Framework to Improve Mobile Robot's Navigation Using Wireless Sensor Modules

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Abstract

As on-going research, this paper presents a framework to improve wireless mobile robot's navigational accuracy in diverse indoor environments where the signals are affected by various types of interference including electromagnetic, multi-path, and fading and scattering. In particular, indoor construction environments pose unique challenges to accurate wireless navigation due to their relative complexity and inherently dynamic nature. Several integrated location and orientation sensors including a digital compass, a gyroscope, wheel encoders, an accelerometer, and Ultra Wideband (UWB) position tracking sensors are introduced in this paper. A distinct cause of error for each sensor is studied based on location, traveling distance, and rotational angle. To improve the position data accuracy, statistical methods such as outlier analysis and the Kalman Filter are applied in this research. A framework for position and orientation error compensation between relative and absolute sensors is described with preliminary research results indicating that position and orientation errors can be statistically adjusted in real time.

Keywords: mobile robot, navigation, dead reckoning, kalman filter, wireless sensor, error

1 Introduction

The competitive, market oriented, and rationalized construction of tomorrow will require developing automated and robotized construction system today [4]. This includes indoor construction applications such as interior finishing, piping, excavation, mining, and earth moving [5] among others. In particular, implementing suitable indoor localization in construction processes will lead to an increase in productivity and improvement in work quality and working conditions [4].

The requirement to have reliable positioning is becoming increasingly important, and can be used for indoor position application such as implementing robots with mobile platform for construction tasks [4]. However, implementing mobile robots for construction tasks has proven to be difficult due to the dynamic and uncertain nature of the construction site [5].

It is critical that mobile robot's absolute and relative positions are accurately determined in both outdoor and indoor environments. Global Positioning Systems (GPS) are widely used to determine the absolute position in outdoor environments where the signals are not obstructed by nearby buildings or trees. It is possible to determine the mobile robot's position with an accuracy of 2-3 cm with well-equipped GPS systems. However, GPS signals cannot travel through walls and thus suffer from signal attenuation, making GPS systems unsuitable for indoor applications. One of the most prominent technologies used for indoor applications is ultra wideband (UWB). UWB provides good performance within the boundaries of a small area, generally within 10-15 cm accuracy.

This paper describes on-going research into the development of a new method of autonomous navigation as applied to wireless mobile navigation. This will provide wireless autonomous mobile navigational functions to a robot on construction sites. The main goal of this research project is to integrate mobile robot's inertial navigation control unit into a UWB indoor positioning system, and identify and correct the source of errors using well-known statistical methods, such as the Kalman Filter and outliers analysis.

2 System Overview

The robot control unit should maximize the chance to reach its goal. The mobile robot should be able to measure progress in its relative frame in order to compare these measurements with its absolute frame. This is shown in Figure 1.

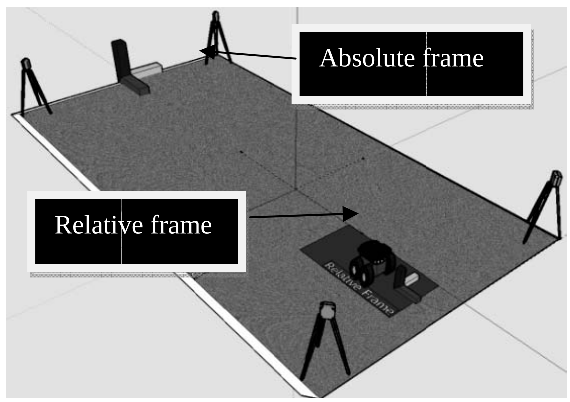

Figure 1. Absolute Frame vs. Relative Frame

Data coming from a gyroscope, an accelerometer and wheel encoders are combined to provide the robot with orientation and position in its relative frame. This is known as Dead Reckoning, or propioceptive navigation. The position accuracy is affected by slippage, uneven surface, wheel disalignment, etc. These errors can increase in severity over time, however they can be modeled, thus predicted and corrected, using statistical analysis.

Data obtained from UWB sensors and a digital compass provides the absolute position and orientation for the robot's absolute frame. This is known as exteroceptive navigation. The accuracy of these devices is limited by the resolution of the devices.

2.1 Localization systems

Estimating the position of a robot in its environment requires the knowledge of the geometry configuration (x, y, θ) for the frame attached to the robot, with respect to a local coordinate frame. This is done by determining two different reference frames. The first one is a relative frame that makes use of wheel encoders and inertial sensors such as a gyroscope or an accelerometer. The second is the absolute frame, which requires the use of external sensors, such as a UWB and a digital compass.

2.1.1 Absolute Localization

The absolute frame will be relative to the space. This frame will have also a 0,0 position, which must be related to the relative frame of the robot. It has to be updated from the robot geometry information. The 2D coordinates are determined by the readings of the UWB sensors in this research. The heading will be determined by the digital compass.

UWB System

The Ubisense system is an ultra wide-band (UWB) position system used in this research which measures Time of Difference of Arrival (TDOA) and Angle of Arrival (AOA) to achieve positioning[6]. The system consists of a number of fixed sensors which receive UWB pulses from active battery-powered tags. The fixed sensors are networked over Ethernet, and the measurement data is processed on the Ubisense software platform to give the real time track of the mobile tag [8].

Digital Compass

This sensor provides the absolute orientation in the navigation control. The main disadvantage of the digital compass is that the earth's magnetic field is affected by electromagnetic fields. This makes the use of this sensor hard to implement in indoor environment for absolute position.

2.1.2 Relative localization

The relative frame supplies the dimensions of the robot. It will be relative to the robot. This frame will have a (0,0) position at the beginning and an angle of 0. The heading of this frame will be determined by the gyroscope, and the translation will be determined by the encoders.

Odometry

Odometry is defined as the use of encoder measurements at the wheels to estimate the configuration of the robot state (position and orientation). To achieve successful autonomous mobile robot navigation, accurate odometry is essential. Localization, mapping and path-planning algorithms are all fundamental for robot navigation and all use odometry information [3].

Wheel Encoders

A wheel encoder is the essential sensor used in odometry. It is a device that is used to convert the angular position of a shaft to a digital code. It provides the distance in which a wheel has travel by basically measuring the relative distance.

Inertial Sensors

The purpose of inertial sensors is to calculate the relative change of a moving target between two consecutive sampling times, based on the measurement of acceleration and angular velocity from the inertial sensors [1]. In order for the inertial sensors to function properly, the gyroscope must be set up parallel to the direction of motion of the robot.

Gyroscope

The gyroscope measures an angular rate by picking up the signal generated by an electromechanical oscillating mass as it deviates from its plane of oscillation under the Coriolis force effect when submitted to a rotation about an axis perpendicular to the plane of oscillation. Gyroscope errors come from bias drift and noise. They are of particular importance for robot positioning because they can compensate the weakness of odometry.

Accelerometer

Accelerometer is used to measure the rate of acceleration. This sensor is used to measure the accelerations of the mobile robot. It enables the control system to know when the mobile robot is at rest.

Gyro + Accelerometer

Gyroscopes and accelerometers are used to measured rotation and acceleration. These sensors have the advantages to be self-contained, meaning that they do not need external references. The bias drift caused by the gyroscope can be fixed by using the accelerometer readings and the Kalman filter.

Relative Location + Absolute Localization

Once the absolute localization is obtained, it can be fused with the estimation of the robot's relative position so that it can correct its trajectory.

3. Source of errors

UWB

The measurement errors increase even when there is a clear open path between the UWB pulse transmitter and receiver. This system requires careful calibration before use. The signal levels for the installed environment must be calibrated. A measurement of the background noise level is required, so signal below that threshold can be excluded. [3].

Digital Compass

There are two problems associated with the digital compass as heading sensor. First, the body orientation changes either during locomotion or while standing on uneven terrain. This produces the pitch and roll of the compass, making its read-out unreliable. Second, the earth field at the compass level may be disturbed by other electromagnetic fields or distorted by nearby ferrous materials. These deterministic interferences can be categorized in two types. First, hard iron effects are caused by magnetized objects, which are at a fixed position with respect to the compass. This relative closeness should be avoided. Second, soft iron effects are caused due to the distortion of the earth field by ferrous materials [10].

Odometry

Odometry errors fall into two categories: systematic odometry errors and non-systematic errors. Usually internal systematic factors cause a rise of systematic errors, which show a biased characteristic. In contrast, non-systematic errors are independent systematic features and have an unbiased characteristic [8].

Inertial Sensors

The stochastic errors present on inertial sensors cause the subsequent numerical integrations of the measurements to exhibit an ever increasing variance. That is, when a gyro or accelerometer output is numerically integrated in a dead-reckoning navigator, the variance in the resulting position and velocity outputs grow unbounded in time [9]. This degradation of measurement accuracy propagates into the navigation solution at rates dependent on the integrity of the component sensors, the algorithms employed, and the duration of the un-aided navigation [9].

4. Proposed Error Correction

UWB

The main problem with UWB is that when there is not a clear path between the tag and sensors, it creates random points that are considered to be outliers. Consequently, outlying points have to be removed by using an outlier analysis. This analysis has to be in real time.

Outlier Removal

In statistics, an outlier is an observation that is numerically distant from the rest of a data set. In our system, this is caused by an indirect path between the sensors and tag located in the wireless robot system. There is not a mathematical definition that determines what constitute an outlier, rather it is a subjective exercise due to the variation of different samples. Many methods are used to determine whether or not an observation is an outlier. These methods are based on the mean and standard deviation of the sample. The method used as a foundation for our outlier removal is based on Grubb's test for outliers and Rosner's Test for Outliers.

Kalman Filter

The second method used to correct UWB reading is Kalman Filter. The Kalman Filter was introduced in the early 1960's and since then it has found widespread use. The purpose of the discrete–time Kalman Filter is to provide the closed form recursive solution for the estimation of linear discrete-time dynamic systems. The Kalman Filter has two steps: the prediction step, wherein the next state of the system is predicted given the previous measurement; and the update step, where the current state of the system is estimated given the measurement at that time step. The further study of these equations is left to the reader.

Digital Compass

In order to compensate the compass errors, the regression analysis is used to find a feasible pattern in a defined test bed area. This area must be located away from ferrous materials and relative closeness to power closes, which generate magnetic fluxes (Beauregard, 2006).

Wheel Encoders

This research analyzes non-systematic errors, those that result from the interaction with the surface with the wheels. The University of Michigan Benchmark (UMBmark) method is employed in the testbed so that the robot is programmed to follow a pre-programmed 4x4 square path and four spots for 90 degrees turns. This has to be completed 4 times in clockwise direction and five times in counter clockwise direction [3].

Gyroscope + Accelerometer (Inertial sensors)

The problem with this system is that path deviation at constant velocity cannot be corrected. The axis of a gyroscope also tends to drift with time, giving rise to errors. Inertial sensors allow a high rate of computation of the robot configurations, but they are not sufficient because errors are accumulated. A statistical method is required to reduce these sources of errors. Here, the Kalman Filter is used to get rid of the notorious gyroscope drift with the presented. The gyro input is a voltage measure by the sensor [12].

$$\theta_{k+1} = \theta_k + \omega_k \delta$$
$$\omega_{k+1} = \omega_k$$
$$bias_{k+1} = bias_k$$

Where θ is the angle; ω is the angular velocity; δ is the sampling period; bias is the gyro bias in angular velocity; u is the gyro output. To convert state to measurement is usually the easiest part,

$$y_k^{gyro} = \omega_k + bias_k$$

It is important to apply these steps in exact order to correct the gyroscope readings.

5 System Model

5.1 Principle

The robot has sufficient information and knowledge concerning its environment. The idea is to generate a local path using the known information, then attempt to locally, in relation to the robot, avoid any obstacles detected by the onboard sensors and return to the orientation relative to its frame.

Dead Reckoning (Relative frame)

The displacement estimates can be in the form of changes in Cartesian coordinates (i.e. x and y coordinates) or, more typically, in heading and speed or distance. With sufficiently frequent absolute position updates, Dead reckoning's linearly growing position errors can be contained within pre-defined bounds [10].

5.2 Path Planning (Absolute Frame)

The path-planning problem is usually defined as follows, "Given a robot and a description of an environment, plan a path between two specific locations. The path must be collision-free (feasible) and satisfy certain optimization criteria." In other words, path planning is generating a collision-free path in an environment with obstacles and optimizing it with respect to some criterion [11]. The robot has a short sensing range compared to the size of the region of interest. It radially senses from its position. Obstacles can block the sensing in some directions [11]. This study assumes that the robot knows its coordinates and orientation via UWB and the digital compass.

5.3 Position Algorithm (Relative + Absolute)

Once the first point is obtained in the path, this data is converted into an angle and distance relative to the robot frame. Whenever the robot reaches the target point provided by the path planning, its absolute position is calculated by using UWB readings and then passed through Kalman estimation. Then the position algorithm compares relative values of the robot, such as distance traveled and angle provided with the gyroscope, with the pre-defined bounds estimated from the UWB readings. If the robot's relative position trajectory is not within the pre-defined bounds provided by the absolute location system, then the system has to reset the robot position to the center of the bound.

6 Mobile Robot Navigation Control Architecture

Figure 2 shows the mobile robot's navigation control architecture designed in this research.

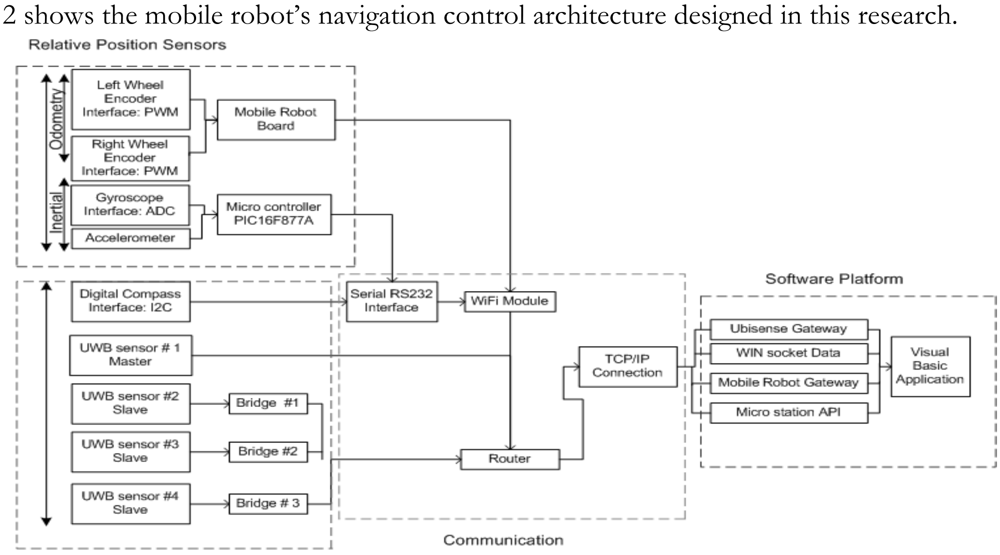

Figure 2. Mobile Robot's Navigation System Architecture

UWB

This system uses a network of sensors installed at known positions and a set of tags located in the mobile robot. The communication between different elements has two options. The first option is using an Ethernet network that basically connects all different sensors using a Cat5 Ethernet cable to a router. The second option is using a wireless interface. This option uses a set of wireless bridges connected to each sensor and respectively to the main router.

Micro controller board

The board used in this research is one of shelf solutions from Olimex™ (Figure 3). This board will be connected with the WiFi Latronix module on the mobile robot platform later. This micro controller offers a low-cost effective platform to interface with the sensor by using different interfaces. The first interface uses I2C interface that connects with the digital compass. The second interface is an Analog to Digital Converter (ADC).

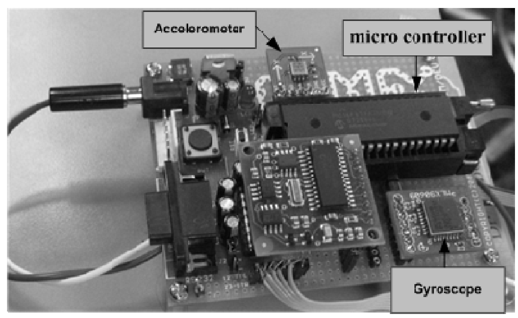

Figure 3. Micro controller board for inertial sensors

Inertial Sensors

The analog signals coming from the accelerometer and gyroscope are fed into the ADC input port from the PIC16F877A to be decoded.

Digital Compass

The compass used in this robot control is the CMPS03 built by Devantech™. It uses two methods of operation, which can be easily integrated with our microcontroller (PIC16F877A). The first option is a PWM signal that outputs a square wave. The second option is an integrated circuit interface, or I2C. This method is faster than the previous one, and allows a faster integration with the micro controller.

WiFi Module

This is a compact embedded solution that connects a UART port into its two inputs and the data can be easily accessed and controlled over a network. Mobile robot's control module uses Port A for its communication. Port B is connected to the Micro controller board.

Mobile Robot

The robot includes a series of sensors on board such as infrared, human detection, microphone, and camera among others. The one mainly used for this project is the wheel encoders that provides the data for the dead reckoning algorithm and regression analysis solution. Figure 4 summarizes the framework for this study described previously.

7. Experiments

The UWB system requires calibration within the absolute and relative frames such that a common point of origin (0,0) is established. Using a Total Station an absolute reference point is established. Each sensor has to be calibrated independently to this point of origin.

Test # 1 UWB- Average + Kalman: A buffer array, which has 5 slots for each data X and Y, is created. Data enters the system every 0.2 seconds. The data is then put into the 5 slot array, an average is calculated, and the array shifts to accommodate incoming data. Each calculated average is stored as a temporary variable and fed into the Kalman filter. The results are shown in Figure 5.

Test # 2 UWB-MidValue + Kalman : This method is similar to the previous, however, the median value is chosen rather than the mean. The result can be observed in Figure 6.

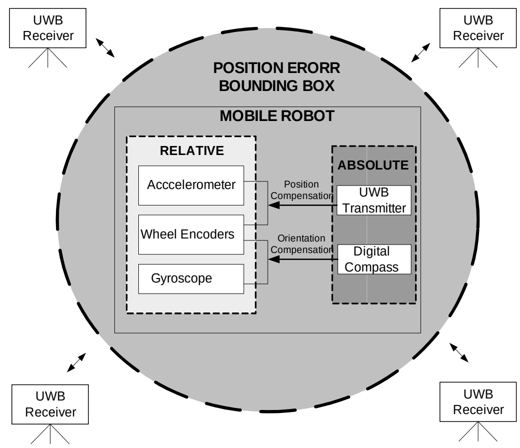

Figure 4. Framework for error compensation between relative and absolute sensors

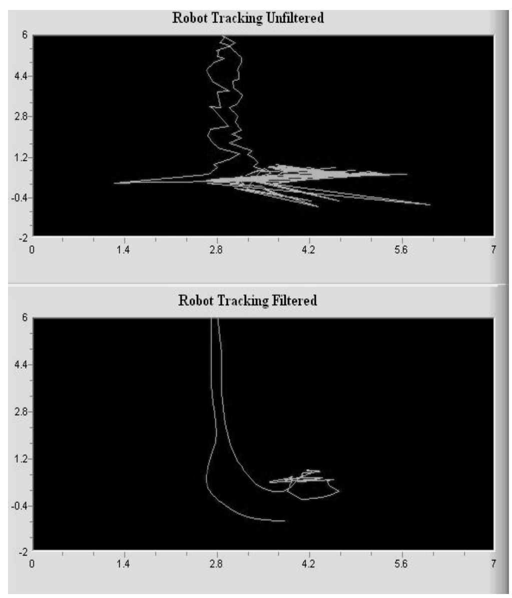

Figure 5. UWB- Average + Kalman

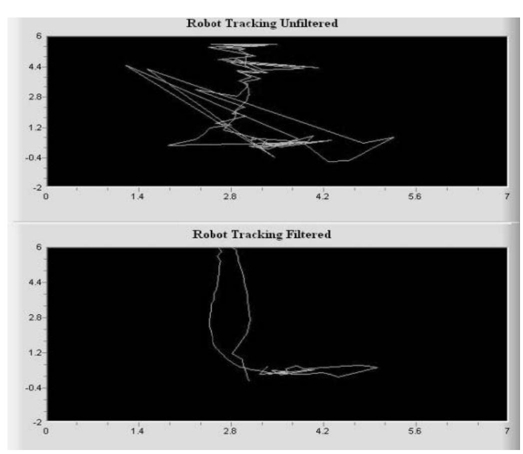

Figure 6. Test # 2 UWB-MidValue + Kalman

Test # 3 UWB- Outliers Removal + Kalman: While similar to the previous methods, this test includes the calculation of a threshold where outliers are removed based on Outlier analysis described in Ronsner's method(Figure 7).

Three methods tested show a significant improvement in UWB localization, and Test # 3 provided the best results.

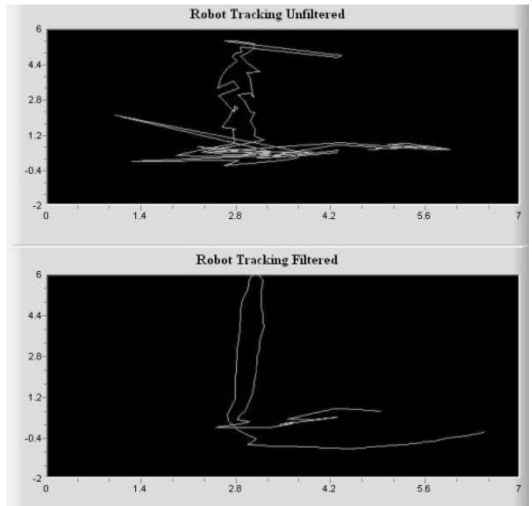

Figure 7. UWB- Outliers Removal + Kalman

8 Conclusions

This paper introduced an on-going research project developing indoor robot wireless navigation leading to the implementation of a suitable localization system within indoor construction environments. A framework has been introduced to improve the mobile robot's navigation in construction processes. The proposed framework introduces methods to detect and correct errors from various sensors including both internal and external sensors. Each sensor's error attributes are identified through intensive and extensive lab tests. Initial results from this research have shown an improvement in real time for the UWB localization system. This improvement was achieved by combining different statistical analysis. Three different experiments were conducted with results supporting the above conclusions.

Further investigation is being conducted to address additional sensor related errors based on the framework which has been established in this study. It is expected to lead to the improvement of the remaining sensors integrated within the system. These improvements will lead a better, more suitable localization system that can be applied to various indoor construction automation applications.

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