Self-Organized, Scalable GPS-Free Localization of Wireless Sensors[*]

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Abstract – **Wireless sensors are expected to be widely deployed in the near future for a vast variety of applications. Sensing data is not useful unless the location where the data is collected is also known to the end users. Although much work has been done on the positioning of sensor nodes, proposed algorithms often are not applicable in certain environments. Furthermore, there is always a need to reduce their complexity and cost, and to improve accuracy for these algorithms.**

This work is primarily motivated by a new research project called WINES to deploy wireless sensors to monitor the conditions of London underground and water systems. Global Positioning System (GPS) based positioning methods are not applicable in the underground environments. In addition, the tunnels and water pipes are not located at the same horizontal level, so existing algorithms proposed for two-dimensional deployment areas become inadequate. To overcome the challenge, we propose and study here a new localization algorithm by extending one proposed for two-dimensional service areas by Capkun *et al.* Our new scheme is a distributed, self-organized, infrastructure-free positioning algorithm that enables easy and flexible sensor deployment in the harsh environments. Furthermore, our computer simulation reveals that the new scheme achieves a satisfactory, relative average position error of less than 5% when the errors for distance estimations among sensors have a standard deviation of no more than 5%.

Keyword: GPS, localization, positioning, range estimation, wireless sensor.

1. Introduction

Wireless sensor networks have been a very active area of research since late 1990's. Despite such intensive efforts, many technical challenges remain for large-scale deployment of wireless sensors in practical environments (see e.g., [1-3]). Nevertheless, with advances of low-cost technologies, wireless sensors are expected to be widely deployed in the near future for a large variety of applications ranging from environmental and building monitoring, healthcare, agriculture, national security, to military operations and home usage, to name a few.

Sensing data is not useful unless the location where the data is collected is also known to the end users. For this reason, localization and positioning of sensor nodes have attracted much research attention and many algorithms have been proposed in the literature (e.g., [4-6-13]). Despite the previous efforts on the subject, the proposed algorithms often are not applicable in certain environments. Furthermore, there is always a need to reduce complexity and cost and to improve accuracy for these algorithms.

This work is primarily motivated by a new research project called WINES [14] to deploy wireless sensors for monitoring the conditions of London underground and water-supply networks. Positioning methods based on Global Positioning System (GPS) are not applicable in the underground environments simply because they are out of reach of GPS signal. In addition, the tunnels and water pipes are not located at the same horizontal level, so the existing algorithms proposed for two-dimensional deployment areas become inadequate. From practical use, the positioning algorithms suitable for our applications should also be distributed, self-organized and scalable. To overcome these challenges, we propose and study in this paper a new localization algorithm by extending the one proposed for two-dimensional service areas by Capkun *et al.* [9]. Our new algorithm is an anchor-free scheme. It has a very high degree of flexibility and scalability because no knowledge about the current network information is needed and new nodes can be added without a need to change the algorithm for existing nodes. Localization is then possible even in environments that are out of reach of GPS signal. In the end, our scheme is a distributed, self-organized, infrastructure-free positioning algorithm that enables easy and flexible sensor deployment in the harsh environments.

Our new algorithm makes use of the techniques based on the Time Difference of Arrival (TDOA) and the Angle of Arrival (AOA) [11, 13, 15] to estimate the range (distance) and angles among sensors. Each sensor uses the estimates obtained locally to build a network coordinate system. Then by communications with neighboring nodes, each sensor adjusts its coordinates by appropriate axis rotations and shifting to finally obtain a consistent, global coordinate system.

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A direct extension of the Capkun's two-dimensional method [9] into three-dimensions (3D) is not straight forward. This is so because the added dimension provides too much "freedom" in fixing the coordinate systems for various nodes. The extension for three-dimension environments is made possible in our new algorithm by using two crucial techniques:

- The combined TDOA and AOA technique to accurately estimate the range and angles among sensors
- The use of the direction of earth gravity as one of the axes in the 3D coordinate systems.

The last bullet point enables easy sensor deployment. It is so because regardless of the nature of operating environments, engineers can always use simple tools to identify the direction of earth gravity. To meet the requirements for monitoring of civil-engineering infrastructures [14], sensors are expected to be deployed manually. As long as sensors are installed with an orientation that the gravity direction becomes one of the axes in their 3D coordinates, sensors can be placed anywhere appropriate for the applications, instead of at particular calculated locations.

The rest of this paper is organized as follows. Previous related work is discussed in Section 2. Section 3 presents the several elements that have been taken into account for the wireless sensor's structure under consideration. Section 4 presents the proposed 3D positioning algorithm. Section 5 reports on the experiments performed to characterize the performance of our algorithm. Finally, Section 6 is our conclusion.

2. A Brief Review of Related Work

A localization method consists of two components: distance and angle measurements, and a localization process. This section presents a brief review of related work for both components.

2.1. Range (Distance) Estimation

Following the U.S. FCC regulations for locating E911 callers, positioning services in mobile systems have attracted much attention recently. RF-based ranging, as exemplified by the SpotON [7] system, is based on the premise that by measuring received signal strength, a receiver can determine its distance from a transmitter. Range estimate errors more than 10% have been reported in the literature, despite using a fairly involved calibration step that estimates the path loss parameters and adjust for variations in transceiver characteristics. Such an accurate calibration can be carried out only with a complete knowledge of the environment, which is not available in practice. Other methods based on received signal strength, such as the RADAR [4] system, are not useful either because substantial effort is involved to calibrate and establish the centralized database of multi-path signatures.

On the other hand, infrared techniques can provide very accurate positioning. However, it cannot be applied to our non-line-of-sight environments.

The Time difference Of Arrival (TDOA) method uses the hyperbolic transmitted function concept. With more than two receivers, we can compute more hyperbolic functions, which ideally intersect in one unique point. The TDOA measurement is computed as follow: the sender transmits a signal $s(\tau)$ to a receiver i , which is delayed by τ_i . A minimum of four receivers (in a 3D environment) is needed to locate the sender through the estimation of the time delay $\tau_i - \tau_j$ corresponding to the path differences between the sender and receivers i and j .

In addition, the Angle of Arrival (AOA) technique enables us to identify the location of the radio source by use of an antenna array as the incoming signal does not reach all the antennas at the same time. This phase shift enables us to obtain the angles of the incoming signal.

The combination of the TDOA and AOA technique, also called TDOA/AOA Hybrid [15], requires only two connections (receivers) with a sensor node to estimate its location. The combined technique also provides far more accuracy than the individual AOA or the TDOA method by itself. For both advantages, we adopt this combined technique in this work.

2.2 Localization systems

Virtually all localization methods proposed in the literature make use of some anchor nodes for localization. Anchor nodes know their exact locations through separate means such as GPS [6].

The triangulation becomes possible when a sensor is connected to 3 or 4 other sensors via wireless links in the 2D and 3D environments, respectively. Triangulation is the process of finding coordinates and distances to a point by calculating the length of a triangle formed by that point and two other points with known positions. Many algorithms have been proposed to perform the triangulation. For example, the Assumption Based Coordinates (ABC) Algorithm [5] determines the location of unknown sensors one at a time in the order that they establish communication, making assumptions where necessary and compensating for errors through corrections and redundant calculations, as more information becomes available. The ABC is an incremental algorithm, which results in error propagation.

An anchor-free method by Capkun et al. [9] is a distributed, infrastructure-free positioning algorithm that does not rely on the GPS. The algorithm uses the distances among nodes to build a relative coordinate system in which the node positions are computed in two dimensions. In the second part of the algorithm, the relative coordinate systems are corrected in order to have the same directions for their axes. The method however applies only to 2D environments and it cannot be readily extended to 3D environments. Furthermore, the algorithm in [9], which does not apply the AOA technique, requires densely deployed sensors to be able to construct the relative coordinate systems accurately.

3. Ad-Hoc sensors structure

Since this work focuses on anchor-free algorithms, all sensors can have the same features and capabilities, thus reducing the equipment cost for a deployment. As shown in Figure 1, each sensor consists of two components: the communication device with a planar antenna array and the sensing unit for the given application such as sensing temperature, water pressure, humidity, presence detection, and vibration.

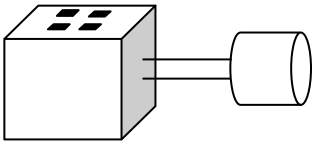

(a) (b)

Figure1. Sensor structure: (a) the communication device with its planar array, (b) the sensing unit (e.g., humidity sensor)

The planar antenna array is used to support the AOA technique for the angle estimations, which make the extension of Capkun's method for 2D to 3D environments possible. Furthermore, using the AOA technique enables our new algorithm to work properly in a much scattered and less dense network because only a single radio connection between two sensor nodes is needed to determine the angles between them. In contrast, for all existing methods, a sensor's position could not be identified without having at least three other sensors connected to it.

To meet the needs of the underground environments, expanding existing positioning techniques for 2D environments to 3D is challenging and a tradeoff must be made between using expensive devices for ranging and angular estimations, and limiting the directional orientation of the sensors during installation. Consider that each sensor node has its own 3D coordinate system with x, y and z axes. Regardless of the operating environments, we make the following observation. Engineers can identify the direction (axis) of earth gravity by simple tools. If each sensor is installed in a way that one of its axes is fully aligned with the gravity direction, then extending the 2D method by Capkun et al. [9] to 3D environments becomes possible by appropriate rotations and translations of the coordinate system of each sensor in a distributed manner. The details of how rotations and translations should be carried out are presented below.

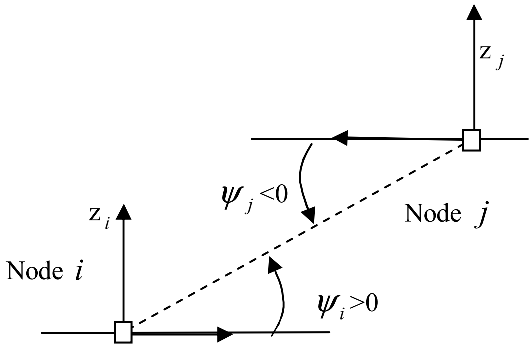
4. Localization Algorithm

The localization algorithm is executed on each sensor in three phases:

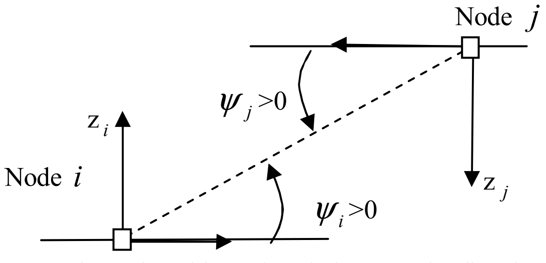
- Define its local 3D coordinate system (with one of the axes aligned with the gravity direction)
- Correct the local coordinate systems with respect to the reference coordinate system
- Define the global coordinate system for positioning.

The scattered sensors use their antenna technology to sense the neighbor sensors and construct their local coordinate systems. The localization process needs a reference. We consider that the whole localization process is done with respect to the reference coordinate system of a particular sensor, to be referred to as node 1 (which can be easily accessible for maintenance and/or directly connected to a gateway node to the Internet). As discussed above, sensor 1 is installed such that its z-axis is precisely aligned with the direction of earth gravity (which points downward towards the earth center) or in the opposite direction pointing upward. Once every sensor has detected all sensors that are within its range of communication, every coordinate system has to be adjusted in order to have the same directions as the reference coordinate system. The adjustment is a step-by-step process that starts from node 1. The adjustment process is then done between the coordinate on a neighboring node with the reference coordinate system. Once the neighbor's coordinates are calibrated with the reference system, the former can now serve as a new reference for adjustment by other nodes. The process continues until the reference system "propagates" throughout the entire system and each node has adjusted its coordinates according to the reference coordinates

As each sensor node has the z-axis aligned with the gravity direction (in either upward or downward sense), the plane defined by its x-y axis is parallel to the x-y plane of the reference coordinate system. The elevation angles are defined as the elevation from the x-y plane. If we define ψ_i the elevation angle of sensor j in the coordinate system of sensor i, and ψ_j the elevation angle of sensor i in the coordinate of sensor j, we can see from Figure 2 that both elevation angles have equal absolute value.



(a) Nodes with aligned z-axis



(b) Nodes with z-axis pointing opposite directions

Figure 2. Having parallel planes, the elevation angles have the same absolute value

If the z-axis is pointing the upward direction, the elevation angles have opposite signs (Figure 2a). If the z-axis points downward, the elevation angles have the same sign as shown in figure 2b. Since both elevation angles between a given node pair i and j have equal values, our localization process for 3D environments is now reduced to that for 2D problems. Indeed, as the z-axis for the two coordinate systems are aligned in either directions, it is just a matter of rotation of the coordinate system along the z-axis using the azimuth angles. To correct the coordinate system of a second sensor node, we need to adjust its x-y plane with a rotation along the z-axis, similar to the adjustments in the 2D method by Capkun et al.

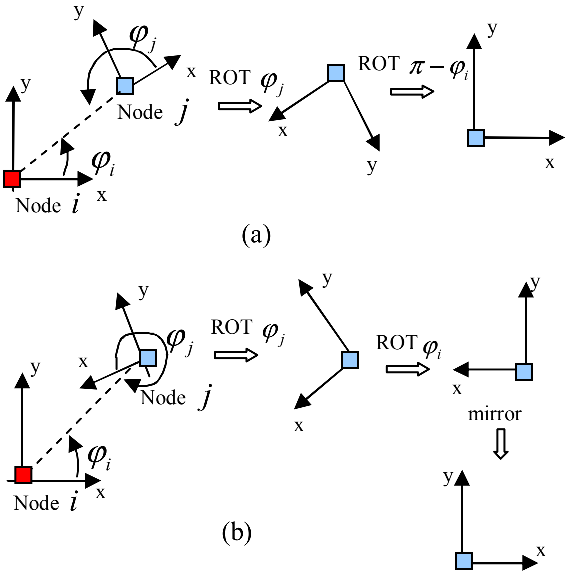


Figure 3. Adjustment of the coordinate system. (a) Z-axis pointing upward, (b) Z-axis pointing downward.

As shown in Figure 3a, the correction angle for the node j in the first situation is $\varphi_j - \varphi_i + \pi$. In the second situation in Figure 3b, the correction angle for node j is $\varphi_j + \varphi_i$, and the mirroring is done with respect to the y-axis. All the rotations are in the positive direction of its local coordinate system.

For certain deployment environments, it may be difficult to align the z-axis of a sensor node (which may represent the normal direction of the planar antenna) with the earth gravity. Instead, it may be more convenient to align the x-axis with the earth gravity. For example, the antenna patch is now pointing towards the center of the tunnel. For the case in which a second sensor node has it x-axis aligned with the earth gravity, its x-y plane is perpendicular to the reference's x-y plane, as shown in figure 4. This case can be easily detected as the elevation angles have different values.

Once this case is detected, a rotation of 90° of the coordinate system along the y-axis is needed. The result of this rotation can give us a z-axis pointing downward or upward direction. In either case, the next adjustments to be taken are exactly those in the situation illustrated in Figure 3.

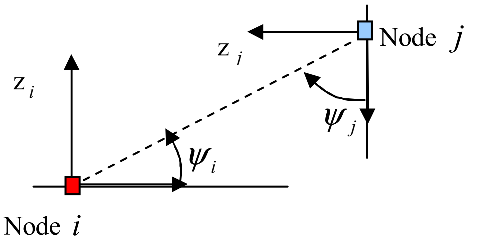


Figure 4. Planes are perpendicular, the elevation angles have different absolute value.

At the end of the correction process, all coordinate systems at all sensor nodes have their axes aligned and pointing towards the same directions.

Consider node k which is two hops from node 1 via node j. Node j defines and adjusts its coordinate system based on the reference system of node 1. In turn, node k calibrates its relative to that of node j. After adjustments, the coordinate systems of the nodes are identical. The position of the node k in the coordinate system of node 1 is obtained by summing two vectors as illustrated in Figure 5.

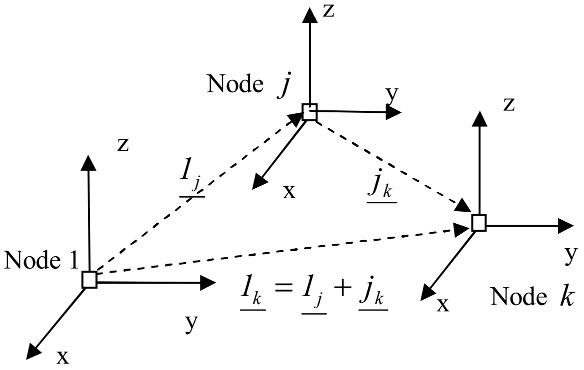


Figure 5. Position computation when the local coordinate systems have the same direction.

The same procedure is applied to adjust and obtain the consistent coordinate systems for all nodes with multiple hops away from node 1. Obviously, estimates of elevation angles and distances between sensor nodes by use of antenna techniques have errors. Thus, errors "propagate" from the nodes surrounding node 1 towards other nodes at the edge of the network. In order to reduce the propagation of estimation errors, it will be advantageous to place the reference sensor at the "middle" of other sensors (e.g., in the middle of the tunnel). In the following section, we study how estimation errors can affect the effectiveness of the new localization method for sensors installed in a tunnel.

5. Performance of the New Scheme

We use Matlab to simulate and verify the correctness of the proposed positioning algorithm. Our simulation model considers a tunnel of 300 meters long where three types of sensors are deployed at the top, side-walls and the bottom of the tunnel, respectively, as shown in Figure 6. Node 1 (the reference system) is located at the coordinates of (2,0,0) in the figure. Sensors of the same type are separated by 20 meters on a straight line along the tunnel. However, sensor communication range is assumed to be an adjustable parameter in the simulation. Specifically, we consider sensors can communicate with a neighboring node of any type located within 20, 30 and 40 meters. That is, a node cannot reach directly to other nodes located beyond the given range parameter. The cross section of the tunnel is represented by a semi-ellipse with 8 meters width at the bottom and 6 meters from the ground to the highest point in the tunnel ceiling.

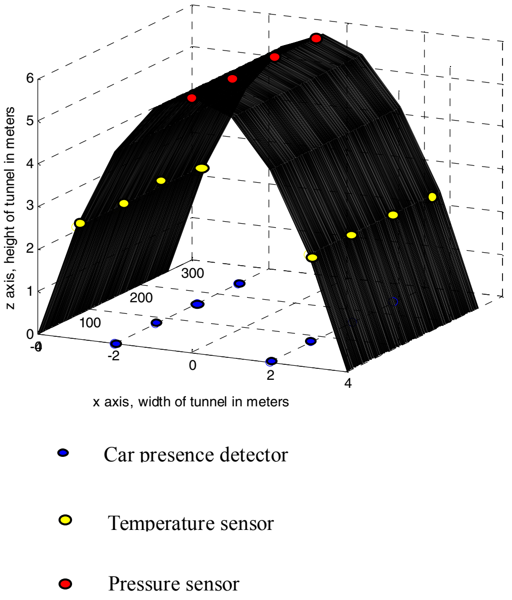


Figure 6. Deployment of sensors along the tunnel.

We first assume that the range estimate errors (the distance between a pair of nodes) have a Gaussian distribution with zero mean and a fixed standard deviation σ normalized to the actual distance between two nodes. We evaluate the proposed algorithm with the normalized standard deviation being 0.1, 1, 2.5, 5, 7.5 and 10%, and three different communication ranges, 20, 30 and 40 m.

Using the proposed algorithm, the estimated positions of all sensors in the tunnel is presented in Figure 7. Clearly, due to range estimation errors, the estimated positions do not lie on a straight line. To quantify the quality of the proposed positioning method, we consider the relative mean estimate error as follows:

$$\varepsilon = \frac{\frac{1}{n}\sum_{i=1}^{n}\sqrt{(x_i-\hat{x}_i)^2+(y_i-\hat{y}_i)^2+(z_i-\hat{z}_i)^2}}{cr}$$

where n is the total number of sensor nodes, (x_i, y_i, z_i) and $(\hat{x}_i, \hat{y}_i, \hat{z}_i)$ are the exact and estimated position of node i by the proposed algorithm and cr is the communication range.

Our results reveal that the longer the communication range, the lower is the relative mean error ε (i.e., the y-axis in Figure 8) because a longer range means less number of hops from the reference node to other nodes in the system, thus less propagation of estimation errors.

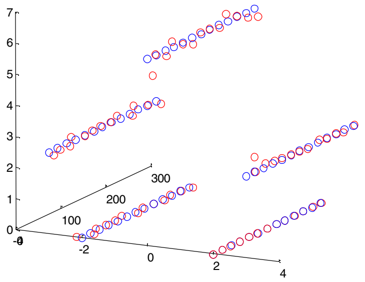


Figure 7. Estimated sensor locations for a 2.5% normalized standard deviation for the range estimations.

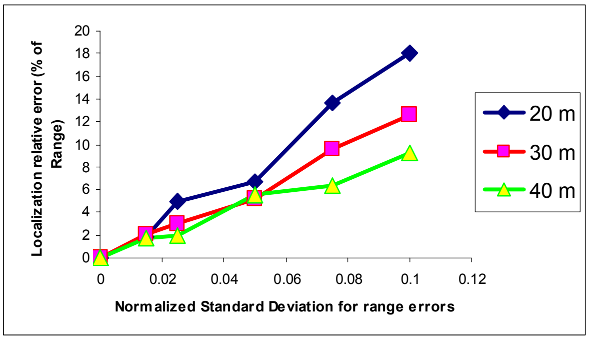


Figure 8. Simulation for different communication radius and different error standard deviation

We also repeat our simulation with uniform, random estimation errors. That is, for a given relative error percentage (say X %) and a communication range of Y meters, the estimation error is uniformly distributed between –XY/100 and XY/100. Our results show that the mean estimate error for the uniform error model is similar to that for the Gaussian distributed errors with the same standard deviation.

Since it is reasonable to expect that TDOA technique can provide a range estimate of 5% error standard deviation, our results in Figure 8 suggest that the relative average position estimate error is in the range of a few percent, which is satisfactory for many applications.

6. Conclusion

This work has been motivated by the need for a new localization algorithm for applications and flexible sensor deployment in underground environments such as train tunnels and water networks. We have proposed and studied a new localization method, which makes use of the direction of earth gravity for sensor installation. It consists of: a) using the TDOA and AOA techniques for estimating the ranges and angles among sensors, and b) a distributed scheme to adjust the three-dimensional coordinate system for each sensor based on local measurements.

A Matlab simulation model has been constructed to validate the proposed algorithm and assess its error performance. Our results indicate that for an example of underground tunnel, the new algorithm yields satisfactory positioning with a relative error of few percent when the standard deviation for the range estimation error is less than 5%. This accuracy would be satisfactory for many applications.

Since no central control is required for the new algorithm, it is appropriate for large-scale sensor networks. Further, new sensor nodes can be added to a network incrementally and they simply adjust their coordinate systems based on measurements exchanged with their neighbors in a distributed manner. Thus, such a distributed, self-organized location technique using available wireless technology is suitable for practical use in harsh environments such as underground tunnels and water networks.

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