A NOVEL APPROACH FOR ROAD CONSTRUCTION

USING AN AUTOMATED PAVING ROBOT

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This thesis entitled

A NOVEL APPROACH FOR ROAD CONSTRUCTION
USING AN AUTOMATED PAVING ROBOT

by

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has been approved for
the School of Mechanical Engineering
and the Russ College of Engineering and Technology by

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Conventional concrete paving construction machinery has insufficient automation for safe and efficient pavement construction. This paper describes an autonomous robot that in practice could be an alternative to conventional paving systems.

The current proposed robot, RoboPaver, is a 1:20 scale model of the intended field version. It 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.

This thesis presents a design of a fully autonomous robot that could be used for concrete pavement construction. It is envisioned that with the aid of an autonomous paving robot, pavement construction can be conducted safer, faster, and with higher levels of productivity.

Approved: Robert L. Williams II
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I. Introduction

In our everyday lives, we are constantly interacting with new technology either directly or indirectly. As our society continues to progress, we will experience and interact with new advancements in technology in all aspects of our lives. Robotics is one key technological element that will play a major role in contemporary society. Along with the United States, other countries such as Japan, Israel, Germany, and Russia are conducting research in applied construction robotics. Robotics and automation technology has and will continue to change the construction field worldwide. These construction robots will increase efficiency, productivity, and safety on the construction site.

In the Unites States construction robot research is being conducted at universities such as Purdue, where they focus on keeping up-to-date on emerging technologies in the civil construction field (www.new-technologies.org). At the University of Texas at Austin, researchers are compiling a database of robots and automation in civil construction (www.texastechnology.com). At North Carolina State University, researchers and students deal with all types of construction robot research, including prototype building and testing. Some aspects of their research involve bridge painting, automated excavation, and brick laying robots (www2.ncsu.edu/CIL/CAR). The Advanced Highway Maintenance and Construction Technology Research Center at the University of California-Davis is concentrating on advancing the methods used for highway operations by incorporating advanced automation and robotics technologies for
the purposes of improving safety and efficiency (www.ahmct.ucdavis.edu). 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 civil construction robots helping to build structures, renovate bridges and tunnels, and to help clear asbestos.

The aforementioned examples show that construction automation is becoming a practical and attractive technology. Robots have the ability to consistently produce high-quality products and to precisely perform tasks. With the aid of construction robots, projects have the potential be completed faster, leading to higher profits and greater customer satisfaction. For service-oriented tasks, robots ensure that the work performed is accurate and reliable.

Many laborers may feel threatened by robots in the work place, but they too can enjoy the many benefits of a robotic workforce. Most importantly, robots will perform their duties in extremely hazardous environments such as in the presence of radioactive material, military applications, and for asbestos removal. Robots can assist a human worker, making his/her job more efficient and manageable. Introducing robots into a work environment does not necessarily mean the elimination of jobs, but the creation of a new highly-skilled work force.

The general public will directly benefit from the work of construction robots. Implementation of robots in construction will produce high quality projects in a shorter amount of time than conventional human labor construction. The time that people are
forced to wait for a project to finish will be lowered. When safety is an issue, robots can serve as good substitutes for humans.

Various types of robots, such as cranes, stationary welders, climbers and single task robots are used in construction areas today. This paper will give a brief overview of construction robot technology advancements and research and propose an autonomous robotic to assist in pavement construction. The automated concrete paving robot, “RoboPaver” will be shown to improve productivity, quality, reliability, and safety in comparison to contemporary methods.

1.1 Literature Review

Low construction labor efficiency, combined with a high accident rate, low product quality, and an insufficient control on the construction site lead researchers to develop autonomous robots to help improve these problems (Cousineau, 1998). A comprehensive literature review was conducted for this project to get a better understanding of the use of robotics in the civil construction industry and to develop a general work flow for conventional concrete road paving.

1.2 General Robotics in Construction

Construction robots must handle large loads of various sizes and they also must be able to function under adverse weather conditions including variations in humidity, precipitation, and temperature. Additionally, construction robots are exposed to dust and dirt on the job site and they must be designed to stand up against wear over time. Construction robots are faced with different demands and expectations than conventional
industrial robots and therefore more time and effort must go into the development of this technology.

Many of the construction robots in use today are being developed and used in Japan. These are single task robots primarily used for building construction. The most widely used of these robots are used to complete concrete operations such as handling framework, rebar bending, placing rebar, pouring and vibrating concrete, leveling, and finishing concrete. According to James Stein (2001) from Eastern Michigan University, Japanese contractors that have used these robots on the job site have reported time savings of 30 percent and labor cost reductions of 50 percent.

In the United States, robots on the construction site are fairly new, but advancements in technology are making them common place. Research is currently being performed at the university level to develop construction robots for highway and building construction. Universities that are participating in construction robotics research include Purdue, North Carolina State, and recently Ohio University (www2.ncsu.edu/CIL/CAR, www.new-technologies.org).

For some military applications, nuclear waste remediation, and radioactive material handling, tele-operated robotics has been used. When a tele-operated robot is used, the human operator must depend on the sensory feedback data to operate the machine. This feedback commonly includes force data and video images from the cameras mounted on the robot being used. Most modern systems also provide some force sensitive joysticks. Developers at North Carolina State University have now introduced a supplementary and innovative display aid, the AutoCAD virtual display system
By integrating the Spatial Positioning System (SPS) and other position sensors on an excavator, the system updates the excavator’s position in global coordinates. The system schematic and field testing is shown in Figure 1.

Figure 1: Tele-Operated Excavator (www2.ncsu.edu)

The system employs two or more laser transmitters and one or more laser receiver. Each transmitter generates two inclined fan-shaped laser beams (planes), which are rotated about an axis at a constant angular velocity. The two receivers provide three-dimensional position data five times per second that is automatically transferred to the main computer. When the rotation of a laser beam is such that it strikes the receiver, a photosensitive detector generates a signal to be used to calibrate its current position. It allows the excavator to acquire data about its actual excavation path and speed. Discrepancies between commanded paths and actual paths can provide information about the environment. Because the SPS is able to electronically store relevant position data,
such information as the final location of a pipe in a trench, and an as-built database can be automatically generated (www2.ncsu.edu).

Traditionally, masonry walls are built on-site by bricklayers and their helpers. An alternative method is prefabrication of brick panels in a plant environment to be erected onsite with the help of cranes. Panels are constructed in-plant under controlled environment conditions unaffected by the weather and later taken to the construction site for assembly. One of the earliest implementations of automation in masonry was developed by a German entrepreneur who created a working semi-automated bricklaying machine able to build prefabricated brick walls up to 8 meters long (Anliker, 1988). Other efforts to produce this type of construction robot include the Massachusetts Institute of Technology, the masonry tasking robot at City University in London, the interior-finishing works robot at the Israel Institute of Technology, and the bricklaying workstation at the University of Maryland. North Carolina State University and the Robotics Institute at Carnegie Mellon University are developing a brick-laying robot in order to create a more efficient, faster-erected wall. A general schematic of North Carolina State University’s prototype can be seen in Figure 2. Currently, there exists no commercially-available advanced robotic brick masonry system in the U.S. (www2.ncsu.edu)
I.3 Robotics in Concrete Construction

A market research questionnaire conducted in 1998 questioned individuals in the construction industry to give the level of importance when introducing automation into construction. Responses came from 24 counties world-wide and nearly one-half of the respondents were chief executives or had over 21 years of experience. The strongest reasons for Robotic Automation were as given (Cobb, 2001):

1. Productivity Improvements
2. Improvements in quality and reliability
3. Improving safety
4. Improvement in Working conditions
5. Savings in Labor costs
6. Standardization of components
7. Overall whole—life cost savings
8. Simplification of workforce

Of the top eight reasons given by the participants in the survey for automation in construction, all can be related to the concept of an automated concrete paving robot. This new automated concrete system technology will integrate the laying of concrete to
post-laying leveling, and the final floor finishing. This system will successfully improve the work environment and increasing productivity. Figure 3 shows a work flow diagram for concrete floor paving. Below, the work flow shows how conventional paving and Japanese single task robot floor paving is done for the different tasks (www.takenaka.co.jp).

Concrete floor finishing is one of the most physically demanding jobs in construction. While bending over, finishers trowel heavy concrete continuously, often working long hours to keep up with curing (Cousineau, 1998).

In order to operate the Japanese single task concrete robot, manual labor is still required. Below are the required manual labor tasks needed during preparation, operation, and clean-up phases (Cousineau, 1998).
Preparation:
- Transporting the robot to the work site
- Planning the robot’s course with each concrete pour
- Arranging a power supply and waiting pad

Operation:
- Finishing areas around columns, walls, and other inaccessible edges
- Required data input such as length and width of work area, trowel overlap, and speed
- Determine when the concrete is ready to be finished

Clean-up:
- Dismantling
- Cleaning
- Storage

Many Japanese companies have developed single task concrete robots, but in this paper only the Takenaka Corporation’s models are presented due to easier access to the information.

The first task to be performed during the concrete paving process is distributing the concrete. Over the past twenty years, Japanese companies have been developing concrete distributors that can supply fresh concrete to workers over already installed rebar. A concrete distributor developed by the Takenaka Corporation can be seen in use in Figure 4.
Concrete distributors developed by various Japanese companies have some basic components in common, (i) they all operate over pre-installed rebar, (ii) they have jointed arms to move around obstacles, and (iii) they are operated by remote control.

Once concrete has been poured, distributed, and compacted, it must be leveled to the desired plane. The single task robot, “Screed Robo” developed by the Takenaka Corporation can be seen doing this task in Figure 5.

---

**Figure 4: Concrete Distributor in Use (www.takenaka.co.jp)**

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<tr>
<th>Lengh</th>
<th>20 m (approx. 66 ft)</th>
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<tr>
<td>Weight</td>
<td>main body: 3,500 kg, attachments: 800 kg</td>
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<tr>
<td>Pipe diameter</td>
<td>125 mm</td>
</tr>
<tr>
<td>Joint drive</td>
<td>quad-sold hydraulic motor</td>
</tr>
<tr>
<td>Operation system</td>
<td>Automatic: 1 lever instruction, Manual: operation for each joint</td>
</tr>
<tr>
<td>Control system</td>
<td>Automatic: computer control, Manual: lever direct control</td>
</tr>
<tr>
<td>Sensor</td>
<td>Touch sensor, rotary encoder</td>
</tr>
<tr>
<td>Drive power supply</td>
<td>7.5 kW, 3 phase, 200 V</td>
</tr>
<tr>
<td>Work range</td>
<td>Approximately 1000 m²</td>
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Concrete leveling robots can travel on a girder, track, or mounted on a motor vehicle. They all utilize laser beams to maintain the level of the robot and have precision that can be measured in millimeters.

After the concrete has been poured and leveled, it needs to be “finished”. The goal of the automated floor finisher is to maintain quality of work while reducing manpower and relieve workers from strenuous work. The “Surf-Robo”, developed by the Takenaka Corporation is able to operate on soft concrete, move in any direction, and uses steel end-effectors to create a smooth surface. This model can be seen in use in Figure 6.
This robot is the most widely used of all construction robots. Comparative testing of concrete finishing robots to manual labor has shown that robot finishing quality to be equal to or better than skilled labor. Robots were also found to be 3 to 8 times faster than skilled labor at the same job. Skilled labor is still needed to judge the quality of finish and finish areas inaccessible to the robots when operating inside buildings. One way to reduce labor would be to develop better sensor technology that can accurately determine the surface quality.

Another robot that is helpful in the concrete process is the automated rebar bender. A variety of rebar bending and tying robots have been developed by the Obayashi Corporation, Shimizu Corporation, Takenaka Corporation, and the Taisei Corporation, whose model can be seen in Figure 7.
Figure 7: Reinforcement Bar Fabrication Robot (Cousineau, 1998)

The different models or prefabricated rebar assembly robots have the capability of bending rebar to pre-specified shapes and tying rebar together. This type of technology can have positive influence on productivity when incorporated into a larger fully-automated concrete distribution machine (or just supplying the required rebar for the construction job).

I.4 Automation in Pavement Construction

Construction automation and robotics has generated interest in the construction community over the last two decades. In this time period autonomous single-task robots have been constructed in Japan, resulting in productivity and efficiency improvements. However, they are generally not able to improve the overall process due to the additional work required for preparation and clean-up (Cousineau, 1998). To enhance productivity of a project, an entire system must be automated to generate the desired productivity and efficiency levels.
The first and most comprehensive attempt to date to fully automate the paving process was the Road Robot (Schraft and Schmierer, 2000). The Road Robot was developed by a collaboration of industrial partners, research institutes, and universities as part of the European Union’s ESPRIT research program and was specifically developed for asphalt paving. The research team, led by Joseph Vögele AG of Mannheim, Germany and the European Center for Mechatronics in Aachen, performed work for the Road Robot from June 1992 to May 1996 in Mannheim, Germany. Figure 8 shows the Road Robot during its demonstration testing.

Figure 8: Road Robot Demonstration Testing (Schraft and Schmierer, 2000)

The aim of the project was to develop a self-navigating, self-steering road paver that would allow road engineers to improve the quality of constructed asphalt pavements, while also being more environmentally friendly.
A systematic study of automated pavement construction conducted by the Joseph Vögele’s research team found that individual tasks in the asphalt paving process could not be automated economically. Thus, the Road Robot consisted of a single piece of equipment that integrated several automated systems. The automated systems included:

- Automated reception of asphalt
- Automatic control of asphalt conveyance
- Automatic control of asphalt spreading
- Automatic steering control with mechanical sensor and automatic control of paving speed
- Automatically controlled start/stop of all paving functions of the Road Robot as a function of the quantity of asphalt in the material hopper.

The Road Robot also included computer-controlled screeding capabilities. However, the screeding operations required operator assistance.

The operation of the Road Robot was divided among four subsystems: (i) asphalt materials logistics; (ii) traveling mechanism; (iii) road surface geometry; and (iv) screeding. The asphalt materials logistics subsystem consisted of onboard sensors that determined the distance from the feed vehicle to the Road Robot and then adjusted the movement and operation of the equipment in order to receive the asphalt into the material hopper. Asphalt was then transported and placed using conveyors. Discharge was controlled by measuring the height of asphalt on the conveyors. The traveling mechanism subsystem controlled the speed of the robot, the start/stop function, and the steering. A paving start or paving stop was initiated as a function of the quantity of asphalt in the material hopper. Provided a correct tolerance on the volume of asphalt was being
maintained, the conveyor system supplied a constant head of asphalt in front of the
screed. The Road Robot automatic steering control was based on mechanical referencing
from a guide line such as a curb or a string line. A second type of travel control system
was installed on the Road Robot, a laser-based navigation system. This steering system
was applied when no reference or other line was available. The laser unit scanned the
area around the Road Robot, and calculated the angle between the robot and the pre-
positioned reflection elements. The accuracy of positioning is increased by adding more
pre-positioned laser transmitters. According to operational information given by the
International Association for Automation and Robotics in Construction (www.iaarc.org),
an accuracy of 20 mm is possible with the laser-based system. The road surface
gometry subsystem controlled the volume of discharge based on the pre-defined
thickness, profile, and lateral inclination of the pavement section. The screeding
subsystem controlled height adjustments, vibrations for compacting, and screed
orientation. However, as was mentioned previously, this subsystem required operator
assistance.

The Road Robot was powered with a diesel-electric drive system. According to
operational information, the diesel-electric drive system decreased the noise levels up to
12 dB, produced 50 percent less exhaust fumes, and required 50 percent less fuel than
that for a conventional road paver of an equal performance level.

Although the Road Robot successfully demonstrated the capabilities and
advantages of a fully automated asphalt paver, further development appears to have been
halted. No research or manufacturer’s information regarding the current status of the Road Robot is available in the literature.

The Computer Integrated Road Paving (CIRPAV) prototype is currently the only other attempt, worldwide, to automate paving operations. As with the Road Robot, the CIRPAV robot was specifically developed for asphalt paving operations. The CIRPAV research is part of the Computer Integrated Road Construction (CIRC) project, which is supported by the European Commission, under the Industrial and Materials Technologies Programme Brite-EuRam III. The research was led by the Laboratoire Central des Ponts et Chaussees (LCPC).

Although the CIRPAV prototype is considered an operator-assisted robot, it actually consists of a set of computer controlled subsystems and control sensors integrated on to a Demag DF135 paver. Figure 9 shows a schematic of the CIRPAV prototype with a ground-based positioning system.

![Figure 9: CIRPAV Prototype (Peyret et al., 2000)](image-url)
The primary functions of the CIRPAV system are to:

- Assist the operator in maintaining the paver on its correct trajectory at the correct speed
- Automatically adjust the position and cross-slope of the screed
- Record actual work performed by the paver and transmit performance data to a remote ground station in order to maintain global quality control at the site level.

The CIRPAV system consists of three main sub-systems: (i) the ground sub-system, (ii) the on-board sub-system, and (iii) the positioning sub-system. The ground sub-system provides the paver with geometric CAD data about the work site, as well as guidelines for operation. The on-board sub-system computes paving results and collects statistics about the work achieved. The positioning component provides real-time positioning of the paver using absolute positioning devices. The positioning sub-system also provides positioning and attitude of the screed.

Extensive trials for the project were performed between November 1999 and March 2000 at LCPC paving tracks in Nantes, France. The CIRPAV researchers, (Peyret et al., 2000) reported that following improvements were achieved when using the CIRPAV system, as opposed to the conventional asphalt paving process:

- The costs of establishing and maintaining references for profile control and equipment operations were reduced from 10% of the total cost of the work to below 5%.
- The fluctuation of the layer thickness was decreased. As a result, the estimated savings of the materials consumption were about 5% of the total cost of the work.
- The quality of the final pavement was improved. The CIRPAV prototype was able to place asphalt within ± 5 cm in both transversal and longitudinal directions, and within ± 0.5 mm for the height component.
The successful demonstration of the CIRPAV prototype demonstrated that operator-assisted robotics can improve the efficiency of the paving process, while at the same time improving the quality of the finished pavement section. However, in comparison with the Road Robot, the CIRPAV prototype is less sophisticated and does not exploit the full possibilities of integrating robotics into pavement construction.

1.5 State-of-the-Practice in Concrete Paving

The state-of-the-practice for concrete paving operations 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 procedure 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. Figure 10 presents a general schematic of the typical concrete paving process. The paving equipment used for the paving and post-paving operations is called a “paving train”. The exact methods and machines used in the construction process vary from job to job and this paper can only give a general understanding. The following is the sequence of separate steps on typical projects:

1. Preparation and preliminary finishing of the sub-grade
2. Placing of forms (where used)
3. Final finishing of the sub-grade
4. Placement of alignment strings
5. Installation of steel reinforcement
6. Mixing and placing concrete
7. Vibrating the concrete
8. Forming the concrete into its final position
9. Screeding, finishing, and texturing the concrete surface
10. Curing.
11. Sawing joints into the concrete
Most concrete highway pavements are constructed with a slip form paver. However, for many city streets and smaller highway projects, steel forms are used. Where steel forms are used, they must be carefully placed and secured into position so that the desired position, width, elevation, and grade may be secured in the final slab. Forms commonly used in highway work are straight 10 foot sections that are aligned both vertically and horizontally by slip joints and are held in position by three or more steel stakes. Several machines are frequently used in connection with placing of the forms. One of these is the so called “form-grader” that cuts a trench of proper size in the correct position to receive the forms. The next step as indicated in the sequence of operations at the job site is the final shaping of the sub-grade to the exact required dimensions. This operation is generally accomplished by a machine called a “sub-grader” or “fine-grader”.
In some instances, trimming of the sub-grade is accompanied by a final rolling with steel rollers, particularly where a granular subbase is being used. The installation of various types of reinforcement elements that may be used in a concrete pavement is also an important step in the construction process. Dowel bars are commonly used and must be carefully placed and aligned parallel to the centerline and sub-grade so that they will properly perform their load transfer functions. Reinforcement assemblies are varied in nature depending on the type of joint that is being used.

Today, on most highway projects, all components of the concrete, including the water, are batched and mixed in a central location. The fresh concrete is then transported to the paving site while mixing in transit. Placing of fresh concrete at the job site can be done in a variety of ways. The number and kind of machines used vary from state to state and among contractors. Two possible concrete placing machines can be seen in Figure 11.
Placing of fresh concrete is done by means of a hopper, conveyor, end-dump truck, or pump. The placing of distributed steel reinforcing in the form of bar mats or wire mesh complicates the spreading operation, but generally leaves the overall operation unchanged.

In the conventional paving train, the spreader is followed by a slip form paver. Vibrators, augers, and dowel placement mechanisms may be mounted on this slip-form paver. The float, which is suspended from the frame moves up and down to create the predetermined thickness of concrete. Two slip form pavers can be seen in Figure 12.

![Figure 12: Slip-Form Pavers (www.gomaco.com)](image)

The final finish is applied to the surface by belting, brooming, or the use of a burlap drag. The joints and edges of the pavement may be given a final finish, generally by the use of hand tools. The burlap drag can be seen in Figure 13 and the hand-finishing process is shown in Figure 14.
Once the concrete has been poured and finished it needs to be properly hydrated to ensure a good cure. The most popular method to ensure a good cure involves the spray application of light-colored fluid curing compound to the entire area of wet concrete. The fluid forms a film over the pavement that prevents moisture loss. Two concrete curing machines can be seen in use in Figure 15.
When the entire process has been completed most states require the sawing of transverse joints. Sawing is done by the use of self-propelled, manual-guided, single-blade concrete saws. The joints are sawed a short time after the final finish. A concrete saw can be seen in action in Figure 16.
All of the machinery and procedures discussed in this section from the laying of steel reinforcement through the finishing of the concrete pavement will be integrated into the proposed concrete paver. Integrating all of these procedures into one unit will improve efficiency, productivity, and safety on the construction site.

In order for construction equipment to progress into faster and safer machines, they must take advantage of and incorporate new technological advancements. A few technological advancements that might assist in a new fully autonomous concrete paver would be laser guided leveling and positioning system.

Currently, most of the methods used to control grading equipment are based on conventional surveying, such as grade stakes or string-lines. Some methods using automatic measurement sensors were also developed to guide and control construction equipment efficiently. The use of laser transmitters and sonic tracers has reduced the cost of construction projects. The transmitter and receiver can be seen in use in Figure 17.
This laser technology was first commercially introduced in the construction industry three decades ago. It was first used for underground pipes and other straight-line positioning applications. However, the use of laser technology for curve application is new. Laser leveling is starting to appear on highway projects in the United States, Australia, France, and Germany (www.new-technologies.org).

The guiding of road construction equipment in curving contours requires references such as hubs, staking, or elevated string lines. These benchmarks limit productivity because their installation is slow, subject to human errors, and require skilled operators to accurately steer the machine using rudimentary control methods (www.new-technologies.org). Attempts to guide equipment in curves using radio communications have been tried but this solution is still slow and unreliable. To solve the problem of speed and reliability, a 3D laser system that uses three modules to control the piece of equipment is utilized (www.new-technologies.org).

In order to use this laser technology, the survey plans are uploaded into a total station using a notebook computer. The total station converts the digital information into an infrared laser beam. A receiver, mounted on the blade of the equipment, intercepts the laser beam emitted by the total station and continuously determines the blade’s current position and grade with respect to the theoretical ones defined by the designer plans. There are typically 20 upgrades per second. The interface between the positioning information and the actual steering of the equipment is performed through the use of a control system device, which converts the digital data into machine hydraulic valve pulses (www.new-technologies.org).
The main benefit of the laser leveling system is the gain of productivity. According to some research performed by manufacturers of the guiding systems, the laser guided device can triple the productivity of equipment on highway projects and increase their levels of precision and performance (www.new-technologies.org). The laser leveling system is the next generation of equipment-controlling devices, bringing an alternative to the existing slower and unreliable radio communication systems.

Another way to reduce cost and increase efficiency is to incorporate Global Position Systems (GPS) into the construction equipment. The Blade-Pro System, developed by Spectra Precision in 1998, is a dual automatic blade control system that uses advanced computer and GPS technology. This system provides contractors a three-dimensional machine control system for roads, railway beds and airport runway construction. Blade-Pro allows motor grader operators to grade complex designs such as vertical curves, transitions, super-elevated curves and complex site designs without stakes or string lines. The system can be seen in use in Figure 18.

Figure 18: Blade-Pro System (www.new-technologies.org)
Blade-Pro reduces surveying and engineering costs by eliminating stakes, hubs and string-lines. It increases productivity up to 50 percent by allowing the operator to grade in fewer passes and to control grade in real time (www.new-technologies.org). It saves materials by placing the planned amount of materials within a quarter inch without additional time and labor. Generally, the Blade-Pro System can be used for any machine that requires dual automatic controls such as motor-graders, dozers, and a possible automated concrete paver. Applications for Blade-Pro include highways, residential roads, railway beds, airport runways, plus commercial and residential developments (www.new-technologies.org).
II. Proposed Concrete Paving Robot

As described previously, there are many competitive advantages to adopting robotic technology in civil construction. A novel design will now be presented that can improve concrete construction productivity, quality, and safety while reducing cost and time of a project.

The goal of this research project is to suggest a technology driven alternative to conventional concrete paving practice. Various technologies have been researched and implemented into a fully autonomous robot for concrete paving. This section explores two preliminary designs and various technologies that must be used to create this robot.

II.1 Contributions from Existing Technology

The main components of an autonomous concrete paver are not new and will be constructed from standard technology. Earlier in the paper different construction technologies were discussed that can be used to further the capabilities of the autonomous concrete paver concept. The first of these technologies was described in section I.2, the Spatial Positioning System (SPS) which when implemented in an autonomous concrete paver will keep operators up-to-date on progress and the exact position and the quality of the concrete being placed. Section I.3 presented the Japanese single-task concrete floor paving robots that are in currently in use. These concrete distributors, levelers, and finishers will be directly implemented in the prototype design. The reinforcement bar fabricator will not be implemented in the robot directly, but the prefabricated cages from such a machine will be represented. Section I.5 dealt with the state-of-the-practice in
concrete paving. The different subsystems (i.e. placing and distributing concrete, vibrating, screeding, final finishing, and curing) depicted in Figures 11, 12, 13, 14, and 15 will be implemented in the prototype. In addition to these processes, steel reinforcement cages will also be placed. The state-of-the-art technology that will be used in steering the prototype consists of laser leveling and laser guiding. The guiding system could also be run by GPS and preprogrammed check points could be established for the robot.

II.2 Development of Proof of Concept

The standard design for slip-form pavers can be seen in Figure 19. One of these machines follows a concrete distributing machine and incorporates vibrators that may be mounted on the front of the finishing machine. The automated paving robot will take up the same volume comparatively with a slip-form paver and will incorporate four more operations and replace three machines with one robot, relative to existing practice.
The proposed proof-of-concept system will incorporate a number of paving operations into one robot. The paving operations are as listed:

1. Place steel dowel baskets
2. Place and distribute concrete
3. Vibrate (Consolidate) concrete
4. Screed
5. Final finish
6. Cure

The first operation that the automated concrete paving robot will perform is the placement of prefabricated rebar cages. The robot will have a racking system that will
store and dispense the prefabricated rebar cages. The general schematic of the rebar placement can be seen in Figure 20.

![Figure 20: Steel Reinforcement Placer](image)

This racking and placing of rebar is a system made up of two conveyor belts that will move in unison to lay the prefabricated rebar cages. Depending on the desired width to be paved the two-conveyor racking system will be able to accommodate different distances by moving closer or farther apart. A robotic arm or forklift mechanism may be added for greater control over the placement of the reinforcement bars.

The next operation is the placement of concrete. For the proof-of-concept system a simple holding tank with a mixer and dispersement mechanism will be sufficient. The general schematic of this subsystem can be seen in Figure 21.
The vibrating, screeding, and final finishing of the concrete will be performed under the main body of the robot. In the full scale design vibrating would be done hydraulically, but for the proof-of-concept the possibilities to perform this task range from using a vibrating motor to developing a reciprocating press. The screeding subsystem will be composed of standard-practice oscillating steel plates that will give a layered finish. The last operation that will be performed underneath the main body will be the final finishing. This subsystem will incorporate laser leveling technology that will control a steel roller that will slide on a track.

The final operation performed by the prototype is the spraying of a curing compound. This subsystem will be constructed of a holding tank, spray nozzles attached to PVC pipe, and a pump to drive the curing compound. The general idea and proof-of-
concept for an autonomous paving robot has been presented and it is believed that the production of this concept is feasible.

II.3 Preliminary Design A

The preliminary design drawings depicted in this section were generated for the proof-of-concept prototype. The basis behind these drawings was the information obtained from the literature review. This literature review included the process flow of standard concrete paving practices and the understanding of what the processes entailed. Using this knowledge the system design was developed and is depicted in Figure 22, Figure 23, Figure 24, and Figure 25.

Figure 22: Preliminary Design A (Front Isometric View)
Figure 23: Preliminary Design A (Rear Isometric View)

Figure 24: Preliminary Design A (Bottom View)
II.4 Field Research with Trimor Construction

On May 12, 2004, a field observation of an actual paving crew in Cleveland, OH was performed. The crew was in the process of constructing roads for a new housing development. The machine that they used for the project is a two-track slip-form paver built by CMI Corporation. The paver weighed 46,000 lbs and was able to pave a 15 to 30 foot wide path. The paver that was observed can be seen in Figure 26.
Figure 26: Slip-Form Paver in Use

The concrete level and the direction of the paver were automated and guided by an elevated string line. The level of the concrete was kept by a red horizontal rod fallowing the string and the direction of the paver was maintained by a red vertical rod fallowing the string. Both of these can be seen in Figure 27.

Figure 27: String Line
The process in which the concrete was distributed to the paver was inefficient. The paving process stopped repeatedly due to the shortage of concrete in its path. For bigger projects paving crews used dump trucks instead of mixers to supply more concrete. The concrete placement can be seen in Figure 28.

![Figure 28: Placing of Concrete](image)

At one point the paver operator was observed in order to witness his responsibilities. The operator’s responsibilities consisted of starting and stopping the machine, directing the augers that are in front of the paver, and adjusting the hydraulic pressure valves to the vibrator. The operator’s controls can be seen in Figure 29.
II.5 Preliminary Design B

Using the information obtained while observing the Trimor Construction paving crew the original prototype design was adjusted accordingly. The current design is similar to the original prototype with few changes to simulate an actual slip-form paver better. The general schematic of preliminary design B can be seen in Figure 30.
The first design change consisted of switching from placing a full rebar cage to placing a steel dowel basket. The change can be seen in Figures 31-33.
The second change consisted of welding curved dowels onto the prototype’s existing vibrator. The full scale paver’s vibrators are the red hoses in Figure 34. The final design’s vibrator is the copper colored device depicted in Figure 35.
The final and most important design change came with the alteration of the concrete form. The prototype’s form design was not satisfactory because it was stationary and it didn’t represent the actual paving process. The new form can be seen in Figure 36.
Figure 36: Preliminary Design B Form
III. Final Robot Design

The flaws from the preliminary designs were resolved and a more specific design was created for the final design. The CAD renderings of the final robot design can be seen in Figures 37-42.
Figure 38: Final Robot Design (Rear Isometric View)
Figure 39: Final Robot Design (Front View)

Figure 40: Final Robot Design (Elevation View)
Figure 41: Final Robot Design (Rear View)

Figure 42: Final Robot Design (Sky View)
A list of hardware and a cost estimate for the robot can be seen in Appendix D. A general cost estimate for the project is estimated at $15,000. 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.

**III.1 Rebar Placement**

In the two previous preliminary designs the prefabricated rebar cages, also known as dowel baskets were merely placed onto the sub-grade. This is unsatisfactory because the dowel baskets might shift when the paver rolls over them. To solve this problem the prefabricated cages are designed to have a stake on each corner. The “holding clamp” was also redesigned 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 sub-system can be seen in Figure 43.
III.2 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 sub-system can be seen in Figure 44.
III.3 Concrete Placement

The final design for the concrete placement can be seen in Figure 45. 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 45: Concrete Placement Sub-System

III.4 Form and Screed System

The final design for the form and screed sub-system is very similar to the preliminary design B, this design can be seen in Figure 46. One design change is the addition of a brass coated guide for the spur gear. This guide is the blue colored object in Figure 46.
Figure 46: Screed and Form Sub-System Design

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.

To determine the specifications for a proper screed system motor, Lagrangian dynamics, based on energy, was used. It states that an externally applied force can directly be related to the kinetic and potential energy in a mechanical system using a generalized coordinate.
\( T = \text{Kinetic Energy} \)
\( U = \text{Potential Energy} \)
\( Q = \text{Externally Applied Force} \)
\( q = \text{Generalized Coordinates} \) \((x, y, z, \theta_x, \theta_y, \theta_z)\)

The general equations of motion are:

\[
\frac{1}{2} m v^2 + \frac{1}{2} I \omega^2 = T \quad (1)
\]
\[
\frac{1}{2} k x^2 + mgh = U \quad (2)
\]

The general Lagrange formula:

\[
Q_i = \frac{d}{dt} \left( \frac{\partial T}{\partial \dot{q}_i} \right) - \frac{\partial T}{\partial q_i} + \frac{\partial U}{\partial \dot{q}_i} \quad (3)
\]

The general coordinate was chosen to be the horizontal distance \( x \) traveled by the screed system. There is also friction in the system so the total force exerted on the mechanical system is the applied force \( Q \) minus the friction in the system \( Q_{\text{friction}} \). The equation of motion used for the screed system is now:

\[
Q_i - Q_{i\text{friction}} = \frac{d}{dt} \left( \frac{\partial T}{\partial \dot{x}_i} \right) - \frac{\partial T}{\partial x_i} + \frac{\partial U}{\partial \dot{x}_i} \quad (4)
\]

The equations of motion for the drive screw are:

\[
T = \frac{1}{2} I \omega_1^2 \quad (5)
\]
\[
U = 0
\]
\( I_1 = \text{mass moment of inertia of the drive screw} \)
\( \omega_1 = \text{angular velocity of the drive screw} \)

\[
\omega_1 = \frac{2 \pi v}{P} = \frac{2 \pi \dot{x}}{P} \quad (6)
\]
v = velocity of screed system

\[ v = \dot{x} = \frac{P \omega}{2\pi} = \frac{(RPM)}{60} P \] (7)

P = pitch of the drive screw

RPM = the rotations per minute of the drive screw

The equations of motion for the revolving screed are:

\[ T = \frac{1}{2} m_2 v^2 + \frac{1}{2} I_2 \omega_2^2 \] (8)

\[ U = 0 \]

\[ m_2 = \text{mass of revolving screed} \]

\[ I_2 = \text{mass moment of inertia of the revolving screed} \]

\[ \omega_2 = \text{angular velocity of the revolving screed} \]

\[ \omega_2 = \frac{v}{R_{\text{gear}}} = \frac{\dot{x}}{R_{\text{gear}}} \] (9)

\[ R_{\text{gear}} = \text{Radius of revolving screed gear} \]

The equations of motion for the screed block are:

\[ T = \frac{1}{2} m_3 v^2 \] (10)

\[ U = 0 \]

\[ m_3 = \text{mass of screed block} \]
Combining all the energy in the system:

\[ T_{total} = \frac{1}{2} I_1 \omega n^2 + \frac{1}{2} m_2 v^2 + \frac{1}{2} I_2 \omega z^2 + \frac{1}{2} m_3 v^2 \]  

\[ = \frac{1}{2} I_1 \left( \frac{2\pi \dot{x}}{P} \right)^2 + \frac{1}{2} m_2 v^2 + \frac{1}{2} I_2 \left( \frac{\dot{x}}{R_{gear}} \right)^2 + \frac{1}{2} m_3 v^2 \]  

\[ \frac{\partial T}{\partial x} = 0 \]

\[ \frac{\partial U}{\partial x} = 0 \]

\[ \frac{\partial T}{\partial x} = I_1 \left( \frac{2\pi}{P} \right)^2 \dot{x} + m_2 \ddot{x} + I_2 R_{gear}^{-2} \dot{x} + m_3 \ddot{x} \]  

\[ \frac{d}{dt} \left( \frac{\partial T}{\partial \dot{x}} \right) = I_1 \left( \frac{2\pi}{P} \right)^2 \dddot{x} + m_2 \dddot{x} + I_2 R_{gear}^{-2} \dddot{x} + m_3 \dddot{x} \]  

The system is assumed to have constant velocity during straight line motion:

\[ \frac{d}{dt} \left( \frac{\partial T}{\partial \dot{x}} \right) = 0 \]

Zero acceleration is assumed for straight line motion, but when the screed system is changing direction it is no longer subjected to constant velocity. Further calculations suggest the following characteristics:
\[ \theta_1 - \theta_0 = \text{One full revolution} \]

\[
A = \frac{P}{2\pi} \tag{15}
\]

During the transition point \((\theta_1 - \theta_0)\):

\[
x = \left( \frac{P}{\pi} \right) \sin \left( \frac{\theta}{2} \right) + B \tag{16}
\]
During the transition point (θ₀⁻θ₁):

\[ \dot{x} = \left( \frac{P \dot{\theta}}{2\pi} \right) \cos\left( \frac{\theta}{2} \right) = \omega \left( \frac{P \theta}{2\pi} \right) \cos\left( \frac{\theta}{2} \right) \]  

(17)

The acceleration in the system can be represented by:

\[ \ddot{x} = \left( \frac{P \ddot{\theta}}{2\pi} \right) \cos\left( \frac{\theta}{2} \right) - \left( \frac{P \dot{\theta}^2}{2\pi} \right) \sin\left( \frac{\theta}{2} \right) \]  

(18)

The shaft is assumed to have a constant angular velocity so:

\[ \ddot{x} = \left( \frac{P \ddot{\theta}}{2\pi} \right) \sin\left( \frac{\theta}{2} \right) - \left( \frac{P \omega^2}{2\pi} \right) \sin\left( \frac{\theta}{2} \right) \frac{\omega}{2} \]  

(19)

The generalized coordinate is x so θ must be substituted out:

\[ x = \left( \frac{P}{\pi} \right) \sin\left( \frac{\theta}{2} \right) \]  

⇒ \[ \theta = 2 \sin^{-1}\left( \frac{x\pi}{P} \right) \]  

(20)

This acceleration during the direction change should be substituted into the original equation:

\[ \frac{d}{dt} \left( \frac{\partial T}{\partial \dot{x}} \right) = I_1 \left( \frac{2\pi}{P} \right)^2 \ddot{x} + m_2 \ddot{x} + I_2 R_{\text{gear}}^2 \ddot{x} + m_3 \ddot{x} \]  

(21)

The Force applied to the system has been calculated as:

\[ \partial W = Q \cdot \partial \theta = Q \cdot \left( \frac{1}{2\pi P} \right) \partial x \]  

⇒ \[ Q = \frac{M}{2\pi P} = \frac{\tau_{\text{motor}}}{2\pi P} \]  

\[ \tau_{\text{motor}} = \text{The torque supplied by the motor} \]
\[ P = \text{pitch of the drive screw} \]

The torque on the motor during straight line motion is only influenced by friction resistance in the mechanical system:

\[ \tau_{\text{motor}} = \theta_1, \omega_1 \]

\[ f_2 = \frac{1}{2} N_2 \]

\[ f_1 = \frac{1}{2} N_1 \]

**Figure 49: Drive Screw Free Body Diagram**

\[ \partial W_{1, \text{friction}} = Q_{1, \text{friction}} \dot{x} \]

**Roller Bearings:**
\[ f_1 = -\mu k_1 N_1 \]  \hspace{1cm} (24)

**Drive Screw Resistance:**
\[ f_2 = -\mu k_2 |N_2 - N_3| \cos(\beta) \text{sgn}(\dot{x}) \]  \hspace{1cm} (25)

\[ \partial W_{1, \text{friction}} = |f_1 + f_2| \dot{x} \Rightarrow Q_{1, \text{friction}} = f_1 + f_2 \]  \hspace{1cm} (26)

\[ N_1 = \text{force of the drive screw exerted on the roller bearings. This is assumed to be 10\% of the total weight of the system and the full load of the screw} \]

\[ N_2 = \text{force on the drive screw roller bearings. This is assumed to be 90\% of the total weight of the system} \]
\( N_3 \) = force exerted on the rotating screed by the concrete

\( \mu_{k1} = .005 \) = kinetic friction coefficient for a roller bearing

\( \mu_{k2} = .004 \) = kinetic friction coefficient for the drive screw on the drive collar

\( \beta \) = slope angle of the drive screw

\[
\beta = \tan^{-1}\left(\frac{D_{\text{screw}}}{P/2}\right)
\]  

\( (27) \)

\[ \partial W_{2\text{friction}} = Q_{2\text{friction}} \partial x \]  

Drag:  \[ f_3 = -\mu_{k3} N_3 \text{sgn}(\dot{x}) \]  

Resistance moment:  \[ M = -\mu_{k3} N_3 r \text{sgn}(\omega_2) \]  

Thrust Roller Bearing:  \[ f_4 = -\mu_{k1} N_4 \]  

\( (28) \)

\( (29) \)

\( (30) \)

\( (31) \)

**Figure 50: Rotating Screed Free Body Diagram**
\[
\omega_2 = \frac{1}{R_{\text{gear}}} \dot{x} \Rightarrow \dot{\theta}_2 = \frac{1}{R_{\text{gear}}} \dot{x}
\]  
\[\text{(32)}\]

\(\mu_{k3} = 0.05 = \text{kinetic friction coefficient for a steel on fresh concrete}\)

\(N_4 = \text{force exerted on the thrust bearing}\)

\[
\partial W_{2\text{friction}} = \left( f_3 + f_4 + \frac{M}{R_{\text{gear}}} \right) \dot{x} \Rightarrow Q_{2\text{friction}} = f_3 + f_4 + \frac{M}{R_{\text{gear}}}
\]  
\[\text{(33)}\]

\(\begin{align*}
\partial W_{3\text{friction}} &= Q_{3\text{friction}} \dot{x} \\
\text{Roller Bearings:} & \quad f_5 = -\mu_{k1}(N_2 - N_3) \\
\partial W_{3\text{friction}} &= f_5 \dot{x} \Rightarrow Q_{3\text{friction}} = f_5
\end{align*}\]  
\[\text{(34, 35, 36)}\]

Summing the friction forces in the system:

\[
Q_{\text{friction}} = Q_{1\text{friction}} + Q_{2\text{friction}} + Q_{3\text{friction}}
\]  
\[\text{(37)}\]
Using the results from equations 1-37 and inputting them into the Matlab program in Appendix C the screed motor torque characteristics are determined. The output from the Matlab program can be seen in Figure 52 and Figure 53.

Figure 52: Motor Torque Graph 1 of 2
The output from the simulation is as follows:

Maximum motor torque needed (N*m) = 14.8368 (130 in*lbs)

RPM needed for motor is (rev/min) = 31.5789

Using this output a proper motor is chosen for the system. The motor chosen can be seen in Appendix D.

III.5 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 the system can be seen in Figure 54.
Figure 54: Curing Sub-System
IV. 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 55.

![Wheel Drive System](image)

**Figure 55: Wheel Drive System**

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, $\Theta$. These variables can be seen in Figure 56.

![Figure 56: Paver Positioning](image)

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).
IV.1 Dynamic Model of the System

The general dimensions for RoboPaver that are needed for the dynamic modeling can be seen in Figure 57. The general forces acting on the robot that are needed to determine the positioning of the robot can be seen in Figure 58. The nomenclature for this section can be found in Appendix A.

![Figure 57: Dimensions](image1)

![Figure 58: Forces Acting on the Robot](image2)
Assumptions:

1. The system has been linearized
2. The vehicle speed is very low
3. Longitudinal wheel slippage neglected
4. Tire lateral force is a function of its vertical load
5. Vehicle is rotating counterclockwise
6. $\tau_l$ & $\tau_r$ are in the same direction
7. $\tau_1$ = the torque shared by both motors. It is related to the longitudinal movement of the robot.
8. $\tau_2$ = the difference in $\tau_l$ & $\tau_r$

The Drive Torque, $\tau_1$ needed to be derived for the simulation. The equation given is what was determined, but it has flaws for if the controller is to be generalized:

The drive torque $\tau_1$ is given in (38).

$$\tau_1 = [\left[|\text{sgn}(\tau_l)| + |\text{sgn}(\tau_r)|\right] \times \text{sgn}(\tau_l + \tau_r) \times ||\tau_r - (|\tau_r| - |\tau_l|)||]$$  \hspace{1cm} (38)

The rotational Torque, $\tau_2$ needed to be derived for the controller simulation and also encounters problems when generalized for clockwise and counterclockwise motion:

The rotational torque $\tau_2$ is given in (39).

$$\tau_2 = \tau_r - \tau_l$$  \hspace{1cm} (39)
The absolute velocities for RoboPaver can be represented by:

\[
\begin{bmatrix}
\dot{X} \\
\dot{Y}
\end{bmatrix} = \begin{bmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{bmatrix} \begin{bmatrix}
\dot{x} \\
\dot{y}
\end{bmatrix}
\] (40)

Where \( \{\dot{X} \dot{Y}\}^T \) is the global Cartesian velocity and \( \{\dot{x} \dot{y}\}^T \) is the local Cartesian velocity. The longitudinal and lateral velocities are given by:

\[
\dot{x}_1 = \dot{x}_4 = \dot{x} - t\dot{\theta} \quad \text{(left)} \quad (41)
\]

\[
\dot{x}_2 = \dot{x}_3 = \dot{x} + t\dot{\theta} \quad \text{(right)} \quad (42)
\]

\[
\dot{y}_1 = \dot{y}_2 = \dot{y} + a\dot{\theta} \quad \text{(front)} \quad (43)
\]

\[
\dot{y}_3 = \dot{y}_4 = \dot{y} - b\dot{\theta} \quad \text{(rear)} \quad (44)
\]

The weight of RoboPaver is not distributed evenly among the wheels so a general relationship must be determined. This will be used when determining longitudinal and moment resistances \( R_x \) and \( M_r \).

\[
F_{z1} = F_{z2} = \left( \frac{b}{a + b} \right) \frac{mg}{2} \quad (45)
\]

\[
F_{z3} = F_{z4} = \left( \frac{a}{a + b} \right) \frac{mg}{2} \quad (46)
\]

Using Newton’s Second Law, the longitudinal dynamics equations of motion can be written in the local coordinates:

\[
ma_x = 2F_{x1} + 2F_{x2} - R_x \quad (47)
\]
The combined longitudinal forces in the robot can be simplified to the longitudinal torque supplied ($\tau_1$) divided by the wheels’ radius $r$. Also, the longitudinal resistance is found in the next equation (49).

\[ 2F_{x_1} + 2F_{x_2} = \frac{\tau_1}{r} \]  

(48)

\[ R_i = \sum_{i=1}^{4} f_i F_{yi} \text{sgn}(\dot{x}_i) = f_r \frac{mg}{2} [\text{sgn}(\dot{x}_1) + \text{sgn}(\dot{x}_2)] \]  

(49)

The longitudinal acceleration can now be described as:

\[ \ddot{x} = \frac{\tau_1}{mr} - \frac{R_x}{m} \]  

(50)

Newton’s Second Law in the lateral direction yields (in local coordinates):

\[ ma_y = -F_y \]  

(51)

Where:

\[ F_y = \sum_{i=1}^{4} \mu F_{yi} \text{sgn}(\dot{y}_i) = \frac{\mu mg}{(a + b)} [b \text{sgn}(\dot{y}_1) + a \text{sgn}(\dot{y}_2)] \]  

(52)

Euler’s rotational dynamics equation yields:

\[ I \ddot{\Theta} = 2t(F_{x_1} - F_{x_2}) - M_r \]  

(53)

Where:

\[ M_r = a(F_{y_1} + F_{y_2}) - b(F_{y_3} + F_{y_4}) + t[(R_2 + R_3) - (R_{x_1} + R_{x_2})] \]

\[ = \frac{ab \mu mg}{(a + b)} [\text{sgn}(\dot{y}_1) - \text{sgn}(\dot{y}_2)] + f_r \frac{mg}{2} [\text{sgn}(\dot{x}_2) - \text{sgn}(\dot{x}_1)] \]  

(54)
The difference in $2F_{x1}$ and $2F_{x2}$ is simplified to the lateral torque $\tau_2$ divided by the wheels’ radius $r$.

\[
2F_{x1} - 2F_{x2} = \frac{\tau_2}{r} \quad (55)
\]

The angular acceleration can now be described as:

\[
\ddot{\theta} = \frac{t\tau_2}{rl} - \frac{M_r}{I} \quad (56)
\]

In order to simplify the input to the controller, two new torques must be derived. These are not actual torques, yet representatives that have addition constants and changing sign terms. These two torque representatives are $\tau_3$ & $\tau_4$:

\[
\tau_3 = -fg \text{sgn}(\tau_1) + \frac{2\tau_1}{mr} \quad (57)
\]

\[
\tau_4 = \left(\frac{-2\mu abmg}{a + b}\right) \cdot \text{sgn}(\tau_2) + \frac{t\tau_2}{r} \quad (58)
\]

Now we have the basis for our linear control design. The rest is just standard state space controls basics:

\[
\dot{X} = Ax + Bu \quad (59)
\]

\[
\begin{bmatrix}
\dot{x}(t) \\
\dot{\Theta}(t) \\
\dot{x}(t) \\
\dot{\Theta}(t)
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
x(t) \\
\Theta(t) \\
x(t) \\
\Theta(t)
\end{bmatrix} +
\begin{bmatrix}
0 & 0 \\
0 & 0 \\
0 & 1 \\
0 & \frac{1}{I}
\end{bmatrix}
\begin{bmatrix}
\tau_3 \\
\tau_4
\end{bmatrix} \quad (60)
\]
\[ Y = Cx + Du \]  

(61)

\[
\begin{bmatrix}
    x(t) \\
    \theta(t)
\end{bmatrix} = \begin{bmatrix}
    1 & 0 & 0 & 0 \\
    0 & 1 & 0 & 0
\end{bmatrix} \begin{bmatrix}
    x(t) \\
    \theta(t) \\
    \dot{x}(t) \\
    \dot{\theta}(t)
\end{bmatrix} + \begin{bmatrix}
    0 & 0 \\
    0 & 0
\end{bmatrix} \begin{bmatrix}
    \tau_3 \\
    \tau_4
\end{bmatrix}
\]  

(62)

**IV.2 Robot Positioning Simulation**

Using the information obtained in section IV.1 a proper controller can be designed. The general schematic for the linear controller can be seen in Figure 59.

![Figure 59: Robot Positioning Schematic](image)

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 60-65.

![Graph showing Global Angle vs. Time]

Figure 60: Global Angle vs. Time
Local-Velocity vs. Time

Figure 61: Local Velocity vs. Time

Angular Velocity vs. Time

Figure 62: Angular velocity vs. Time
Figure 63: Global Velocity (Closed-Loop)

Figure 64: Global Position (Closed-Loop)
Figure 65: Global Position
V. Implications on Productivity and Safety

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. A methodology used to identify productivity benefits and safety improvements in an automated paving operation is presented. Two paving processes will be compared using the simulation software STROBOSCOPE. One process is the conventional paving operation using intensive labor, slip form paving machine and auxiliary equipment. The other process is the automated paving operation using a fully autonomous robot. The assessment methodology based in simulation will allow for the determination and comparison of productivity and safety levels.

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.

V.1 Productivity and Safety Indicators in Concrete Paving

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.

V.2 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; West 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
The automation of various isolated construction and paving processes has brought substantial benefits in workplace safety (Skibniewski and Hendrickson 1990; 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.

Other important aspects in the paving process include control of the paving equipment trajectory and control of the pavement surface profile (i.e. 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.

Conventional concrete paving operations require a great deal of resources and are labor intensive, even with state-of-the-art pavement equipment. It is perceived that incorporating robotics into the concrete pavement process would be very beneficial. 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. 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. It is anticipated that the robot will also improve the quality of the finished pavement. In addition, with less required people and machines an added benefit of a robot will be an inherent increase in construction site safety.

V.3 Productivity Analysis using Simulation

In order to identify productivity and safety benefits in the paving operation, two processes will be compared using engineering simulation. One process is the conventional paving operation using intensive labor, slip form paving machine and auxiliary equipment. Data for this operation was gathered from 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 will be 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.

Values from standard manuals for heavy construction and pilot inventory data populated the assembly of linear workflows that yielded daily operational values using discrete event simulators specialized in construction operations. For instance, a 10 inch thick concrete pavement operation, including joints, finishing and curing has a theoretical daily output of 2,100 square yards (SY) and a cost of $33.00 per SY (R.S. Means 2000). Based on a survey of repetitive concrete paving on 125 jobs in the state of Ohio, the average unit cost to a contractor is $24.50 per SY. The crew involved in this operation consists of: 1 labor foreman, 6 laborers, 1 equipment operator, 1 roadman and 1 cement finisher. This crew yields a national average, according to standard data, of 0.042 labor hours per SY and 0.1190 labor hours per SY according to the pilot study from Ohio data.

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 typical practices due to the reduction of task interferences and crew. With the simulation results, it was intended to corroborate the level of magnitude of the values such as 2,100 SY per day indicated in standard manuals (R.S. Means 2000). A workflow that represents the existing paving process is shown in Figure 66.
Data for the conventional and proposed concrete pavement construction workflows based on a standard 5,000 SY project are presented in Table 1. Units for task duration are hours and are 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.
Table 1: Task Duration for Conventional Concrete Paving Operation

<table>
<thead>
<tr>
<th>Task (1)</th>
<th>Resources (2)</th>
<th>Duration (hrs) (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>P5\textsuperscript{a}</td>
</tr>
<tr>
<td>Staking</td>
<td>Surveying crew</td>
<td>4</td>
</tr>
<tr>
<td>String line</td>
<td>Laborers</td>
<td>12</td>
</tr>
<tr>
<td>Subgrade prep</td>
<td>Foreman</td>
<td>4</td>
</tr>
<tr>
<td>Proof rolling</td>
<td>Operator</td>
<td>4</td>
</tr>
<tr>
<td>Aggregate base</td>
<td>Operator, laborer, foreman</td>
<td>8</td>
</tr>
<tr>
<td>Place rebar</td>
<td>Laborer</td>
<td>2</td>
</tr>
<tr>
<td>Mainline setup</td>
<td>Foreman, operator, laborer</td>
<td>2</td>
</tr>
<tr>
<td>Mainline paving</td>
<td>Foreman, operator, laborer, finisher</td>
<td>4</td>
</tr>
</tbody>
</table>

\textsuperscript{a} 5\textsuperscript{th} percentile of Beta Distribution

\textsuperscript{b} 95\textsuperscript{th} percentile of Beta Distribution

Durations of tasks as indicated in Table 1, are represented by PERTPG distributions. These distributions are used in probabilistic evaluation and review technique (PERT) methodologies that rely upon assumptions of an optimistic, most likely and pessimistic activity duration. For instance, the duration of the activity “Staking” defined in Table 1 would be determined by sampling from a Beta distribution with 5\textsuperscript{th} percentile 4 hours or 0.5 days, Mode 8 hours or 1 day, and 95\textsuperscript{th} percentile 12 hours or 1.5 days, resulting in a PERTPG distribution with parameters 4, 8, 16.
V.4 Concrete Paving Simulation

Simulation tools are a quantitative approach that provides statistical measures of performance for the paving workflow. These techniques can be applied to the modeling of present and proposed workflows, in order to establish productivity measures. 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 of STROBOSCOPE uses an Activity Cycle Diagram (ACD) to represent idle resources, activities and their precedence. The ACD is used as a guide for coding the model using a general-purpose simulation programming language. The models for conventional and automated concrete paving operations will be represented using ACDs with networks of circles and squares that represent idle resources, activities, and their precedence. The ACD for the existing concrete paving workflow is shown in Figure 67.
As indicated in Figure 67, the process starts with the generation of work zone space, which is indicated by the queue “Work Zone” connected to the task “Staking”. The link between the queue and the task is displaying “>=5, 5”, which is a STROBOSCOPE protocol that tells the queue mechanism to release five thousand square yards of working space. However, when the task “Staking” is over, only one unit will pass through to the following task. The resource “nSurveyors” is needed to perform the task “Staking”. This is the first task in the workflow, and is composed of the survey crew in charge of staking the site for paving construction. In order to track the utilization of
resources in the process workflow, intermediate queues are identified as WT1, WT2, W3, W4, W5, W6 and W7.

The next task is “StringLine”, which requires laborers and space generated from the previous task. The remaining processes can be observed in Figure 67 with the accompanying resources obtained from Table 1. The ACD takes into consideration particular situations like the one presented with the resource Foremen1, which is shared between tasks “SubgradePrep” and “Aggregate”. Likewise, another sharing of resources can be observed in tasks “MainlineSetup” and “MainlinePaving”, in which the foreman is shared, as well as the machine operator. In order to establish priorities for resource allocation, the task “MainlinePaving” has a higher priority, indicated by the number two in the task square, while “MainlineSetup” had a number one. This means that if the operator is available at a given time and both tasks are ready to start, the operator will be allocated to the task with the highest priority, or “MainlinePaving”. The unit that was generated at the completion of the first task (“Staking”) will be flowing through the system until the completion of the workflow at the last task (“MainlinePaving”), in which five units are generated again and stored in the sink queue (“SinkWZone”). An examination of the sink queue at any given time during the simulation will yield the amount of square yards that have been paved, thus providing an indication of the productivity of the operation. Prior to running the simulation, it is necessary to initialize the resource queues.
Table 2 and Table 3 display the parameters or resource initialization values, as well as the mathematical expressions for the results. These results are going to serve as basis for the comparison with the proposed automated process.

Table 2: Conventional Paving Process Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter Identification (1)</th>
<th>Description (2)</th>
<th>Initial Units (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>nSurveyors</td>
<td>Number of survey crew</td>
<td>1</td>
</tr>
<tr>
<td>nForemen1</td>
<td>Number of foremen1</td>
<td>2</td>
</tr>
<tr>
<td>nForemen2</td>
<td>Number of foremen2</td>
<td>1</td>
</tr>
<tr>
<td>nOperators1</td>
<td>Number of operators1</td>
<td>1</td>
</tr>
<tr>
<td>nOperators2</td>
<td>Number of operators2</td>
<td>1</td>
</tr>
<tr>
<td>nOperators3</td>
<td>Number of operators3</td>
<td>1</td>
</tr>
<tr>
<td>nLaborers1</td>
<td>Number of laborers1</td>
<td>2</td>
</tr>
<tr>
<td>nLaborers2</td>
<td>Number of laborers2</td>
<td>2</td>
</tr>
<tr>
<td>nLaborers3</td>
<td>Number of laborers3</td>
<td>1</td>
</tr>
<tr>
<td>nLaborers4</td>
<td>Number of laborers4</td>
<td>1</td>
</tr>
<tr>
<td>nFinishers</td>
<td>Number of finishers</td>
<td>1</td>
</tr>
<tr>
<td>AmtOfWZone</td>
<td>Amount of work zone in sq yds</td>
<td>20000</td>
</tr>
</tbody>
</table>
Table 3: Variable Output for Simulation Results. Conventional Process

<table>
<thead>
<tr>
<th>Variable Identification (1)</th>
<th>Description (2)</th>
<th>Derivation (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1Utl</td>
<td>Foreman utilization</td>
<td>1-Foreman1Wt.AveCount</td>
</tr>
<tr>
<td>ProdRate</td>
<td>Production rate in SY/hr</td>
<td>5000/MainlinePaving.AveInter</td>
</tr>
<tr>
<td>DailProdRate</td>
<td>Production rate in SY/day</td>
<td>5000/MainlinePaving.AveInter*8</td>
</tr>
<tr>
<td>Time</td>
<td>Time of operation in hours</td>
<td>SimTime</td>
</tr>
</tbody>
</table>

V.5 Automated Paving Process Simulation

The use of simulation is intended to assess the feasibility of an automated concrete paving operation with relation to productivity improvement and safety considerations. 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 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 will definitely provide initial indicators and expose 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. 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. The ACD for the autonomous concrete paving operation is shown in Figure 68.
As shown in Figure 68, the ACD for the automated process consists of a combination of tasks, some of them from the conventional paving operation using tasks that require multiple resources and others directly incorporating the robot in a linear sequence of normal tasks.

Once again, the process starts with the generation of the work zone space, as explained in the conventional case. 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
installation of subbase and base aggregate, or “AggrBase”. Resources utilized in these cases are consistent with the ones employed in the conventional case. 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. Table 4 and Table 5 exhibit the parameters or resource initialization values for each of the tasks, as well as the mathematical expressions for the results. These results served as the basis for the comparison with the conventional concrete paving operation.
Table 4: Automated Paving Process Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter Identification (1)</th>
<th>Description (2)</th>
<th>Initial Units (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>nForemen</td>
<td>Number of foremen</td>
<td>2</td>
</tr>
<tr>
<td>nOperators1</td>
<td>Number of operators1</td>
<td>1</td>
</tr>
<tr>
<td>nOperators2</td>
<td>Number of operators2</td>
<td>1</td>
</tr>
<tr>
<td>nLaborers</td>
<td>Number of laborers</td>
<td>2</td>
</tr>
<tr>
<td>AmtOfWZone</td>
<td>Amount of work zone in sq yds</td>
<td>20000</td>
</tr>
<tr>
<td>AutoSegment</td>
<td>Space for automated paving</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5: Variable Output for Simulation Results. Automated Process

<table>
<thead>
<tr>
<th>Variable Identification (1)</th>
<th>Description (2)</th>
<th>Derivation (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ForemanUtl</td>
<td>Foreman utilization</td>
<td>1-ForemanWt.AveCount</td>
</tr>
<tr>
<td>ProdRate</td>
<td>Production rate in SY/hr</td>
<td>0.4*1000/FinalFinish.AveInter</td>
</tr>
<tr>
<td>DailProdRate</td>
<td>Production rate in SY/day</td>
<td>0.4<em>1000/FinalFinish.AveInter</em>8</td>
</tr>
<tr>
<td>Time</td>
<td>Time of operation in hours</td>
<td>SimTime</td>
</tr>
</tbody>
</table>

V.6 Simulation Results

Both processes were run for a simulated time of 500 hours. Results of the simulation are presented in Table 6.
### Table 6: Simulation Results

<table>
<thead>
<tr>
<th>Process</th>
<th>Conventional (1)</th>
<th>Automated (2)</th>
<th>Gain/Loss (%) (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (hours)</td>
<td>500</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td>Units in Sink Queue</td>
<td>125,000</td>
<td>151,600</td>
<td>21.3</td>
</tr>
<tr>
<td>Production Rate (SY/hr)</td>
<td>250</td>
<td>300</td>
<td>20.0</td>
</tr>
<tr>
<td>Production Rate (SY/day)</td>
<td>2,000</td>
<td>2,400</td>
<td>20.0</td>
</tr>
<tr>
<td>Steady State Productivity (SY/hr)</td>
<td>297.6</td>
<td>319.9</td>
<td>7.5</td>
</tr>
<tr>
<td>Steady State Productivity (SY/day)</td>
<td>2,380.7</td>
<td>2,559.9</td>
<td>7.5</td>
</tr>
<tr>
<td>Foreman Utilization (%)</td>
<td>42.7%</td>
<td>99.1%</td>
<td>56.4</td>
</tr>
</tbody>
</table>

Results from Table 6 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 (Foremen1) 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
foreman are needed because if one is removed, then the overall productivity will decay,
as it was proved when the software was run.

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 shown in Table 5 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 proof of productivity improvement using simulation also yields strong
support for a decrease of safety risks in the workplace. Instead of having fifteen people
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.
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.

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 the theoretical value from the R.S. Means, or 2,100 SY/day, the automated process reaches 2,560 SY/day, representing a gain of about 22%. 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.

Continued research on the subject should further investigate the navigation simulation. The present simulation is a linear controller model, but it needs to be compared to a non linear model to ensure the information acquired from the simulation is acceptable. The present final design is very useful, but before the whole robot is to be assembled the individual subsystems need to be built and tested. Once these test have been conducted the design can be updated and full assembly can take place

RoboPaver is a fully autonomous robot that could be used for concrete pavement construction. It is envisioned that with the aid of an autonomous paving robot, pavement construction can be conducted safer, faster, and with higher levels of productivity.
References


Appendix A: Nomenclature

\( m \)  
robot mass (kg)

\( g \)  
gravitational acceleration (m/sec\(^2\))

\( I \)  
robot mass moment of inertia (kg-m\(^2\))

\( \tau_l \)  
left motor torque (Nm)

\( \tau_r \)  
right motor torque (Nm)

\( \tau_1 \)  
torque shared by both motors; drive torque (Nm)

\( \tau_2 \)  
difference between \( \tau_l \) and \( \tau_r \); rotational torque (Nm)

\( \tau_3 \)  
longitudinal input pseudo-torque (Nm)

\( \tau_4 \)  
lateral input pseudo-torque (Nm)

\( a \)  
distance from the center of mass to the front wheel axle (m)

\( b \)  
distance from the center of mass to the rear axle (m)

\( r \)  
wheels’ radius (m)

\( f_r \)  
coefficient of rolling resistance

\( \mu \)  
lateral friction coefficient

\( R_x \)  
total longitudinal resistance force (N)

\( F_y \)  
total lateral resistance force (N)

\( F_{x1} \)  
longitudinal force generated by the left motor (N)

\( F_{x2} \)  
longitudinal force generated by the right motor (N)

\( M_r \)  
resistive moment (Nm)
Appendix B: Matlab Navigation Code

This is the Matlab code and results that was generated to for the navigation section of the paper.

% Christopher M Maynard
% Thesis Work
% Navigation simulation
clc;
clear;

a=.37;
b=.55;
m=116;
r=.25;
t=.315;
l=30;
f=.1;
% mu=.895;
mu=.005;
g=9.81;  % m/sec^2
T=[0:.01:10]';

T1=10;
Tr=15;
T1=(abs(sign(Tl))+abs(sign(Tr))*sign(Tl+Tr)*abs(abs(Tr)-(sign(Tr)*abs(Tr)-abs(Tl))));
T2=(Tr-Tl);
T3=(-f*g*sign(T1))+((2*T1)/(m*r));
T4=-(2*mu*a*b*m*g)/(a+b)*sign(T2)+((t*T2)/r);

% Xdot= AX+BU

X0=[0,0,0,0]';
A=[0,0,1,0; 0,0,0,1; 0,0,0,0; 0,0,0,0];
B=[0,0; 0,0;
1,0;
0,(1/I)];

U=[T3*ones(size(T)) T4*ones(size(T))];

% Y= CX+ DU
C=[1,0,0,0;
    0,1,0,0];
D=[0,0;
    0,0];

P=ctrb(A,B);   %Calculate controllability matrix P
if(rank(P)==size(A,1))   %Logic to determine controllability
    disp('system is fully state-controllable');
else
    disp('system is NOT fully state-controllable');
end

Q=obsv(A,C);   %Calculate observability matrix P
if(rank(Q)==size(A,1))
    disp('System is fully state-observable');
else
    disp('System is not fully state-observable');
end

poles=eig(A);

% poles =
%
% 0
% 0
% 0
% 0
%

% [Td,E]=eig(A)   % Transform to Diagonal cononical form (DCF) via formula
% Ad=inv(Td)*A*Td
% Bd=inv(Td)*B
% Cd=C*Td
% Dd=D
\[ [A_m,B_m,C_m,D_m,T_m] = \text{canon}(A,B,C,D,'modal'); \] % Determine DCF using Matlab function canon

\% DIAGONAL CONNICAL FORM
\% Am =
\% 0 0 0 0
\% 0 0 0 0
\% 0 0 0 0
\% 0 0 0 0
\% Bm =
\% 1.0e+291 *
\% 2.4948 0
\% 0 0.0832
\% 2.4948 0
\% 0 0.0832
\% Cm =
\% 1 0 -1 0
\% 0 1 0 -1
\% Dm =
\% 0 0
\% 0 0
\% Tm =
\% 1.0e+291 *
\% 0.0000 0 2.4948 0
\% 0 0.0000 0 2.4948
\% 0 0 2.4948 0
\% 0 0 0 2.4948

\[ P = \text{ctrb}(A,B); \] %Calculate controllability matrix P
\[ C\_poly = \text{poly}(A); \] %Determine the system characteristic polynomial

\[ a1 = C\_poly(4); \] %Extract a1
\[ a2 = C\_poly(3); \]
\[ a3 = C\_poly(2); \]

\[ M = [a1,a2,a3,1]; \] %calculate matrix M
\[ a2, a3, 1, 0; \]
\[ a3, 1, 0, 0; \]
\[ 1, 0, 0, 0; \]
Tccf=P*M;       %calculate CCF tranformation matrix

Accf=inv(Tccf)*A*Tccf;  %Transform to Controller Canonical Form (CCF) via formula
Bccf=inv(Tccf)*B;
Cccf=C*Tccf;
Dccf=D;

% Controller Canonical Form
% Tccf =
%   0   1.0000   0   0
%   0.0333   0   0   0
%   0   0   0   1.0000
%   0   0   0.0333   0
%
% Accf =
%   0   0   1   0
%   0   0   0   1
%   0   0   0   0
%   0   0   0   0
%
% Bccf =
%   0   0
%   0   0
%   0   1
%   1   0
%
% Cccf =
%   0   1.0000   0   0
%   0.0333   0   0   0
%
% Dccf =
%   0   0
%   0   0

Q=obsv(A,C);   %Calculate observability matrix Q

M2=[a1,a2,a3,1,0,0,0,0;      %calculate matrix M
     a2,a3,1,0,0,0,0,0;
     a3,1,0,0,0,0,0,0;]
\[1,0,0,0,0,0,0,0\];

\[\text{Tocf} = \text{inv}(M2*Q); \% \text{calculate OCF tranformation matrix}\]

\[\text{Aocf} = \text{inv}(\text{Tocf})*A*\text{Tocf};\]
\[\text{Bocf} = \text{inv}(\text{Tocf})*B;\]
\[\text{Cocf} = C*\text{Tocf};\]
\[\text{Docf} = D;\]

\[
\% \text{Observer Canonical Form} \\
\% \text{Aocf} = \\
\% \;
\begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
\end{bmatrix}
\%
\]

\[
\% \text{Bocf} = \\
\% \;
\begin{bmatrix}
0 & 0.0333 \\
1.0000 & 0 \\
0 & 0 \\
0 & 0 \\
\end{bmatrix}
\%
\]

\[
\% \text{Cocf} = \\
\% \;
\begin{bmatrix}
0 & 0 & 0 & 1 \\
0 & 0 & 1 & 0 \\
\end{bmatrix}
\%
\]

\[
\% \text{Docf} = \\
\% \;
\begin{bmatrix}
0 & 0 \\
0 & 0 \\
\end{bmatrix}
\%
\]

\[\text{PO}=3;\] \% Specify percent overshoot and setting time
\[\text{ts}=3;\]
\[\text{zeta}=\text{abs}(\text{log(PO/100)}/\sqrt{\pi^2+\text{log(PO/100)^2}});\] \% Damping ratio from percent overshoot
\[\text{wn2}=4/(\text{zeta}^2);\] \% Natural frequency from setting time and zeta
\[\text{num2}=\text{wn2}^2;\] \% Generic desired 2nd-order system
\[\text{den2}=[1 \; 2*\text{zeta}*\text{wn2} \; \text{wn2}^2];\]
\[\text{Poles} = \text{roots}([1 \; 2*\text{zeta}*\text{wn2} \; \text{wn2}^2]);\] \% Desired controller poles

\[
\% \text{OUTPUT:} \\
\%
\]
% zeta =
%  0.7448
%
% wn =
%  1.7902
% Poles2 =
%
%  -1.3333 + 1.1946i
%  -1.3333 - 1.1946i

s1=-1.3333+1.1946i;
s2=-1.3333-1.1946i;
s3=10*(real(s2));            %  s*10 real poles
s4=(10*(real(s2)))-1;

S=[s1,s2,s3,s4];

den_augmented=conv(conv([1 -s1],[1 -s2]),conv([1 -s3],[1 -s4]));
num_augmented =den_augmented(1,length(den_augmented));

% OUTPUT:
%
% den_augmented =
%  1.0000  30.3326  268.0808  598.2551  612.4353
%
% num_augmented =
%  612.4353

% ITAE 4th-order coefficients and poles

wn=3;
num4=wn^4;
den4=[1 2.1*wn  3.4*wn^2  2.7*wn^3  wn^4];

Poles4=roots(den4);
% OUTPUT:
%
% Poles =
%  -1.2719 + 3.7890i
%  -1.2719 - 3.7890i
%  -1.8781 + 1.2424i
Order2=tf(num2,den2);
Augmented=tf(num_augmented,den_augmented);
ITAE4thOrder=tf(num4,den4);

K=place(A,B,S);
% K =
% 1.0e+003 *
% 0.0032    0    0.0027    0
% 0    5.7331    0    0.8300

Ac=A-B*K;
Bc=B;
Cc=C;
Dc=D;

X1=[19.9155  6.3048  3.9831  1.2610]; OLD
X1=[4.9911  1.5708  3.9831  1.2610]; % turn arround in a half Circle
X2=[0.1243  0.0007 -0.0000  0.0000];
X3=[0.1243  0.0007  0.0000 -0.0000];

C1=X1(1)/X2(1);
C2=X1(2)/X2(1);
%  C1 =160.2212
%  C2 =9.0069e+003

PolesObs=10*S;

L=place(A',C',PolesObs');
% L =
% 1.0e+003 *
% 0.1467   0.0129
% -0.0110  0.1566
% 1.7897  1.7234
% -1.5816  1.8990

Ahat=A-L*C;
eig(Ahat);

p1=  -13.33 + 11.95i;
p2=  -13.33 - 11.95i;
p3=  -133.33;
p4=  -143.33;

Xr0=[0.1;0.2;0.3;0.4;0.1;0.2;0.3;0.4];
Ar=[(A-B*K) B*K;zeros(size(A)) (A-L*C)];
Br=[B;zeros(size(B))];
Cr=[C zeros(size(C))];
Dr=D;

Closed=tf(num_augmented,den_augmented);

den_closed=conv(conv([1 -s1], [1 -s2]),conv([1 -s3],[1 -s4]));
um_closed =den_closed(1,length(den_closed));
closed=tf(num_closed,den_closed);

SysName= ss(A,B,C,D); % define state-space data structure with the name SysName
[y,t,x]=lsim(SysName,U,T,X0);
[Yc,Xc]=lsim(Ac,Bc,Cc,Dc,U,T,X0);
[Yr,Xr]=lsim(Ar,Br,Cr,Dr,U,T,Xr0);

i=2;
X_position(1)=0;
Y_position(1)=0;
distance(1)=0;
Closed_Velocity(1)=0;
Closed_Velocitytheta(1)=0;
distance_theta(i)=0;
X_closedposition(1)=0;
Y_closedposition(1)=0;

while (i<1002)

theta_x=cos(x(i,2)); % Open-loop Global Postioing
theta_y=sin(x(i,2));
velocity=x(i,3);
X_velocity(i)=velocity*theta_x;
Y_velocity(i)=velocity*theta_y;
delt_X_position(i)=velocity*.01*cos(x(i,2));
delt_Y_position(i)=velocity*.01*sin(x(i,2));
X_position(i)=delt_X_position(i)+X_position(i-1);
Y_position(i)=delt_Y_position(i)+Y_position(i-1);

distance(i)=Yc(i,1)*C1;  % CLosed-loop Global Positioning
Closed_Velocity(i)=(distance(i)-distance(i-1))./01;
distance_theta(i)=Xc(i,1)*C2;
Closed_Velocitytheta(i)=(distance_theta(i)-distance_theta(i-1))./01;

% % % % % %
closedtheta_x=cos(Xc(i,1)*C2);  % Closed-loop Global Positioning Countinued
closedtheta_y=sin(Xc(i,1)*C2);
closedX_velocity(i)=Closed_Velocity(i)*closedtheta_x;
closedY_velocity(i)=Closed_Velocity(i)*closedtheta_y;
delt_X_closedposition(i)=Closed_Velocity(i)*.01*cos(Xc(i,1)*C2);
delt_Y_closedposition(i)=Closed_Velocity(i)*.01*sin(Xc(i,1)*C2);
X_closedposition(i)=delt_X_closedposition(i)+X_closedposition(i-1);
Y_closedposition(i)=delt_Y_closedposition(i)+Y_closedposition(i-1);
i=i+1;
end;

figure;                 % Figure #1
step(Order2,'r',Augmented,'g',ITAE4thOrder,'b');  %For right-clicking to place
performance measures
set(gca,'FontSize',18);
title('Open-Loop Step Responce');
legend('Order2','Augmented','ITAE4thOrder');

figure;                 % Figure #2
impulse(Order2,'r',Augmented,'g',ITAE4thOrder,'b');  %For right-clicking to place
performance measures
set(gca,'FontSize',18);
title('Open-Loop Impulse Responce');
legend('Order2','Augmented','ITAE4thOrder');

figure;                 % Figure #3
step(closed,'r');  %For right-clicking to place performance measures
set(gca,'FontSize',18);
title('Closed-Loop Step Responce');

figure;                 % Figure #4
% For right-clicking to place performance measures
set(gca,'FontSize',18);
title('Closed-Loop Impulse Responce');
figure; % Figure #5
plot(t,x(:,1),t,Yc(:,1)*C1,'g',t,Xr(:,1)*C1,'b');
set(gca,'FontSize',18);
title('Local-Disatnce x vs. Time');
legend('Open Loop','Closed-loop','Observer');
ylabel('distance (meters)')
xlabel('time (sec)');
figure; % Figure #6
plot(t,y(:,2)*180/pi,t,Yc(:,1)*180/pi*C2,'g');
set(gca,'FontSize',18);
title('Global Angle vs. Time');
legend('Open Loop','Closed-loop');
ylabel('Theta (Deg)')
xlabel('time (sec)');
figure; % Figure #7
plot(t,x(:,3),t,Closed_Velocity,'g');
set(gca,'FontSize',18);
title('Local-Velocity vs. Time');
legend('Open Loop','Closed-loop');
ylabel('Velocity')
xlabel('time (sec)');
figure; % Figure #8
plot(t,x(:,4)*180/pi,t,Closed_Velocitytheta*180/pi,'g');
set(gca,'FontSize',18);
title('Angular Velocity vs. Time');
legend('Open Loop','Closed-loop');
ylabel('Angular velocity Deg/sec')
xlabel('time (sec)');
figure; % Figure #9
Uc=K*Xc';
plot(t,Uc);
set(gca,'FontSize',18);
Title('Input Effort');
legend('T3','T4');
ylabel('U');
xlabel('time (sec)');
figure; % Figure #10
subplot(211),plot(t,X_velocity,'r');
set(gca,'FontSize',18);
title('Global Velocity (Open-loop)');
ylabel('X Direct.(m/sec)');
xlabel('time (sec)');
subplot(212),plot(t,Y_velocity,'bl');
set(gca,'FontSize',18);
ylabel('Y direct.(m/sec)');
xlabel('time (sec)');
figure; % Figure #11
subplot(211),plot(t,X_position,'r');
set(gca,'FontSize',18);
title('Global Position (Open-loop)');
ylabel('X Position (m)');
xlabel('time (sec)');
subplot(212),plot(t,Y_position,'bl');
set(gca,'FontSize',18);
ylabel('Y Position (m)');
xlabel('time (sec)');
figure; % Figure #12
subplot(211),plot(t,closedX_velocity,'r');
set(gca,'FontSize',18);
title('Global Velocity (Closed-loop)');
ylabel('X direct.(m/sec)');
xlabel('time (sec)');
subplot(212),plot(t,closedY_velocity,'bl');
set(gca,'FontSize',18);
ylabel('Y direct.(m/sec)');
xlabel('time (sec)');
figure; % Figure #13
subplot(211),plot(t,X_closedposition,'r');
set(gca,'FontSize',18);
title('Global Position (Closed-loop)');
ylabel('X Position (m)');
xlabel('time (sec)');
set(gca,'FontSize',18);
title('Global Position (Closed-loop)');
ylabel('X Position (m)');
xlabel('time (sec)');
subplot(212),plot(t,Y_closedposition,'bl');
set(gca,'FontSize',18);
ylabel('Y Position (m)');
xlabel('time (sec)');
figure; % Figure #14
plot(X_position,Y_position,'r',X_closedposition,Y_closedposition,'bl');
set(gca,'FontSize',18);
title('Global Position');
legend('Open Loop','Closed-loop');
ylabel('Y Position (m)');
xlabel('X Position (m)');
axis('square'); axis([-4 4 -1 7]); grid;
Global Position (Open-loop)

X Position (m)

Y Position (m)

Global Velocity (Open-loop)

X Direct. (m/sec)

Y Direct. (m/sec)
Local-Velocity vs. Time

- **Velocity (m/sec)**
- **Time (sec)**

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (m/sec)</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Closed-loop vs. Open Loop

Global Angle vs. Time

- **Theta (Deg)**
- **Time (sec)**

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theta (Deg)</td>
<td>0</td>
<td>100</td>
<td>200</td>
<td>300</td>
<td>400</td>
<td>400</td>
</tr>
</tbody>
</table>

Closed-loop vs. Open Loop
Local Distance x vs. Time

Distance (meters)

Time (sec)

Open Loop
Closed-loop
Observer

Closed-Loop Impulse Response

Amplitude

Time (sec)
Open-Loop Step Response

- Order2
- Augmented
- ITAE4thOrder
Appendix C: Matlab Screed Motor Specification Code

This is the Matlab code and results that was generated to specify which motor to use for the screed system.

% Christopher M Maynard
% Motor torque Characteristics

% Final Program
clc;

m1=input('What is the mass of the drive screw?\n'); %4.5
m2=input('What is the mass of the revolving screed?\n'); %3
m3=input('What is the mass of the screed block?\n'); %5
I1=input('What is the mass moment of Inertia for the drive screw?\n'); %8
I2=input('What is the mass moment of Inertia for the revolving screed?\n'); %19
X_dot=input('How fast would you like the screed to move horizontally?\n'); %0.1

g=9.81;
D_screw=.0127; %diameter of the drive screw
R_gear=.03;
R_shaft= D_screw/2;
r=.06; %radius of the screed
P=.019; %Pitch
Beta=atand(D_screw/(P/2));
RPM=X_dot*60/P;
w1=2*pi*X_dot/P;
t=[0:.01:.8]; %distance of drive screw
i=[0:.01:(2*pi)]; %radians of revolution around turn

N1=g*(m1+.1*(m2+m3));
N2=g*().9*(m2+m3));
N3=4.5; %force exerted on the screed by the concrete
N4=g*m2; %force exerted on the thrust bearing

mu1=.005; %kinetic friction coefftient for a roller bearing
mu2=.004; %kinetic friction coefftient the pin on the drive screw
mu3=.05; %kinetic friction coefftient of steel on fresh concrete
\[ f_1 = \mu_1 N_1; \]
\[ f_2 = \mu_2(N_2-N_3) \cos(B) \]
\[ f_3 = \mu_3 N_3; \]
\[ M_{\text{resist}} = \mu_3 N_3 r; \]
\[ f_4 = \mu_1 N_4; \]
\[ f_5 = \mu_1 (N_2-N_3); \]

\[ Q_{\text{friction}} = f_1 + f_2 + f_3 + (M_{\text{resist}}/R_{\text{gear}}) + f_4 + f_5; \]
\[ \text{Motor\_torquelinear} = (Q_{\text{friction}}) R_{\text{shaft}}; \]

\[ \text{Motor\_torquenonlinear} = (Q_{\text{friction}} + (I_1((2\pi)/P)(w_1^2/2) + m_2((2\pi)/P)(w_1^2/2) + (I_2/R_{\text{gear}}^2)((2\pi)/P)(w_1^2/2) + m_3((2\pi)/P)(w_1^2/2)) \sin(i/2)) R_{\text{shaft}}; \]

\[ \text{disp('Maximum motor torque needed (N*m)=')} \]
\[ \text{disp(1.3*Motor\_torquenonlinear(314))}; \]
\[ \text{disp('RPM needed for motor is (rev/min)=')} \]
\[ \text{disp(RPM)}; \]

figure; % Figure #1
plot(t, Motor\_torquelinear);
set(gca,'FontSize',18);
Title('Motor Torque for linear motion');
ylabel('Torque N*m');
xlabel('distance (meters)');

figure; % Figure #2
plot(i, Motor\_torquenonlinear);
set(gca,'FontSize',18);
Title('Motor Torque for change of direction');
ylabel('Torque N*m');
xlabel('rotation (radians)');
axis([0 2*pi 0 20]);

Maximum motor torque needed (N*m) = 14.8368

RPM needed for motor is (rev/min) = 31.5789
## Appendix D: RoboPaver hardware list and cost estimate

<table>
<thead>
<tr>
<th>PART</th>
<th>DESCRIPTION</th>
<th>PART PHOTO.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel</td>
<td>Use #35 chains. Complete pneumatic assembly with ball bearings. 2-piece rim with 3/4in. Bore</td>
<td>![Wheel]</td>
</tr>
<tr>
<td>Battery</td>
<td><strong>NPC-B2812</strong>, 28AH @ 12V, 600 Max Amp Discharge</td>
<td>![Battery]</td>
</tr>
<tr>
<td>Controller</td>
<td><strong>AX2550</strong>, Dual Channel Forward/Reverse Speed controller up to 40V and 120 SmartAmps per channel</td>
<td>![Controller]</td>
</tr>
<tr>
<td>Curing Pump</td>
<td>12 Volt, 2.8 GPM, Model# <strong>1202.1000</strong></td>
<td>![Curing Pump]</td>
</tr>
<tr>
<td>Encoder</td>
<td><strong>HB6M</strong>, 0.250&quot; to 0.750&quot; hallow bore encoder</td>
<td>![Encoder]</td>
</tr>
<tr>
<td>Actuator</td>
<td>Unit model # <strong>CCHD-3605</strong></td>
<td>![Actuator]</td>
</tr>
<tr>
<td>Double Threaded Lead screw</td>
<td>Model # <strong>BR1754-1</strong></td>
<td>![Double Threaded Lead screw]</td>
</tr>
<tr>
<td>Vibrator Motor</td>
<td>12 volt Dewalt drill Motor</td>
<td>![Vibrator Motor]</td>
</tr>
<tr>
<td>PART</td>
<td>DESCRIPTION</td>
<td>PART PHOTO</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>Drive Motor</td>
<td><strong>NPC-R81</strong>, 24 Volt with standard 3/4&quot; shaft and 3/16&quot; keyway. 896 in-lbs of torque at stall</td>
<td><img src="image1" alt="Drive Motor" /></td>
</tr>
<tr>
<td>Other Motors</td>
<td><strong>NPC-41250</strong>, 12 Volt motor with a 1/2&quot; shaft. 260 in-lbs of torque at stall</td>
<td><img src="image2" alt="Other Motors" /></td>
</tr>
<tr>
<td>Thrust Bearing</td>
<td><strong>5909K31</strong>, Needle-roller thrust bearing.</td>
<td><img src="image3" alt="Thrust Bearing" /></td>
</tr>
<tr>
<td>Structure</td>
<td>2&quot; diameter 1/4&quot; thick square aluminum bar stock and 1/4&quot; aluminum sheet</td>
<td><img src="image4" alt="Structure" /></td>
</tr>
<tr>
<td>Screed Track</td>
<td>Stud-Mount Crowned Track Rollers and Rails</td>
<td><img src="image5" alt="Screed Track" /></td>
</tr>
<tr>
<td>Screed Gear</td>
<td>16 Pitch Steel Spur Gears - 1/2&quot; face</td>
<td><img src="image6" alt="Screed Gear" /></td>
</tr>
<tr>
<td>Sprocket</td>
<td>3/8&quot; Pitch Sprocket for #35 chain</td>
<td><img src="image7" alt="Sprocket" /></td>
</tr>
<tr>
<td>Chain</td>
<td>Size # 35 Chain</td>
<td><img src="image8" alt="Chain" /></td>
</tr>
<tr>
<td>Concrete Pump Track</td>
<td>UHMW-Lined Plain-Bearing Guide Blocks and Extruded Aluminum Rails</td>
<td><img src="image9" alt="Concrete Pump Track" /></td>
</tr>
<tr>
<td>Additional parts</td>
<td>This section is an estimate of various bearings, custom parts, and electrical wiring</td>
<td><img src="image10" alt="Additional parts" /></td>
</tr>
<tr>
<td>PART</td>
<td>VENDOR</td>
<td>COST ($)</td>
</tr>
<tr>
<td>----------------------</td>
<td>-------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>Wheel</td>
<td>Northern Tool</td>
<td>$37.99</td>
</tr>
<tr>
<td>Battery</td>
<td>The Robot Marketplace</td>
<td>$139.00</td>
</tr>
<tr>
<td>Controller</td>
<td>Roboteq</td>
<td>$495.00</td>
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<tr>
<td>Curing Pump</td>
<td>SHURflo</td>
<td>$74.99</td>
</tr>
<tr>
<td>Encoder</td>
<td>US Digital</td>
<td>$195.00</td>
</tr>
<tr>
<td>Actuator</td>
<td>Nook Industries</td>
<td>$285.00</td>
</tr>
<tr>
<td>Double Threaded Lead screw</td>
<td>Marathon Norco Aerospace</td>
<td>$1,345.83</td>
</tr>
<tr>
<td>Vibrator Motor</td>
<td>The Robot Marketplace</td>
<td>$23.99</td>
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<tr>
<td>PART</td>
<td>VENDOR</td>
<td>COST ($)</td>
</tr>
<tr>
<td>----------------</td>
<td>-----------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>Drive Motor</td>
<td>The Robot Market Place</td>
<td>$285.00</td>
</tr>
<tr>
<td>Other Motors</td>
<td>The Robot Market Place</td>
<td>$155.00</td>
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<tr>
<td>Thrust Bearing</td>
<td>McMaster-Carr</td>
<td>$3.69</td>
</tr>
<tr>
<td>Structure</td>
<td>Online Metals</td>
<td>$500.00</td>
</tr>
<tr>
<td>Screed Track</td>
<td>McMaster-Carr</td>
<td>$46.77</td>
</tr>
<tr>
<td>Screed Gear</td>
<td>The Robot Market Place</td>
<td>$25.53</td>
</tr>
<tr>
<td>Sprocket</td>
<td>The Robot Market Place</td>
<td>$10.00</td>
</tr>
<tr>
<td>Chain</td>
<td>The Robot Market Place</td>
<td>$25.99/ 10 feet</td>
</tr>
<tr>
<td>Concrete Pump Track</td>
<td>McMaster-Carr</td>
<td>$87.57</td>
</tr>
<tr>
<td>Additional parts</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>$15,000</strong></td>
</tr>
</tbody>
</table>