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Ultrasound-based orientation and location of mobile nodes combining TOF and RSSI measurements

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***Abstract*— In this work we present a method to estimate the spatial orientation of a mobile node using the time-of-flight (TOF) and the signal strength (RSSI) of the ultrasound signals emitted by a set of fixed reference nodes with known positions. The orientation of the node is estimated from the power level of the received signal by applying a power-loss model that takes into account the signal propagation and the radiation pattern of the ultrasonic transducers. The accuracy of the proposed method has been evaluated in a real environment of 2 x 2 x 1.5 m, obtaining an average orientation error less than 18 degrees.**

Keywords—orientation; positioning; TOF; RSSI; ultrasound

I. INTRODUCTION

In recent years, a wide variety of local positioning systems based on different technologies has been proposed to determine the position and even the orientation of a mobile node in indoor environments. Among them, the ultrasounds have been postulated as one of the most used and more accurate technologies.

In the literature, different techniques [1-3] and indoor positioning systems [4-5] capable of estimating the position and orientation of a mobile node with high accuracy using an array of ultrasound transducers can be found. In most cases, the measurements of time-of-flight (TOF), angle-of-arrival (AoA) and/or signal strength (RSSI) are used for this purpose.

In this work we use the infrastructure of the TELIAMADE system [6] to obtain the location and orientation of a mobile node. The TELIAMADE system consists of a set of wireless ultrasonic nodes that typically operate as transmitters (beacons), which are placed at fixed and known positions within the location environment and mobile nodes configured as receivers. The position of the mobile node is calculated using trilateration or multilateration from the distances estimated to three or more beacons. The distance between nodes is calculated from the TOF measurement of the ultrasonic signal emitted by the beacons (typically signals of 1 ms) considering the propagation speed of sound. We perform quadrature detection on the signal received in the mobile node to estimate both the TOF and RSSI measurements. The details of the mathematical formulation can be consulted in the references [6] and [7], respectively.

In this work we propose to combine TOF and RSSI measurements to estimate the orientation and location of the mobile node, by modeling the power loss of the signal due to propagation path and the radiation pattern of the ultrasonic transducers. As far as we are aware, it is the first indoor location system based on ultrasound which allows 5D positioning (location + orientation) using a single transducer in the receiver, with no need for additional instruments.

II. ESTIMATING ORIENTATION

The orientation of the mobile node is estimated using a loss model of ultrasound signal strength. In this work we propose a loss model where we assume that the received signal strength in the receiver (expressed in dB) is given by the expression:

$$\mathrm{RSSI}_{\mathrm{model}} = \mathrm{RSSI}_{\mathrm{p}} - \mathrm{L}_{\mathrm{RSSI}}(\varphi) - \mathrm{L}_{\mathrm{RSSI}}(\beta) \quad (1)$$

The term $\mathrm{RSSI}_{\mathrm{p}}$ represents the power level that would be obtained if the beacon node and the mobile node were faced with their transducers in perfect alignment. This term takes into account the distance (d) between the nodes to determine the signal strength drop due to the wave dispersion and propagation attenuation (details in section II-A). On the other hand, the received signal power will depend on the radiation pattern of the transducers and their orientation with respect to the propagation direction (i.e., the straight line between nodes). The terms $L_{RSSI}(\varphi)$ and $L_{RSSI}(\beta)$ represent, respectively, the power loss associated with the orientation of the transmitter node and the receiver node with respect to the propagation direction (see section II-B). Finally, in section II-C we describe the algorithm that estimates the incidence angle (β) and orientation $(\vec{R})$ of the mobile node.

A. *Modeling the power-loss with the distance*

The power loss due to distance is modeled using the passive sonar equation and a signal propagation model including losses due to spherical divergence and atmospheric absorption [7]:

$$\mathrm{RSSI_p} = \mathrm{RSSI_0} - 20\log_{10}\left(\frac{\mathrm{d}}{\mathrm{d_0}}\right) - \alpha(\mathrm{d} - \mathrm{d_0}) \quad (2)$$

The first term $RSSI_0$ is the signal power (expressed in dB) measured in reference conditions when the beacon node and mobile node are faced at a known reference distance (d_0) with their transducers in perfect alignment (i.e., with an incidence angle of 0°). The second term represents the power-loss due to spherical divergence, where d is the distance between the beacon node and mobile node (calculated from the TOF measurement and the speed of sound [6]). Finally, the third term corresponds to the power-loss due to atmospheric absorption, where α is the absorption coefficient (expressed in dB/m) and whose value is estimated considering the ambient temperature and relative humidity [8]. It is important to highlight that the signal strength measurement may also be affected by the battery voltage level of the nodes. In [7] we analyzed the effect of battery level on the RSSI measurement and we proposed an algorithm to compensate for that.

The value of $RSSI_0$ has been experimentally determined from a set of 50 RSSI measurements by setting $d_0 = 1.5$ m and a null incidence angle between nodes ($L_{RSSI}(\varphi) = L_{RSSI}(\beta)$). Values of temperature and relative humidity also were registered to provide the calculation of α. Our loss model has been evaluated from experimental measurements with different pairs of nodes (Tx-Rx) placed at different distances (d) (ranging between 1.5 m and 4 m) to obtain the power drop curve with the distance. A fitting of the experimental data with this model (minimizing the error between the RSSI provided by equation (2) and the experimental RSSI measurements) provides a determination coefficient R^2 = 0.990 and a root mean square error smaller than 0.38 dB. These results validate the proposed modeling.

B. *Modeling the power-loss with the orientation*

The nodes of the TELIAMADE system have ultrasonic transducers with a directional radiation pattern and a narrow beam width. This implies that the RSSI measurement varies according to the angle of incidence of the transducers. A greater angle of incidence implies a lower radiation power and therefore lower signal amplitude. The power loss due to the incidence angle is estimated by applying a theoretical model that takes into account the shape of the surface of resonance of the transducers (typically circular) (see details in reference [7]):

$$\mathrm{L_{RSSI}}(\theta) = \left|20\log_{10}\left(\frac{1+\cos(\theta)}{2}\cdot \mathrm{f_{Airy}}(\theta,\lambda,\mathrm{r})\right)\right| \quad (3)$$

where θ is the incidence angle (in radians), $(1+\cos\theta)/2$ is the obliquity factor and $f_{Airy}(\theta,\lambda,\mathrm{r})$ is the Airy function particularized for a uniform circular aperture of radius r (for more details, see [9]). The proposed model was fitted from experimental measurements for each pair of nodes (Tx-Rx), assuming a fixed distance of 2.5 m between nodes. The mobile node was oriented with different incidence angles (θ) in the range between $-45°$ and $+45°$, maintaining fixed the beacon node. Figure 1 shows the power-loss curve due to the orientation obtained with a pair of nodes, including experimental measurements and the model fitted with equation (3). The similarity between experimental and theoretical measurements (with a root-mean-square error less than 0.64 dB) demonstrates the proper functioning of our model with incidence angles smaller than 40 °.

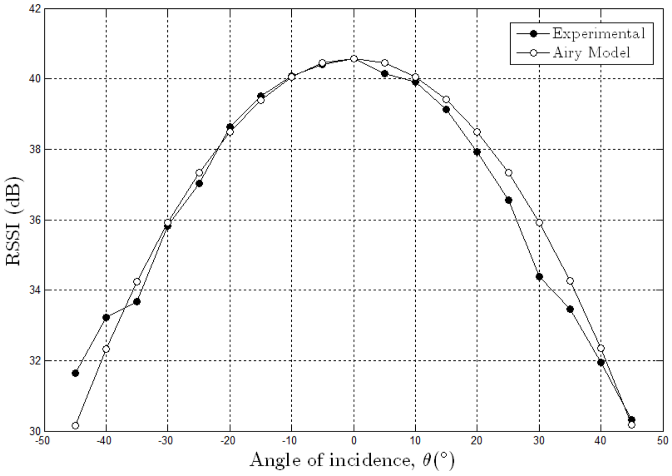


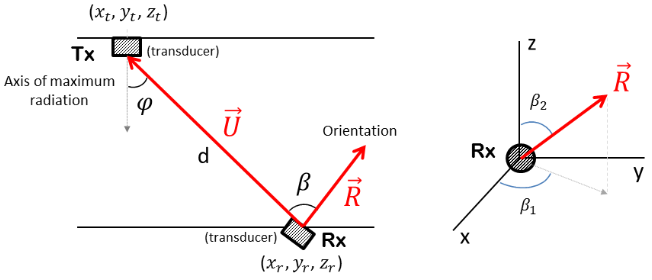
Figure 1: Power-loss curve due to orientation obtained with a pair of nodes. The filled dots correspond to RSSI values experimentally measured, while the unfilled dots are RSSI values obtained with our approach based on the Airy model.

C. *Estimate of the angle of incidence and orientation*

In a typical deployment for indoor location, the beacon nodes are usually placed in different positions of the ceiling with their ultrasound transducers pointing down (i.e., perpendicular to the floor). The mobile node position is calculated by applying multilateration using the estimated distances to several beacon nodes with a subcentimeter-accuracy location [6]. Figure 2a shows a simple scenario composed of a beacon node (Tx) and a mobile node (Rx), where we assume that the location and orientation of their transducers as the distance between them are well known. In this figure, the incidence angles resulting for a certain orientation ($\vec{R}$) of the mobile node are displayed.

The incidence angle (φ) that forms the beacon node with propagation direction can be directly estimated if the orientation of the transmitter and the locations of the transmitter and the receiver are known. Furthermore, the incidence angle (β) that forms the mobile node with respect to the propagation direction is intrinsically associated with the orientation vector ($\vec{R}$) of the mobile node. This vector can be represented by two angles: azimuth (β_1) and elevation ($90° - \beta_2$) (expressed in degrees), as shown in Figure 2b. If we assume that $\vec{R}$ is a unitary vector, then:

$$\vec{\mathrm{R}} = [\sin(\beta_2)\cdot\cos(\beta_1), \sin(\beta_2)\cdot\sin(\beta_1), \cos(\beta_2)] \quad (4)$$



(a) (b)

Figure 2: (a) Illustration of the incidence angles (φ, β) between one beacon node (Tx) and the mobile node (Rx) for a given orientation $(\vec{R})$ of the mobile node. (b) Representation of $(\vec{R})$ in spherical coordinates.

On the other hand, we can also calculate the vector that aligns the centres of the transducers by using the coordinates of the nodes:

$$\vec{U} = [(x_t - x_r), (y_t - y_r), (z_t - z_r)] \tag{5}$$

Accordingly, the incidence angle β can be determined from the normalized scalar product with both vectors:

$$\cos(\beta) = \left(\frac{\langle \vec{U}, \vec{R} \rangle}{\|\vec{U}\| \cdot \|\vec{R}\|} \right) \tag{6}$$

From the above formulation and equation (1), we propose to estimate the orientation vector $(\vec{R})$ from β_1 and β_2 angles by applying a minimum square error (MSE) estimator to minimize the following cost function:

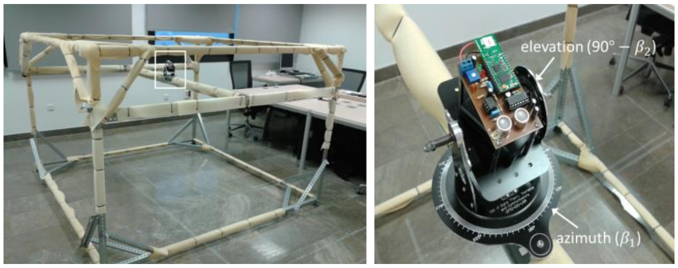
$$MSE = \frac{1}{N} \sum_{i=1}^{N} {e_i}^2$$

$$e_i = RSSI_{model} - RSSI_{meas} \tag{7}$$

where N is the number of beacons involved in the calculation of the mobile node position (with $N \geq 3$), $RSSI_{meas}$ is the actual signal-strength measured at the receiver and $RSSI_{model}$ is the estimated signal-strength using equation (1). Since the beacon nodes are fixed and their orientations are known, it is possible to estimate the incidence angle φ and the term $L_{RSSI}(\varphi)$ using equation (3). However, we do not know a priori the orientation of the mobile node, and therefore, the term $L_{RSSI}(\beta)$ in equation (1) is unknown. The aim of the cost function is to find β_1 and β_2 values providing a $L_{RSSI}(\beta)$ factor that minimizes the MSE. To do this, we evaluate different azimuth (β_1) and elevation(β_2) angles to obtain the $\vec{R}$ vector using equation (4), and with it the incidence angle β from equation (6). Thus, the term $L_{RSSI}(\beta)$ is finally estimated using equation (3) to evaluate the cost function. The orientation of the mobile node $(\vec{R})$ is given by β_1 and β_2 angles that provide the lowest MSE.

III. EXPERIMENTAL RESULTS

The proposed method has been evaluated in a real office environment using the TELIAMADE system. The experiment was performed using a deployment with 5 beacon nodes (Tx) and one mobile node (Rx) within a location area of 2 x 2 x 1.5 m. The beacon nodes were attached to the ceiling with their ultrasound transducers oriented to the floor, while the mobile node was placed in different test positions taking into account several orientations of the node for each position. The placement of the mobile node in each position was carried out using a metal structure (see Figure 3a) with a location error of a few millimeters. For each position, different orientations of the node were evaluated using an angular platform (see Figure 3b) by setting $\beta_1 = \{0°, 90°, 180°, 270°\}$ and $\beta_2 = \{0°, 15°, 35°\}$ with an orientation error of less than 1°.



(a) (b)

Figure 3: Test-bed used to evaluate the efficiency of the proposed method in a real environment by considering different 3D positions and orientations of the mobile node.

For each orientation, at least 60 measurements of RSSI and TOF were registered with each pair of nodes (Tx-Rx) in different test positions (6 positions, at two different heights). The TOF measurements were used to estimate the distance to the beacon nodes and from them the mobile node position using multilateration. Finally, the orientation of the node was estimated from the RSSI measurements by applying the procedure described in section II. Note that, depending on the orientation of the mobile node, the TOF measurement can be affected by near-field interference, leading some location errors (E_L). This error is calculated from the theoretical position (x_r, y_r, z_r) and the estimated position $(\hat{x}_r, \hat{y}_r, \hat{z}_r)$, as:

$$E_L = \sqrt{(x_r - \hat{x}_r)^2 + (y_r - \hat{y}_r)^2 + (z_r - \hat{z}_r)^2} \tag{8}$$

The location error, along with other factors, can affect the orientation estimation. The orientation error (E_R) is calculated as the angular difference between the theoretical orientation vector $(\vec{R})$ and the estimated orientation vector $(\hat{\vec{R}})$ using the normalized scalar product $(\bar{P})$:

$$\overline{\mathrm{P}} = \langle \vec{\mathrm{R}}, \widehat{\vec{\mathrm{R}}} \rangle \big/ \left(\|\vec{\mathrm{R}}\| \cdot \|\widehat{\vec{\mathrm{R}}}\| \right) \quad (9)$$

$$\mathrm{E_R} = \cos^{-1}(\overline{\mathrm{P}}) \quad (10)$$

Table 1 shows the root-mean-square errors in location and orientation obtained taking into account all the measurements acquired at the test positions for different angles of azimuth (β_1) and elevation ($90° - \beta_2$) evaluated. The spatial distribution of the errors obtained for each position is approximately log-normal. The most favourable scenario to estimate the position and orientation of the mobile node is when $\beta_2 = 0°$ (same incidence angle between the beacon node and the mobile node, $\varphi = \beta$), obtaining a location error less than 7 mm and an orientation error less than 10°. The results show a worse estimate of the orientation when the angle β_2 is increased. This is due to several factors. Firstly, the estimated location of the node is less accurate for higher angles β_2 (location errors in the order of 1 to 2 cm) due to higher incidence angles (β) with respect to beacon nodes. Furthermore, the Airy model proposed in (3) works well for incidence angles not exceeding 40 °. The drop in power observed for incidence angles greater than 40° (see Figure 1) has an anomalous behaviour. This involves a poor performance of our model for angles greater than these, which entails an error when we estimate the φ and β angles that determine the node orientation. The overall results obtained with our method shows an error in the orientation accuracy less than 18 °.

Table 1: Root-mean-square errors in location ($\overline{E_L}$) and orientation ($\overline{E_R}$) obtained with all the measurements at the different test positions for each orientation ($\vec{R} = \{\beta_1, \beta_2\}$).

	$\beta_2 = 0°$		$\beta_2 = 15°$		$\beta_2 = 35°$	
	$\overline{E_L}$ (mm)	$\overline{E_R}$ (°)	$\overline{E_L}$ (mm)	$\overline{E_R}$ (°)	$\overline{E_L}$ (mm)	$\overline{E_R}$ (°)
$\beta_1 = 0°$	1.15	10.50	9.18	16.91	13.43	21.06
$\beta_1 = 90°$	7.83	10.00	8.58	11.71	15.56	14.74
$\beta_1 = 180°$	7.26	9.50	12.24	9.09	18.32	15.15
$\beta_1 = 270°$	11.11	9.50	10.80	14.66	21.10	20.63
Average	**6.83**	**9.87**	**10.20**	**13.09**	**17.10**	**17.89**

IV. CONCLUSIONS

In this work, we propose a method to estimate the location and orientation of a mobile node by implementing quadrature detection from ultrasound signals emitted by a set of reference nodes with known positions. Herein, measurements of time-of-flight (TOF) and signal strength (RSSI) are combined to achieve this aim. The orientation of the node is estimated using its location and the received signal strength by applying a model that includes signal power losses due to the propagation path and the radiation pattern of the ultrasonic transducers. The proposed method has been evaluated in a real office environment of dimensions 2 x 2 x 1.5 m using the TELIAMADE system. The results show an orientation accuracy less than 18 °. The methodology described in this work provides 5D positioning of a mobile node taking advantage of the same infrastructure typically used for 3D positioning, with no need for additional measurements.

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