Wireless Sensor-driven Intelligent Navigation Robots for Indoor Construction Site Security and Safety

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Abstract: This paper introduces an on-going research effort at the Peter Kiewit Institute (PKI) at Omaha, Nebraska for developing sensor-aided intelligent mobile robots that provide high-level navigation functions for indoor construction site security and safety using wireless sensor networking (WSN) technology. The ultimate goal of the research is the complete integration of the sensor-equipped robots into the WSN system to visualize sensed data information into 3D graphical control interface for advanced planning and execution against any anomalies that have been detected in warehouses, office buildings, manufacturing facilities, and various construction sites - everywhere there's a need for advanced frontline security.

Keywords: mobile robot, CAD, wireless sensor network (WSN), security, position tracking

1. INTRODUCTION

Security on construction sites especially in the commercial construction industry are a big problem. The achievement of the project objectives can be jeopardized by thieves and vandals which can directly impact the success of a project with job delays, downtime for operators, higher insurance premiums, possible cancellation of an insurance policy, and diminished profitability of the project being constructed [1]. The construction industry in the United States lost nearly $1 billion in 2001 because of the theft of equipment and tools, according to the National Insurance Crime Bureau [7]. In Japan more than 1,000 construction machines were stolen in 2001 [10] and the annual insurance claims in Canada represent theft losses that total more than $46 million [8]. McDowall [7] reported that 90% of the equipment and tool thefts occur on job sites with little security and where these assets remain unattended over the weekends or holidays. Also, a typical construction site turns into a "ghost town" after 4 or 5 p.m. and this often makes it vulnerable to theft and vandalism. Interestingly, research has shown that the majority of theft and vandalism incidents are not done by strangers, but rather by individuals familiar with the jobsite [5]. In this paper, therefore, this study will introduce advanced security technologies which can be applied to after-hours construction sites.

A small force of guards patrolling an area with flashlights and batons, on the lookout for trouble was a model that worked well enough over the years in the past. Today, the convergence of intelligent sensors, embedded systems, streamlined remote control mechanisms and applications promise to reduce the risk as well while tightening security. Instead of using sensors fixed to one location such as motion detector, window-break detector, and surveillance cameras which are limited to their built-in sensing ranges, it would be far better to use remotely controlled robots to patrol the area, spot anomalies, and notify security personnel over a wireless network or via a hand held, PDA-like device, which are all possible and available technologies now [11]. For this reason, there have been several efforts to develop mobile robots equipped with various sensors for military and public security and surveillance applications.

While several mobile robot products are available on the market, in this study, we used off-the-shelf mobile robot platforms which were manually controlled with equipped Wireless Fidelity (WiFi) network devices. More sensors were added and some of hardware devices were modified in this study. Also, sensor-integrated advanced manual control and autonomous navigation functions were developed. Unlike battle field or unknown region exploration applications, in this study, the operating environment is known a priori, is normally under friendly control, and can to some degree be tailored to support robotic operations. From the following sections, mobile robot position accuracy issues, graphical user interface development, and applied wireless sensor networking (WSN) technology will be mainly discussed.

2. Mobile Robots

In order to operate independently and effectively, a robot must be able to autonomously explore its own space. Autonomous exploration is a recursive process that utilizes the relationship between sensing and movement of the robots through a map whose success depends on the quality of the coupling between sensing, map building map and navigation [6]. However, mobile robots are plagued with communication problems while tethered robots are physically hampered when going around corners or running over their own tether, which causes entanglement, stretching, or breaking. 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 [4].

2.1 Issues in indoor localization of mobile robots

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, laser rangefinder, and 3D laser sweeper [3][10]. However, these technologies require line of sight to register robot's location in a map, which limits its applicability to open space only.

Figure 1. Five mobile robots navigating a hall way

For this study, five mobile robot platforms were obtained (Figure 1)[3]. The robots may not be rugged enough for real-world applications, but they were sufficiently enough to represent WiFi field robots for the purpose of control algorithm and graphical user interface development in our testbed. 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 5-meter range. Also, camera, microphone and speaker are installed to each robot (Figure 2). 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 to robot's multimedia controller board directly. The image size can be up to CIF format (353x288) and the operation frame range up to 15fps.

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 the building while avoiding static or mobile obstacles using aforementioned sensors. Figure 3 shows robot's control and communication architecture.

Figure 2. Mobile Robot Sensor Systems

AutoCAD™ and Microsoft Visual Basic 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, generally dead-reckoning fails to accurately position the robot for many reasons, including wheel slippage (Figure 4). 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, does not reflect the robot's net motion, thereby causing positioning error [2]. Besides, each robot's wheel encoders needed to be calibrated into the control program respectively.

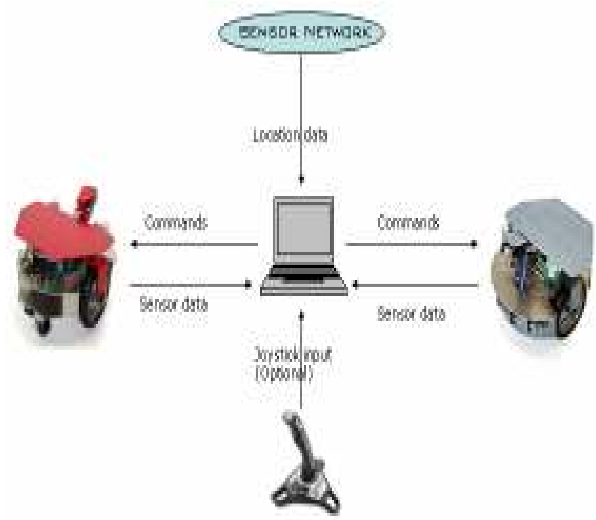

Figure 3. WiFi robot control system architecture within a WSN system

2.2 Path finding algorithm

Since the environment is known a priori, as one of the approaches, the paths were assigned to room to room or to hallway using the shortest path graph theory also known as Floyd-Warshall algorithm in computer science. Figure 5 shows the paths deployed in AutoCAD™ graphical user interface (GUI).

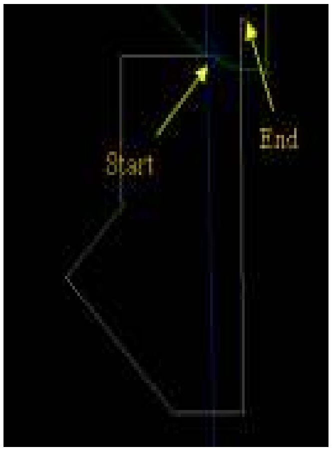

Figure 4. Dead-reckoning accuracy test

A global positioning systems (GPS) offers an alternative to dead-reckoning, but have inefficiency in indoor applications as well. In this study, a prototype of wireless networking real-time indoor position tracking system was applied which was developed and currently being tested at the Peter Kiewit Institute (PKI) at Omaha.

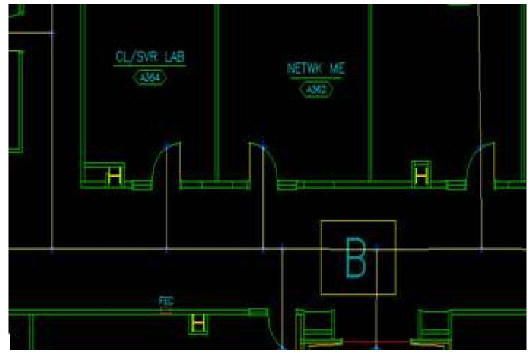

Figure 5. Pre-defined robot paths in GUI

3. Wireless Sensor Networking (WSN) Environment

3.1. WSN test bed

Landmarks (a.k.a. sensor nodes, beacons, access points) using the WSN technology with known locations (x,y,z) was deployed on the third floor of PKI building (See Figure 6). The current system uses Radio Frequency (RF) operating at 2.4 GHz bandwidth.

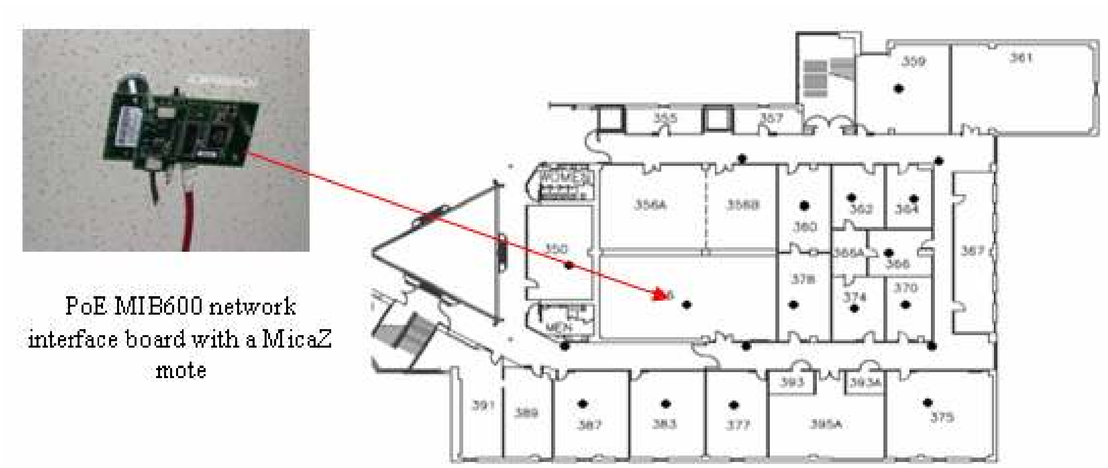

Figure 6. Current map of sensor deployment at the Peter Kiewit Institute (PKI)

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

A GUI was developed to control robots while receiving sensor data from WiFi robot and WSN nodes (Figure 7). Integrated with the GUI, robot's actual location and orientation is displayed in the CAD building map. Once sensor data was received from wheel encoders, the robot's location was displayed to the GUI in real time. Simultaneously, another position symbol was displayed based on position data received from the WSN nodes. Figure 8 shows a dead reckoning position as a capital letter A and a sensor network position as a capital letter B. The sensor network position was referred as a phantom of robot since the sensed position rapidly changed and moved around the dead reckoning position within its position accuracy range even when the robot did not move.

Figure 7. Real-time robot control GUI

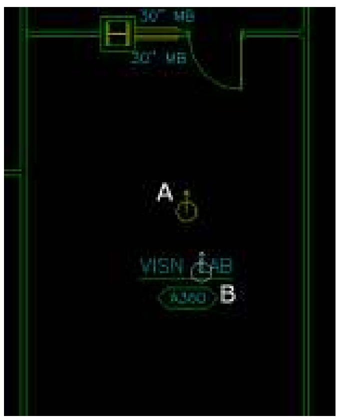

Figure 8. Robot's dead reckoning position A and WSN position B

3.3. Alarming System
Using human detection/ motion sensors which has 5 meter range, suspected intruder's location can be mapped to the GUI while simultaneously sound an alarm or page the security personnel. With equipped two-way communication system, the security personnel can safely speak with the suspected intruder. Also any anomalies related to sound, light, temperature, smoke, humidity can be monitored with add-on sensors in real-time manner (Figure 9).

3.4. Test-results
Dead-reckoning showed about 35cm positional error when the robot traveled about 7 meters mainly due to built-in inconsistent rpm for each wheel motor which tended to cause curving paths even for a straight movement command. Also downward looking infrared sensors to detect deep holes or edges of down stairs reported different values depending on the reflectivity of the floor surface, which often delude robots. A possible solution may be replacing the infrared sensors with ultrasonic sensors.

If the dead reckoning position is beyond the WSN's position accuracy range either caused by malfunctions of object detection sensors or by external forces, the path planning algorithm adjusts robot's position based on WSN position data. Often robot's infrared and ultrasonic sensors did not recognize thin-leg chairs, which make a robot get stuck in one place while wheels were still running. It means, as mentioned earlier, dead-reckoning position keeps changing in the GUI while the reality does not. To remedy this situation, WSN position data was integrated to positioning algorithm in this study. However, current WSN's accuracy is too low (about 3 meters) to assist dead-reckoning system. Therefore, the current position calculation algorithm needed to be modified to filter out false WSN position data based on a simple physics theory. For example, robot's traveling distance cannot exceed the certain value that is calculated from robot's current speed and traveling time. To apply this theory, robot's initial position should be known.

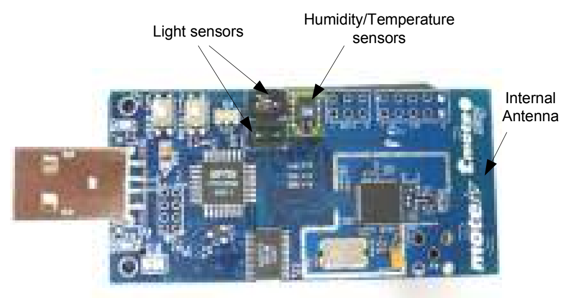

Figure 9. Add-on wireless sensor [9]

4. Current work
As an on-going research project, this study currently focuses on improving autonomous path finding algorithm for the robots to patrol from one location(x1, y1, z1) to another specific location (x2, y2, z2) while sensing any anomalies in traveling areas. To improve robot's position accuracy, Ultra-wide band (UWB) sensors have been obtained and being tested. Figure 10 shows four UWB nodes installed in a test room. To identify a UWB tag location, a minimum of four nodes are required which cover about 400 m^2. More nodes can be added to extend the coverage. Figure 11 shows 3D GUI for real-time position tracking for two mobile robots. Currently, sensor nodes and tags are being calibrated for higher accuracy with wired connection (Figure 12). After successful test of the wired system, the whole units will be tested in wireless configuration.

While 802.11 systems use standard 2.4 GHz bandwidth, the current UWB system provides 5.8-7.2 GHz bandwidth. Also, while 802.11 uses signal strength, the current UWB system uses time of flight and angle of arrival technologies which enable UWB sensors to have better signal penetration capability and less multi-path signals problems, thus better position accuracy can be obtained. This research expects position accuracy under 45cm from the wireless UWB system, which will provide much more reliable position and significantly improve the robot control in compact areas.

Figure 10. UWB nodes locations in a test room

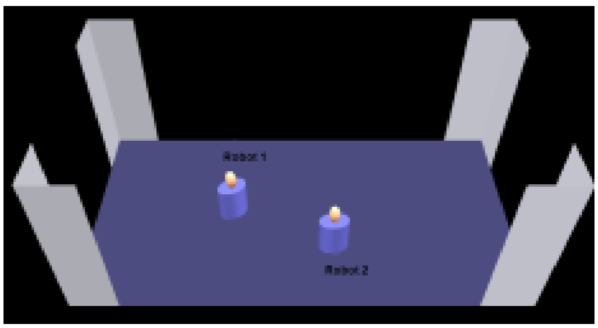

Figure 11. 3D GUI showing real-time robot location

Figure 12. Wired UWB node installed to the ceiling

Most of the construction sites may not have WSN infrastructure installed yet. Also, determining a fixed location (e.g. ceiling, wall, and column) for such an infrastructure (i.e. access points) is not an easy task in the mid of the 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 the construction sites, the base stations may need to be either frequently relocated to another tentative location or mobile. Therefore, an iterative multilateration technique is being adapted to locate large number of mobile sensors by using a small number of precisely positioned references as an ad-hoc networking system. To efficiently relocate the sensor node systems without power supply constraints, an individual rechargeable battery pack will be attached to each stand-alone portable node system.

5. Conclusion and Future work

In this paper, an on-going research effort to integrate WSN position data with a wireless mobile robot control system was introduced. Visualizing sensed information into a graphical control system was demonstrated to provide mobile robots with intelligent navigation functions for known indoor environment for high-level security and safety. The preliminary results showed that we needed to use higher RF bandwidth (e.g. UWB) to increase the position accuracy although it will decrease the signal range. The short signal range problem can be solved by adding more sensor nodes. Then, this research expects that the mobile robot may zero out its accrued dead-reckoning error within 45 cm accuracy. However, the major weakness of using UWB sensors is complicate hardware and software setup and hardware cost which is much higher than other radio frequency(RF) technologies.

Future work includes performance tests of the developed robot and position tracking system in actual construction sites. To extend the obtained knowledge, this research will further study on construction resource management system to track important mobile asset (e.g. crews, equipment, and materials) as well. Also this study will investigate new methods for energy-efficient data gathering protocols that forward sensing data within a specified latency constraint without sacrificing energy efficiency, thus longer life of batteries would be achieved for wireless mobile sensors.

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