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A BIM and UWB integrated Mobile Robot Navigation System for Indoor Position Tracking Applications

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Abstract: This research presents the development of a self-governing mobile robot navigation system for indoor construction applications. This self-governing robot navigation system integrated robot control units, various positioning techniques including a dead-reckoning system, a UWB platform and motion sensors, with a BIM path planner solution. Various algorithms and error correction methods have been tested for all the employed sensors and other components to improve the positioning and navigation capability of the system. The research demonstrated that the path planner utilizing a BIM model as a navigation site map could effectively extract an efficient path for the robot, and could be executed in a real-time application for construction environments. Several navigation strategies with a mobile robot were tested with various combinations of localization sensors including wheel encoders, sonar/infrared/thermal proximity sensors, motion sensors, a digital compass, and UWB. The system successfully demonstrated the ability to plan an efficient path for robot's movement and properly navigate through the planned path to reach the specified destination in a complex indoor construction site. The findings can be adopted to several potential construction or manufacturing applications such as robotic material delivery, inspection, and onsite security.

Keywords: indoor tracking, UWB, BIM, wireless sensor, mobile robot, navigation

I. INTRODUCTION/ LITERATURE REVIEW

A. Background

The notion of automation has been perceived by industry long ago, and it has been already achieved and successfully implemented in some industrial sectors, such as manufacturing industry. Trends towards automation have gained in popularity among most of the industrial sectors, and they are moving towards its development. Characteristics of construction, such as intense competition, complexity in nature, high labor costs, rapid advancement in technology, and market oriented operation, motivate and necessitate the automated construction systems [1], [2]. The construction industry is the prime sector with one of the largest economy scales to the U.S. industry. According to the U.S. Census Bureau, there were approximately 981,305 million dollars of total construction value work done (seasonally adjusted) and 6 million workers in 2014, which accounts for about 4% of the total U.S. employment [3], [4]. Many researchers have discussed the issues and problems that occur during construction; they lower the productivity rates, thus increase the overall construction costs [5]–[7]. Among these issues and problems, many are location-based problems. With location awareness, they can be more efficiently managed and properly incorporated in construction processes. For example, construction personnel often get situated in a hazardous work environment during dynamic construction operations, such as hazardous proximity situation [8], and general safety related situations. With properly implemented automated systems, hazardous situations can be recognized in advance through alerting systems [8] and scene visualization [9]-[11]. Such systems, therefore, can serve as a solution to these problems by proving the workers an additional opportunity to escape or take a proactive action to avoid accidents.

B. Research in Construction Automation

With the rapid pace of technological advancement over the last decades, the construction industry has undergone substantial evolution. As part of evolution, Building Information Modeling (BIM) has made significant impacts on both academia and industry. Interoperability has been investigated to provide a global data exchange format that enables seamless connections among various sectors related to the completion of a project. Although these efforts have been positively proven to the industry, they are limited in the scope of software related aspects and fabrication of building components [12]–[14]. [15] states that the manufacturing industry has about twice higher labor productivity rates than the construction industry. The cost and time are not efficiently utilized in the conventional construction and thus offer great potential for savings [12]. The operation of construction and its industry can only successfully function when an enough number of supplies of skilled man workforce are given. This was brought into attention in countries, such as, the U.S., UK and Germany in recent years, as the countries experienced a shortage of skilled labor [16], [17]. An automated and robotized construction methodology can be used to accommodate various types of discrepancies observed in construction, and increase productivity, quality, and safety. The related previous research includes robotic excavation [1], concrete floor finishing [15], aerial robotic construction [18], robotic crane erection processes [2], site security navigation [19],

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[20], and interior finishing work [12]. Other research in another perspective is construction site real-time monitoring and tracking [21], [22].

C. Research in Positioning Technology

Advancements in the wireless technology over the past decade have greatly benefited various segments of industries. These technologies are considered pervasive, widespread, and play an important role in many aspects of our daily lives [23]. Various applications were developed with these technologies; they included GPS, object tracking, emergency detection, surveillance, and many other location sensing related products/services [24], [25]. GPS has become an industry standard for every mobile vehicle driver for their navigating tools. The GPS technology is mainly suitable for outdoor applications but limited in the indoor applications due to the disrupted, scattered signals, that is, the microwave signals get significantly attenuated through the building materials [26]–[29]. Over the last two decades, indoor positioning system has gradually received considerable attentions from various industries. Research efforts have been made for indoor tracking area with a multiple of technologies including Wi-Fi [26],[30], Ultra Wideband (UWB) [19],[31],[32], Bluetooth [22],[28], [33], Radio Frequency Identification (RFID) [10], Infrared, and Ultrasound based systems. Yet, none of the indoor positioning systems has rooted into the industry as a widely accepted standard like GPS for outdoor positioning applications. Many of the researched systems have their own limitations in terms of accuracy, cost (hardware and software requirements), scalability, robustness, installation, and many others. The type of technology used and the type of applications needed are examples of the most critical components that impede rapid penetration of indoor tracking systems into the construction industry. In addition, the required hardware and its ease of deployment are the key factors in scalability aspects [34]. Many efforts have been exerted to address these limitations, yet failing to provide an accurate, precise indoor positioning, and robot's path planning and navigation for construction applications. Based on the scrutiny of the advantages and disadvantages offered by each technology, this research selected and was conducted with UWB technology incorporated with other localization sensors. The following subsection briefly discusses the advantages and disadvantages of each of the tracking systems.

1) Infrared and Ultrasound: These sensor systems require hardware infrastructure for communicating signals, and they impose limitation on scalability. They are rather focused on high accuracy than ease of deployment [35]. Infrared also requires line of sight due to its inability to penetrate materials.

2) Wi-Fi: For buildings with available existing WLAN, it is one of the most ideal solutions because most of the mobile devices nowadays are Wi-Fi enabled. However, unique characteristics of environments seen at a construction site, having this infrastructure is generally not common. In addition, it suffers from the multipath effects.

3) Bluetooth: This technology is recently getting in popularity with the introduction of Bluetooth Low Energy (BLE) technology in 2010. This is claimed to operate, depending on the user's setting, up to three to four years with a single small coin battery. High industry demands keep lowering the price of a Bluetooth transmitter (about $5 to $40), and it is embedded in most of the mobile devices as well. In contrast to Wi-Fi, the battery usage on the client side is very low. However, the downside of this technology is the fluctuation of the received signal strength. As it is inherent nature of the system, for accurate positioning, it is highly recommended incorporating good algorithms with other techniques, such as filtering, motion sensors. Another disadvantage is, similarly for Wi-Fi, it suffers from the multipath effects.

4) Ultra Wideband: UWB offers a wide spectrum and fine time resolution of the signal, which contributes to reliable positioning capability in dense multipath environments [29], [31], [32]. The signals' short durations result in very high accuracy around a fraction of a meter [36]. However, violation of line of sight tends to degrade the signal strength, which requires accurate designing and strategically placing the sensors. Also, the cost of UWB sensors is still high and not yet on a par with competing sensors.

II. OBJECTIVE AND SCOPE OF THE STUDY

This paper introduces a self-governing robotic mobile navigation system that could be used in an indoor construction environment. A successfully developed and implemented such construction system would contribute to resolving aforementioned problems and in achieving more effective and beneficial construction application technology in the future. Such a system requires an accurate and reliable positioning capability for intelligent controls and managements. Acquiring this reliable position capability in an indoor environment has always been the greatest challenge in the field. The main objective of the study was to develop, implement, and validate the wireless mobile robot system by integrating robot control units and the BIM-driven software platform with a UWB indoor positioning technique and various sensors within an environment known a priori.

III. LOCATION ESTIMATION AND MAPPING METHODS

This section describes some of the most commonly used indoor positioning methods and their brief theoretical backgrounds. Discussed positioning methods in the following subsections include (A) trilateration, (B) fingerprinting, (C) cell-based positioning, and (D) triangulation. (E) introduces a popular mapping technique for an unknown environment.

A. Trilateration/ Improved Trilateration

This scheme is one of the simplest techniques with its well-known mathematical background. It basically utilizes sensor signals to estimate a distance between a transmitter and a target. The enough number of distance measurements allows the formation of mathematical equations to solve the intersecting coordinates of circles. With over-determined distance measurement data, the trilateration algorithm can be improved. This improved trilateration (maximum likelihood estimation) poses an optimization problem with a least square method. As it involves more than the required number of distance measurements, the reliability on each data point becomes less critical. This optimization minimizes the errors in the position estimation with respect to the given distance measurements, and therefore, one can expect more accurate location estimation than the original trilateration method.

B. Fingerprinting

Many researchers found this method the most accurate when it can be implemented. It is composed of two phases. The first phase is a training phase, also known as offline phase; one collects data to construct a database. This database is then used in the second phase to estimate the target's location based on a pattern matching algorithm, such as K-nearest neighbor (KNN) algorithm. The main disadvantage with this method is that the offline phase is a very lengthy, and exhaustive process, which can takes several hours and even days depending on the size of the building. In addition, it is site-time-specific, which is highly affected by the changes in the environment. Construction sites are generally expected to experience dynamic changes in environment, and therefore it would not be an ideal choice to implement in construction sites [37].

C. Cell Based Positioning

This method divides an indoor map into segments, and each of the segments (cells) is covered by a different set of transmitters. Localization is based on a detected set of transmitters. It requires a database that contains the set of transmitters and their corresponding cell information for estimation.

D. Triangulation

With angle of arrival (AOA) measurements from available sensor signals, the triangulation method can be utilized, similar to the trilateration method. Knowing the position of transmitters and their AOA measurements with respected to the target, the position of the target can be obtained with simple geometry.

E. Simultaneous Localization and Mapping (SLAM)

SLAM exploits a mobile robot to construct the surroundings of the robot, as it moves in an unknown environment. [38], [39] utilize laser scanners for a map construction. This construction is based on the navigation of the moving robot and landmark measurements obtained from the laser scanners, and the system finally generates a map of the explored environment. Although this is a popular method to construct an as-is map of an unknown environment in 2D and 3D, our research uses a BIM-driven navigation map, thus the environment is known a priori, which offers the advantages such as simplicity of required sensory data and faster data process for a real time navigation application.

IV. SYSTEM ARCHITECTURE

A self-governing robot navigation system was applied to our wireless mobile robot system by integrating robot control units, various positioning techniques including a dead-reckoning system, a UWB platform and motion sensors, with a BIM path planner solution. The first three components played a crucial role in controlling the unit to best position the wireless mobile robot in an indoor working environment.

The robot navigation on our mobile wireless system utilized left and right wheel encoders for odometry measurements. Gyroscope and accelerometer were used for inertial motion measurements to serve as relative positioning sensors. UWB sensors that consisted of one master node and three slave nodes, and a digital compass have also been integrated to accurately estimate the absolute position and orientation of the mobile robot (Figure 1). This integrated system utilized the relative movement of the system with respect to the previously known position in refining its position with absolute positioning estimation. Data were obtained from two different (relative and absolute) frames and fused in a software platform that was connected to a computer-aided solution. This process generated a reliable and robust solution to positioning and navigating the mobile robot system. Figure 2 depicts the overall framework and the work flow in achieving accurate position of the moving robot. The following subsections describe estimation methods implemented in this robot system.

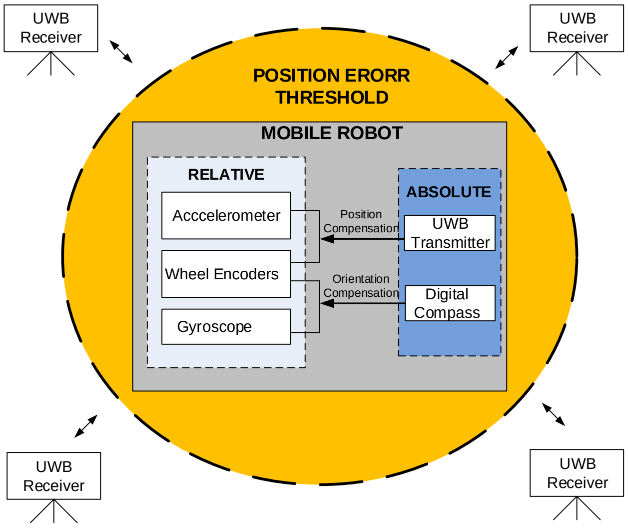


FIGURE I
Overview of the Robot Navigation System

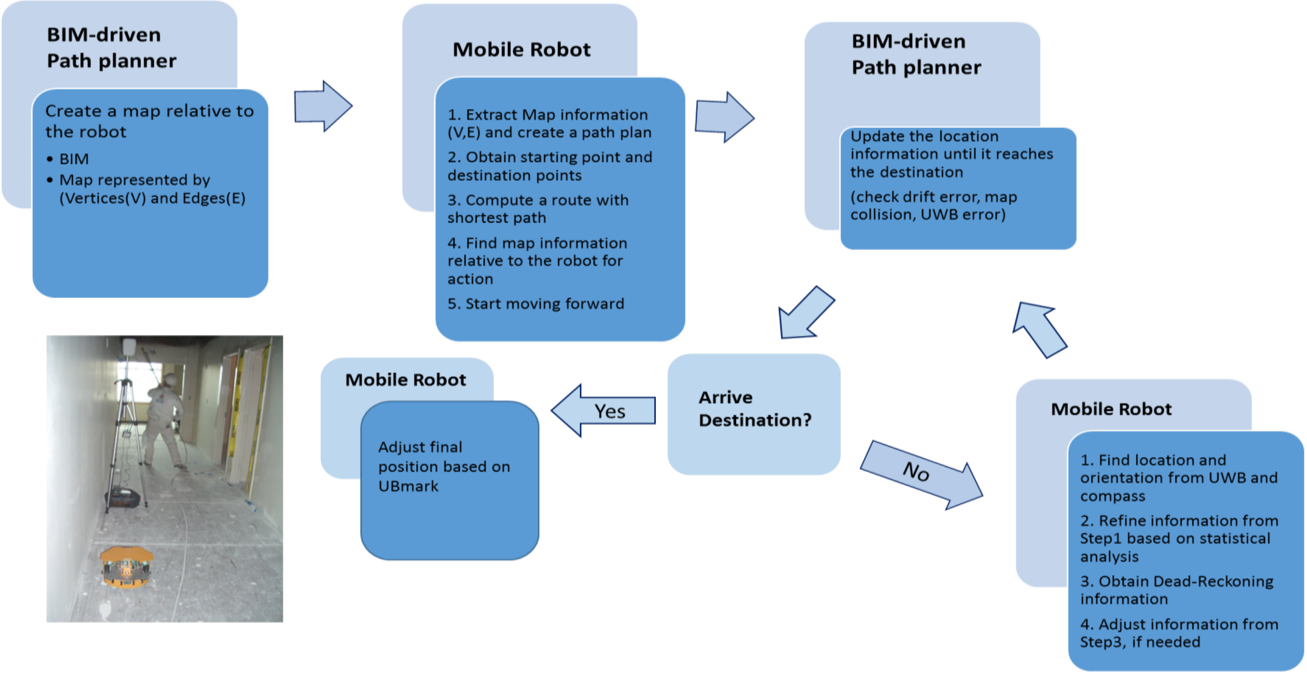


FIGURE III
Overview of framework and work flow

A. Dead Reckoning

Dead Reckoning uses the target's relative motions, such as relative orientation, speed and a time interval to calculate the target's new position based on its previously estimated position. To realize a reliable controlling system over a mobile robot system, it is necessary to fully appreciate the geometric properties of the system and its mechanical behaviour. The key movement is made by the rotation of the wheels of the robot. Rotation measurements from the wheel encoders and their geometric properties, such as the radius, enable to formulate a kinematic equation with the directional information (θ) of the movement that estimates the amount of movement occurred over an elapsed time. A simple trigonometry transforms the movement from a local coordinate to a global coordinate. The velocity state is also simply found by taking derivative with respect to the elapsed time, and the result is known for both the global and local coordinate systems (Figure 3). The mechanical characteristic of the system limits the local movement in the y-direction, resulting in a simpler mathematical equation as shown in Equations 1-2.

For this dead reckoning process, obtaining parameters to formulate the local velocity (or travel distance) vector was inevitable, and data (kinematic components and geometric properties) from the previously mentioned sensors were used for this purpose. The left and right wheel encoders gave the wheel angular velocities of the shafts, which were multiplied by the radius of the wheel to produce the velocity. With two velocity measurements from the two encoders, the overall velocity of the robot system was computed as the average of the two. The angular velocity of the system was induced by the

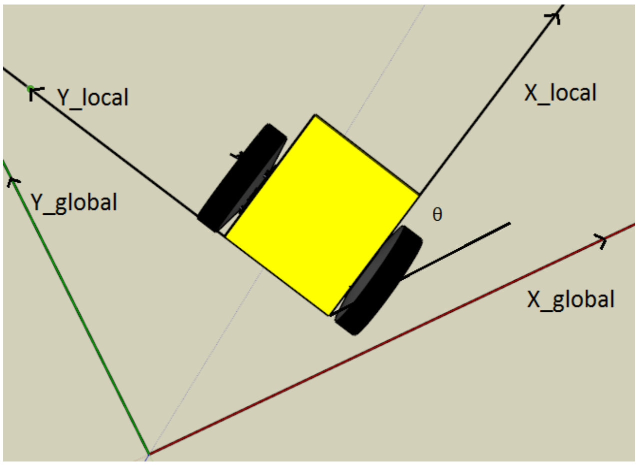


FIGURE IIIIVI
Global and Local Reference Frames

$$\begin{pmatrix} \dot{x}_{global} \\ \dot{y}_{global} \\ \dot{\Theta}_{global} \end{pmatrix} = \begin{pmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \dot{x}_{local} \\ \dot{y}_{local} \\ \dot{\Theta}_{local} \end{pmatrix} \qquad \text{(Equation 1)}$$

$$\begin{pmatrix} \dot{x}_{global} \\ \dot{y}_{global} \\ \dot{\Theta}_{global} \end{pmatrix} = \begin{pmatrix} \cos(\Theta) & 0 \\ \sin(\Theta) & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \dot{x}_{local} \\ \dot{\Theta}_{local} \end{pmatrix} \qquad \text{(Equation 2)}$$

difference in the velocities of the two wheels as shown in the second element in the vector in Equation 3. Combining Equations 2 and 3 with considering the time interval, the travel distance was found. Depending on the measurement the wheel encoders provided, the travel distance was calculated similarly. With the travel distance, the current position of the system was updated as seen in Equation 4. Figure 4 shows a visual representation of the parameters used in Equation 3.

$$\begin{pmatrix}\dot{x}_{local}\\ \dot{\theta}_{local}\end{pmatrix} = \begin{pmatrix}v\\ w\end{pmatrix} = \begin{pmatrix}\frac{r\dot{\varphi}_1}{2}+\frac{r\dot{\varphi}_2}{2}\\ \frac{r\dot{\varphi}_1}{2L}-\frac{r\dot{\varphi}_2}{2L}\end{pmatrix} \qquad \text{(Equation 3)}$$

$$\begin{aligned} x_i &= x_{i-1} + \Delta x \\ y_i &= y_{i-1} + \Delta y \qquad \text{(Equation 4)} \\ \Theta_i &= \Theta_{i-1} + \Delta\Theta \end{aligned}$$

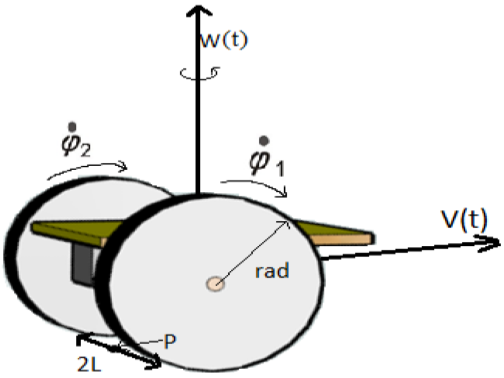


FIGURE VV
Wheel Configuration

B. UWB Absolute Positioning

The UWB system consisting of one master node and three slave nodes and a digital compass served as a secondary positioning system in our approach. Calibration of the UWB system needs to be established first with respect to the origin of the relative and absolute frames. UWB readings are aligned with the pre-established absolute reference points to compare the absolute estimated points, and the digital compass is employed to verify/refine the orientation of the robot. These are a back-up system in the purpose of correcting the position estimated by the primary motion sensors (encoders, gyroscope, and accelerometers) when robot's position is beyond the predefined thresholds (e.g., over 50cm or passing walls in a navigation map). The UWB systems were connected via a local ad-hoc network system that allowed a quick data processing over our software platform. The entire estimation process is depicted in Figure 5.

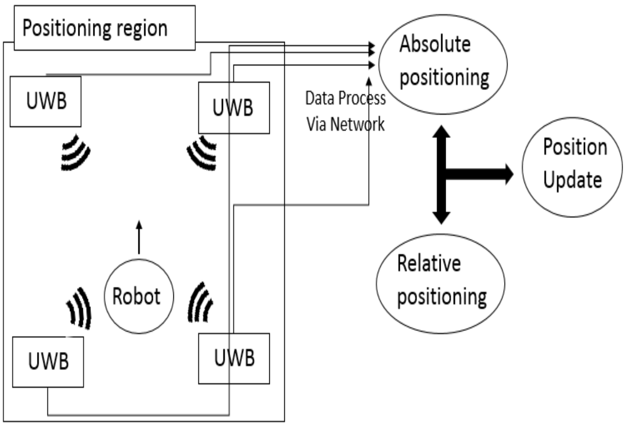


FIGURE V
Software System Interaction

C. Planning and Navigation

The previous two sections described the positioning implementations in terms of the parameters and their logical sequences up to an update of position. This update is then enhanced by adding path planning and navigation capacity to the system; it can improve the overall integrity of the system as a self-governing robot system. This step is to design and implement the robot's intelligence to move from point A to point B efficiently in a systematic manner. Point A is considered as an initial point, point B as a final destination, and the edge connecting from point A to point B is a path that needs to be designed at the path-planning stage. At the initiating stage, the BIM model environment is translated into a navigation map with representations of nodes and edges. A floor map building is shown in Figure 6. Then, the destination point is entered into the system. It is critical for the mobile robot to recognize its current position (starting position) and determine an efficient path to the destination by utilizing the map and a path planning algorithm. The map handles obstacle avoidance issues by excluding node connections between obstacles, such as walls. Also the geometry constraint in the map (e.g., walls) is integrated to the localization algorithm to improve the robot's relative position estimation based on dead-reckoning. Obstacles such as wall, human and equipment can be detected and avoided with the built-in proximity sensor including infrared, sonar and thermal sensors on the robot. The path planning algorithm is executed with a shortest path algorithm, such as Dijkstra's algorithm and Floyd-Warshall algorithm.

Shortest path algorithm basically finds a path from point A to point B that offers the smallest sum of the weights of the edges that connected the two points. In computing the point-to-point (node-to-node) distance (weight), the Euclidean distance was used as it best represented our space environments over other distance measures, such as Manhattan distance. In this robot navigation application, the Floyd-Warshall algorithm was applied due to its advantages over others; the advantages include simple implementation and simple data structure requirements. In order to realize a feasible application of

FIGURE VI
2D/3D BIM model Map Integrated with a Robot Control User-interface

this algorithm, a shortest path matrix was computed for all node connections in the beginning of the application so that the real time application extracted and used the computed point-to-point shortest distance path in the path planning phase. Another important aspect in implementing positioning algorithms is to detect and correct the errors introduced by each component. The components include the wheel encoders, digital compass within the robot system and the UWB system. The errors in each component are individually treated based on the characteristics of the errors and available correcting methods. These error analysis and correction are, however, beyond the scope of this paper, and therefore, they are not fully discussed in detail herein. Outlier removal and Kalman filter were applied to the UWB readings to handle incomplete and noisy data. Practical patterns were found and used along with the inputs from a digital compass. For dead reckoning, a uni-directional square path and a bi-directional square path were used.

D. System Hardware

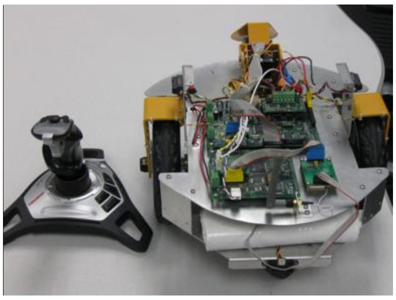
The tested mobile robot (Figure 7a) is composed of various sensors and interactive components. As discussed in the earlier sections, the focus was on the motion sensors and UWB system. Wheel encoders are attached near the wheel to measure the travelled distances. The board shown in Figure 7b is linked to a WiFi module on the robot system, which further enables data transfer and process over a configured ad-hoc local network system.

V. EXPERIMENTS AND RESULTS

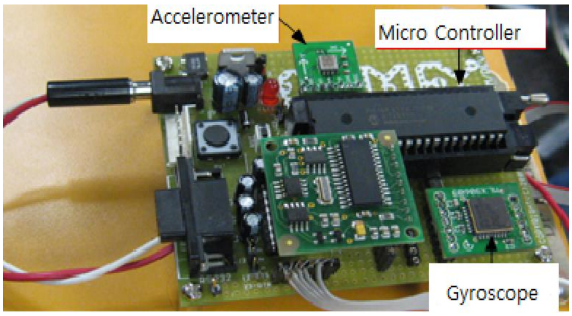
This section introduces various tests conducted to evaluate the path-planning and navigation capability of the wireless self-governing robot. First, the path-planning with an integration of BIM was examined. Then, an onsite test was conducted to validate the developed path-planning to be a feasible solution for the navigation of an autonomous robot at a building site.

A. Path Planning

This sub-section is to evaluate the path-planning solution of the system as a candidate to the solution for the use of a mobile robot unit for construction related applications. A controlled small-scale test bed with a 2 x 2 meters grid was realized as a 2D simple floor model, and the model was then turned into a map composed of nodes and edges with weights. Nodes are representations of locations, the edges are the paths, and the weight of an edge between two nodes is the travel distance between the two nodes. With a map acquired, a shortest path algorithm, as discussed previously, was applied to obtain a path for the robot. As seen in Figure 8 (a), some adjacent nodes are not connected by an edge. This disconnection was properly recognized by the map, and the shortest path algorithm found a correct path in the test. Figure 8 shows a map (a) and the corresponding path given a starting point and destination (b).

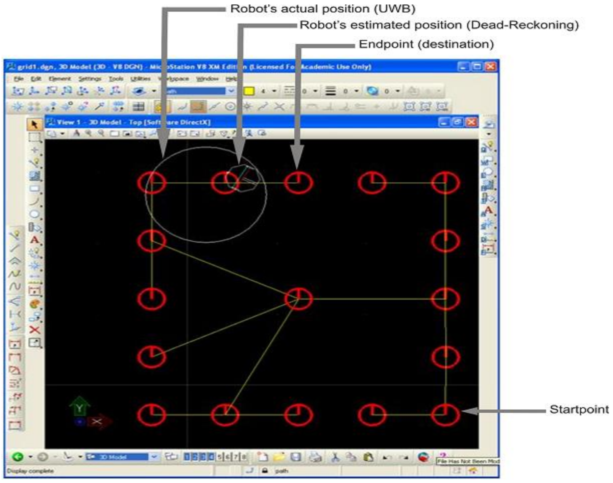


(a) Mobile Robot Platform

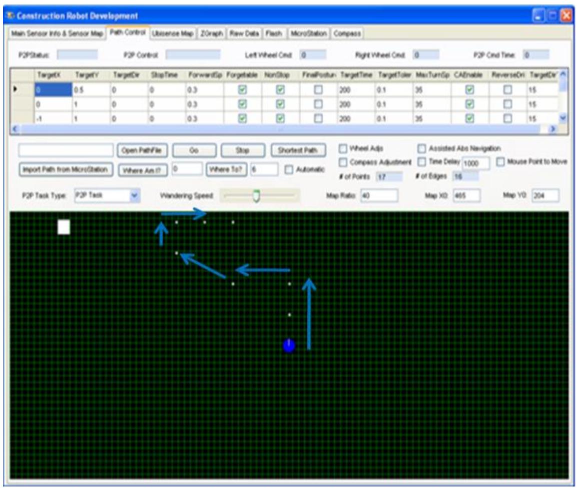


(b) Added Inertial Sensor Board

FIGURE VII
System Hardware



(a) Simple 2D map with node and edge representation



P2PStatus:
P2P Control:
Left Wheel Cmd: 0
Right Wheel Cmd: 0
P2P Cmd Time: 0

TargetX	TargetY	TargetDir	StopTime	ForwardSp	Forgetable	NonStop	FinalPostur	TargetTime	TargetToler	MaxTurnSp	CAEnable	ReverseDri	TargetDir
0	0.5	0	0	0.3	☑	☑	☐	200	0.1	35	☑	☐	15
0	1	0	0	0.3	☑	☑	☐	200	0.1	35	☑	☐	15
-1	1	0	0	0.3	☑	☑	☐	200	0.1	35	☑	☐	15

Where Am I? 0
Where To? 6
☐ Automatic
☐ Wheel Adjs
☐ Compass Adjustment
☐ Assisted Abs Navigation
☐ Time Delay 1000
☐ Mouse Point to Move
# of Points 17
# of Edges 16
P2P Task Type: P2P Task
Wandering Speed
Map Ratio: 40
Map X0: 465
Map Y0: 204

(b) Determined shortest path

FIGURE VIII
Path Planning User Interface

B. Dead Reckoning

A dead reckoning test was performed to see how accurately the movement was captured by the system as compared with the actual movement. The same test bed was used, and the robot moved along the perimeter of the 2 x 2 meters bed in a clockwise direction. Some errors were observed, but the magnitude was not significant. The errors were mainly from the wheel encoders and parameters used in estimation. The system itself may have contained some design errors. For example, the radii of the wheels may not be exactly dimensioned as designed. The distance from the wheel to wheel may also have some deviations from the design. However, these errors were corrected by calibrating the elements with errors, which was performed with the uni-directional and bi-directional square path test, as mentioned before. Figure 9 shows the test result.

C. Positioning Estimation Using UWB

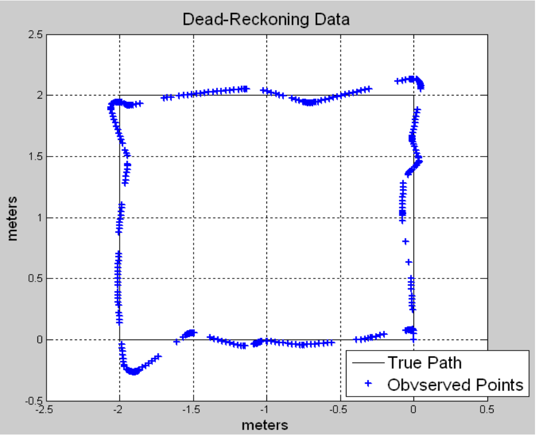
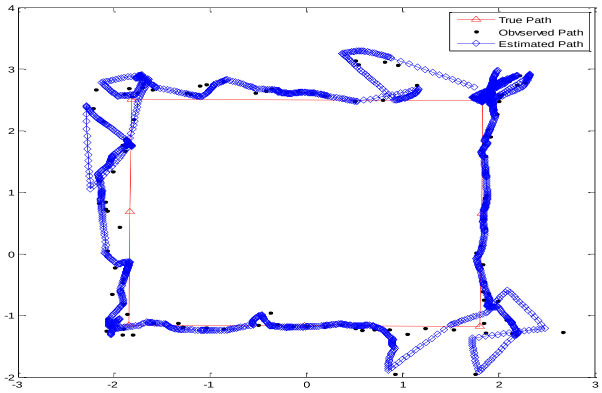


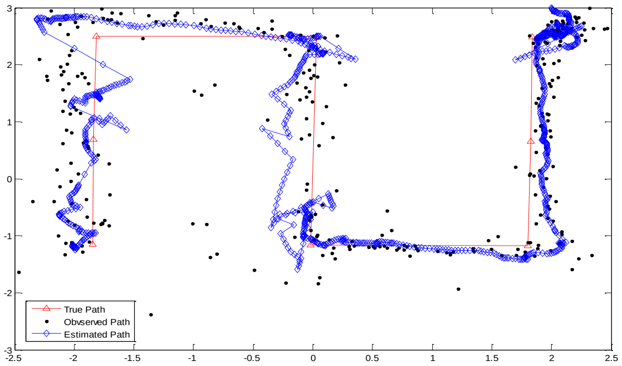
FIGURE IX
Dead Reckoning Test Result

Three different tests with the UWB sensors are presented in this sub-section to demonstrate the viability of the UWB sensors, and to show improvements made by the tested algorithms and error correction methods.

The robot moved in two different paths, and the data from the UWB sensors were collected for the two paths. These tests were conducted, and the collected data were post-processed with a Kalman filter algorithm. The results are provided in Figure 10. Improvements were observed in the both of the trials.



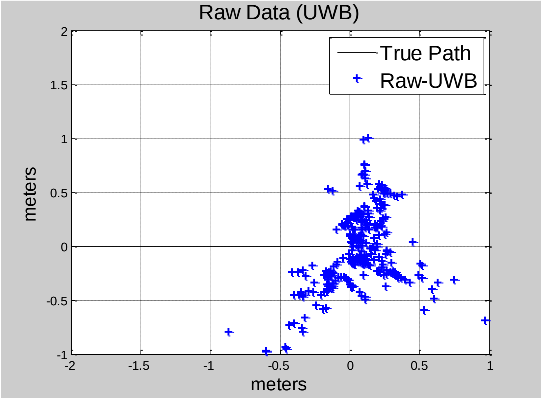
(a) Square Path



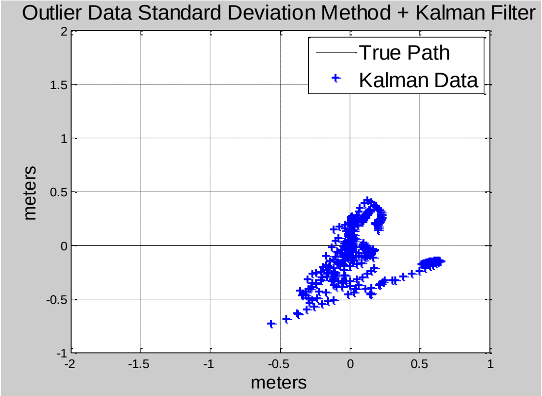
(b) S Shaped Path

FIGURE X
UWB Calibration with Kalman Fiter

For real time tests, several static and dynamic tests were performed to compare various algorithms and error correction methods to determine the most suitable combination of algorithm and error correction method. For static tests, we have tested 1) Average Data Point, 2) Outlier Removal (Rosner's method and standard deviation method), 3) Kalman Filter, 4) and combinations of 1) ~ 3). For the scope of this paper, we only present herein the best suitable method selected from our various tests. The algorithm with the Kalman filter and outlier removal using the standard deviation method provided the best solution with smallest errors. Figure 11 shows the position estimations from raw data (a) and the chosen algorithm (b). The results showed that a significant improvement was made by the chosen method with 64.9% accuracy increase in error comparison.



(a) Raw Data



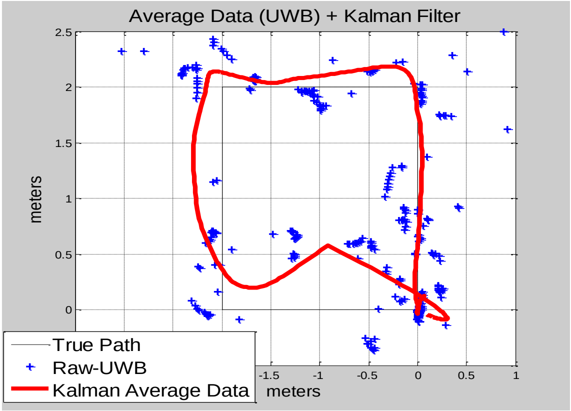
(b) Outlier removal (Standard Deviation Method) and Kalman Filter for a static position (0,0)

FIGURE XI
Static Test with UWB

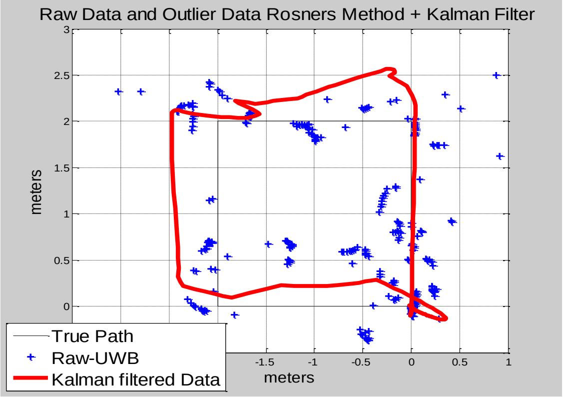
For dynamic tests, the mobile robot moved along the perimeter of a 2 x 2 meters test bed until a cycle was completed. Similar to the static tests, we have tested 1) the average data point method, 2) the outlier removal method (Rosner's method and standard deviation method), 3) Kalman Filter, 4) and combinations of 1) ~ 3). In this set of tests, two sets of the tested algorithms proved to be suitable with an acceptable level of accuracy. These utilized Kalman Filter with 1) the outlier removal using Rosner's method for one and with 2) the average data point method for the other. Figure 12 shows the true path that the robot moved along, raw estimation from UWB, and the estimation from the selected sets of algorithms. In average, the estimated path was within 50 cm from the true path.

D. Integration of the components

Finally, all of these components were integrated as one whole system. This served as a solution for a mobile robot platform in a real-time construction indoor application. Basic set-up was preceded before implementing the navigation system. It includes 1) a navigation map from a BIM model that emulates the construction work environment and 2) setting an origin for the mobile robot. Setting an origin was accurately performed with the use of a total station.



(a) Kalman Filter with Average Data Point



(b) Kalman Filter with Outlier Removal (Rosners)

FIGURE XII
Dynamic Test with UWB

Based on the origin and environment condition, the locations of UWB sensors were determined. The exact location measurements of the UWB sensors were measured and recorded into the UWB control system. When the system was launched, a navigation map was extracted into our software platform and interpreted as a map with nodes and edges with distance weights. Based on the starting point and our specified destination, a path planner was implemented to acquire a shortest path, which was used as a path that the robot moved along. The robot system then obtained the path information, which was converted to a proper layout for the wheel encoders. Last, as the robot moved, the position and orientation of the robot was updated in real time by integrating all of the positioning and navigating components, such as dead-reckoning data, UWB readings, and digital compass data. The test results show that the dead-reckoning was more reliable as a primary localization estimation method against UWB and a digital compass. Only when the drift error became greater than the predefined threshold (e.g., passing a wall component from a navigation map), the robot's position was automatically corrected based on the UWB data, and the robot successfully reached the programmed destination point.

VI. CONCLUSION AND RECOMMENDATION

This paper introduced a self-governing robot navigation system; it was developed as a wireless mobile robot system that integrated robot control units, a dead-reckoning system, a UWB platform, motion sensors, and a BIM-driven path planner solution. Various algorithms and error correction methods have been tested for each component and the whole integrated system to improve the positioning and navigation capability of the system. The research demonstrated that the path planner utilizing BIM could effectively extract an efficient path as a road for the robot, and could be executed in a real-time application for a construction environment. The introduced positioning methods with wheel encoders, UWBs, and a digital compass have potential to provide a relatively accurate navigation and positioning solution at a built environment. The system successfully demonstrated the ability to plan a path for its movement and properly navigate through the planned path to reach the specified destination. In the future research, the presented path planning system will be integrated into other tracking network protocols such as BLE beacons as a low-cost alternative compared to UWB. Further, the path planning system would be associated with potential safety issues and realistic site condition involving temporary structures within Building Information Models (BIM) [40].

REFERENCES

[1] Q. Ha, M. Santos, Q. Nguyen, D. Rye, and H. Durrant-Whyte, “Robotic excavation in construction automation,” *IEEE Robot. Autom. Mag.*, vol. 9, no. 1, pp. 20–28, 2002.

[2] S. Kang and E. Miranda, “Planning and visualization for automated robotic crane erection processes in construction,” *Autom. Constr.*, vol. 15, no. 4, pp. 398–414, Jul. 2006.

[3] U. C. B. C. E. Branch, “US Census Bureau Construction Spending Survey.” .

[4] Bureau of Labor Statistics, “Industry at a Glance: Construction.” .

[5] K. Kimoto, K. Endo, S. Iwashita, and M. Fujiwara, “The application of PDA as mobile computing system on construction management,” *Autom. Constr.*, vol. 14, no. 4, pp. 500–511, 2005.

[6] Y. S. Kim, S. W. Oh, Y. K. Cho, and J. W. Seo, “A PDA and wireless web-integrated system for quality inspection and defect management of apartment housing projects,” *Autom. Constr.*, vol. 17, no. 2, pp. 163–179, 2008.

[7] J. Park, Y. K. Cho, and K. Kim, “Field Construction Management Application through Mobile BIM and Location Tracking Technology,” in *ISARC Proceedings*, 2016, no. Isarc.

[8] J. Park, E. Marks, Y. K. Cho, and W. Suryanto, “Performance Test of Wireless Technologies for Personnel and Equipment Proximity Sensing in Work Zones,” *J. Constr. Eng. Manag.*, p. 04015049, Jul. 2015.

[9] J. Park, Y. Cho, and S. Timalsina, “Direction Aware Bluetooth Low Energy Based Proximity Detection System for Construction Work Zone Safety,” in *ISARC Proceedings*, 2016, no. Isarc.

[10] Y. Fang, Y. K. Cho, S. Zhang, and E. Perez, “Case Study of BIM and Cloud–Enabled Real-Time RFID Indoor Localization for Construction Management Applications,” *J. Constr. Eng. Manag.*, pp. 1–12, 2016.

[11] Y. Fang and Y. Cho, “Advance Crane Lifting Safety through Real-time Crane Motion Monitoring and Visualization,” in *The 6th International Conference on Construction Engineering and Project Management (ICCEPM)*, 2015, pp. 321–323.

[12] T. Bock and K. Kreupl, “Procedure for the implementation of Autonomous Mobile robots on the Construction site,” in *ISARC Proceedings*, 2004, pp. 304–309.

[13] Y.-S. Jeong, C. M. Eastman, R. Sacks, and I. Kaner, “Benchmark tests for BIM data exchanges of precast concrete,” *Autom. Constr.*, vol. 18, no. 4, pp. 469–484, Jul. 2009.

[14] N. Lu and T. Korman, “Implementation of Building Information Modeling (BIM) in Modular Construction: Benefits and Challenges (ASCE),” in *Construction Research Congress*, 2010, pp. 1136–1145.

[15] Y. Hasegawa, “Construction Automation and Robotics in the 21 St Century,” *Int. Symp. Autom. Robot. Constr.*, pp. 565–568, 2006.

[16] S. MacKenzie, A. R. Kilpatrick, and A. Akintoye, “UK construction skills shortage response strategies and an analysis of industry perceptions,” *Constr. Manag. Econ.*, vol. 18, no. 7, pp. 853–862, Oct. 2000.

[17] I. M. Srour, C. T. Haas, and D. P. Morton, “Linear Programming Approach to Optimize Strategic Investment in the Construction Workforce,” *J. Constr. Eng. Manag.*, Nov. 2006.

[18] J. Willmann, F. Augugliaro, T. Cadalbert, R. D'Andrea, F. Gramazio, and M. Kohler, “Aerial Robotic Construction Towards a New Field of Architectural Research,” *Int. J. Archit. Comput.*, vol. 10, no. 3, pp. 439–460, Sep. 2012.

[19] Y. K. Cho and J. Youn, “Wireless Sensor-driven Intelligent Navigation Robots for Indoor Construction Site Security and Safety,” in *23rd ISARC*, 2006, pp. 493–498.

[20] J. Youn and Y. K. Cho, “Portable ultra-wideband localization and asset tracking for mobile robot applications,” in *Special Issue, Ultra Wideband*, Rijeka, Croatia: Sciyo's publications, 2010, pp. 98–108.

[21] Y. Cho, C. Wang, M. Gai, and J. W. Park, “Rapid Dynamic Target Surface Modeling for Crane Operation Using Hybrid LADAR System,” in *Construction Research Congress 2014*, 2014, pp. 1053–1062.

[22] J. Park, K. Kim, and Y. K. Cho, “Using BIM Geometric Properties for BLE-based Indoor Location Tracking,” in *Seoul International Conference on Applied Science and Engineering*, 2016.

[23] D. Zhang, F. Xia, Z. Yang, L. Yao, and W. Zhao, “Localization technologies for indoor human tracking,” *2010 5th Int. Conf. Futur. Inf. Technol. Futur. 2010 - Proc.*, no. 60903153, 2010.

[24] T. Fernandes, “Indoor localization using Bluetooth,” *6th Dr. Symp. Informatics Eng.*, pp. 1–10, 2011.

[25] M. L. Sichitiu and V. Ramadurai, “Localization of Wireless Sensor Networks with a Mobile Beacon,” *2004 IEEE Int. Conf. Mob. Ad-hoc Sens. Syst.*, no. July, pp. 174–183, 2004.

[26] S. Woo, S. Jeong, E. Mok, L. Xia, C. Choi, M. Pyeon, and J. Heo, “Application of WiFi-based indoor positioning system for labor tracking at construction sites: A case study in Guangzhou MTR,” *Autom. Constr.*, vol. 20, no. 1, pp. 3–13, 2011.

[27] T. Wei and S. Bell, “Indoor localization method comparison:

Fingerprinting and Trilateration algorithm," *Rose.Geog.Mcgill.Ca*, 2006.

[28] D. Pandya, R. Jain, and E. Lupu, "Indoor location estimation using multiple wireless technologies," *14th IEEE Proc. Pers. Indoor Mob. Radio Commun. 2003. PIMRC 2003.*, pp. 2208–2212, 2003.

[29] D. S. Chiu and K. P. O'Keefe, "Seamless outdoor-to-indoor pedestrian navigation using GPS and UWB," in *21st International Technical Meeting of the Satellite Division of the Institute of Navigation, ION GNSS 2008,* 2008, vol. 1, no. September, pp. 322–333.

[30] Y. K. Cho, J. Youn, and N. Pham, "Performance Tests for Wireless Real-Time Localization Systems to Improve Mobile Robot Navigation in Various Indoor Environments," in *Robotics and Automation in Construction*, C. Balaguer and M. Abderrahim, Eds. InTech, 2008.

[31] Y. K. Cho, J. H. Youn, and D. Martinez, "Error modeling for an untethered ultra-wideband system for construction indoor asset tracking," *Autom. Constr.*, vol. 19, no. 1, pp. 43–54, 2010.

[32] K. KÜÇÜK, "Horizontal dilution of precision-based ultra-wideband positioning technique for indoor environments," *TURKISH J. Electr. Eng. Comput. Sci.*, vol. 22, no. 5, pp. 1307–1322, Sep. 2014.

[33] J. Park, Y. K. Cho, and C. Ahn, "Wireless Tracking System Integrated with BIM for Indoor Construction Applications," in *Proceedings of The 2016 Construction Research Congress (CRC)*, 2016.

[34] I. Guvenc, "Enhancements to RSS Based Indoor Tracking Systems Using Kalman Filters," *Ieee Pervasive Comput.*, no. 505, pp. 91–102, 2003.

[35] A. LaMarca, Y. Chawathe, S. Consolvo, J. Hightower, I. Smith, J. Scott, T. Sohn, J. Howard, J. Hughes, F. Potter, J. Tabert, P. Powledge, G. Borriello, and B. Schilit, "Place Lab: Device Positioning Using Radio Beacons in the Wild," *Pervasive Comput.*, vol. 3468, pp. 116–133, 2005.

[36] M. Kuhn, C. Zhang, and B. Merkl, "High accuracy UWB localization in dense indoor environments," *Ultra-Wideband, 2008. ICUWB 2008. IEEE Int. Conf.*, vol. 2, pp. 129–132, 2008.

[37] F. Subhan, H. Hasbullah, and K. Ashraf, "Kalman filter-based hybrid indoor position estimation technique in bluetooth networks," *Int. J. Navig. Obs.*, vol. 2013, 2013.

[38] A. Diosi and L. Kleeman, "Laser scan matching in polar coordinates with application to SLAM," *Intell. Robot. Syst. (IROS 2005). 2005 IEEE/RSJ Int. Conf.*, 2005.

[39] M. Bosse and R. Zlot, "Map matching and data association for large-scale two-dimensional laser scan-based slam," *Int. J. Rob. Res.*, vol. 27, no. 6, pp. 667–691, 2008.

[40] K. Kim and Y. Cho, "BIM-Based Planning of Temporary Structures for Construction Safety," *Comput. Civ. Eng. 2015*, 2015.