Mobile Paving System (MPS): A New Large Scale Freeform Fabrication Method

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Abstract

In the last decade, significant opportunities for automation have been identified in the area of construction. Soaring labor and material costs have driven multiple research efforts in construction automation. In this paper, we present a novel means for construction automation that involves the fusion of the rapid prototyping, controls and mechatronics technologies. The resultant autonomous construction mechanism has been designed for commercial applications. Mobile Paving System (MPS) is a new freeform fabrication process which is capable of rapidly producing variable profiles such as curbs and sidewalks out of materials like cement and asphalt. Path generation and guidance of the construction operation is controlled by a mobile robot. This article presents an overview of research and development efforts that are aimed at establishing the feasibility and the potential of the process.

1- Introduction

In industrialized nations about 7-10% of the gross domestic product in contributed by construction industries [1]. In the U.S., nearly $1 trillion is spent on construction projects [2]. However, Warszawski and Navon report that serious problems are faced by construction industries [3]. These include: low labor efficiency, high accident rate, low work quality and the dearth of skilled workforce. The U.S. Department of Labor's, Bureau of Labor Statistics (BLS) also reports that construction work is physically demanding [4]. BLS also suggests that through the year 2012 the demand for construction labor is expected to grow at the rate of 10-12%. Thus a demand for construction labor clearly exists. The same report indicates that many workers enter the occupation with few skills. Automation is clearly a potential solution of the aforementioned problem. According to Balaguer, however, the level of automation in construction is very low and consequently there is a need for researchers and companies to make new efforts to increase the automation level of this important sector [5].

Accordingly, the broad objective of this research is to establish the feasibility of an automated, rapid construction system entitled "*Mobile Paving System*" (MPS) which targets structures such as sidewalks and curbs. The MPS concept was invented in the Engineering & Technology Department at Texas State University-San Marcos. Currently, with institutional funding, the MPS research effort has generated alternative designs, conducted tests and generated preliminary prototypes of some subsystems. In the proposed research, we intend to extend the MPS's capabilities to be able to pave features such as sidewalks and curbs with variable profile by the use of adjustable side trowels and without the use of any sort of frames and supports. The MPS process will find its path using one of different mobile robot technologies.

2- Other Similar Technologies.

2-1- Rapid Construction Systems

No single similar technology that is able to provide the same service as the MPS was found. However, there are other technologies/machines that currently apply some of the concepts used in this system.

- **Contour Crafting**

Contour Crafting (CC) is a layered fabrication technology developed by Dr. Behrokh Khoshnevis of the University of Southern California. Contour Crafting uses computer control to exploit the superior surface-forming capability of troweling. To produce exceptionally smooth and accurate planar and free-form surfaces, the process utilizes trowels that function as solid planar surfaces [6]. In the CC process an extrusion nozzle is equipped with a top and a side trowel. As the material is extruded, the traversal of the trowels creates smooth outer and top surfaces on the layer. The side trowel can be deflected to create non-orthogonal surfaces. The extrusion process builds only the outside edges (rims) of each layer of the object. After complete extrusion of each closed section of a given layer, a filler material such as concrete can be poured into the volume defined by the extruded rims [7].

- **Commercial concrete paving systems**

GOMACO Corporation is a leading manufacturer of curb and gutter machines, concrete slipform pavers, and canal machinery systems. GOMACO's method of simultaneously trimming and slipforming makes curb and gutter, barrier wall, bridge parapet, and monolithic sidewalk curb constructions easier and faster. Some other companies such as, Lil' Bubba have also made and are selling commercial, small scale, manually driven curb generating machines.

2-2- Mobile Robotics Technology

Mobile robots have become a key focus in robotics research with many applications in various industries. Applications include agricultural tasks such as harvesting or spraying operations [8][9][10] or hazardous environment tasks such as atomic waste treatment, rescue operation, or army weapon systems. Mobile robots gain more momentum as they come into play in the vicinity of human residency areas, such as golf courses, or gardening areas. In order to handle rough terrain, or more general cases of navigation, biological forms [11], or anthropomorphic forms [12], have been investigated as well.

2-3- Limitation of current approaches

- The CC process has not been integrated with mobile robots. Doing so will enable the system to become delocalized and provide automated guidance for fabrication coverage over extended distances.
- The GOMACO system needs several operators and requires that the mixed materials be transferred to the site.
- There are current limitations in terms of the cross-sectional shape and size of the extruded materials. The key limitation is that only fixed cross-sectional size and shape are accommodated.

The proposed MPS system will obviate all of the aforementioned limitations and extend the state of the technology.

3-What is MPS?

As envisioned the MPS system consists of: a) a mobile platform and navigation system and b) the paving system which includes raw material transferring, mixing, mixed material internal transferring, and extruding subsystems. The paving system generates structural forms such as sidewalks and curbs, while the platform guides the paving system to the points of usage. Figure 1 illustrates the concept.

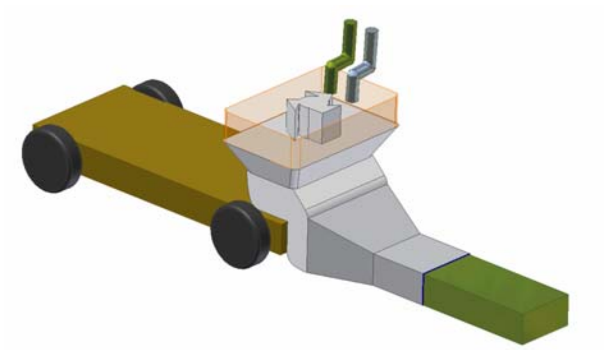

Figure 1. The MPS concept.

The mobile platform guides the paving system automatically. In order to promote maximum mobility and portability, a nonholonomic platform is proposed. Other design features include an autonomous navigation system with collision detection capability and a “uniform” material dispensing capability. These choices promote construction accuracy to the maximum extent. Three strategies have been identified for navigational control: 1. CAD data based system, 2. Trace follow system, and 3. Teleoperated remote control system. The paving system includes raw material transferring, material mixing, mixed material internal transferring, and extruded material shaping sub systems. Shaping is accomplished to a large degree through the use of trowels.

4- Potential Applications of the MPS

The MPS can be used in variety of applications wherein labor cost is high or the work situation is hazardous. This section provides some examples.

- **Curbs, roads, sidewalks**

  Standard and custom design shape can be made by using adjustable trowels/ extruders.

- **Irrigation**

  Manual and semi automatic irrigation channel constructions can be converted to fully automated system with flexibility in size and shape.

- **Lava controlling**

  In hazardous situations such as sending human forces to a volcano’s ground zero, mobile paving systems can be sent to redirect lava streams. This will save many lives and assets.

- **Homeland security**
  Mobile paving systems can be sent to battle zone to quickly build a shield before sending infantry divisions to the area.

5- Paving System Design

In this section, raw material transferring, material mixing, mixed material internal transferring, and extruded material shaping sub systems are discussed.

5-1- Raw material transferring

Raw material including water, cement, and other materials should be transferred to the mixer. Materials should be transferred to the mixer in appropriate amounts that have been determined in advance. Quick processing time (few minutes for the transformation from raw material to solid extruded mixture) and continuity of the process should be considered in the design of the raw material transmission system. Also, an alternative design, especially for the emergency cases such as lava controlling and battle zone shield, have been considered that utilizes raw materials that are available onsite (e.g., soil, small rocks) to which small amounts of binder material will be added. The system then will not need to engage in mass transmission of material as described earlier.

5-2- Material mixing

Currently several types of mixers that are being used in construction projects can be applied in the mobile paving machine. Also, an alternative design has been considered, in the case of which, mixed material is directly transferred to the site. In this alternative, mixing of the components can be eliminated. However rapid solidification time of the mixed material will impose more restrictions on this alternative.

5-3- Mixed material internal transferring

The produced mixture should be guided shaping trowel. There is a tradeoff between the softness of the mixture and its ability to be readily shaped. Low viscosity can be transferred easily without any additional transferring tool. Highly viscous material will not readily flow. A vibrator will help with the transfer of the average viscous material from the mixer toward the trowels.

5-4- Extrusion

To extrude air free mixture, force should be applied toward the mixture material. Gravity/vibration based design is the easiest, however applying other subsystems such as pump, spiral gear, and piston is possible as well. In some cases pressure/extrusion speed control should be considered.

5-5- Extrusion shape

Depending on the application, the shape system implementation can vary from very easy (fixed shape) to very difficult (freeform)(Figure 2).

- Fixed shape: In this design, the extruded material cross section is always a fixed shape.
- Freeform by adjustable trowels: In this design, an adjustable mechanism controls slope and length of each of many individual trowels that are connected (Figure 3).

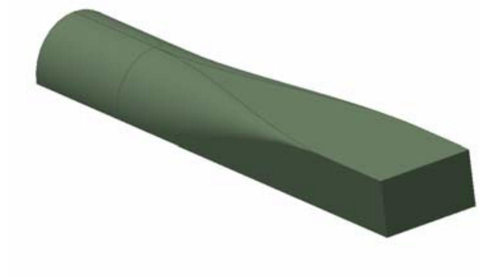

Figure 2: Adjustable shape extrusion

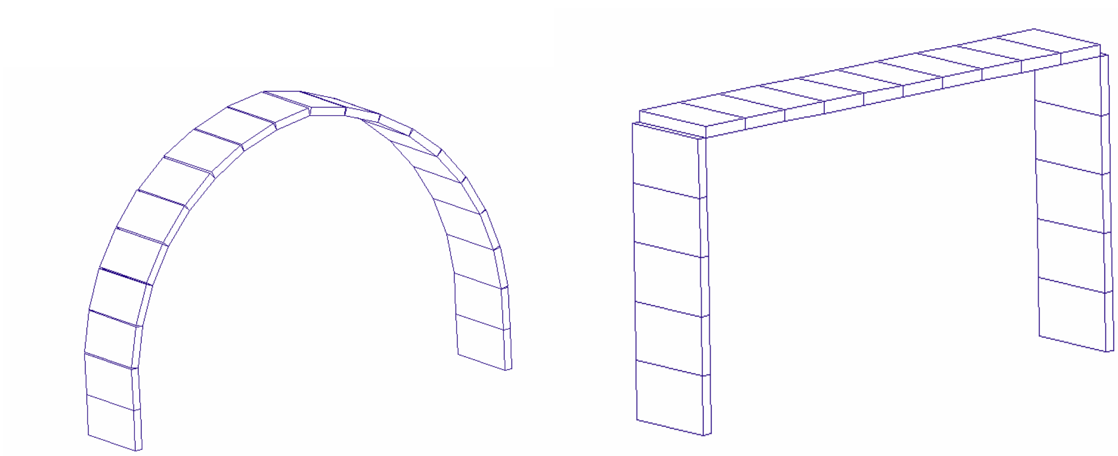

Figure 3: Freefrom trowel concept

6- Freeform Generation by Trowel Adjustment

6-1-Towel Rotation

With the use of the freeform adjustable trowel, various shapes can be built with smooth intersection transition. Two alternatives have been proposed for this purpose:

6-1-1- Hydraulic system

One unit of trowel is composed of two flat plates connected by a circular cylinder as shown in Figure 4 a circular cylinder, as the name implies, is a curved hydraulic cylinder driven by a hydraulic power unit, capable of adjusting the relative angle between the two plates. In order to control the angle, a rotary encoder is attached for providing positional feedback. With the hydraulic power lock system, the relative position between two plates in a unit can be controlled and maintained accurately. One advantage of the proposed configuration is the compactness, simplicity and capability of shape modification with minimum hardware and sensory devices on the trowel. Another is the fact that the actuators and controllers are all remotely placed. A solenoid that drives a hydraulic valve exercises directional control of the fluid. Once multiple units are connected in sequence, a continuous trowel configuration can be formed.

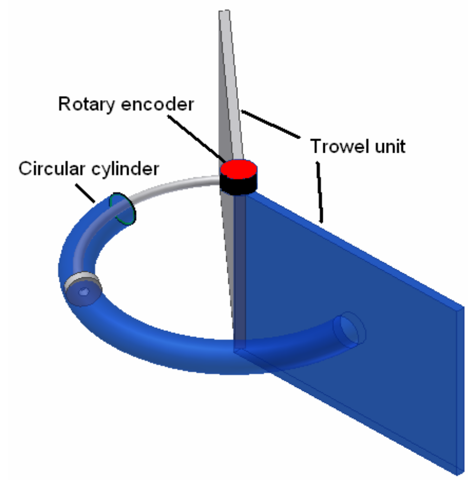

Figure 4: Trowel unit with circular cylinder

With a fluid flow multiplexer, the overall hardware for power transmission can be further simplified as well. One concern is the resolution of a continuous patch constrained by the width of a plate. The less the width of the plate, the better the resolution of a continuous patch. However, the power transmission and control scheme of the overall hardware becomes inevitably complex as requirement for better resolution increases.

6-1-2- Mechanical mechanism

An alternative way to control side trowels is to provide motor powered rotation for every individual trowel. However, installing one motor on each pivot joint will make the system heavy and inflexible. The solution will be transferring the rotational motion by using universal joint mechanisms. An universal joint transmits rotary motion between two shafts which are not in a straight line. Depending on its design, a universal joint can accommodate a large angular variation between its inputs and outputs. In this mechanism, one side of a trowel is connected to an axis and the other is connected to a pivot (Figure 5). The only exception is the case where on both ends the trowels are connected to their axes. Each trowel will rotate individually powered by a servo motor and transmitted by a universal joint mechanism.

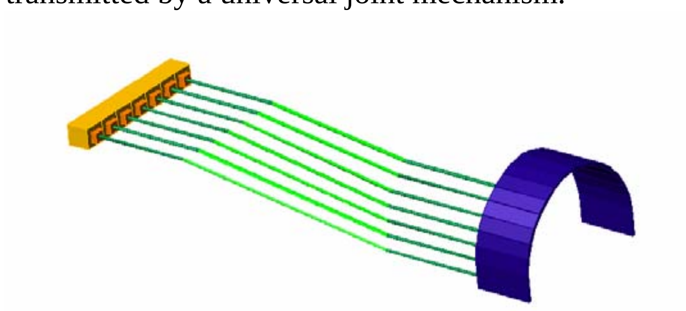

Figure 5: Trowels rotation to adjust for a curve output

To cut the cost of the multi-actuation design, the concept of the underactuation of a mechanical system is considered. In an underactuated robotic hand, the number of actuators is less than the hand's degrees of freedom (DOFs). Advantages of the aforementioned mechanism are, that they are much simpler to control, consume less power, and are more task specific (with some design complexity).

6-2-Towel size

Another issue regarding trowel controls is the adjustability of the trowel lengths. Different profiles have different perimeters (= total of the trowels lengths). Therefore, total trowels lengths should be adjustable to be flexible enough to fabricate a variety of profiles. Different mechanisms can be proposed to solve the adjustability of the trowel lengths:

- Trowel bending: In this method, redundant length will be reduced by bending number of trowels (Figure 6).

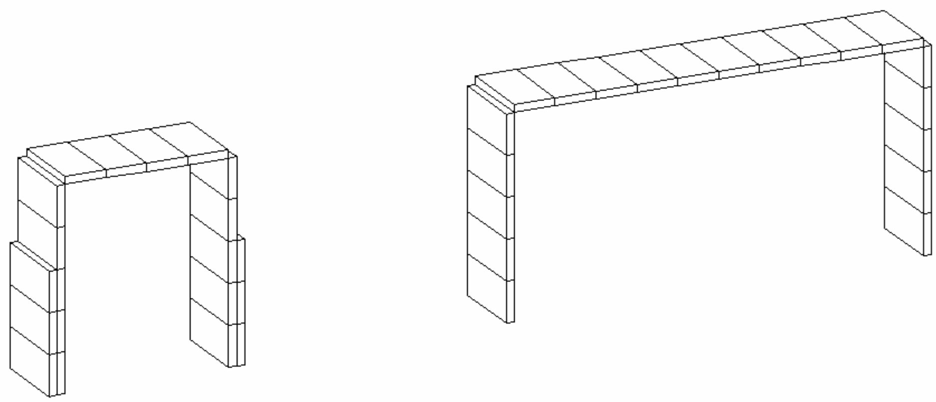

Figure 6: Profile size and shape (perimeter) adjustment by using trowel bending

- Trowel hydraulic stretch: In this method, the trowel is a flat, stretchable polymer which is connected to two hydraulic pistons. Depending on the required length, liquid is pumped into the pistons' tanks, which move in turn, and as a consequence, the polymer surface stretches in the direction of the piston's movement. This method is subject to polymer availability (Figure 7 left).

- Accordion trowel: In this method, trowels are formed from many small, expandable tanks. These tanks are filled by liquid. A control system pumps the required amount of liquid into (sucked out of) the tanks. The external surface of the trowel is covered with stretched polymer which creates a smooth extrusion (Figure 7 right).

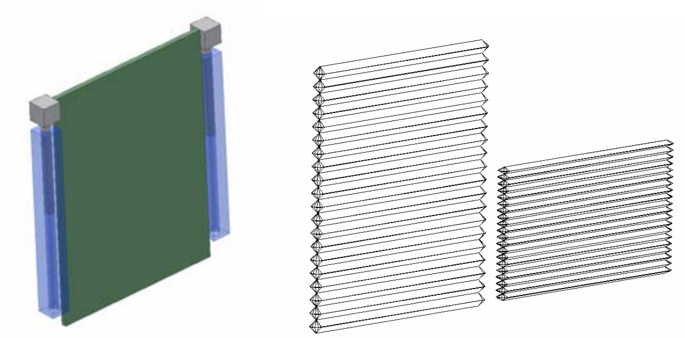

Figure 7: Trowel with adjustable length (left) and Expandable Trowel (right)

7- Mobile platform design

The mobile platform guides the paving system automatically. In order to promote maximum mobility and portability, a nonholonomic platform is proposed. Other design features include a autonomous navigation system with collision detection capability and a "uniform" material dispensing capability. These choices promote construction accuracy to the maximum extent. Three strategies have been identified for navigational control: 1. CAD data based system, 2. Trace follow system and 3. Teleoperated remote control system.

7-1- CAD data based system

The mobile platform in this particular case is composed of a navigation system using CAD data and localization subsystem. Once the CAD data downloaded, the robot operates either in dead reckoning mode utilizing the encoder signal feedback or uses beacon triangulation for localization. The dead reckoning requires a sensory device such as an incremental or an absolute encoder to integrate infinitesimal motion of the robot, while the beacon triangulation calls for three ultrasonic beacons. In dead reckoning mode, accumulated position vector localizes the robot. The current location provides feedback for comparison with the specified path in the CAD data. The CAD data can be either a continuous path such as a spline curve or discrete data points along the path. One benefit of CAD data based system is its capability of running multiple passes for sizable construction with flexibility in path construction.

7-2- Trace follow system

In this strategy, the robot simply follows a line laid on the ground by using a black tape or a spray marker. It performs a simple PID feedback control in conjunction with the tracking sensor that is employed as a mean for feedback. In this particular case, the construction is constrained to be a single pass. A pair of optical sensors mounted in front provides navigation feedback signal. The robot navigation system is a simple PID feedback system composed of optical sensors, steering, and driving system. This control concept is similar to that of the AGV (Automatic Guided Vehicle). The control goal is to have the AGV follow the guidance line precisely. Tracking accuracy is the key issue that impacts navigation accuracy. Therefore, the proper choice of control parameters is an important factor for the geometric accuracy of the construction.

7-3- Teleoperated remote control system

In this configuration, a mobile platform is controlled via telepresence technology, in which a human operator beholds the situation remotely. Advancements in the telepresence technology renders the third option promising taking the complexity of the task into consideration. Virtual reality technology, such as active force feedback by a sensory device can be utilized to avoid unseen obstacles. To that end, the robot needs to be equipped with non-contact distance measurement sensor on all sides. The human, in this case, functions as a decision maker for the move of the mobile platform. The stereovision system mounted on the mobile platform can provide 3D visual detail to an operator equipped with 3D enabled HMD (Head Mount Display). The advantage of the 3rd option includes, firstly, that the robot can be deployed immediately to respond to any exigency at a ground zero with a full control of the robot motion. Secondly, human intelligence can provide adaptive capability for the changing environments to the maximum extent. But for the most part, it is more effective than others in hazardous environment operation with minimum presence of human at the ground zero. One disadvantage is its dependability on a human operator with no intelligence of guidance.

8- Preliminary experiments

To evaluate the feasibility of the MPS idea, several experiments were designed and implemented. These preliminary experiments investigated the suitability of specific building materials for the rapid construction process. Results from preliminary experimentation with 30 different materials and mixtures show that, from surface quality and strength points of view, fast solidifying/low shrinkage cements with about 33 percent fiber glass produce the best results (Figures 8 and 9).

Figure 8. Solidification speed and shrinkage evaluation

Figure 9. Strength test

In addition, several designs for the MPS feasibility study were proposed and a simple prototype machine was fabricated. Extrusion effects were examined in the cases of direct side extrusion using centrifuge effect (Figures 10 and 11 design I) and direct bottom extrusion using gravity and vibrator (Figures 10 and 11 design II). Results from experiments with the prototype machine show that direct extrusion from side using centrifuge effect is more effective (higher material flow) however, both designs seem to be imperfect for some mixtures with high viscosity. An additional material mover (e.g., spiral gear or piston) is needed to push the material out of the extrusion die. Overall, preliminary results are encouraging and are strongly indicative that further work needs to be undertaken to establish the commercial feasibility of the MPS system.

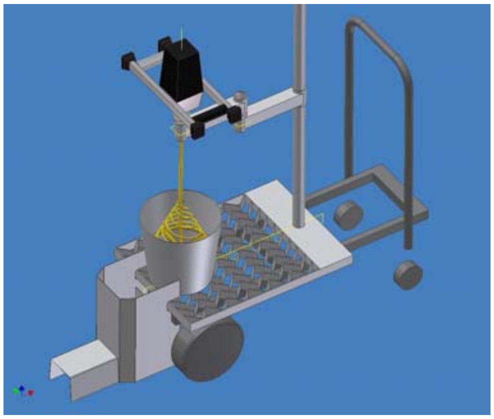
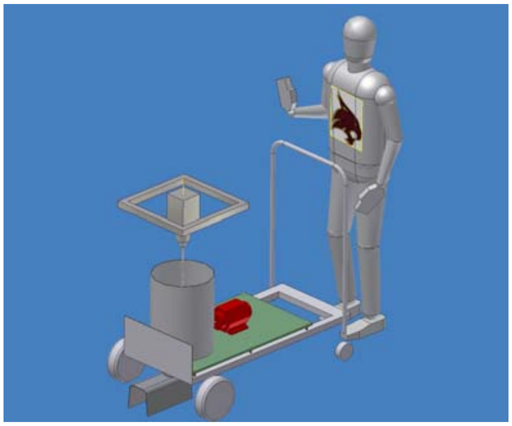

Figure 10: Design I: direct extrusion by centrifuge effect from mixer, Design II: direct extrusion by using vibrator and gravity effect


Figure 11: Machine prototype using design I and II

9- Future Work

Future work in MPS research will address the following:

- the development and optimization of a mobile platform and its navigational controls.
- the development and optimization of systems for the localized transfer, mixing, delivery and freeform extrusion of construction materials.

the development and optimization of freeform trowel mechanism and its adjustment controls.

10- Summary

A new freeform construction process called MPS is introduced which has the capability of extruding material with continuous profile change. Path generation and guidance of the construction operation is controlled by a mobile robot. Alternative designs, a prototype machine, and preliminary experiments show very promising potential for the commercialization of a new, low cost, high speed, automated freeform process in construction.

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