PRODUCTIVITY ANALYSIS OF A MULTI-TASK AUTONOMOUS ROBOT FOR CONCRETE PAVING

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ABSTRACT

Autonomous robots that perform specific tasks are being developed to perform repetitive operations common in conventional concrete construction, to gain benefits in safety, productivity, costs, quality control, and security of the workforce in hazardous environments. Single-task robots are capable of enhancing specific functions, though their impact on the overall productivity remains unclear. Assessing potential productivity from the use of a fully automated process is a required step for developing a full scale-system. Based on prototypical models of a robot that incorporates each task-specific piece of machinery used in the concrete paving process into one fully autonomous unit, a process workflow is presented. With the purpose of quantifying productivity outputs in an automated concrete paving operation, the autonomous process workflow is analyzed using simulation tools. Results from the simulation show that the autonomous operation is capable of yielding productivity outputs greater that in conventional construction.

KEYWORDS: Concrete, Pavement, Robotics, Computer-based Simulation, Productivity.

INTRODUCTION

Robotics has been subject of study in civil engineering for the past twenty years, thereby generating great interest in the construction community (Warszawski and Navon, 1998; Cobb, 2001). Theoretical benefits based on prototypical performances have the potential to provide competitive advantages for construction firms, given the productivity, safety and quality improvements offered by robots when performing both simple and complex construction tasks.

Efficiency is low in conventional concrete construction. This fact, combined with high accident rates at construction sites, low product quality, and insufficient controls of the project schedules for conventional concrete construction have led researchers to develop autonomous robots to perform specific tasks. These robots are referred to as single-task robots and generally result in productivity and efficiency improvement. However, one disadvantage of single-task robots is that they are typically not able to improve the overall process. This is primarily due to the additional efforts required to assemble and disassemble the various robots for the required tasks. To enhance the overall productivity and efficiency of a project without forfeiting safety, the entire system must be automated. Prior to the development of an autonomous robot capable

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of automating a complete construction process made up of many single tasks, it is necessary to assess the productivity and safety of the operation. Such a robot would be advantageous for a multi-task operation such as concrete paving, but the hypothetical benefits need to be verified using analytical tools. Before embarking on the expensive and resource-intensive process of prototype assembly and testing, a framework is needed for quantitatively assess the improvements in productivity and for qualitatively consider safety aspects of the proposed robotic operation.

This paper presents the performance assessment of a fully autonomous robot that will be used for concrete pavement construction, and its implications in productivity and safety. Concrete pavement construction is suited for robotics in that the complete construction process is made up of many single tasks that can be automated and integrated into one single machine. A fully autonomous robot will have the ability to consistently produce high-quality products and to precisely perform tasks. It is envisioned that with the aid of an autonomous robot, construction projects will be able to be completed better, faster, and safer, which will lead to greater productivity and reduce costs.

AUTOMATION OF PAVING OPERATIONS

Most concrete highway pavements are constructed with a slip form paver, and paving operations are executed within the framework of a “paving train”. The actual concrete paving operation is a combined process of a large number of specially-designed machines, each with a specific function in the construction process. Once paving operations have begun, the various steps in the construction process are arranged in the form of a continuing series of separate operations that are planned and coordinated so that the construction proceeds with minimum loss of time and effort.

Other important aspects in the paving process include control of the paving equipment trajectory and control of the pavement surface profile, or screeding. Currently, most of the methods used to control equipment trajectory are based on conventional surveying techniques, such as hubs, grade stakes and string-lines. These types of controls limit productivity, because their installation is slow and are subject to human errors. In addition, manual-type trajectory controls require skilled operators to accurately steer the equipment, using rudimentary techniques. There is ongoing research in the evaluation of stringless paving using a combination of global positioning and laser technologies (Cable et al. 2004). However, results are indicating that GPS control is a feasible approach to controlling a concrete paver, but further enhancements are needed in the physical features of the slip-form paver hydraulic system controls and in the computer program for controlling elevation. In some state-of-the-art paving operations, laser leveling systems have been introduced to improve productivity and accuracy of the paving process. These systems consist of a ground-based laser source that emits a linear beam or light pulses, with target receivers mounted on the paver. Although the use of laser technology is widespread in the excavation industry for grade control, only a few of the commercially available pavers have the capability for minimal laser control. No current commercially-available paver has the ability for semi-autonomous operation of the screed and trajectory using laser-based or any other technology. Furthermore, control of the screeding operation is also based on conventional surveying techniques.

State-of-the-art highway paving operations include a high degree of automation. Modern paving operations consists of equipment and various control systems that regulate conveyance and placement of the paving materials, control the direction and rate of paving, and provide surface finishing capabilities for the final pavement. Unfortunately, each of these aspects of the paving operation represents a separate piece of equipment, equipment operators and the supporting laborers. Thus, although the state-of-the-art paving process includes automation, 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. An effort was made to fully automate asphalt paving (Schraft and Schmierer, 2000), but appears to be halted after the initial developments. Other attempts to utilize robotics in pavement applications have been limited to using operator-assisted robots to automate only aspects of pavement construction. In addition, these efforts have been limited to asphalt pavement (Peyret et al., 2000).

Productivity Indicators in Concrete Paving Operations

In spite of discussions about positive and negative trends in productivity for the construction industry (Hendrickson 2005), performance indicators at the macro and micro level still govern the level of attention that the construction industry attracts. At the micro level and with regards to the assembly operation, there are many performance indicators in the construction industry. Some of these indicators are related to productivity while others address safety issues. For construction robotic applications, new indicators that represent a more realistic metrology are incorporated. Metrics used for robotic operations include measures of manipulability, redundant space, obstacle avoidance and accuracy of manipulation.

Some performance indicators are based on measurements of placed cubic meters of concrete per unit of time. For the case of a slip form paving process, the advancement distance per unit of time is an acceptable metric. Other performance indicators are associated with cost, such as the output of cubic meters of paved concrete divided by the costs associated with the operation. However, when the overall operation is composed of many individual tasks that require monitoring and control, partial task durations are also tracked as indicators of productivity and safety. Regarding this last factor, some indicators are related to safety measures in construction, such as injury incidence, causation and risk exposure.

Safety Considerations

Over the years, the construction industry has consistently been among those industries with the highest injury and fatality rates. Thus, accident prevention has been a consistent objective for practitioners and researchers (Hinze and Gambatese 2003). Paving operations are exposed to safety risks due to the interactions between workers and heavy equipment. These interactions during highway construction and maintenance operations, as well as the traffic control required to keep vehicles away from the work zone lead to a work environment prone to accidents. Proper traffic control is critical in highway work zones, but this sole factor cannot be considered as deterrent of fatalities in the workplace. Some efforts to automate the placement of safety devices such as mobile safety barrel robots have been evaluated (Farritor and Rentschler 2002). However, these initiatives acknowledge that malfunctions can make the robot enter traffic and create a significant hazard. Other researchers believe that work zone safety can be increased not only by improving traffic control devices, but also by providing laborers with smart data, proper protection and removing them from the dangerous work environment (Luces et al. 1995; Ha and Nemeth 1995). These initiatives are aimed at equipping the workforce with better safety devices or even at separating the equipment from the workforce, while little has been done on automating the overall concrete paving process with the intention of improving safety. The automation of various isolated construction and paving processes has brought substantial benefits in workplace safety (Hemami 1995; Osmani et al, 1996). Fully autonomous robots may represent a valid alternative for the improvement of safety in the work zone. This improvement, coupled with an increase in productivity will lead to dramatic benefits in the way paving operations are currently conducted.

RoboPaver: Fully Autonomous Robot for Concrete Paving

Ohio University is in the process of developing a prototype of a fully autonomous robot for concrete paving dubbed RoboPaver (Bryson et al. 2005). As discussed previously, there are many competitive advantages to integrating robotic technology with concrete pavement construction. Although the concept of using a robot for asphalt paving has been shown to be valid with the development and demonstration of the Road Robot (Schraft and Schmierer, 2000), no attempts have been made to expand that research to concrete paving. The RoboPaver prototype is a 1:20 scaled model of the intended field version. The purpose of the prototype is to serve as a proof-of-concept concrete pavement construction robot. It is anticipated that the full-scale version of the RoboPaver will occupy about the same volume as a typical commercially-available slip form paver, but will combine all the operations of a conventional paving train into one robot.

The RoboPaver proof-of-concept hardware prototype will incorporate each task-specific piece of machinery used in the concrete paving process into one fully autonomous unit. The RoboPaver prototype will be a battery-operated robot that will consist of several different operations: placing pre-fabricated steel reinforcement bar cages; placing and distributing concrete; vibrating; screeding; final finishing; and curing.

PRODUCTIVITY ANALYSIS USING SIMULATION

Simulation tools are a quantitative approach that provides statistical measures of performance for the paving workflow. STROBOSCOPE (Martinez, 1996) is a simulation system designed specifically for construction, and uses a network of elements to represent the essentials of a model. The visual interface uses an Activity Cycle Diagram (ACD) to represent idle resources, activities and their precedence. Data for the assembly of the workflow will be based on: the process layout derived from prototypical performance estimates; the addition or elimination of tasks that are required or no longer needed; and the reduction of variability of task duration. The ACD for the autonomous operation is shown in Fig. 1.

In order to identify the best scenarios for paving performance, resource allocation and productivity output, the deployment of a robot has several expectations that need to be corroborated via simulation. The robot prototype will also provide insights on the ultimate performance of the full scale robot, and its development and construction will prove or reject some of the findings of this paper, but simulation will provide initial indicators and expose opportunity areas for further research. Among others, the robot will be achieving a reduction in surveying time with the use of GPS technologies, and decrease the duration of particular tasks such as rebar placing, mainline setup, screeding and finishes due to the lack of crew interferences and set up times. Safety will be also enhanced by reducing the accidents to the crew through the autonomous operation and the absence of workers. Since the robot will operate with a minimum of labor in order to execute an equivalent set of tasks, it is expected that both the safety and security risks will be diminished. The robot will receive instructions via remote sensing technology, and instead of using conventional surveying equipment or crew, it will be guided by laser and GPS instrumentation. The only piece of equipment or labor involved in the automated operation consists of a logistics crew (one truck and one operator) that refills the hopper with concrete material, storage tanks with water and other assemblies with rebar or curing compound as advised by the signals read in the control office.

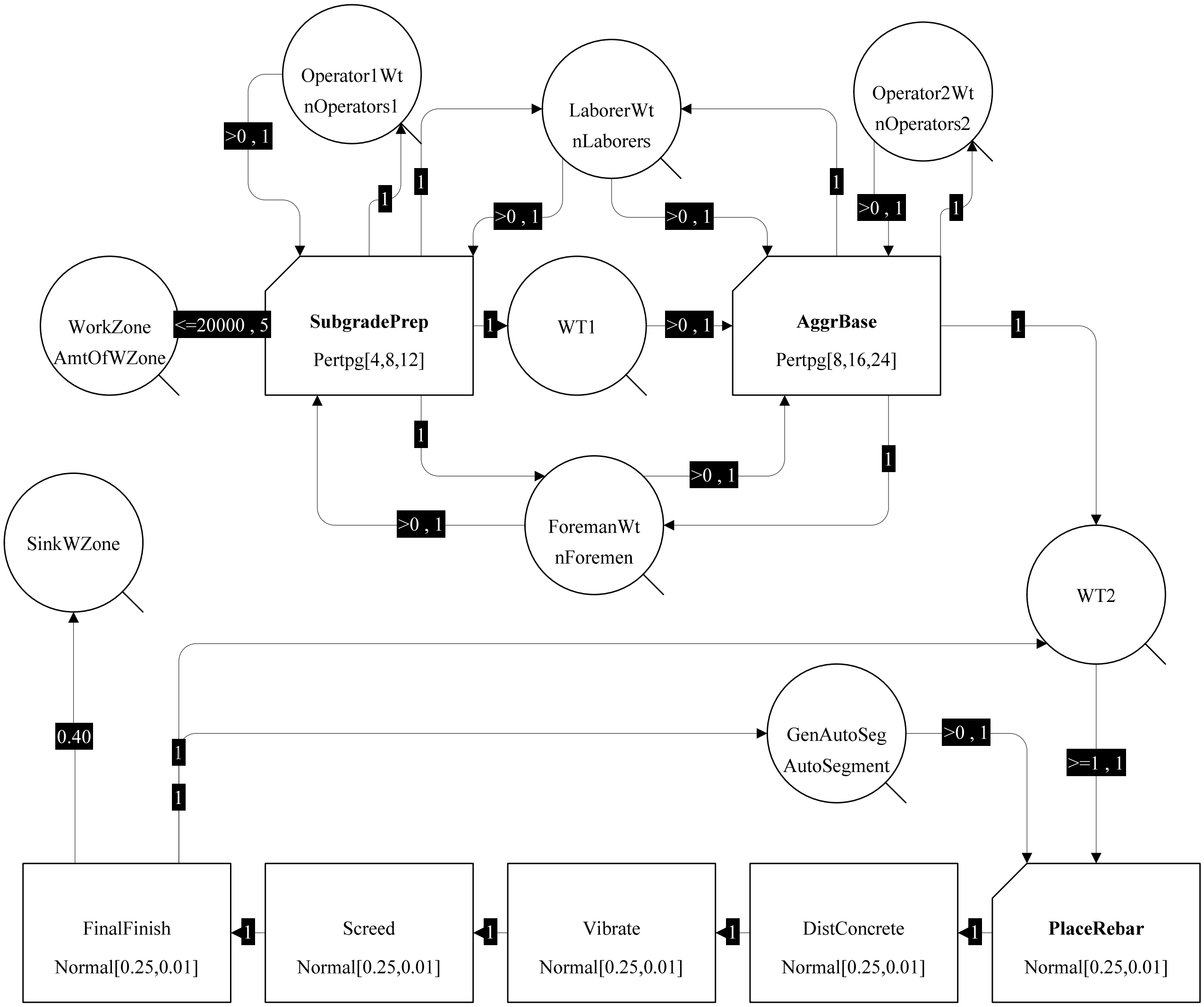

Figure 1. Automated paving process ACD.

The testing phase of the RoboPaver prototype will comprise measurements of productivity that intend to be comparable to theoretical values. The RoboPaver is expected to be more productive than conventional practices due to the reduction of task interferences and crew. With the simulation results, it is intended to corroborate the level of magnitude of the values such as 2,100 SY per day indicated in standard manuals (R.S. Means, 2003). Table 1 exhibits the parameters or resource initialization values for each of the tasks, as well as the mathematical expressions for the results.

Table 1. Simulation parameters and variable outputs.

Parameter Identification	Description	Initial Units / Derivation
nForemen	Number of foremen	2
nOperators1	Number of operators1	1
nOperators2	Number of operators2	1
nLaborers	Number of laborers	2
AmtOfWZone	Amount of work zone in sq yds	20000
AutoSegment	Space for automated paving	1
ForemanUtl	Foreman utilization	1-ForemanWt.AveCount
ProdRate	Production rate in SY/hr	0.4*1000/FinalFinish.AveInter
DailProdRate	Production rate in SY/day	0.4*1000/FinalFinish.AveInter*8
Time	Time of operation in hours	SimTime

The process starts with the generation of the work zone space. No staking is needed since the robot will be guided with a GPS for navigation. Two conventional tasks have to be performed prior to the robot start. These tasks are the preparation of the subgrade, or "SubgradePrep" and the installation of subbase and base aggregate, or "AggrBase". The completion of this task will determine the start of the autonomous operation. At this point, five thousand square yards of work zone space have been prepared, thus letting the robot start its operation in small portions of four hundred square yards (8 yards wide by 50 yards long). The robot will conduct serial tasks such as place rebar, distribute concrete, vibrate, screed and final finish until the whole area is paved. It is expected that the autonomous operation and the robot itself will greatly reduce variability. This is reflected in the durations allocated for each of the normal tasks, in which each task has duration of 0.25 hours and a variance of 0.01 hours. These predicted durations, however, are based on prototypical estimates that need to be corroborated in the field.

SIMULATION RESULTS

Using the ACD of Fig. 1 and the parameters shown in Table 1, the results of the simulation are presented in Table 2, for a simulated time of 500 hours.

Table 2. Simulation results.

Time (hours)	500
Units in Sink Queue	151,600
Production Rate (SY/hr)	300
Production Rate (SY/day)	2,400
Steady State Productivity (SY/hr)	319.9
Steady State Productivity (SY/day)	2,559.9
Foreman Utilization (%)	99.1%

Results from Table 2 suggest that the automated process can reach a productivity value greater than the one found in standard manuals for conventional operations. For the controlled run of 500 hours, the gain was 14%; for the productivity at steady state the gain was about 22%. Another objective was to test the percent utilization of a critical resource (Foremen1). Even though the automated operation does not call for the utilization of many resources, as it is indeed the case in the conventional situation, it is possible to determine the percent utilization of a single resource. Results show that the utilization of the foremen when adopting the automated process reaches a full value of 99.1%, thereby optimizing the use of this resource.

Another benefit of simulation is the determination of the most adequate scenario for the deployment of the automated paving process. In other words, the robot has to meet the prototypical estimates for the task durations in a working area of 400 square yards; otherwise, the productivity of the overall operation system will be compromised. By concentrating on this aspect of the operation performance, the design of the full scale robot can be adjusted to comply with these parameters. This productivity analysis using simulation also yields strong support for a decrease of safety risks in the workplace. Instead of having fifteen or more workers involved with the construction operation, the automated process will incorporate only six, who are not present by the time of concrete paving. They will be preparing the subgrade and laying aggregate for the base and subbase.

CONCLUSIONS

The performance assessment of a fully autonomous robot that will be used for concrete pavement construction is presented, and its implications in productivity and safety. Conventional concrete paving operations require a great deal resources and are labor intensive, even with state-of-the-art pavement equipment. By increasing productivity while decreasing the personnel and equipment required performing the work, a concrete paving robot would also reduce the cost of pavement construction. In addition, with less required people and machines an added benefit of a robot will be an inherent increase in construction site safety.

The productivity of a fully automated paving process was analyzed using a simulation tool, incorporating the resources needed for the completion of tasks and representing the durations with standard data and prototypical estimates. In comparison with theoretical values from a widely used standard manual, results show that the automated process is more productive, thus yielding productivity values up to 14% higher when simulated for 500 hours, or 22% higher after reaching steady state in the curve of productivity versus time. The automated process utilized considerably less labor than the conventional one, thus making the construction work zone less prone to accidents involving construction workers. The robot is designed to conduct the paving process without operators, laborers or foremen involved. Finally, simulation allowed for the determination of the most adequate scenario for the deployment of the automated paving process, guiding robot designers to meet the most appropriate parameter estimates for task durations.

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, 188-197.

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

Cobb, D. (2001), “Integrating automation into construction to achieve performance enhancements”, *Conference Proceedings of the CIB World Building Congress*, Wellington, New Zealand, April.

Farritor, S., and Rentschler, M. (2002) “Robotic highway safety markers”. *Proceedings of the IMECE2002 ASME International Mechanical Engineering Congress and Exposition*, November, New Orleans, Louisiana, 1-7.

Ha, T.J., and Nemeth, Z.A. (1995). “Detailed study of accident experience in construction and maintenance zones”, *Transp. Research Record*, 1509, 38-45.

Hemami, A. (1995). “Fundamental analysis of automatic excavation”. *J. Aerospace Engineering*, ASCE, 8(4), 175-179.

Hendrickson, C. (2005). “Discussion of ‘Is construction labor productivity really declining?’”. *J. Constr. Engr. and Mgment.*, ASCE, 131(2), 269-270.

Hinze, J., and Gambatese, J. (2003). “Factors that influence safety performance of specialty contractors”. *J. Constr. Engr. and Mgment.*, ASCE, 129(2), 159-164.

Luces, E., Moon, S., Rihani, R., and Bernold, L. (1995). “Robotics for increased safety in highway construction and maintenance”. *TR News*, 176, 12-16.

Martinez, J.C. (1996). “STROBOSCOPE – State and resource based simulation of construction processes”. Doctoral Dissertation, University of Michigan.

Osmani, A., Haas, C., Hudson, R. (1996). “Evaluation of road maintenance automation”. *J. Transportation Engineering*, ASCE, 122(1), 50-58.

Peyret F., Jurasz J., Carrel A., Zekri E., and Gorham, B., (2000), “The computer integrated road construction project”, *Automation in Construction*, 9, 447-461.

R.S. Means. (2003), “Heavy Construction Cost Data”. 14th edition, CMD Group.

Schraft, R. D. and Schmierer, G. (2000). “Service robots: Products, scenarios, visions”. A.K. Peters, Ltd. Natick, MA.

Warszawski, A. and Navon, R. (1998), “Implementation of robotics in building: Current status and future prospects”, *J. Constr. Engr. and Mgment*, ASCE, 124(1), 31-41.