovate bridges and tunnels, and to help clear asbestos. robots will perform their duties in extremely hazardous environments such as in the presence of radioactive material, military applications, and for asbestos removal. When safety is an issue, robots can serve as good substitutes for humans. The automated concrete paving robot, “RoboPaver” will be shown to be capable of operating in challenging environments on Earth and on other planetary bodies such as the Moon and Mars with minimal assistance. Other authors presenting relevant results in automation for construction and paving include Skibniewski and Hendrickson (1990), Luces et al. (1995), Osmani et al. (1996), Cousineau (1998), Peyret et al. (2000), Cobb (2001), and Cable et al. (2004). Some pertinent websites are also given in the reference list. For more complete literature and paving state-of-the-art reviews, please see Bryson et al. (2005) and Maynard (2005).

Autonomous Paving Robot Design

The current RoboPaver hardware design is a 1:20 scale model. It combines all the operations of a conventional paving system into one robot. The paving robot will incorporate an intelligent concrete construction system that will allow real-time remote control of the paving operations. Mechanical designs were completed for the automated placement of pre-fabricated rebar baskets and the concrete placement system. Sensors and controllers have been designed to aid in system automation. The solid model of the final prototype robot design can be seen in Figure 1.

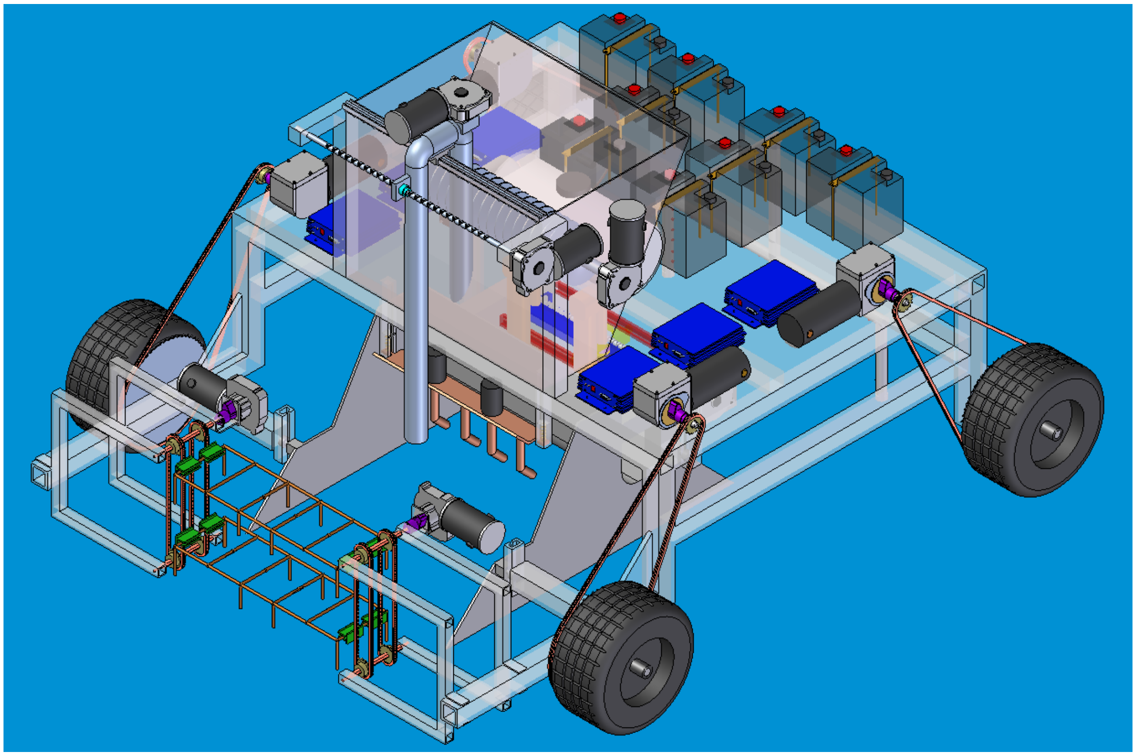

Figure 1. Final Robot Design (Front Isometric View)

The final design images are lacking protection from possible splattering of concrete. The screws, chains, gears, and controllers are all exposed to clearly show their orientation and design. To solve this problem, protective covers made of sheet metal can be used to cover these moving parts.

Rebar Placement. The prefabricated cages used for the paving process are designed to have a stake on each corner. The “holding clamp” is designed so that chain conveyors can drive the dowel baskets into the ground and release the dowel baskets when they get to a pre-specified depth. To ensure that the conveyors move the correct distance encoders were placed onto both the drive motors. A CAD rendering of the rebar placement subsystem can be seen in Figure 2.

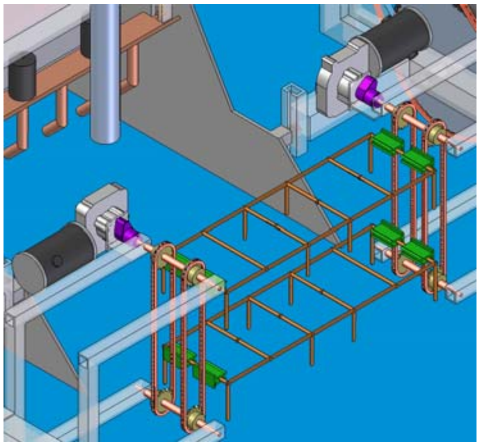

Figure 2. Rebar Placement

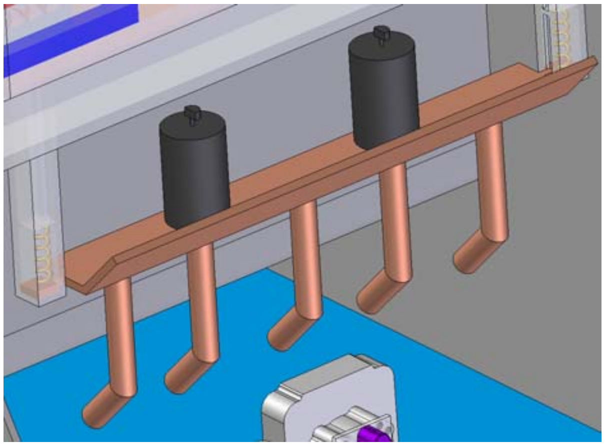

Figure 3. Vibrating Subsystem

Vibrator. The vibration, also known in the industry as consolidation of the concrete is done with internal vibration. The vibrations are generated by an unbalanced weight on the shaft of a high rpm Dewalt drill motor. The motors in the system are placed upright, but future testing might reveal that the motors should be placed on their side for better performance. Springs are placed on both sides of the vibrator to dampen the effects of the vibrations onto the robot itself. A CAD rendering of the concrete vibration subsystem can be seen in Figure 3.

Concrete Placement. The final design for the concrete placement can be seen in Figure 4. The concrete is drawn up through the pipe by an auger driven by the motor mounted on the top of the pipe. In order to disperse the concrete evenly, the pipe is attached to a double threaded lead screw that will cause the pipe to oscillate back and forth in the two foot cross section being paved. Different batches of concrete will vary in content and viscosity. To monitor this, testing should be done on the draw current of the mixing motor for an optimal batch of concrete. If there is a large change in the draw current between two batches the mix may be out of specification, RoboPaver will be able to notify the operator that there is a problem. Laser profiling sensors can also be placed in front of the paver to ensure that there is enough concrete on the ground to continue moving the paver forward.

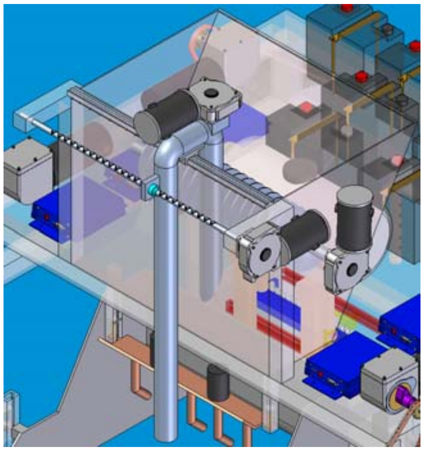

Figure 4. Concrete Placement

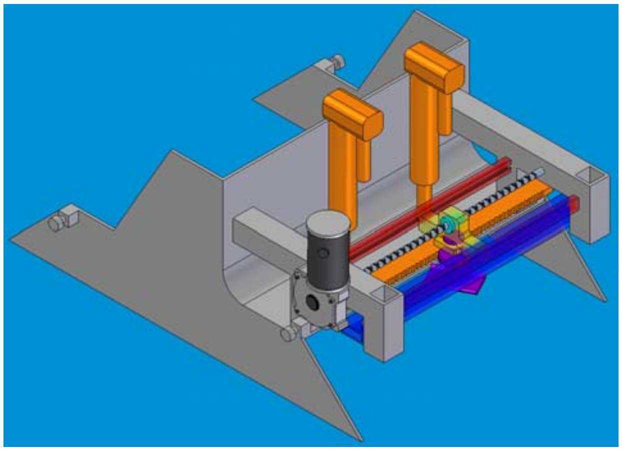

Figure 5. Screed and Form

Form and Screed System. The final design for the form and screed subsystem is shown in Figure 5. One design change is the addition of a brass coated guide for the spur gear, the blue colored object in Figure 5. To allow for the form to move up and down, two sets of track bearings were added, plus two linear electric actuators that can supply 700 lbs of force apiece. Because the form will be moving, the final screed must move along with it. In order to do this, the prototype's screed system is welded onto the form.

Curing. The curing sub-system is fairly simple. It consists of a holding tank, a DC water pump, PVC pipe, and spray nozzles. The CAD rendering for this subsystem can be seen in Figure 6.

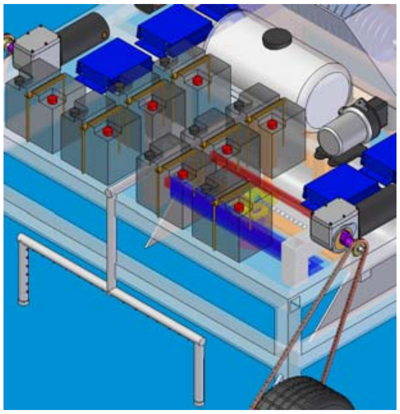

Figure 6: Curing Subsystem

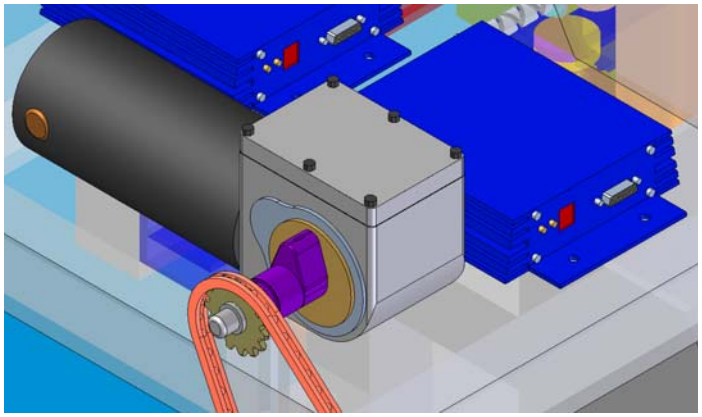

Figure 7: Wheel Drive Subsystem

Robot Navigation

In order to ensure automation in the proposed paver, the positioning and navigation must be conducted with minimal assistance. In order to do this the preplanned path for the paver can be programmed into the on board computer and with GPS and encoder feedback the paver will stay on path. The components of the navigation system can be seen in Figure 7.

The modeled system is an autonomous 4-wheel differentially driven (4wdd) robot. The robot is simplified so that one motor drives both left wheels as one, and another motor drives both right wheels as one. The inputs to the system are the left and right side motor torques. These two torques, acting in the same direction cause longitudinal movement of the robot while the difference in the left and right torques is responsible for steering (the lateral movement and the change in direction of the robot). The two motion outputs are the longitudinal distance traveled, X and the robot heading angle, Θ. These variables can be seen in Figure 8.

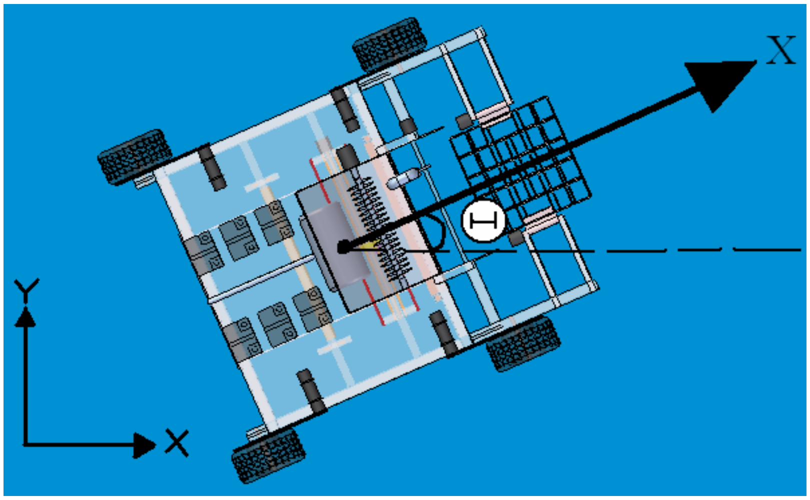

Figure 8. Paver Positioning Diagram

Using standard robotics equations, the motion relative to the robot into motion in the global coordinate frame XY can be derived. The goal is to design a controller that will direct the navigation of RoboPaver through its paving process in a preplanned path. GPS feedback using satellite triangulation and differential GPS with fixed stations along the work path will help to achieve the desired 3D positional tolerances. The dynamics model presented for the controller development was adapted from Caracciolo et al. (1999).

Dynamic Model of the System. A general dynamic model has been derived for RoboPaver for use in navigation and controller design. Due to lack of space, please see this model in Maynard (2005).

Robot Positioning Simulation. Using the information obtained in the previous section a proper controller can be designed. The general schematic for the linear controller can be seen in Figure 9.

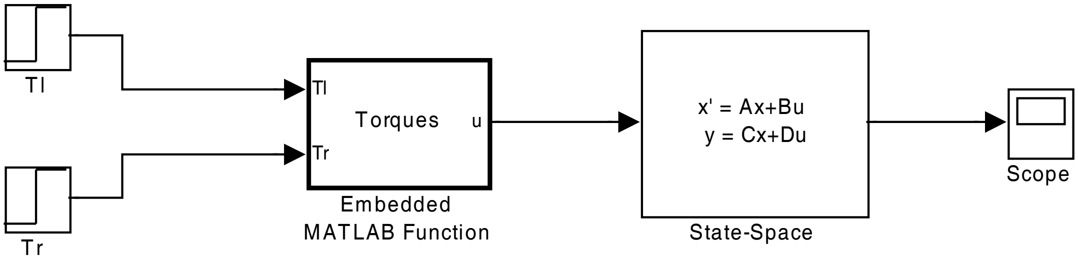

Figure 9. Robot Positioning Schematic

For simulation purposes the robot's dynamic information was implemented into a Matlab program to analyze. The full program and graphical outputs can be viewed in Appendix B. The program is a linearized controller design that gives a closed-loop and an open-loop scenario output. The inputs to the program are the left and right motor torques and the closed loop characteristics. Some of the useful outputs from the navigation simulations can be seen in Figures 10 and 11 (two separate motion simulations).

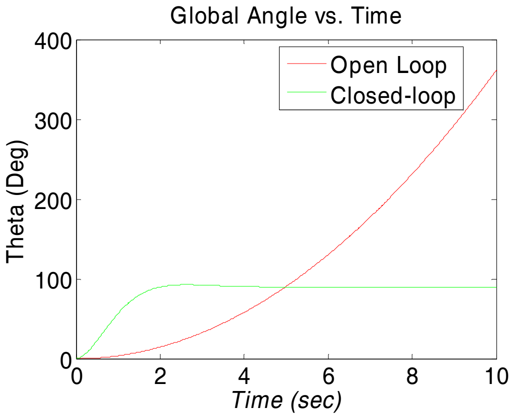

Figure 10a. Global Angle vs. Time

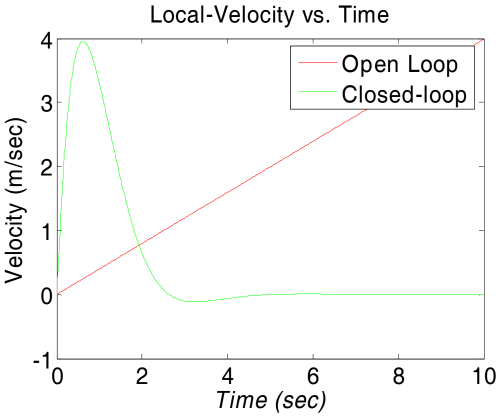

Figure 10b. Local Velocity vs. Time

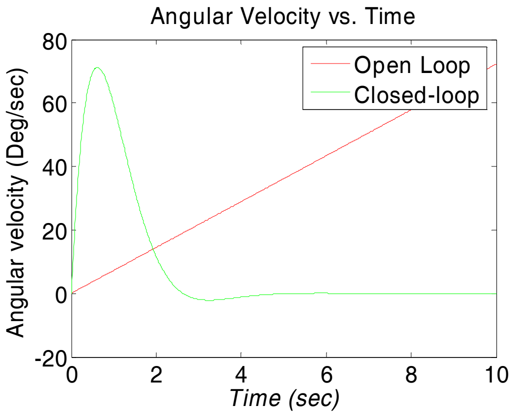

Figure 10c: Angular velocity vs. Time

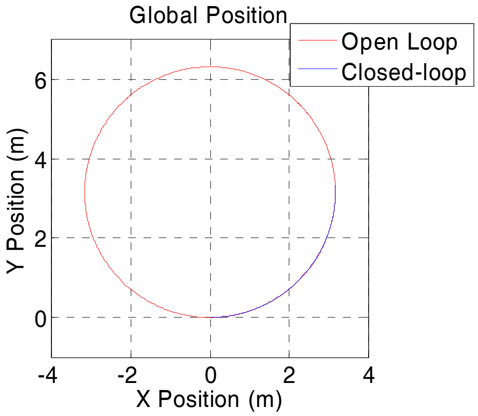

Figure 11a: Global Position

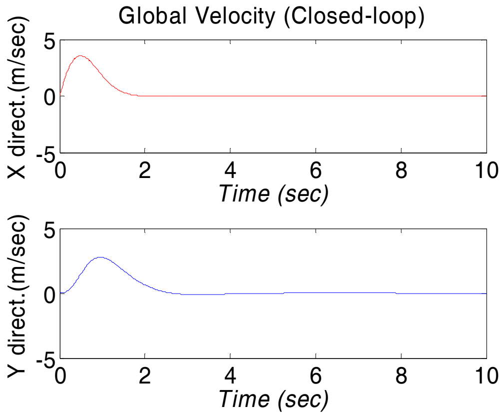

Figure 11b: Global Velocity

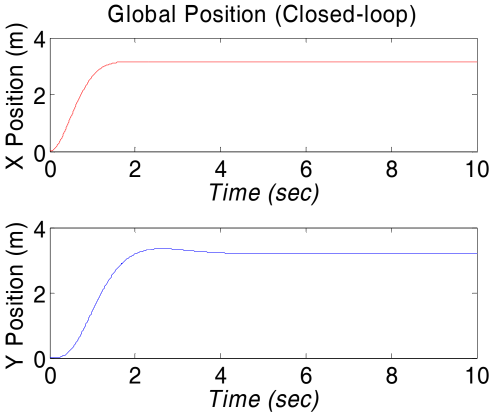

Figure 11c: Global Position

Conclusions

Conventional concrete paving construction machinery has insufficient automation in design, standardized process, and controls for paving construction in hazardous environments on earth as well as other planets. Although the state-of-the-art paving process includes a high level of automation, the process is still labor intensive which hinders its use due to operation cost and safety in hazardous environments. Researchers at Ohio University are developing an autonomous robot to perform the rebar placement, vibration, screed, and curing tasks associated with a concrete paving process. These single tasks can be automated and integrated into a novel single paving robot called RoboPaver. This single robot is capable of operating in challenging environments on Earth and on other planetary bodies such as the Moon and Mars with minimal assistance

Conventional concrete paving construction machinery has insufficient automation for safe and efficient pavement construction. State-of-the-art highway paving operations include a high degree of automation, but the process is still labor intensive and the final quality of the pavement section is a function of the skill of the paving crew. Introducing autonomous robotics into paving operation provides a means to improve quality while at the same time increase productivity and efficiency. Increased productivity and efficiency yield a corresponding decrease in operational costs.

The current proposed robot, RoboPaver, combines all the operations of a conventional paving system into one robot. The paving robot incorporates a novel design that allows for minimal human labor in paving operations. Mechanism design, control algorithms, and sensors assist in automating the concrete paving process. Several kinematics, dynamics, sensors, and controller issues have been addressed for the proposed paving robot. A linearized controller design was developed to aid in the automation of the paver. Simulation shows that the navigation and positioning can be automated with such a controller design. The cost for the proposed final design is estimated at $15,000.

References

Bryson, L.S., Maynard, C., Castro-Lacouture, D., and Williams, R.L. (2005). “Fully Autonomous Robot for Paving Operations”. Proceedings of the 2005 ASCE Construction Research Congress, San Diego, California, April 5-7, in press.

Cable, J.K., Bauer, C., Jaselskis, E.J., and Li, L. (2004). “Stringless Portland Cement Concrete Paving”, report submitted to Iowa DOT, Project TR-490, Center for Portland Cement Concrete Pavement Technology, Iowa State University, February 2004, pp. 53

Caracciolo, L., De Luca, A., and Iannitti, S. (1999), “Trajectory Tracking Control of a Four-Wheel Differentially Driven Mobile Robot”, Proceedings of the IEEE International Conference on Robotics and Automation, May 10-15, 1999, Detroit, MI, pp. 2632-2638.

Cobb, D. (2001). “Integrating Automation into Construction to Achieve Performance Enhancements”, Conference Proceedings of the CIB World Building Congress, Wellington, New Zealand, April 2-6.

Cousineau, L. (1998). “Construction Robots: The Search for New Building Technology in Japan”, ASCE Press. Reston, Virginia.

GOMACO (2005). “The Worldwide Leader in Concrete Paving Technology”, <http://www.gomaco.com> (Jan. 30, 2005).

IAARC (2004). “International Association for Automation Robotics in Construction”, <http://www.iaarc.org/frame/main.htm> (Oct, 2004).

Luces, E., Moon, S., Rihani, R., and Bernold, L. (1995). “Robotics for Increased Safety in Highway Construction and Maintenance”. Transportation Research News, 176 (January-February), pp. 12-16.

Maynard, C.M. (2005). “A Novel Approach for Road Construction Using an Automated Paving Robot”, MS Thesis, Mechanical Engineering, Ohio U.

North Carolina State (2004). “Innovation with a Vision”, <http://www2.ncsu.edu/ncsu/CIL/CARL> (Oct, 2004)

Osmani, A., Haas, C., Hudson, R. (1996). “Evaluation of Road Maintenance Automation”. Journal of Transportation Engr, ASCE, 122(1), pp. 50-58.

Peyret F., Jurasz J., Carrel A., Zekri E., and Gorham, B., (2000), “The Computer Integrated Road Construction Project”, International Journal for Automation in Construction, vol. 9, pp. 447-461.

Purdue University (2004). “Emergent Construction Technologies”, <http://www.new-technologies.org> (Oct, 2004)

Skibniewski, M., and Hendrickson, C. (1990). “Automation and Robotics for Road Construction and Maintenance”. Journal of Transportation Engineering, ASCE, 116(3), pp. 261-271.

Takenaka Corp (2004). “Takenaka’s Research and Development” <http://www.takenaka.co.jp/takenaka_e/techmenu_e/index.html> (Oct, 2004)

University of California Davis (2004). “Advanced Highway Maintenance and Construction Technology”, <http://www.ahmct.ucdavis.edu> (Oct, 2004).

University of Texas at Houston (2004). “Center for Technology Literacy”<http://www.texastechnology.com > (Oct, 2004).