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CONCRETE PAVING PRODUCTIVITY IMPROVEMENT USING A MULTI-TASK AUTONOMOUS ROBOT

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ABSTRACT

To improve productivity in conventional concrete construction, autonomous robots that perform specific tasks are being developed. Single-task robots are capable of enhancing specific functions, though their impact on the overall productivity remains unclear. A robot that incorporates each task-specific piece of machinery used in the concrete paving process into one fully autonomous unit is evaluated. Assessing potential productivity from the use of a fully automated process is a required step for developing a full scale-system. With the purpose of identifying productivity benefits in an automated concrete paving operation, two concrete paving processes will be compared using simulation tools. One process is the conventional operation using intensive labour, slip form paving machine and auxiliary equipment. The other process is the automated operation using a fully autonomous robot. Applications of this assessment methodology based in simulation will allow for the determination of productivity indicators of automated operations in hazardous environments, using the respective results to complement prototypical tests.

KEYWORDS

Pavement, Robotics, Computer-Based Simulation, Productivity

1. INTRODUCTION

Robotics has been subject of study in civil engineering for the past twenty years, thereby generating great interest in the construction community [1, 2]. 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.

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 and faster, which will lead to greater productivity and reduce costs.

1.1 Concrete Paving Operations

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. Each of the separate steps must be done carefully and precisely so that the completed pavement will meet the applicable standards for structural strength and smoothness. Other important aspects in the paving process include the control of the paving equipment trajectory and the 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 [3]. 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 levelling 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. Furthermore, 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.

Conventional concrete paving operations require a great deal of resources and are labour intensive, even with state-of-the-art pavement equipment. 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 [4], no attempts have been made to expand that research to concrete paving. Integrating the paving and post-paving operations into one fully autonomous robot, which also included a laser-based guidance and positioning system, sensors to monitor materials and machine operation, and providing remote data reporting capabilities would significantly improve efficiency and productivity in concrete paving. 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.

1.2 Robopaver: Fully Autonomous Robot for Concrete Paving

A prototype of a fully autonomous robot for concrete paving, dubbed Robopaver, is presently being developed [5, 6]. The 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. Figure 1 presents the conceptual design of the Robopaver prototype.

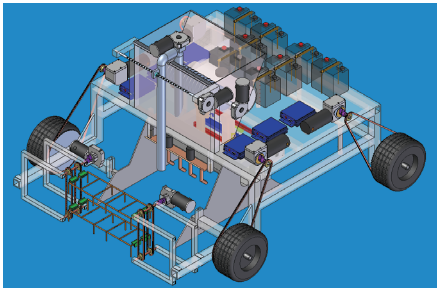

Figure 1 Conceptual Design of Robopaver [6]

The first operation that the autonomous concrete paving robot will perform is the placement of pre-fabricated steel reinforcement cages. In conventional concrete paving operations, dowel bar baskets are manually assembled and placed along the sub grade prior to the paving operation. Automating placement of these baskets will improve efficiency and decrease costs by decreasing the number of required pre-paving activities. The pre-fabricated steel reinforcement cage and the placement system included in the Robopaver simulates placement of the dowel bars and tie bars. The Robopaver will have a racking system that will store and dispense the pre-fabricated reinforcement cages. The reinforcement racking and placing system is made up of two conveyor belts that will move uniformly to place the prefabricated reinforcement cages. Depending on the desired width to be paved, the two-conveyor racking systems will be able to accommodate different distances by moving closer or farther apart. A robotic arm or fork lift mechanism may be added for greater control over the placement of the reinforcement bars. Placement of the cages will be controlled by onboard sensors that compare the position of the robot with the specified location of the reinforcement. Once at the prescribed location, the side conveyors will advance to drop down the reinforcement.

A holding tank with a mixer and dispersing mechanism will be used to place concrete, while the mixer will be a motor-driven auger screw. The dispersing mechanism will consist of a pump and a pipe mounted on a double threaded screw. The vibrating, screeding, and final finishing of the placed concrete will be performed under the main body of the robot. In the full-scale design, the vibrating would be done hydraulically. For the proof-of-concept hardware prototype, the possibilities to perform this task range from using a vibrating motor to developing a reciprocating press. Vibrator mechanisms for both Robopaver and a conventional slip-form paver are depicted in Figure 2.

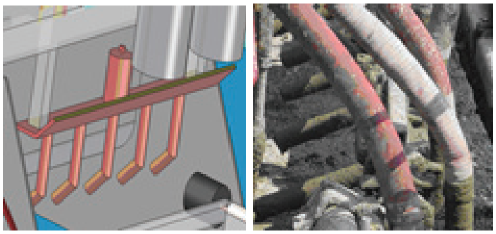

Figure 2 Vibrator Mechanisms of Robopaver and Conventional Slip-form Paver

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 section being paved.

Different batches of concrete will vary in content and viscosity. Testing should be done on the draw current of the mixing motor for an optimal batch of concrete. 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. 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. The screeding subsystem will be composed of oscillating steel plates that will produce a layered finish. This approach is similar to what is done in standard practice. Another operation performed underneath the main body will be the final finishing. This subsystem will incorporate laser levelling technology controlling a steel roller that will slide on a track.

2. PRODUCTIVITY ANALYSIS

In order to identify productivity benefits and safety aspects in the paving operation, two processes were compared using simulation tools. One process is the conventional paving operation using intensive labour, slip form paving machine and auxiliary equipment. Data for this operation was available through a pool of 125 paving projects in the state of Ohio, United States, during 2003 and 2004. The other process is the automated paving operation using a fully autonomous robot. Data for the assembly of the workflow was based on three sets of sources: First, process layout derived from prototypical performance estimates; second, addition or elimination of tasks that are required or no longer needed; and third, reduction of variability of task duration.

2.1 Conventional Paving Process

STROBOSCOPE [7] is a simulation system designed specifically for construction, and uses a network of elements to represent the essentials of a model. The models were represented using activity cycle diagrams (ACD) with networks of circles and squares that represent idle resources, activities, and their precedence. Values from standard manuals for heavy construction and pilot data populated the assembly of linear workflows that yielded daily operational values using discrete event simulators specialized in construction operations. For instance, a 25 cm thick concrete pavement operation, including joints, finishing and curing has a theoretical daily output of 1,756 square meters (m^2) and a cost of \$44.85 per m^2 [8]. Based on a survey of repetitive concrete paving on 125 jobs in the state of Ohio, the average unit cost to a contractor is \$29.30 per m^2. The ACD for the existing concrete paving workflow is shown in Figure 3.

The crew involved in this operation consists of 1 labour foreman, 6 labourers, 1 equipment operator, 1 rodman and 1 cement finisher. This crew yields a national average, according to standard data, of 0.050 labour hours per m^2 and 0.142 labour hours per m^2 according to the pilot study from Ohio data

The testing phase of the Robopaver prototype comprised measurements of productivity that intend to be comparable to theoretical values. The Robopaver is expected to be more productive than typical practices due to the reduction of task interferences and crew.

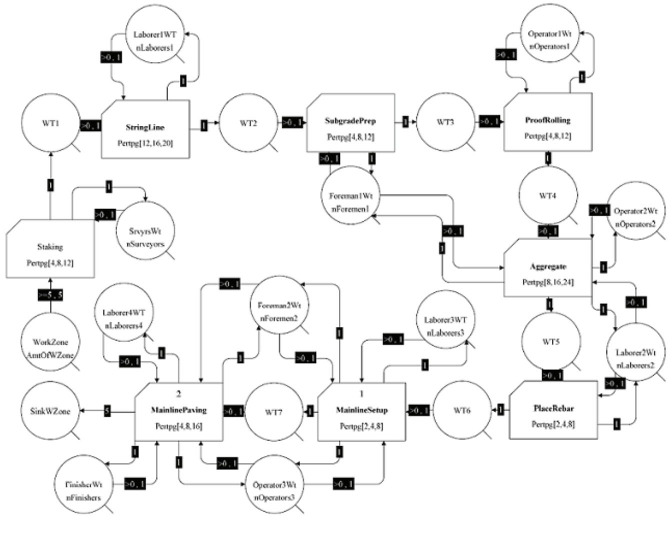

Figure 3 Existing Paving Process ACD

With the simulation results, it was intended to corroborate the level of magnitude of the values such as 1,756 m^2 per day indicated in standard manuals. Data for the conventional and proposed concrete pavement construction workflows were based on a standard 4,180 m^2 (5,000 square yards) project. Units for task duration are hours and were represented by probabilistic distributions, which originate from a pool of 2003 and 2004 project data for a typical paving contractor in the state of Ohio, United States. Durations of tasks were represented by PERTPG distributions, that rely upon assumptions of an optimistic, most likely and pessimistic activity duration.

2.2 Robopaver Process

The ACD for the autonomous concrete paving operation is shown in Figure 4. The only piece of equipment or labour 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. The robot prototype will provide insights and clues 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 provided initial indicators and exposed opportunity areas for further research. Among others, the robot will have expectations in productivity improvement by achieving a reduction in surveying time with the use of GPS technologies, decrease in duration of particular tasks such as rebar placing, mainline setup, screeding and finishes due to the lack of crew interferences and set up times.

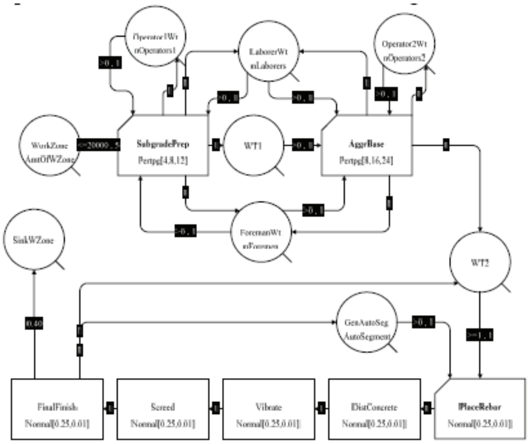

Figure 4 Robopaver Process ACD

2.3 Simulation Results

Both processes were run for a simulated time of 500 hours. Results of the simulation are presented in Table 1.

Results from Table 1 suggest that the automated process is more productive than the conventional, for both the controlled run of 500 hours (gain of 20%) and the productivity at steady state (gain of 7.5%). Units in the sink queue at the end of the simulation exercise are also an indication of productivity improvement when adopting the automated process (gain of 21.3%). Another objective was to test the percent utilization of a critical resource (Foreman1) in both scenarios. 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 and compare between both scenarios. Results show that there is an increase in 56.4% in the utilization of the foremen when adopting the automated process, thus optimizing the use of this resource. In the conventional operation, however, two foremen are needed because if one is removed, then the overall productivity will decay, as it was proved when the software was run.

Table 1 Simulation Results

Process	Current	Robopaver	Gain(%)
Time (hr)	500	500	
Output (units)	125,000	151,600	21.3
Productivity (m^2/hr)	209	251	20.0
Productivity (m^2/day)	1,672	2,008	20.0
Steady State (m^2/hr)	248.8	267.5	7.5
Steady State (m^2/day)	1,990.5	2,140.0	7.5
Foreman Utilization (%)	42.7%	99.1%	56.4

Another benefit of simulation is the determination of the most adequate scenario for the deployment of the automated paving process. Furthermore, the robot has to meet the prototypical estimates shown in Figure 4 for the task durations in a working area of 334 m^2 (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.

3. 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. 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.

Two equivalent paving processes, one conventional and one automated, were compared with the use of simulation tools, incorporating the resources needed for the completion of tasks and representing the durations with field data and prototypical estimates. Results show that the automated process is more productive, thus yielding productivity values up to 20% higher when simulated for 500 hours, or 7.5% higher after reaching steady state in the curve of productivity versus time. In comparison with theoretical values from a widely used standard manual, e.g., 1,756 m^2/day, the automated process reaches 2,140 m^2/day, representing a gain of about 22%. The automated process utilized considerably less labour 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, labourers 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. Applications of this assessment methodology based in simulation will allow for the determination of productivity and safety indicators of automated operations in hazardous environments or construction in the space, using such results to complement prototypical tests.

4. REFERENCES

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