Sensor Localization for Indoor Wireless Sensor Networks

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Abstract – Although numerous solutions have been proposed to the sensor area localization problem, most of them are aimed at two-dimensional (2D) planes rather than the three-dimensional (3D) scenarios in real world applications. This study presents a novel approach to indoor localization of a mobile object that is equipped with sensors and cameras by utilizing Building Information Modeling (BIM) and 3D stereo image measurements. Based on some experiments conducted, the proposed scheme has shown its potential to be useful in real world applications.

Keywords - Wireless Sensor Networks; Building Information Modeling (BIM); Sensor Area Localization (SAL); Stereo Vision

I. INTRODUCTION

Sensor Area Localization (SAL) refers to the ability of estimating and computing the physical positions of all or a subset of sensor nodes in a wireless sensor network (WSN). For a wide range of monitoring applications, such as target tracking or smart environments, it is essential to address the SAL problem in an effective and efficient manner, so that the environment data collected by sensor nodes can be empowered with accurate and precise location information [1].

Even though the typical applications of sensor localization in real scenarios of WSNs are in 3D terrains, most of the solutions proposed to SAL in the past decades primarily emphasized on how to localize the sensor nodes in two-dimensional (2D) surface [2]. This can be contributed to the fact that 3D localization is a much greater challenge compared to 2D localization and the 2D solutions are often either difficult or impossible to extrapolate to their 3D counterpart solutions. Therefore, the objective of this study is to develop an indoor 3D localization prototype that is low cost, scalable and easily implementable. The proposed approach takes advantage of the Building Information Modeling (BIM) [3, 4] and 3D image measurements. According to the national BIM standard [3], BIM is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle. The proposed methodology consists of two phases: region determination (RD) and sensor node localization (SNL). RD attempts at approximately localizing the physical area in which the object is by deploying a group of sensor nodes with 3D coverage of the working space. Once the physical area is determined, SNL can obtain the exact location of the object.

The rest of the paper is organized as follows. Section II provides some background information on the SAL problem in WSNs. Section III discusses the general methodology of the study followed by the implementation of a case study in Section IV. The case study is conducted in the Peter Kiewit Institute (PKI) of the University of Nebraska. Section V concludes the paper with some remarks on future studies.

II. BACKGROUND

The solutions to SAL can be classified into two broad categories of centralized and distributed localizations. In the centralized localization approaches [5], sensor nodes receive their positions from a central unit. In particular, the central unit computes the physical location of the sensors based on the localization data collected by the sensors. The physical positions are then sent back to their corresponding sensor nodes. In the distributed localization solutions [6], sensor nodes are capable of handling the relevant computation by themselves, without the support of a central unit.

Contemporary well-known approaches on SAL consist of two phases: (1) distance measurement or angle determination and (2) distance or angle combination. The purpose of the first phase is to determine the pairwise distance between sensors by employing approaches such as Received Signal Strength Indicator (RSSI), Time of Arrival (TOA), and Time Difference of Arrival (TDOA) techniques; or using the approach of Angle of Arrival (AoA) to determine the angle of signal reception from a sensor [7]. In the second phase, the information from the first phase are combined to localize objects. The most popular alternatives to the combination phase are primarily composed of Hyperbolic Trilateration (HT), Triangulation, and Maximum Likelihood (ML) estimation [2].

There are already several technologies for the sensor localization, for instance, Satellite Navigation System (SNS), Received Signal Strength Indicator (RSSI), Time of Arrival (TOA), Time Difference of Arrival (TDOA), and Angle of Arrival (AOA) [7]. Their advantages and disadvantages will be discussed as follows.

A. Satellite Navigation System (SNS)

Satellite Navigation System (SNS) refers to a space-based satellite navigation system which provides location information with critical capabilities to civil, commercial users and military. Examples of SNS include Global Positioning System (GPS) developed by the United States, Global Navigation Satellite System (GLONASS) by Russia, European Union Galileo Positioning System (GALILEO), Chinese Compass Navigation System (COMPASS), and Indian Regional Navigational Satellite System (IRNSS). Because of the line-of-sight requirement, these navigation systems suffer from implementation issues in environments like mountains and indoor scenarios where obstacles may block the satellite signals. In addition, the particular hardware requirements like antenna receivers are critical limitations to the cost factor and power consumption of SNS-based solutions.
B. Received Signal Strength Indicator (RSSI)

RSSI-based solutions measure the power of the received radio signal. Based on the received signal strength, distance values can be computed relatively according to the propagation of radio signals. However, measurements based on RSSI are confronted with noises from surrounding obstacles and link reliability issues \[7, 13\].

C. Time of Arrival (TOA)/Time Difference of Arrival (TDOA)

TOA/TDOA-based measurements compute the range value according to the travel time propagation of a radio signal between a signal transmitter and a receiver. In particular, TOA utilizes the absolute travel time between signal units while TDOA takes advantages of the arrival time difference, which can be directly interpreted to a ranging value. This category of solutions can be employed with different signal types such as ultrasonic, acoustic and radio frequency. In addition, the design can be small and cost effective because there are many sensor alternatives with such capabilities. Nevertheless, TOA and TDOA can present inaccuracy \[8\] in some environments because of the interference. For instance, ultrasonic signal propagation varies with environmental humidity and temperature while acoustic signals suffer from multipath propagation effects.

D. Angle of Arrival (AOA)

In contrast to the previous approaches that require some form of cooperation and tight timing synchronization between the sender and receiver, AOA has the advantage of locating objects in a stealth and passive manner, which is a desirable feature for military applications. AOA is based on the capability of sensing the direction of the signal received. AOA requires an antenna array (base stations), which are able to determine the compass direction of the sensor’s signal. The collected information from the base stations is then analyzed to determine the sensor’s location \[13\]. With the help of antenna array, AOA-based methods can provide reliable measurement accuracy compared to the techniques discussed above. But the drawbacks of this solution are in the additional requirements of hardware equipment and their deployment difficulties.

III. METHODOLOGY

Stereo vision technology \[9, 10\] has attracted sufficient attention and shown its great potential for ubiquitous sensor localization as it is capable to accurately obtain 3D distance parameters. A stereo vision system is equipped with at least two cameras displaced horizontally from one another in a manner of human binocular vision. Two images from the cameras are compared in order to obtain the depth information of their common points. Generally, several pre-requisite processes are necessary such as camera calibration to remove image distortions and image rectification in order to project two images back to a common plane for computation.

By investigating the principles of stereo vision technique, a Distance Measurement Sensor (DMS) is built with a stereo camera and a laser pointer (see Fig. 1). The DMS behaves as the object to be localized. The purpose of the laser is to detect the depth of the laser pointer reference shining on the surrounding areas so that the DMS can be localized. The laser pointer can be set to rotate in 180 or 360 degrees.

On the other hand, BIM provides a new perspective on viewing the environment such as buildings as 3D images. It has a wide range of applications on generation and management of virtual representations of physical facilities. In this study, BIM is used to generate 3D spatial information (\(x, y, z\) coordinates) for sensor localization. As shown in Fig. 2, the working process of the proposed methodology primarily consists of three phases: 3D database generation, local distance measurement, and global sensor localization.

In the figure, before the 3D coordinates of PKI can be generated and stored in a database, its image as a 3D BIM model is needed. Generally, the BIM model is chiefly utilized to visualize the design and functional procedures in a 3D view. The realistic 3D BIM model of PKI (Fig. 3) is provided by Kiewit Corporation. The PKI second floor is considered as the primary test environment due to its spatial arrangement and sufficient 3D building information. The 3D spatial information (SI) for object localization is then obtained by converting the BIM image to the 3D coordinates. The SI model is generated through sampling every surface of the BIM image via the method proposed by Mark et al. \[4\] and integrated in the open-source Point Cloud Library (PCL) \[11\]. In particular, the SI model provides a bunch of 3D spatial points with specific coordinate values (\(x, y, z\)).
During the phase of local distance measurement, DMS will measure its 3D distance values from its surrounding working space. Here “local” means the process of distance measurement is implemented based on the coordinate system of DMS. Using the SI model as a reference, the DMS distance measurements will be converted to global coordinates. The relationship between the local and global coordinate system will be discussed in Section IV.

Finally, the responsibility of the global region localization phase is mainly to determine the region where DMS is located and ultimately localizing DMS precisely according to the global coordinate system. The 3D spatial information of the test space is partitioned into sections called regions. In particular, ZigBee-based wireless sensor nodes are pre-installed in the working space to determine the spatial region where the mobile target node, i.e. DMS, belongs to. For instance a region could be a room in the PKI building. The traditional RSSI-based ranging measurement is used to determine the region in which DMS is localized. This information is then combined with the information in the local distance measurements phase to determine the actual location of DMS. Recall that RSSI measurements may not be accurate because of the noises created by the surrounding obstacles. Therefore, once the approximate location of DMS is provided, local distance information will be used to determine the exact location of DMS.

IV. IMPLEMENTATION

A. The Coordinate Systems

Four levels of coordinate systems are defined in this study, as shown in Fig. 4a: Geographic Coordinate System (GC) as the level I coordinate system, the local spatial information coordinate (LC-SI) system as level II, local DMS coordinates (LC-DMS) as level III, and the local coordinates for the cameras (LC-Camera) as the level IV coordinate system. Each coordinate system has its own origin $O(0, 0, 0)$ in 3D space. Based on these coordinated systems, a 3D point can be described in four different coordinate values, which can be converted from one coordinate system $a$ to a corresponding point in a different coordinate system $b$ using a transformation matrix $T_{a \rightarrow b}$. For example, Fig. 4b shows a point in the third coordinate system that is being converted to its corresponding point in the fourth coordinate system using the transformation matrix $T_{3 \rightarrow 4}$. Transformation matrices are described later in the section.

Fig. 3. 3D Bird view of the PKI building.

Fig. 4. (a) The coordinate systems and their relationships (b) Example showing transforming one coordinate point from one system to another.

Level I: Geographic Coordinate System -- Geographic coordinate (GC) system refers to the coordinate system that the whole test space belongs to. Since the global geographic coordinate values of the PKI building (Fig. 3) are 41.2477208 degree (latitude), -96.0154971 degree (longitude), and 316 m (altitude), the origin $O(0, 0, 0)$ of GC system can be actually mapped to this geographic point. As a result, each point in the PKI building can be endowed with real geographic values on the earth.

Level II: 3D Local Spatial Information (SI) Coordinate System (LC-SI) -- The local coordinate system in 3D spatial information model aims at providing the coordinates for the test space (PKI second floor). LC-SI system localizes its original point as $O_2(0, 0, 0)$ in the bottom left corner of the PKI second floor. This origin, i.e. $O_2(0, 0, 0)$ of LC-SI system, is actually the origin point $O_I$ in GC system with transition of 15.5 meters in $x$-axis, 27.9 meters in $y$-axis, and 39.1 meters in $z$-axis direction from $O_1(0, 0, 0)$.

Level III: Local Coordinate System in DMS -- The DMS local coordinate system (LC-DMS) (Fig. 5) serves as the base coordinate system for the functional implementations of DMS (Fig. 1). With its origin at $O(0, 0, 0)$, used as the third origin $O_3(0, 0, 0)$ localizing in the center of two cameras, i.e. the laser point. LC-DMS system performs differently compared to the GC and LC-SI systems in that it is mobile while the other coordinate systems are fixed. Correspondingly, the process of calculating the transformation matrix related to this system is...
also different than the other coordinate system transformation because of the DMS mobility. In this scenario, the \( T_{a \rightarrow b} \), where \( x \) is either 2 or 4 (see Fig. 4), describes at least two transformations: translation by a distance \( d \) and rotation by an angle \( \theta \) about \( x \), \( y \), or \( z \) axis, which are explained below. These two transformation matrices along with the spatial relationship between the DMS and the SI model will be used to determine the DMS’s position in the GC system.

**Fig. 5. LC-DMS system**

**Level IV: Local Coordinate System in Cameras** -- The local coordinate system in the cameras (LC-Camera), as shown in Fig. 5, provides the pixel positions in 2D images obtained by the two cameras. The two cameras with lens length \( f \) are mounted with their optical axes parallel and separated by a distance \( d \). The LC-Camera systems are 2D-based due to the image characteristic and firmly fixed within the LC-DMS system. The target point \( P(x, y, z) \), i.e. the laser point reference, captured by the cameras has the image coordinates \( P_1(x_1, y_1) \) and \( P_2(x_2, y_2) \) in the left and right LC-Camera systems. In the figure, \( O_1(0, 0) \) and \( O_2(0, 0) \) represent the local origin coordinates of the images taken by the cameras.

The notion of multiple coordinate systems is not new. For example, multiple coordinate systems are normally used in robotics to solve different problems. For the purpose of this study, a separate spatial correlation exists between two adjacent coordinate systems with the transformation matrix \( T_{a \rightarrow b} \) that allows the points in coordinate system \( a \) to be converted to their corresponding neighbour points in coordinate system \( b \). For this conversion to take place, one needs to obtain two matrices: translation and rotation. A *translation matrix* simply captures the distance between the two sets of coordinate point values between the two systems, so that the coordinate values in one system can be adjusted correctly as they are moved to the other system. Since the axes of the two coordinate systems may not be in parallel, the rotation matrix captures the rotation degree along each axis of system \( a \) so that it becomes aligned with the corresponding axis in system \( b \). As these rotations take place, the coordinate values are adjusted accordingly to keep pace with the rotations.

*Fig. 4b shows a 3D point in coordinate system \( O_3 \) (level III) whose coordinate values are \( A: (O_{ax}, O_{ay}, O_{az}) \). Fig. 4b also shows the corresponding 3D point \( B: (O_{bx}, O_{by}, O_{bz}) \) in the coordinate system \( O_2 \) (level II). Assume, the angles of rotation along each axes \( x, y, \) and \( z \) in the coordinate system \( O_2 \) are \( \theta_x, \theta_y, \) and \( \theta_z \), respectively. Further assume that translation along the axes of \( x, y, \) and \( z \) are \( dx, dy, \) and \( dz \), respectively. Then, the translation matrix \( B_1 \) and the rotational matrices \( B_2, B_3, \) and \( B_4 \) along the axes \( x, y, \) and \( z \), respectively, are as follows [12]:*

\[
B_1 = \begin{bmatrix}
1 & 0 & 0 & dx \\
0 & 1 & 0 & dy \\
0 & 0 & 1 & dz
\end{bmatrix}, \quad B_2 = \begin{bmatrix}
cos\theta_x & -\sin\theta_x & 0 & 0 \\
\sin\theta_x & cos\theta_x & 0 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\]

\[
B_3 = \begin{bmatrix}
cos\theta_y & -\sin\theta_y & 0 & 0 \\
\sin\theta_y & cos\theta_y & 0 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}, \quad B_4 = \begin{bmatrix}
cos\theta_z & -\sin\theta_z & 0 & 0 \\
\sin\theta_z & cos\theta_z & 0 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\]

The transformation matrix is then: \( T_{a \rightarrow b} = B_2B_3B_4B_1 \).

Finally, the point \( A \) in Fig. 4b will be converted to the corresponding point \( B \) by doing:

\[
\begin{bmatrix}
O_{bx} \\
O_{by} \\
O_{bz} \\
1
\end{bmatrix} = T_{a \rightarrow b} \begin{bmatrix}
O_{ax} \\
O_{ay} \\
O_{az}
\end{bmatrix}
\]

**B. Region Determination**

*Fig. 6 shows the test space on the second floor of the PKI building, which consists of a hallway and several rooms. Separate regions in this test space are pre-defined according to the spatial range of coordinate values. For example, a coordinate point in Region#1 is defined as \( x \in \{x_1, ..., x_2\}, y \in \{y_1, ..., y_2\}, \) and \( z \in \{z_1, ..., z_2\}, \) where the pairs \( [x_1, x_2] \), \( [y_1, y_2] \), and \( [z_1, z_2] \) are constant threshold values which determine the range values spanned along each axis in Region#1.**
developed sensor localization system introduced in the previous sections. The MEMSIC kit is mainly equipped with sensor devices, server gateways, and user interfaces. In particular, sensor nodes are able to perform the low-power wireless sensor network measurements including temperature, humidity, barometric pressure, acceleration and ambient light. The gateway module is not only able to communicate with the server (PC) through its USB interface, but it can also collect data from sensor nodes through ZigBee wireless communication protocol. The sensor nodes communicate with the gateway that in turn communicates to the computer host. The gateway gathers RSSI values from the sensor nodes in order to estimate their corresponding distance relationships from the DMS, so that its region can be determined. Compared to other alternatives such as AoA and TDoA, the cost of a RSSI-based system is generally lower and the measurement and calculations involved in RSSI are simpler and less complicated [2, 13, 14]. Fig. 7 illustrates the high level configuration of the ZigBee sensor network employed in this study which is composed of a gateway base station attached to the DMS and a number of ZigBee sensor nodes.

The following will introduce the process of RSSI-based distance estimation of sensor nodes implemented in this study. Because the gateway attached to the DMS might receive signals from many sensors attached to the test space, and since the RSSI signals used in the distance measurement may not be accurate due to the building construction material and obstacles, this study attempts to select sensors based on their measured signal strengths within a specified range.

Specifically, the signal strength of sensors for various distances to about 4 meters have been obtained and physically validated for their accuracy. MoteView that came with the development kit was used for the measured signal strengths. In particular, a message can be sent by the gateway asking the sensors to send a reply message to determine their signal strengths. Fig. 8 reflects the relationship between the measured distances and their corresponding RSSI proportional values. For each signal strength received, MoteView provides a corresponding proportional value. Fig. 8 further shows the linear best fit of the RSSI proportional values versus the measured distances, which is \( \text{dis} = -7.3 \times \text{sig} + 460.0 \), where \( \text{dis} \) shows the distance and \( \text{sig} \) is the RSSI proportional value received by the gateway. The approximate range of \( \approx 0 \ldots \approx 60 \) is used as the proportional values to decide which sensors to select. The corresponding distances are then used to determine the DMS region using the trilateration method.

The process of obtaining Fig. 8 follows the concept of location fingerprinting [15], where the received signal strength is compared against a radio map of signal strengths for various locations. The advantage of the radio map, which is constructed off-line, is that the signal strengths measured are customized toward a particular environment. Therefore, more trust can be placed on the accuracy of the measured distances \( \text{dis} \). The other advantage of \( \text{dis} \) is to reduce the false positives caused by sensors from other regions whose signals might reach other regions.

C. Sensor Node Localization (SNL)

Once the region is determined (Fig 7), SNL is used to localize the DMS accurately. Theoretically, a cloud of \( x-y-z \) point values for a 360-degree view are expected to be entirely matched with the corresponding point values provided by the 3D SI model (Fig. 2). The conversion process from the DMS’s local coordinate system to the digital images pixels that are matched against the SI model is the key in object localization.

The 3D spatial data, i.e. the coordinates, are measured based on the common coordinates of the images captured by the cameras and the DMS’s coordinate system. The images that contain the laser point references, i.e. the points \( P(x, y, z) \) in Fig. 5, are used to determine the distances between the DMS and the laser point references. Specifically, as the laser pointer rotates, the cameras capture images that contain the laser references. The set of points in each image is then compared against the set of coordinates in the 3D SI model. Since the coordinate values of the SI model are pre-known, once the image match is found in the SI model, the laser reference coordinates can be determined easily. The typical Iterative Closest Point (ICP) algorithm [16] provided by Point Cloud Library is employed to implement the point matching process. Also, the distances are determined using the stereo vision technique [9, 10]. Consequently, the coordinates of laser references in multiple images along with their corresponding distances are combined using trilateration to determine the location of DMS. There needs to be at least 3 such laser references to successfully use the trilateration method.

Fig. 9 is an example of the 3D point values obtained by DMS. As the DMS moves (Fig. 10), it is able to obtain its accurate position by detecting the coordinate values that are mapped against the corresponding point values of the SI model for the region determined by the pre-installed sensors.
V. CONCLUSIONS AND FUTURE WORK

The ability of accurately localizing indoor objects equipped with sensors and cameras in WSNs has been demonstrated by taking advantage of BIM, 3D stereo techniques, and the PCL open source library. The target space visualized by BIM has been converted to a 3D spatial information that is partitioned into specific regions. The region in which a mobile target is localized is determined using a group of pre-installed sensors. The accurate location of the target is then determined based on the image matching algorithm, i.e., ICP algorithm, and the distance measurement technique using stereo image computations. The successful experiments conducted by allowing the object to roam in different connected regions and recording its position at various points of time show that the proposed methodology is potentially useful for real-world applications such as in smart buildings, security, and surveillance.

The current study can be enhanced in multiple ways. Since the 3D spatial model is generated directly from the BIM model, region determination and sensor localization depends on the generated SI model. Therefore, the proper accuracy and precision of the SI model is crucial. For instance, higher resolution SI models are better but require more storage. Furthermore, the current developed DMS system provides cm-resolution SI models are better but require more storage. Therefore, the proper accuracy and speed of localization by either using better equipment such as higher resolution cameras with depth sensors or by devising better mathematical schemes to account for lower quality hardware and better comparison process.

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