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Inertial measurement unit based indoor localization for construction applications

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ABSTRACT

Localization and tracking of resources on construction jobsites are an emerging area where the location of materials, labor, and equipment is used to estimate productivity, measure project's progress and/or enhance jobsite safety. GPS has been widely used for outdoor tracking of construction operations. However, GPS is not suitable for indoor applications due to the lack of signal coverage; particularly inside tunnels or buildings. Several indoor localization research studies had been attempted, however such developments rely heavily on extensive external communication network infrastructures. These developments also are susceptible to electromagnetic interference in noisy construction jobsites. This paper presents indoor localization system using a microcontroller equipped with an inertial measurement unit (IMU). The IMU contains a cluster of sensors: accelerometer, gyroscope and magnetometer. The microcontroller uses a direct cosine matrix algorithm to fuse sensors data and calculate non-gravitational acceleration using nine-degrees-of-freedom motion equations. Current position is calculated based on measured acceleration and heading, while accounting for growing error in speed estimation utilizing jerk integration algorithm. Experimental results are presented to illustrate the relative effectiveness of the developed system, which is able to operate independently of any external aids and visibility conditions.

1. Introduction

The fact that indoor localization research is to date a very active research area indicates that there are still many challenges left to resolve. The challenges depend on the required accuracy and reliability dictated by the application. Recent advances in sensing technologies have enabled the deployment of a wide range of technologies for identification, location sensing, and tracking of resources. Consequently many research works had been developed for asset tracking, earthmoving operations, surveying, safety hazards predicting, and context aware construction [1–10].

Over the past few years, several researchers have experimented with indoor positioning technologies, which can be grouped in three major categories: (1) wave propagation; (2) image based; and (3) inertial navigation. Wave propagation technologies are based on the physical propagation properties of radio, ultrasonic or sound waves over distances [11–16]. Ultra wideband, infrared, WLAN and RFID are examples for radio frequency (RF) localization technology. However, even if they suffer from several limitations, infrared technology provides room-level accuracy and performs poorly in the presence of sunlight [16]. WLAN technology localization accuracy had been investigated by different researchers, and found to be varying from 4 to 9 m depending on localization algorithm utilized and number of WLAN access points [17–19]. Varying accuracies of RFID localization systems had been reported by researchers, from 5 to 9 m depending on the tags' configuration and the density of tag deployment [20–22]. Ultra wideband-based systems have a very high accuracy of approximately 20 cm [23], however the cost of commercially available ultra wideband localization systems is very high. Ultrasound technology is based on sound wave propagation. The reported accuracy of an ultrasound system is 9 cm [23], however, it requires line of sight for deployment of transmitters, and the cost is comparable to ultra wideband transmitters [16]. Narrow Bandwidth Phase Analysis is an emerging radio frequency based technology for indoor localization, which is based on a high-resolution spectral analyzing method to measure the phase differences of a set of 2.4 GHz frequencies, with an average localization accuracy of 1.26 m [24].

Image-based localization technology involves image matching and computer vision techniques. Computer vision techniques have been categorized as (1) global methods such as edge detection and feature recognition, and (2) local methods based on landmark detection using visual tags or image matching [25]. However, these methods yield coarse accuracy (room-level) and are susceptible to occlusions and changes in the environment.

Inertial navigation localization technology utilizes an accelerometer and a gyroscope for sensing and detecting motion. The accelerometer measures acceleration in three dimensional spaces. The displacement

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is calculated by double integration of the acceleration. The gyroscope combined with the accelerometer is used to calculate the heading. This principle is called dead reckoning technique [26]. The dead reckoning is based on fusing the acceleration, and heading direction during a time step to determine how far and in what direction the user has moved from last known position. Unlike WLAN and RFID, motion sensing technology is independent from any infrastructure [27]. However, accelerometers are susceptible to acceleration caused by random movements, which might not necessarily be human motion, and magnetometers are susceptible to magnetic fields generated by electrical equipment and electronics [27]. Overall, motion sensing does not provide high location accuracies, but the accuracy can be improved by smart algorithms, which are able to correct drift errors [28].

Several methods recently developed to compensate the inherited errors in inertial navigation system by integrating different technologies and algorithms. A fusion of IMU and RGB-D camera based visual gyroscope is utilized to avoid the drift errors in common gyroscope sensors [29]. Twice position-fix reset (TPR) method is introduced recently to improve the accuracy of a dual-axis rotational INS for long term navigation applications [30]. The TPR method is designed to compensate for the stochastic errors by estimating the azimuth error and the position error with two observations.

Several researchers attempt to use inertial navigation in construction, Joshua [31] applied accelerometers to classify workers' masonry activities in order to investigate workers' productivity. Taneja [32] investigated inertial measurement unit (IMU) sensors for location-tracking in a building site as compared to other sensors that were used to establish local area networks (WLAN) and radio frequency identification (RFID).

Although significant research attempts have been made in developing several indoor localization systems using various technologies, the performance of these systems is still expensive and not robust enough for usage in dense and noisy indoor environments such as construction jobsites. Further research work is needed to develop robust, cost-effective and accurate indoor localization solutions for supporting rugged construction applications, such as automated progress reporting and jobsite safety.

This paper presents a newly developed extension to the inertial navigation technique for indoor localization system using a microcontroller equipped with an inertial measurement unit (IMU). This extension is intended to reduce accumulated errors in measured acceleration and heading utilizing a jerk integration algorithm.

2. Developed method

The developed method encompassed hardware prototypes and software algorithms. The hardware development consists of a microcontroller equipped with an inertial measurement unit (IMU) and barometric pressure sensor as shown in Fig. 1.

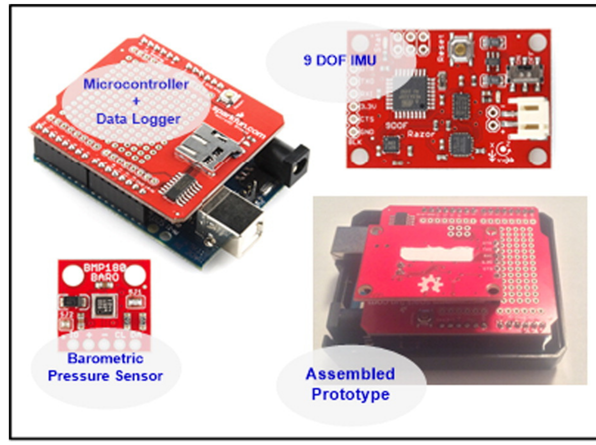

Fig. 1. Developed hardware prototype.

The IMU incorporates three sensors—an ITG-3200 (MEMS triple-axis gyro), ADXL345 (triple-axis accelerometer), and HMC5883L (triple-axis magnetometer), which give 9 degrees of inertial measurement. The barometric pressure sensor provides the tenth degree of freedom for the system.

The outputs of all sensors are processed by an on-board ATmega328 processor and output over a serial interface. This hardware configuration provides 10 degrees of freedom to calculate the current position in three dimensional spaces as shown in Fig. 2.

The software development consists of three modules, namely: inertial measurement module, altitude measurement module and localization module as shown in Fig. 3. The inertial measurement module processes and fuses inertial sensors using a Direction Cosine Matrix (DCM) algorithm. This algorithm accounts for gyro drift correction using accelerometer (gravity) vector and the magnetometer (compass) vector, and compensates for tilt on X and Y magnetic components and provide correction for yaw angle magnetic heading. The altitude measurement module calculates the altitude based on the measured barometric pressure taking into account current weather condition (humidity, temperature, etc.).

The localization module calculates current position based on acceleration, heading and barometric pressure from the data acquisition module. The linear displacement is calculated using the displacement calculation algorithm by differentiation of the measured acceleration to calculate the jerk and then triple-integrates the jerk to calculate velocity and distance. The differentiation allows to correct DC margin errors in accelerometer readings and provides detection for detection of zero velocity intervals. The position estimation algorithm estimates current position based on calculated displacements, heading and altitude using extended Kalman filter. A detailed description of these algorithms is presented in the following sections with their mathematical background.

2.1. Displacement calculation algorithm.

Traditionally the displacement is calculated by double integration of acceleration, however the global displacement error will grow by time due to drift associated with DC bias in the acceleration signal. To minimize these errors, a triple integration approach is presented in this research, where the acceleration is first differentiated to calculate the rate of change of acceleration (jerk). The jerk also allows for removal of gravity acceleration components.

Jerk can be defined as the changing rate of acceleration with respect to time [33], and its international unit is m/s^3. According to Newton's second law of motion, jerk is viewed as the change of force magnitude for a unit mass in unit time. In recent years, jerk is applied in the tracking and positioning for Global Positioning System (GPS), the high-speed dynamic vehicle tracking, the automatic control of high-speed machines, and comfort evaluation for high speed trains and elevators [34–37]. It is obvious that the jerk and the integral of the displacement with respect to time also have determined an important significance.

The jerk value can be calculated by solving the time derivative of acceleration.

$$\text{Jerk} = \frac{d(\text{Acceleration})}{dt}. \qquad (1)$$

Then the jerk is triple integrated using numerical integration method to obtain the acceleration, velocity, and displacement. Some traditional integration methods such as the Newmark method and Wilson-θ method are commonly used in earthquake engineering for jerk integration, however these methods assume that the acceleration is constant or linear variation during the interval of time [37,38], which will lead to the jerk in the interval, is assumed to be 0 or a

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