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Portable ultra-wideband localization and asset tracking for mobile robot applications

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1. Introduction

This chapter introduces our on-going research at the Peter Kiewit Institute, Omaha, Nebraska, to investigate the performance of Ultra-Wideband (UWB) localization technologies that can be applied to sensor-aided intelligent mobile robots for high-level navigation functions for construction site security and material delivery.

Security at construction sites, especially in the commercial construction industry, is a widespread problem. Construction site can be jeopardized by thieves and vandals, which can cause job delays, downtime for operators, higher insurance premiums, possible cancellation of insurance policies, and diminished profitability of projects under construction (Berg & Hinze, 2005). The U.S. construction industry lost nearly $1 billion in 2001 due to theft of equipment and tools, according to the National Insurance Crime Bureau (McDowall, 2002), and the annual insurance claims in Canada represent theft losses of more than $46 million (Mechanical, 1999). McDowall (McDowall, 2002) reported that 90% of the equipment and tool thefts occur on job sites with little security and where assets remain unattended over the weekends or holidays. A typical construction site turns into a "ghost town" after 4 or 5 p.m., which often makes it vulnerable to theft and vandalism. Interestingly, research has shown that the majority of theft and vandalism incidents are not caused by strangers, but rather by individuals familiar with the jobsite (Gardner, 2006).

Unlike fixed facilities, tracking the location of mobile assets in a dynamic indoor environment is not an easy task. Emerging technologies such as mobile devices and wireless technologies have already demonstrated the capability of identifying the location of mobile assets. However, the penetration of these technologies into indoor building environments has been limited, especially in highly congested areas with room partitions, metal structures, furniture, and people. In this chapter, we present the results of our experimental investigations on the accuracy of an Ultra Wideband (UWB) system for tracking mobile assets in various indoor environments and scenarios. We also demonstrate the integration of a UWB tracking technology into a path planning system of mobile robots for improved navigation.

2. Mobile Robot Platform and Graphical User Interface

In order to operate independently and effectively, a robot must be able to autonomously explore its own space. Autonomous navigation is the ability of a wheeled mobile robot system to purposefully steer its course through a physical medium with the knowledge of where it is, other places it might want to go, and paths it would take to get there safely. Therefore, the precise position information of the robot is a key to the development of an autonomous navigation system.

2.1 Issues in indoor localization of mobile robots

Autonomous navigation is one of the most basic behaviors needed in many applications and especially in mobile robotics. However, it is quite challenging since mobile robots are plagued with communication problems. Wireless communications between a robot and an operator suffer from multi-path interference, signal loss, and non-Line of Sight (NLOS) as a robot penetrates deeper into an unknown environment (Farrington, 2004).

Localization is a major area of mobile robotics and sensor-based exploration enables a robot to localize its position, explore an environment and build a map of that environment using sonar sensors, a laser rangefinder, and a 3D laser sweeper. However, these technologies require a line of sight to register the robot's location in a map, which limits its applicability to open space only.

In this study, five mobile robot platforms were obtained from Dr. Robot Inc. (Dr. Robot, 2010). The robots were not rugged enough for real-world applications, but they were sufficient enough to represent wireless robots for the purpose of control algorithms and graphical user interface development in our testbed. As shown in Fig. 1, each robot was equipped with six ultrasonic range sensor modules, nine infrared distance measuring sensors, two wheel encoders, and two human detect/motion sensors detecting infrared energy radiation from human bodies within a 5-meter range. A camera, microphone and speaker were installed on each robot. The camera system has a color image module with a mini-color camera head which is a CMOS image sensor module that can be connected directly to its multimedia controller board. The image size and frame rate can be up to 353x288 pixels and 15fps respectively.

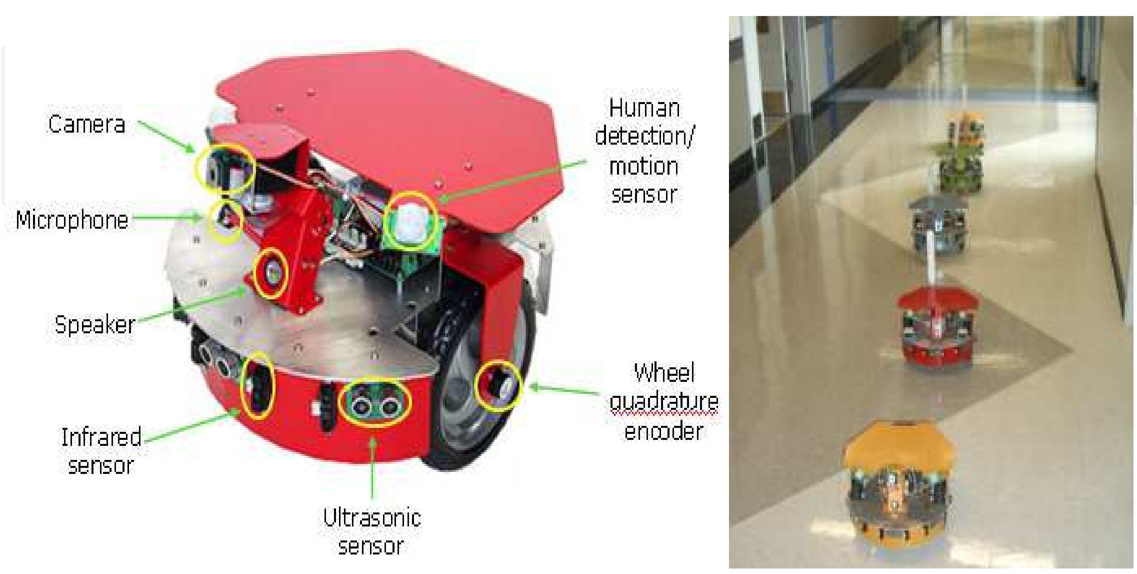


Fig. 1. Mobile robot sensor systems

Each robot was assigned with its own IP address. With its integrated WiFi 802.11 wireless module, the system can transmit all sensor data to a PC or server. Commands and data can be also sent to the robots via the same wireless link for real-time control and access. In this study, the robot control program was programmed to manually or autonomously maneuver around the building while avoiding static or mobile obstacles using the aforementioned sensors. Fig. 2 shows the robot control and communication architecture.
AutoCAD™ and Microsoft Visual Studio were used to develop a graphical user interface (GUI) for multi-robot control. Theoretically, one can determine the (x, y) coordinates of the robot using dead-reckoning, a process that determines the robot's location by integrating data from wheel encoders that count the number of wheel rotations. However, in general, dead reckoning fails to accurately position the robot for many reasons, including wheel slippage. If the robot slips, the wheel rotation does not correspond to the robot's motion and thus encoder data, which reflects the state of the wheel rotation, do not reflect the robot's net motion, thereby causing positioning errors (Choset & Nagatani, 2001). In addition, each robot's wheel encoders need to be calibrated to their respective control programs. According to the results of our experiments at PKI using the mobile robot platform shown in Fig. 1, deadreckoning showed about 35cm positional error when the robot traveled about 7 meters, mainly due to a built-in inconsistent rpm for each wheel motor which tended to cause curving paths even for a straight movement command (Cho et al., 2007).

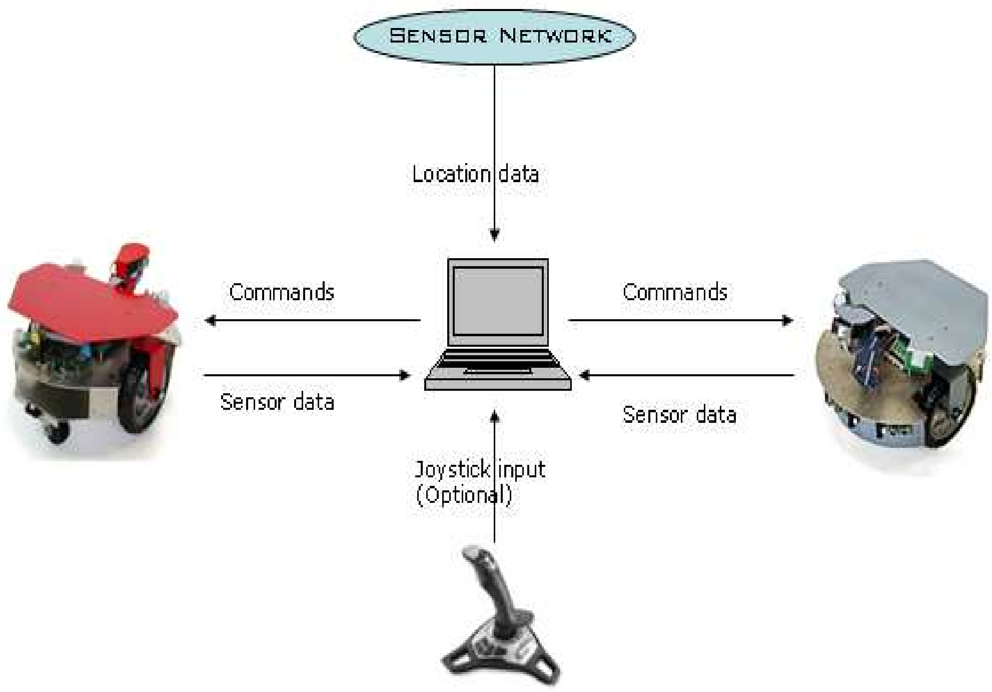
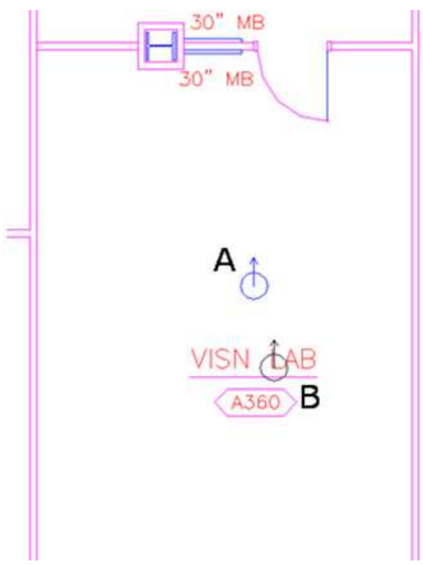


Fig. 2. Wireless robot control system architecture within a UWB sensor system

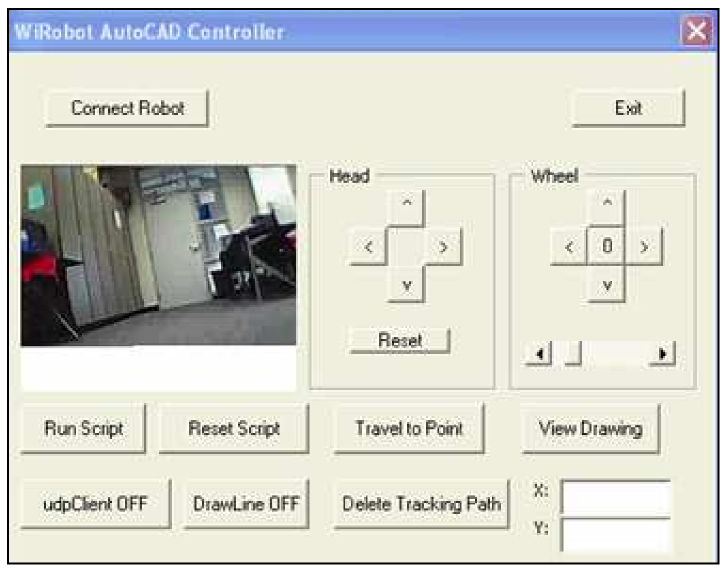
2.2 Real-time graphical user interface (GUI) for mobile robots

In this study, software modules for a robot control and a UWB position tracking were developed, which can be easily imbedded into standard CAD programs such as Microstation (Microstation, 2010) and AutoCAD (AutoCAD, 2010). Since most of the building construction projects already have either 2D or 3D CAD floor drawings available,

the developed modules can save enormous amounts of time in generating a new graphical user interface when applied to different building applications.
Integrated with the GUI, the robot's actual location and orientation is displayed on the CAD building map. Once sensor data is received from wheel encoders, the robot's location is displayed to the GUI in real time. Simultaneously, another position symbol is displayed based on position data received from the UWB location system. Fig. 3 (a) shows a dead reckoning position as a capital letter *A* and a UWB sensor network position as a capital letter *B*. The UWB position is referred as a phantom of robot since the sensed position may rapidly change and move around the dead reckoning position within its position accuracy range even when the robot does not move. Fig. 3 (b) shows a visual representation of the robot's control interface.



(a) Robot's dead reckoning position (A) and UWB position (B)



(b) Real-time robot control GUI

Fig. 3. GUI showing the robot's position along with a robot control program.

3. Accuracy of Ultra-wideband (UWB) Positioning Systems

In this study, a commercial UWB system developed by Ubisense (Ubisense, 2010) was used for implementation and performance analysis in several building spaces. The hardware of the ultra-wideband sensor network consists of tags and sensors. A tag is attached to an object that requires location tracking. As each tag emits an UWB signal, location is calculated using both the time difference of arrival between different sensors (a.k.a., receivers) and the angle of arrival at each sensor. Each sensor employs a minimum of four UWB receivers which allow the angle of arrival to be determined (Ubisense, 2010).
The standard UWB configuration consists of a single master sensor and three slave sensors, and requires wired communication cables and timing cables. In order to properly calculate the time of arrival, each slave sensor must synchronize with the master sensor. In the standard configuration, this is done through timing cables between each slave sensor and the master sensor. The Ubisense system spans 5.8-7.2 GHz bandwidth. The system measures time of flight and angle of arrival using directional antennas.

In the next sub-sections, we present our experimental results of the UWB positioning system. To evaluate the sensitivity of multi-path signal problems, the accuracy of UWB sensors was tested in an open space as well as a closed space.

3.1 Open space test

The open space test was conducted in a local building's basement. Four sensors were mounted on tripods and multiple known positions were marked on a floor. Then, a total station was used to get the (x, y, z) position of the sensors and the points on the floor. Fig. 4 shows the surveyed positions of the sensors (402-405) and points on the floor (400, 1000-10013). A UWB tag was then placed on each marked point on the floor to measure the accuracy in difference in distance between a surveyed known position and a wirelessly estimated tag position. The four sensors can cover about 400 square meters.
The obtained average accuracy of the open space test was 19.1cm when the UWB tags were placed on the floor. When the tag was raised by 35cm from the floor level, there was a slight accuracy improvement (1.7 cm) for most of the central points (1001, 1004, 400, 1009 and 1012), as shown in Fig. 4. However, there was a significant accuracy improvement by 13.5 cm for the outermost points (1000-1002 and 1011-1013) when the tag was raised by 35 cm. The results of our open space test verify that, in order to accurately determine a tag position, a multiple number of receivers (typically three) must have a direct line-of-sight or at least a strong attenuated line-of-sight transmission path (Fontana 2003). In particular, the receiver did not catch a signal from the tag when the tag was located just below the receiver. Therefore, it is recommended to install the receiver as high as possible from the floor and face down to cover a large area of the space.

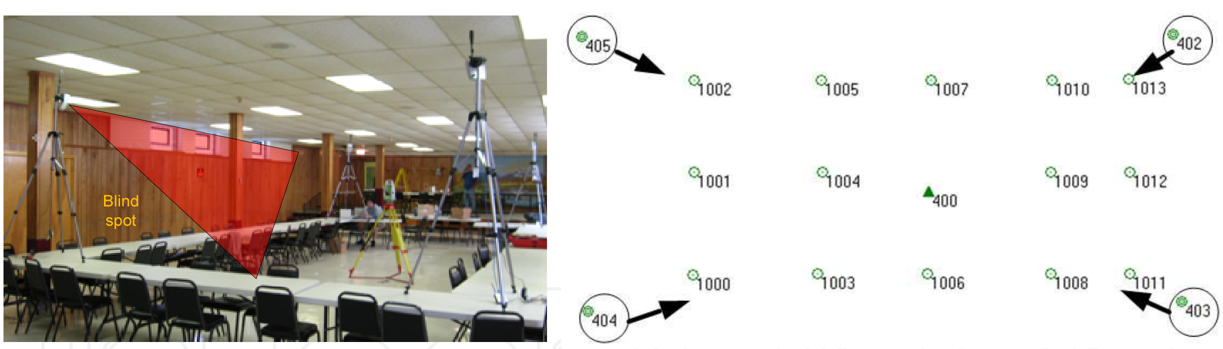


Fig. 4. Open space test in a basement (up) and test area layout (down)

3.2 Closed space test

To conduct a closed space test, an office area of the Peter Kiewit Institute (PKI) at the University of Nebraska-Omaha was selected. The PKI building was the most challenging environment in which to test the UWB system because the building (1) was built with steel frames and metal studs, (2) was furnished with all metal furniture and electronics such as printer and copy machines, and (3) had computer electronics and wireless telecommunication labs nearby the test area which may cause interference with the UWB communication system. In addition, heavy people traffic in this area also negatively impact on the accuracy of the positioning system, since human bodies can absorb wireless signals. Especially, 5.8 GHz cordless phones should be turned off before testing the UWB system because 5.8 GHz phones may significantly interfere with signals from the UWB positioning system which uses 5.8-7.2 GHz frequency bands.

Fig. 5 shows the test area layout with four receiver positions (left) and measured tag positions (marked "+" in the right figure of Fig. 5). The first set of tests was conducted by placing a tag at the floor level. Then the tag was raised by 104 cm for the second test set. Each set of tests was conducted twice. The average of floor level (0 height) tests showed 41 cm accuracy. When the tag was raised by 104 cm, the test showed 48cm accuracy. Unlike the previous open space test which used a stand to raise the tag position, the tag was carried by a human subject in the closed space testbed. Although it was identified that a higher position of the tag showed better accuracy to improve the line-of-sight transmission path, it was noted in the closed space test that the human carrier significantly affected the accuracy based on its orientation.

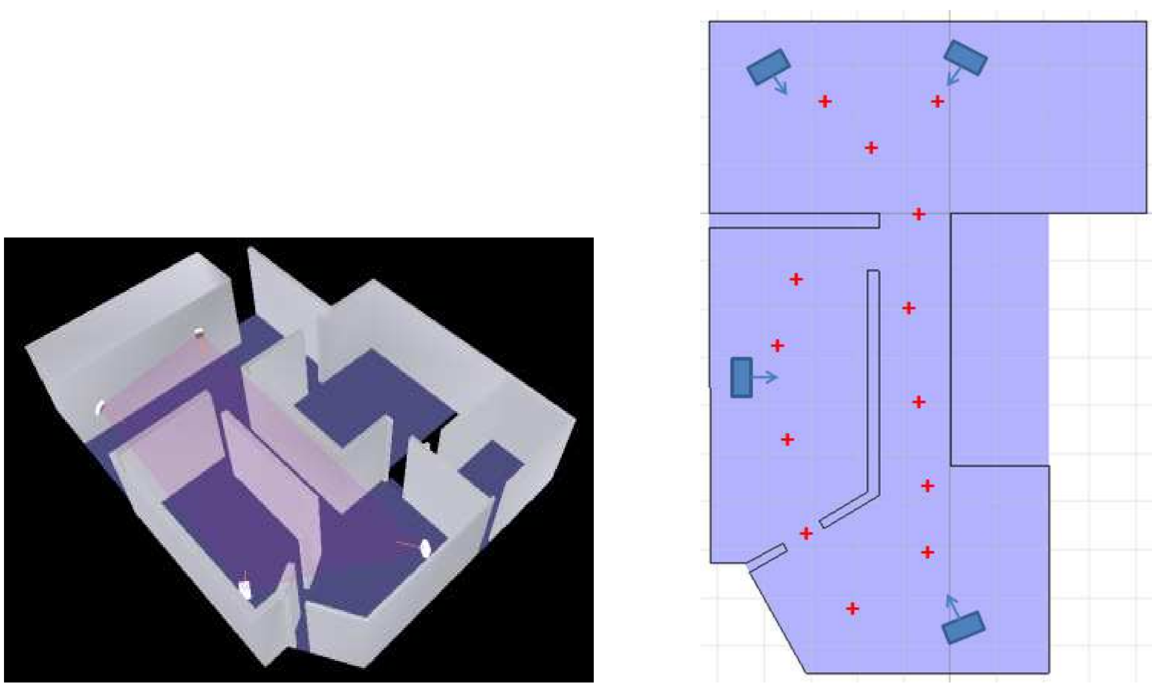


Fig. 5. Closed space test area layout (left) and data points (right).

4. Integration with Ultra-wideband (UWB) Positioning Systems

As mentioned earlier, many outside factors such as wheel slippage can have an adverse effect upon dead reckoning values, which make the technique unreliable. For example, often a robot's infrared and ultrasonic sensors do not recognize thin-leg chairs, and a robot may get stuck in one place while the wheels are still running. This means that the dead reckoning position keeps changing in the GUI while reality does not. Therefore, a more effective method of position tracking and movement control is required.

To remedy this situation, the position information was integrated into the navigation algorithm in this study. If the dead reckoning position is beyond the precision range of the UWB positioning system, the path planning algorithm adjusts the robot's position based on the recent samples of UWB location data.

4.1 Portable Ultra Wideband Positioning System

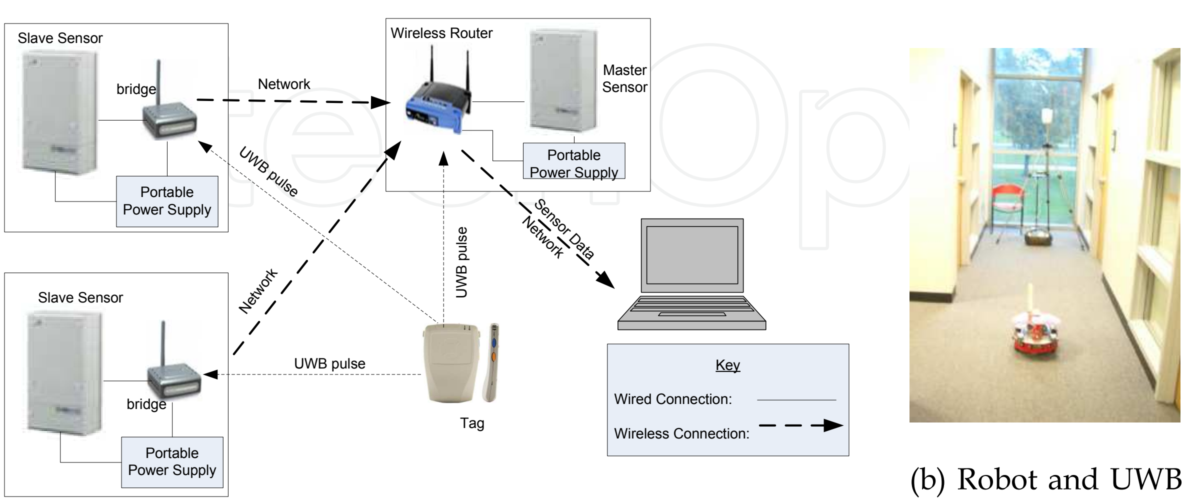
The basic UWB positioning system consists of a single master sensor and three slave sensors, and requires wired communication cables and timing cables. In order to properly calculate the time of arrival, each slave sensor must be synchronized with the master sensor. In a standard configuration, this is done through timing cables between each slave sensor and the master sensor. However, a dynamically changing environment may not have a wireless infrastructure installed yet. For example, in a construction site, determining a fixed location (e.g., ceiling, wall, and column) for UWB sensors is not an easy task in the middle of construction unless the construction is near completion, because the surface should be finished before a sensor node is attached to it.

To apply this technology at dynamic sites, we decided to design a stand-alone wireless UWB configuration for each sensor which can be easily relocated as needed. In order to remove the Ethernet cables, each slave sensor is connected to a wireless bridge, and the master sensor is connected to a wireless router. The wireless router provides a gateway through which a laptop is able to access sensor readings. Furthermore, the software configuration of the UWB sensors is changed to synchronize them via wireless channels. The untethered configuration of the Ubisense positioning system is shown in Fig. 6.

In the proposed system, the communication between the UWB sensors and a laptop is also performed wirelessly through the 802.11 network, and each UWB sensor drains power from a portable battery in order to operate. The sensors are mounted on tripods which allows for easy transport and deployment. In addition, each sensor is connected to a wireless bridge which is then connected to the laptop. The laptop transmits the boot files to the sensors, allows the user to configure the system's behavior and collects position information.

After surveying the relative coordinates of four UWB sensors using a total station, we are able to track a tag by collecting and analyzing the received wireless signals from the tag. This position data is produced by the estimation of UWB signals between sensors on tripods and a tag placed on a mobile robot.

The relative local values from the UWB sensors are reconciled with the global drawing coordinate system by allowing the user to specify the origin (0, 0, 0) of the sensor network on the drawing during operation.



(a) Architecture of the portable UWB system

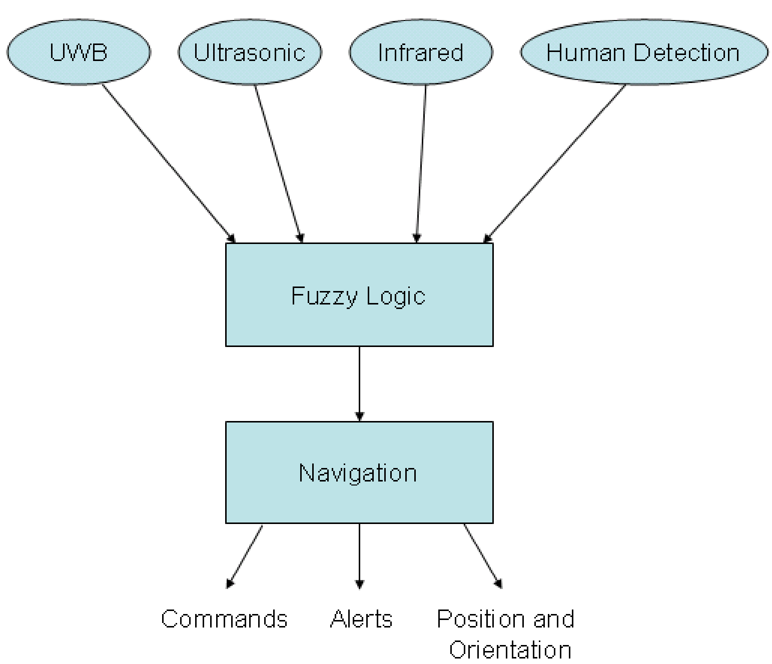
(b) Robot and UWB sensor on a tripod

Fig. 6. A proposed portable UWB tracking system architecture

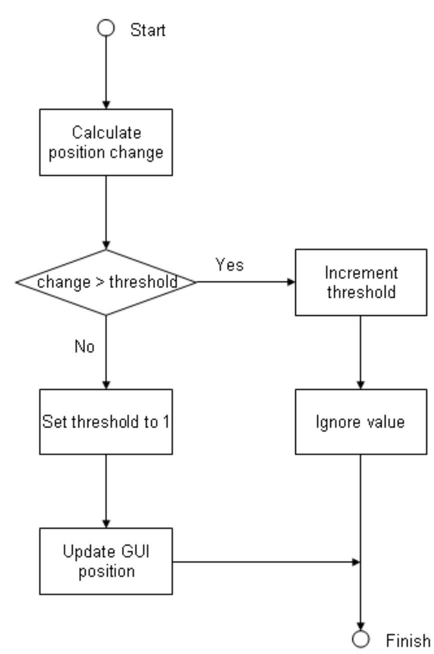
Location values are collected as a relative (x, y, z) coordinate on a per request basis. Each robot is assigned a tag. The location of the robot is updated when the controller sends a request for the location of a particular tag. Multiple robots using multiple tags are able to operate simultaneously.
Unfortunately, the UWB sensors come with some difficulties in setup and configuration. Configuring the system from a tethered to untethered system requires a great deal of experience and knowledge of the wireless connections between sensors and a controller. One of the main limitations of the UWB system used in this study is that the system suffers from interference from IEEE 802.11a wireless local networks and 5.8 GHz cordless phones.

4.2 Path finding and planning algorithm

Accurate sensor data is vital for the object avoidance algorithm and position reporting. Any incorrect sensor values will create inconsistent robot behavior and/or location reporting. As mentioned earlier, we are currently investigating a fuzzy logic model for cleaning up the noisy readings because each sensor reading is, by itself, unreliable. Fig. 7 shows a fuzzy logic model which will be developed in the course of this study.
Rather than defining specific slow and stop distances for ultrasonic and infrared sensor values, we create membership functions for far, medium, and near which map to a truth value between 0 and 1. Using these truth values, our navigation model can appropriately change speed or halt the robot.
Our filtering model also performs simple checks such as comparing incoming sensor values against their pre-defined minimum and maximum thresholds to ensure they are within bounds. For example, location data from the UWB sensors are checked using the robot's maximum speed of 1 meter/second as the greatest possible change in position. If an incoming positioning value indicates that the robot is traveling more than several meters per second, the value will be ignored. The flow chart of the algorithm can be seen in Fig. 7 (b).



(a) Fuzzy logic and navigation



(b) Fuzzy logic flow chart

Fig. 7. Path planning and fuzzy logic

The path planning algorithm is divided into two levels. The first is reaction control which handles avoiding obstacles not present in our drawing. This level also uses human detection readings to avoid and/or report human presence. If human presence is detected, the robot controller would send an alert to the user and stop any current movement so the user could intervene and act appropriately.
The second part is the rail-based movement control scheme. Fig. 8 shows the rail paths deployed in the AutoCAD™ graphical user interface (GUI). To construct this network of rails, a graph of points and lines is added to the CAD drawing. A line follows the center of each hallway with points on this line perpendicular to doorways. Lines then connect this hallway point with a point within the room at each door. Here, a well-known all-to-all shortest path algorithm, Floyd-Warshall's algorithm (Cormen et al., 1990), is used to pre-compute the shortest path from room to room or to the hallway along the rails graph. When the user selects a start and end point, the robot is guided to the starting point and follows the rail paths of the graph along the shortest route to the end point.

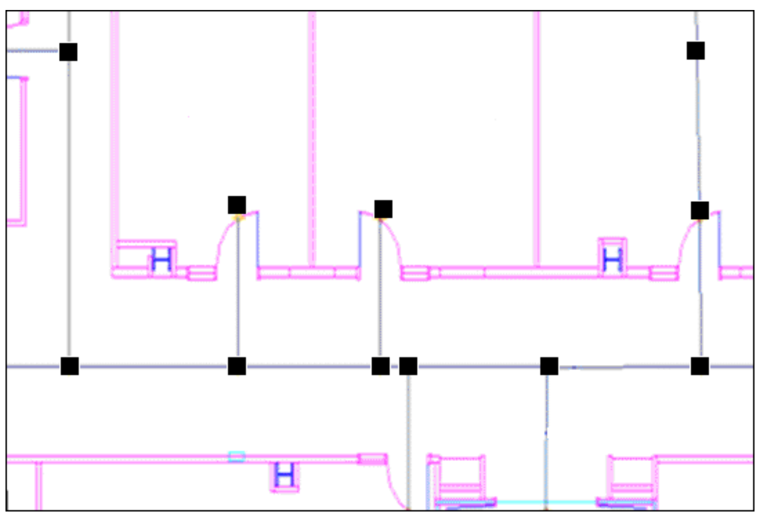


Fig. 8. Rail paths

4.3 Positional error analysis

A preliminary positional error test has been conducted to verify the accuracy of a fully-untethered UWB configuration. Fig. 9 displays the test results. Using the Pythagorean Theorem, positional errors are computed by comparing known points (x, y, z) with points reported from the UWB system. Category 1 describes the error for the fully wired configuration of the UWB setup, Category 2 describes the results of wireless communications using wireless bridges (with synchronization via wired timing cables), and Category 3 describes the results of the fully-untethered configuration with wireless bridges.
Table 1 summarizes the analyzed average positional errors shown in Fig. 9. The fully untethered configuration yielded higher errors than the other two configurations, although 35.6cm is a still acceptable level of accuracy for this study's application. UWB sensors provide positional data that are sufficiently accurate for the robot navigation, but require additional time and effort to set up properly. Since the range of sensors restricts the range of the robot, additional sensors may be added to the network cell to increase range and accuracy. Once the robot moves outside of the sensor network cell, the robot controller

application must recognize this and attempt to return the robot to the sensor cell, if necessary for that scenario.

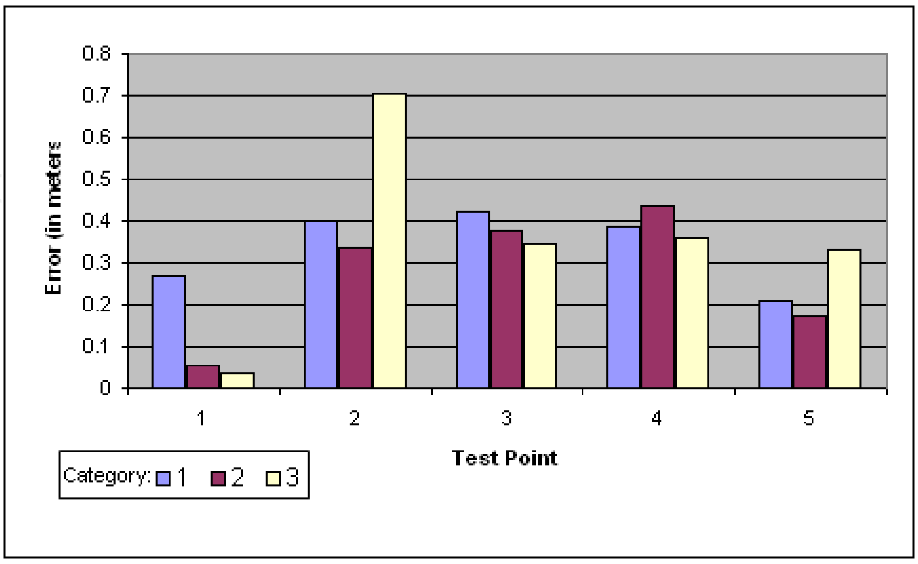


Fig. 9. Error over five positions

Configuration	Error (cm)
Standard (Category 1)	26.3
Wireless bridges (Category 2)	27.5
Untethered with wireless bridges (Category 3)	35.6

Table 1. UWB average error

The proposed rail-based movement algorithm may provide a simple way to implement the method of end-to-end path traversal, but it has some problems that must be addressed. For example, the controller must be able to identify if an obstacle is blocking one of the points on the graph in its path and react appropriately.

5. Conclusion and Future Work

According to the results of our experimental study, the accuracy of the UWB position system depends upon several factors, including precise knowledge of all receiver and reference tag locations. Absolute tag position accuracy of better than 19 cm has been demonstrated in an open space and 48 cm for a closed space. It is recommended that the receiver be located as high as possible to cover a larger area. Also, it is important to strategically select the direction of the receiver and have a minimum of one set of line of sight between a receiver and a tag in any location, which can significantly affect a tag's position accuracy.

This chapter also presented a methodology for autonomous end-to-end navigation of mobile wireless robots for automated construction applications when the working environment is known a priori. As an on-going research effort, this study investigates methods to determine position and direction along with a process to detect and avoid incorrect sensor values. The key advantages of the proposed approach are: (1) this approach is a fully untethered self-powered ad-hoc wireless networking system which is mainly designed for construction sites or locations where communication infrastructure may not be installed, and (2) the developed position tracking and robot control software modules can be easily imbedded into a standard CAD package (e.g., AutoCAD, Microstation), thus reducing computational burden on developing a new graphical user interface (GUI) for different building applications.

Future challenges include minimizing UWB errors caused by reflection from metal obstacles, maximizing the battery lifespan of the tags, rectifying orientation errors produced by a digital compass when interfering with surrounded magnetic objects, and developing effective dynamic pathing algorithms which best coordinate location data, robot sensor data, and floor plan information.

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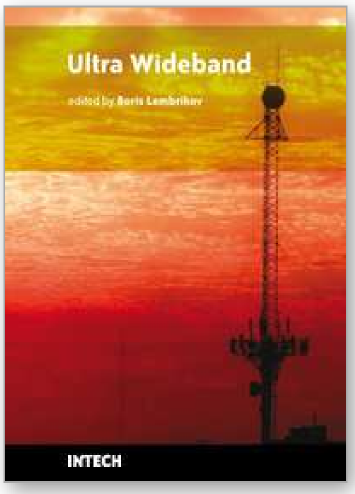

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Ultra wideband technology is one of the most promising directions in the rapidly developing modern communications. Ultra wideband communication system applications include radars, wireless personal area networks, sensor networks, imaging systems and high precision positioning systems. Ultra wideband transmission is characterized by high data rate, availability of low-cost transceivers, low transmit power and low interference. The proposed book consisting of 19 chapters presents both the state-of-the-art and the latest achievements in ultra wideband communication system performance, design and components. The book is addressed to engineers and researchers who are interested in the wide range of topics related to ultra wideband communications.

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