An Operations Planning System for Asphalt Pavement Compaction

Hui-Ping Tserng[a], Jeffrey S. Russell[b], Bharath K. Krishnamurthy[c],
and Robert L. Schmitt[d]

[a] Ph.D. Candidate and Grad. Res. Asst., Dept. of Civil & Environ. Engrg., University of Wisconsin - Madison, Madison, WI 53706.

[b] Assoc. Prof., Dept. of Civil & Environ. Engrg., University of Wisconsin - Madison, Madison, WI 53706.

[c] Grad. Res. Asst., Dept. of Civil & Environ. Engrg., University of Wisconsin - Madison, Madison, WI 53706.

[d] Ph.D. Candidate and Grad. Res. Asst., Dept. of Civil & Environ. Engrg., University of Wisconsin - Madison, Madison WI 53706.

ABSTRACT

Asphalt density after compaction by the breakdown roller is a key factor influencing asphalt pavement performance. Among the several factors influencing asphalt pavement density, the number of passes required for a rolling operation is a critical factor and difficult to determine and measure appropriately. Furthermore, it is difficult to ensure that the roller will uniformly cover the entire length and width of the pavement mat. Without an efficient path planning system, errors in human judgment may cause variation in overlap areas and reduce compaction efficiency. The significance of achieving optimal asphalt density coupled with the problems associated with the present system of operation, motivates the search for a system that can more accurately decide coverage location, number of passes, and control the overlap area for the pavement compaction operation. Such a system could increase the operational efficiency, uniform compaction, and pavement performance.

This research aims at establishing the framework for an affordable path planning system for the compaction operation using an on-board guidance facility. This facility would integrate an Asphalt Knowledge-Based System with an economical sensing system, such as

a Global Positioning System (GPS), and a navigational compass. The design for the proposed sensing system will be presented along with an algorithm for an efficient motion plan for the compactor using the results of laboratory and field test data.

1. INTRODUCTION

The importance of U.S. highway infrastructure in an industrial economy cannot be over-emphasized. Highway construction and maintenance operations have far-reaching ramifications both in industry and with the general public. To a large extent, the existing system of pavement compaction operations is not standardized, and is not amenable to strict quality control. Proper compaction of the asphalt mat to achieve the requisite final density is critical to ensure that highway pavements withstand dynamic and repetitive loads from traffic.

Currently, the compaction operator makes an approximate determination for the number of passes based on prior experience and subjective judgment. This human element can lead to erroneous decisions and an incorrect number of passes. A method for automating the operation will lead to more uniform pavement, resulting in adequate pavement performance and a standardized operation that is amenable to quality control.

Existing asphalt paving operations are performed primarily without the use of any sensing systems, as cost considerations preclude the installation of sensing systems and development of completely robotic systems. It may not be economically feasible to overhaul and replace the existing system completely. However, there exists an inexpensive semi-automated hybrid sensing system that is economically feasible and realistically implementable on actual paving projects.

2. PROBLEM STATEMENTS AND OVERVIEW

2.1 Asphalt Density after Compaction

Virtually all asphalt paving contract specifications in the U.S. require contractors to construct a specified pavement density to ensure satisfactory pavement performance. Thus, adequate and uniform compaction of the pavement mat is critical for achieving the desired pavement density after compaction. A number of factors influence the in-situ pavement density including variability in the asphalt mixture, and variability in the frequency and overlap of passes made during a compaction operation.

2.2 Over-compaction and Under-compaction

An inappropriate number of passes may result in over- or under-compaction that is undesirable for satisfactory pavement performance. Over-compaction results if the number of passes is more than required causing crushing of constituent aggregates, and a decrease in the desired percentage of air voids that often leads to surface bleeding and a reduction in the strength and durability of the pavement. Conversely, under-compaction results if the number of passes is less than required producing pavement that does not have the desired density, strength, and durability. Thus, a correct estimation of the number of passes made over different portions of the pavement mat is necessary to ensure the desired level of compaction has been reached[1].

2.3 Overlap Areas and Number of Passes

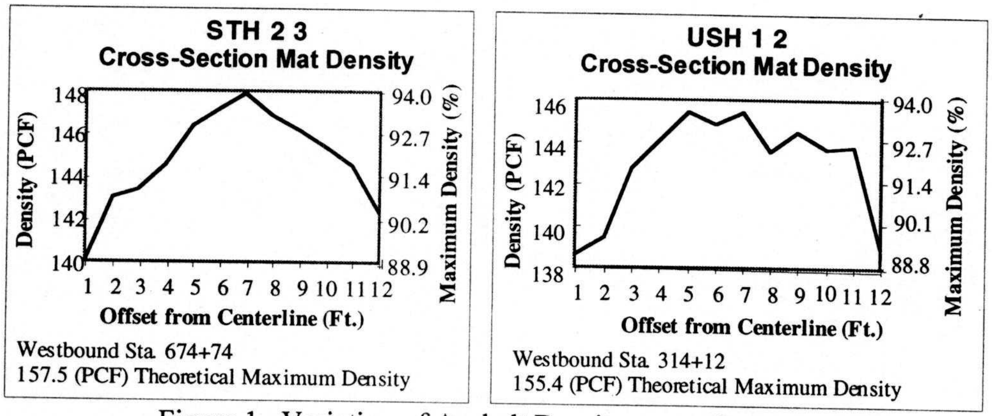
In practice, contractors determine the number of passes required for adequate compacted density by performing rolling patterns on a test strip.[2] There are no standard methods for determining the number of passes and coverage location by the compactor. The compaction operators use their experience, subjective judgment, and discretion to ascertain whether the entire pavement surface has been covered uniformly to a reasonable extent. This human element often leads to over-compaction near the center of the mat and under-compaction along the edges. There are overlap areas that must be optimized by the compactor to produce uniform pavement compaction, efficiency in the paving operation, and adequate pavement performance.

3. RESEARCH OBJECTIVES

The primary objective of this research is to develop a path planning system for asphalt compaction operations on asphalt pavements. This system will estimate the appropriate number of passes to be made by the roller and generate a path motion that controls the overlap area. Monitoring the number of passes and overlap coverage is also a primary feature of this system. The design for an on-board guidance system will be developed using GPS and compass orientation. The resulting system will be a semi-automated hybrid planning system, with an on-board monitor continuously tracking the roller path and performing real-time processing of the motion information.

4. RESULTS AND SUGGESTIONS FROM FIELD EXPERIMENTS ON ASPHALT PAVEMENT DENSIFICATION [3]

A study of compaction density across an asphalt paving mat was conducted on several highway projects in Wisconsin during a 1994 density study that compared nuclear gauges to core samples[3]. Nuclear density readings were taken across the mat immediately behind the last compaction roller (cold roller) in the paving train. Test sites were marked in one-foot increments beginning at the centerline and extending perpendicular 12 feet to the edge of the mainline pavement. The total width of the paving mat was 15 feet with integral 12-foot mainline and 3-foot shoulder sections. Two consecutive one-minute nuclear density tests were taken at each test site and averaged. The results of the density tests for two projects are provided graphically in Figure 1. The graph clearly indicates that the center of the mat has a higher density than the centerline and shoulder.



Westbound Sta. 674+74
157.5 (PCF) Theoretical Maximum Density

Westbound Sta. 314+12
155.4 (PCF) Theoretical Maximum Density

Figure 1. Variation of Asphalt Density across Pavement

From Figure 1, it is evident that the density across the mat is not uniform. Hence a motion planning model should be developed to provide more uniform compaction of the paving mat.

5. PROPOSED SENSING SYSTEM

An aerial-view illustration of the automated highway pavement system is shown in Figure 2. Based on this automated system, the proposed sensing system will have the following components and provides the following information:

- An inexpensive global positioning system, with accuracy to a centimeter, that will track and provide the positional coordinate information of the compactor throughout its motion. Receivers will be installed on the roller and paver, and if required, along the road edges to improve efficiency and accuracy of range measurements.

- A high-accuracy navigational compass installed on both the paver and the compactor, will provide orientation and angular information for the motion.

- Gauges and temperature sensors that measure and monitor the temperature and consistency of the pavement mat during the paving operation. This feature is very important because the temperature of the mat requires continuous monitoring and directly influences the compaction rate. Additionally, gauges to measure the ambient temperature, wind, pressure and humidity data could also be incorporated in the sensing system to monitor the surrounding atmospheric conditions that significantly affect the cooling rate of the pavement mat and final compaction. Inputs and outputs of this system are provided in Table 1.

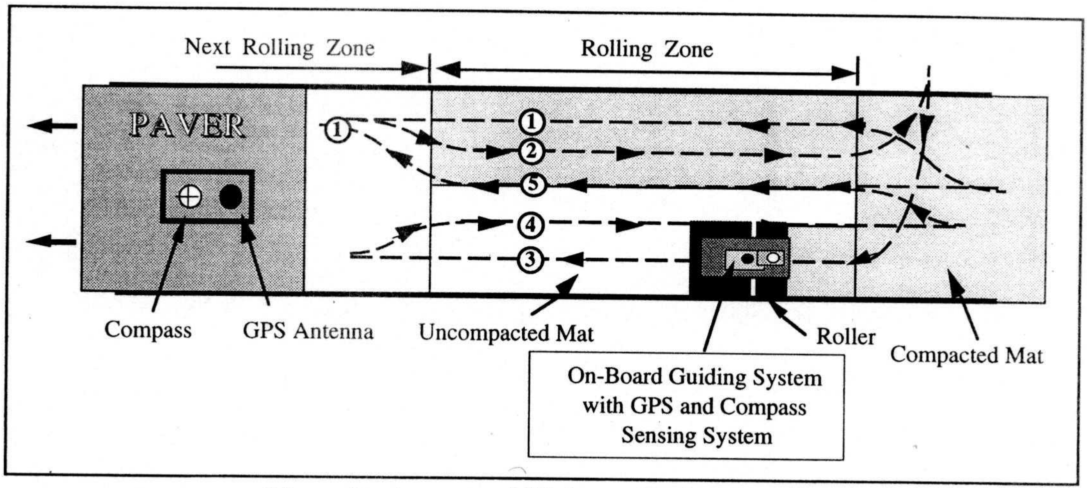


Figure 2. Automated Highway Paving System

Table 1. Input and Output Variables of Automated Highway Paving System

Input Variables (1)		**Output Results** (2)
Global position	Highway geometrics	Number of passes
Thickness of mat	Roller vibrating frequency	Overlap
Paver rate	Ambient weather conditions	Length of rolling zone
Temperature of mat	Roller weight	Coverage pattern
Roller speed range	Width restrictions	Motion path
Roller type (steel, rubber, etc.)	Pavement structures	Pavement cooling rate

6. RESEARCH METHODOLOGY

Motion planning is implemented under the premise of available and complete information before and during the compaction operation. The technique of successive spatial decomposition is used for reducing the complexity of the problem from a project level to an operational level. The complexity of the problem is reduced from three-dimensional to one-dimensional. Thus, a top-down approach for motion planning is implemented for solving this problem[4,5]. A flowchart showing the sequence of steps to be followed by the computational algorithm is presented in Figure 3. The research methodology adopted for this problem includes (1) Collection of design information, (2) Determination of number of coverages and length of rolling zone, (3) Selection of compactor motion model, (4) Determination of dimensions of the motion model, (5) Updating of highway configuration, and (6) Compaction in rolling zone.

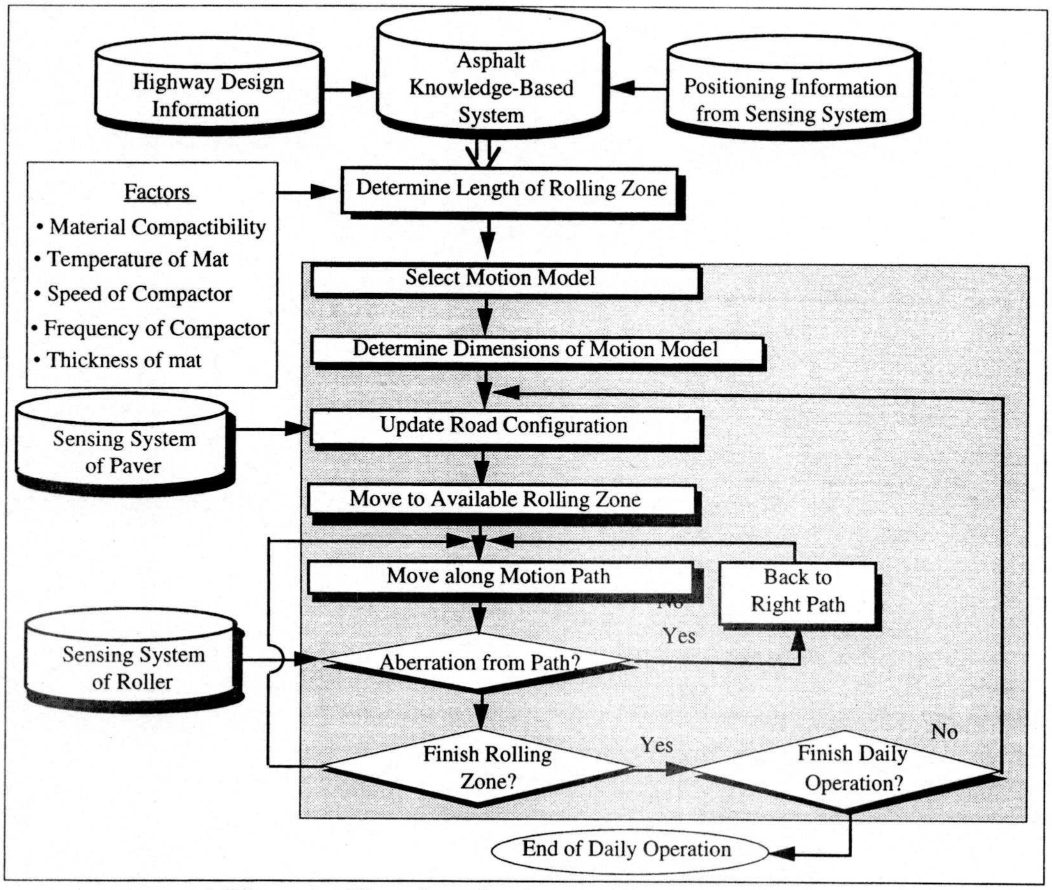


Figure 3. Flowchart for Computational Algorithm

6.1 Collection of Design Information

An Asphalt Knowledge-Based System containing asphalt properties and characteristics is linked to a highway design database that includes the required pavement design information, such as pavement thickness, types and specifications of equipment (i.e., rollers, paver, trucks) to be selected for the pavement operation, crew information, pavement mix design, and specifications[1,6]. Additionally, the real-time input data from the sensing system is read into the knowledge-base that monitors all the information and updates its decision-making capabilities.

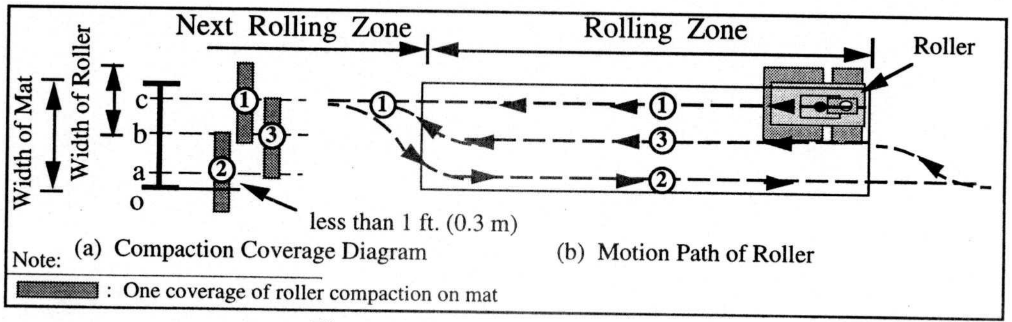
6.2 Determination of Number of Coverages and Length of Rolling Zone

The number of times a particular pavement strip is to be covered depends on its location relative to the centerline. The number of passes to reach desired density will be provided by a probabilistic model generated by the knowledge-based system. Based on the various input data on material compactability including temperature and thickness of the mat, and speed and frequency of the compactor, the Asphalt Knowledge-Based System will provide the required length of the rolling zone.

6.3 Selection of Compactor Motion Model

The proper motion model for the compactor path is selected from the width of the roller and width of the pavement. The motion model can have three or more passes to cover the entire rolling zone. Based on the laboratory tests conducted, it is observed that three, five, and seven strip models are suitable for achieving more uniform compaction along the length of the rolling zone (refer to Figures 4 through 6). The algorithm to determine the appropriate motion model is briefly described in the following pseudo-code:

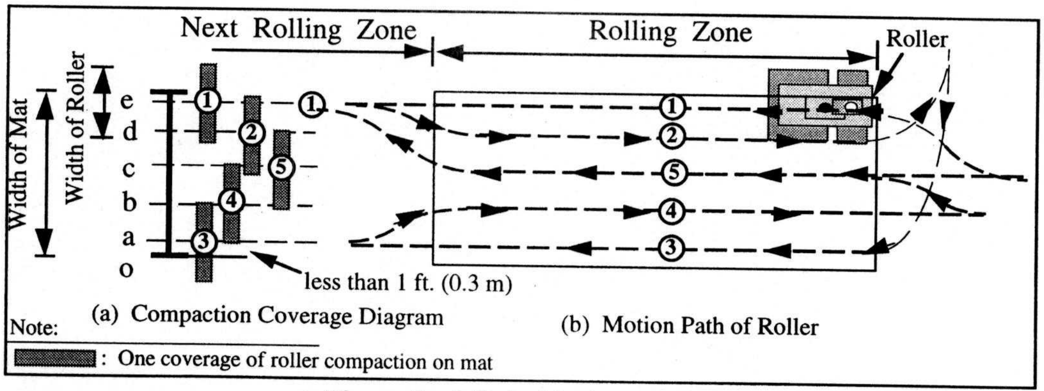
```
Algorithm Determination_of_Motion_Model
  begin
    if (((½(Length of ① + ②) - 6 in) + 2 ft) > Width) of Mat (see Figure 4(a))
      then select and execute the 3-strip motion model.
  else
        if (((½(Length of ① + ③) - 1 ft) + 2 ft)
            + ((½(Length of ② + ④) - 6 in) > Width of Mat) (see Figure 5(a))
          then select and execute the 5-strip motion model.
        else select and execute the 7-strip motion model.
  end
```



Note: (a) Compaction Coverage Diagram (b) Motion Path of Roller

▬ : One coverage of roller compaction on mat

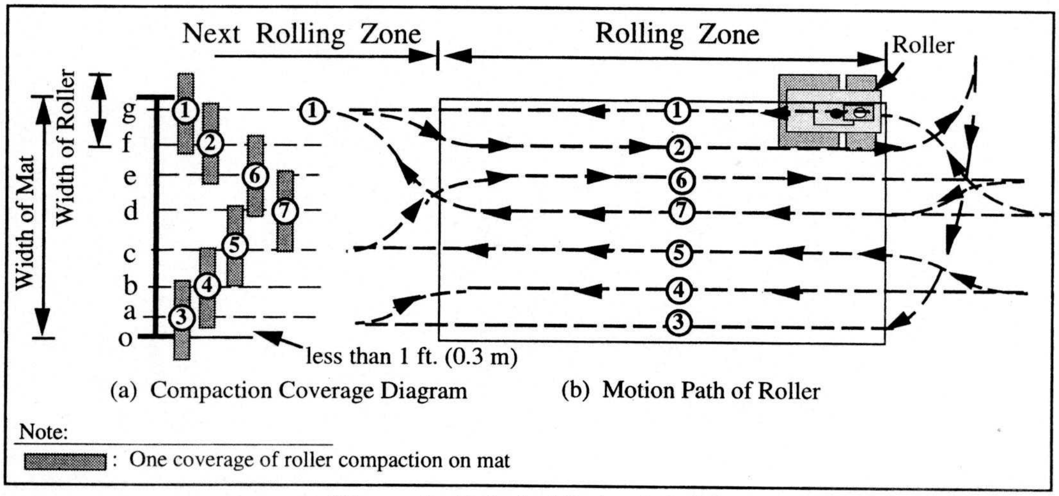
Figure 4. 3-Strip Motion Model



Note: (a) Compaction Coverage Diagram (b) Motion Path of Roller

▬ : One coverage of roller compaction on mat

Figure 5. 5-Strip Motion Model



(a) Compaction Coverage Diagram (b) Motion Path of Roller

Note:

▨ : One coverage of roller compaction on mat

Figure 6. 7-Strip Motion Model

6.4 Determination of Dimensions of Motion Model

The dimensions and calculations for the motion model are provided Table 2. The values specified for distances are recommended from asphalt densification experiments developed by Hanna, et al., 1995[3]. Based on these values, the appropriate number of passes and the suitable motion path can be determined for the motion of the compactor.

Table 2. Dimensions of Motion Models

Motion Model (1)	Distance from origin 'o'						
	oa (2)	ob (3)	oc (4)	od (5)	oe (6)	of (7)	og (8)
3-Strip	W/2 - S/2 + 6"	W/2	W/2 + S/2 - 6"	-	-	-	-
5-Strip	W/2 - 2*(S/2 - 6")	W/2 - S/2 + 6"	W/2	W/2 + S/2 - 6"	W/2 + 2*(S/2 - 6")	-	-
7-Strip	W/2 - 3*(S/2 - 6")	W/2 - 2*(S/2 - 6")	W/2 - S/2 + 6"	W/2	W/2 + S/2 - 6"	W/2 + 2*(S/2 - 6")	W/2 + 3*(S/2 - 6")

Note: S = width of the roller and W = Width of the pavement.

6.5 Updating of Highway Configuration

The GPS receiver and compass located on the paver, will provide the position and orientation information for the paver motion during the paving operation. Based on this information, the area of the currently paved zone can be calculated. This information can be displayed graphically to the operator using CAD-based model. In particular, GPS could be used very effectively for this purpose[7].

6.6 Compaction in Rolling Zone

The compactor moves to the current rolling zone following the specified motion path, depending on the decided motion model. If the compactor deviates from the specified path, the guidance system displaying and tracking the motion will warn the operator.

The previous and current coordinates of the compactor are maintained in memory and the coordinates of the maximum allowable deviation from the correct path are continually calculated. If the deviation of the current location from the centerline exceeds the maximum allowable value, then the guidance system will interactively guide the operator to the desired path until it comes within a tolerable level of accuracy. This is continued the entire rolling zone is completely compacted. Additionally, the motion of the compactor has to be coordinated with the motion of the forward asphalt paver to synchronize the parallel execution of both the paving and the compaction operations, and increase the operational productivity. Subsequently, this automated system is also capable of warning the operator of any unexpected obstacles and would suggest alternative paths.

7. CONCLUSIONS

A brief overview of the key aspects of asphalt pavement compaction planning system was presented. This research explored the potential for automation in the area of asphalt compaction in highway pavement operations using GPS. An algorithmic strategy for path planning was developed and implemented. A framework was presented for an automated on-board guidance system with an affordable sensing system using GPS that continuously monitors the path of the compactor and guides the operator interactively throughout the paving operation.

This application of motion planning to an asphalt compaction operation is envisioned to have considerable potential for further research. This will certainly enhance the efficiency of the operation and significantly increase operational productivity. It may also lead to improved integration of the design and construction phases of the highway project. Additionally, integrating this motion planning system with other construction operations in the highway project, that may be fully automated/semi-automated, could be evaluated. Such systems could involve multi-robotic operations planning systems.

8. REFERENCES

1. Roberts, F. L., Kandhal, P. S., Brown, R. E., et al., (1991). Hot Mix Asphalt Materials, Mixture Design and Construction, *National Center for Asphalt Technology*, Auburn University, Alabama, NAPA Research and Education Foundation, First Edition.

2. Kanzaki, T., and Nizhizawa, T. H., (1993). "Survey Robot using Satellite GPS," *Proceedings of the 10th International Symposium on Automation and Robotics in Construction*, Houston, Texas, pp. 479-486.
3. Hanna, A. S., Russell, J. S., Noyce, D. A., and Schmitt, R. L. (1995). Asphaltic Pavement Density Measurement Comparison Using Coring and Nuclear Methods, *Internal Technical Report*, University of Wisconsin - Madison, Madison, WI.
4. Skibniewski, M.J. and Russell, J.S., (1989). "Robotic Applications to Construction," *Cost Engineering*, Vol. 31, No. 6, pp.10-18.
5. Brady, M., and John, M., (1983). Robot Motion: Planning & Control, The MIT Press, Cambridge, Massachusetts.
6. McShane, W. R. & Roess, R. P., (1990). Traffic Engineering, Prentice Hall Polytechnic Series in Traffic Engineering, Prentice Hall, New Jersey.
7. Li, C. C., Thomas, R., and Oloufa, A. A., (1995). "Development of an Automated Real-Time Tracking System for Pavement Compaction," *Proceedings of the 12th International Symposium on Automation and Robotics in Construction*, Warsaw, Poland, pp. 49-54.