Physical Communication 30 (2018) 97–106

Contents lists available at ScienceDirect

Physical Communication

journal homepage: www.elsevier.com/locate/phycom

Full length article

3-D localization of wireless sensor nodes using near-field magnetic-induction communications

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ARTICLE INFO

Article history:
Received 4 May 2017
Received in revised form 3 June 2018
Accepted 9 July 2018
Available online 19 July 2018

ABSTRACT

This paper proposes two localization methods for wireless sensor nodes that utilize an arbitrarily oriented tri-directional coil as both magnetic induction (MI) transmitter and receiver for wireless communications. Taking advantage of magnetic field measurements of a tri-directional coil antenna in the near-field, the two localization algorithms use only two anchor nodes to locate a sensor node in the 3-D space. Assuming each anchor node transmits the communication signals by three coils sequentially, which are received by the three coils at a sensor node simultaneously, this paper derives closed-form formulas for estimating the transmission distance and the polar angles to yield eight possible location points based on the signals of each anchor node. Then a rotation matrix (RM)-based method derives the orientation rotation matrix between the transmitter and receiver to find two possible location vectors with opposite directions in each anchor node. Then, we use maximum likelihood to estimate the location with two anchor nodes assisted. Another method called the distance-based method, taking into account the locations of the two anchor nodes and the two sets of eight possible location estimates of the sensor node, estimates the location by minimizing the distance. The RM-based method can achieve high localization accuracy while the distance-based method has less computational complexity. However, the distance-based method may encounter location ambiguity when the orientations of the two anchor nodes are the same. Simulations were performed to compare these two algorithms and the existing localization algorithm in this scenario. The results show that the proposed two localization algorithms and the derived closed-form formula of distance achieve good accuracy under large measurement errors.

1. Introduction

Magnetic induction (MI) communication has been developed for wireless communication in challenging environments, such as underwater and underground, where traditional radio frequency (RF) communication technologies encounter formidable difficulties [1,2]. The advantages of MI communications are low cost, negligible propagation delay, no multipath interference, and no requirement of line of sight. The limitations of MI communications include small bandwidth, severe range attenuation, and strong directionality of antenna coils. With short range and low data rate, MI communication has been applied to underwater or underground wireless sensor networks (UWSN), which in turn find important applications [3] in underground structure monitoring, earthquake and landslide prediction, bridge scour monitoring, river bank monitoring, landscape management, border patrol and security, etc.

An important task of UWSNs is the localization of sensor nodes in the network because it is often desirable to collect sensing data associated with position information. The knowledge of geographic positions of nodes is also required for mobility tracking, routing, and coordination purposes. Indoor robot navigation is reported in [4–8]; underground target localization and tracking are reported in [7,9–12]; and tracking medicine application in human bodies is reported in [13,14]. Localization in randomly-deployed underground sensor networks based on MI communications are studied in papers [15,16].

Typically, a node localizes itself by communicating with other nodes around it. In a wireless sensor network, a node whose absolute location is known to all nodes is termed as an *anchor* node which is used as a reference in the global coordinate system (GCS). The other ordinary nodes are called *sensor* nodes which have to estimate their own locations. Taking advantage of the knowledge of anchor nodes and communications between nodes, the locations of sensor nodes are usually estimated via tri-lateralization or triangularization if the sensor node can communicate with three or more anchor nodes [17]. In a dense network, if the percentage of anchor nodes is small, then the recursive position estimation method [18,19] is commonly used to cover the whole network of sensor nodes.

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https://doi.org/10.1016/j.phycom.2018.07.011
1874-4907/

On the other hand, in sparse wireless sensor networks where the node degree is very small due to limitations in communication range, as is often the case in MI sensor networks, the localization of sensor nodes faces many technical challenges because the number of neighboring nodes is often less than three and the percentage of anchor nodes can be very small. The directionality of MI coils also causes ambiguity in range estimation if the orientations of the transmitter and receiver coils are unknown because the received signal strength indicator is affected by the range as well as the coil orientations [2,7,20–22]. Besides, a magnetic field is easy to be interfered with by metals nearby and the earth's geomagnetic field, causing localization errors [23–26].

Remedies to the challenges of MI sensor localization include: (1) in special environments such as pipeline systems and indoor environments, coil orientations are constrained to a fixed known direction [27–29] and range estimation is obtained with RSSI measurements; (2) localization is constrained to a 2-D plane [30] by using input impedance measurements at several reference nodes; (3) orientation sensors are used in addition to communication signals to aid the range estimation, as reported in [31]; and (4) large coils are arranged in a 2-D plane to form a magnetic grid, then the received signals on these large coils are estimated to find the coarse locations of the transmitter [7]. All these methods suffer from stringent constraints, inflexible implementation or high localization errors. Paper [32] uses multiple tri-directional coils to locate a sensor node, while paper [33] gives a localization method in a 3-D space using only two anchor nodes.

In this paper, we propose two novel methods for MI sensor localization in 3-D space using only two anchor nodes and their communication signals with the sensor node. We compared our proposed methods with the method in paper [33]. In our methods, all nodes can have arbitrary orientations and positions in the 3-D space, and they all employ tri-directional coil antennas for MI communication. By taking advantage of the directionality of the three orthogonal transmitting (source) coils at each of the two anchor nodes, the sensor node, also equipped with a tri-directional coil that is receiving (sensor) coils, can estimate its transmission distance to the anchor nodes without ambiguity, and can estimate two possible polar angles for each transmitting coil. This results in two sets of eight possible location estimates for the sensor node. Rotation matrix (RM)-based method uses eight location estimates to compute the rotation matrix between the transmitting and receiving coils and identify one pair of diagonal points with the opposite directions in each anchor node, and then utilizes the maximum likelihood and gradient ascent algorithm to estimate the sensor node location. The RM-based method yields high localization accuracy under measurement errors. The distance-based method uses the minimal distance rule to select the best pair of location estimates from the two sets of eight points, and determines its location by the minimum mean-square error (MMSE) estimation. This method has less computational complexity and is faster, but might encounter estimation ambiguity when the two anchor nodes have the same orientation. This localization ambiguity can be solved by the RM-based method. Through computer simulations, we verify that the two methods work well even if large errors exist in measurements, have no deployments on the deployment, and are more robust against coil structure errors.

2. Background

Assume that the anchor nodes and sensor nodes are equipped with tri-directional coil antennas, as shown in Fig. 1, where the three coils are orthogonal to each other and their centers are co-located. Let R be the distance between node S and the center of the coils. The local coordinate system (LCS) of the anchor node is defined with the x, y, and z axes aligned with the axes of the three coils, respectively. The three coils are excited sequentially by a current source $i(t) = I\exp\{j\omega t\}$ with $j = \sqrt{-1}$, each of which produces an magnetic flux density at the sensor node location S.

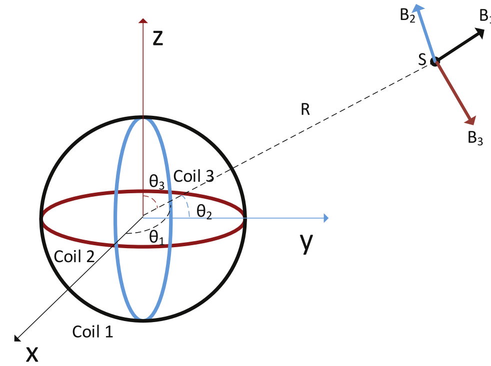

Fig. 1. Magnetic field generated by a source tri-directional coil.

Let $\mathbf{B}_k$ be the magnetic flux density at S generated by the kth transmitting coil, and θ_k be the polar angle of S against the x, y, z axis, respectively, where $k = 1,2$, and 3. If the distance R is more than four times of the radius r of the coil, the magnetic field produced by the current loop is equivalent to that from a magnetic dipole [34]. In other words, the source and sensor coils can be treated as single points [35]. Hence, the magnetic flux density $\mathbf{B}_k$ at node S only depends on the distance R and the polar angles θ_k as

$$\mathbf{B}_k = \begin{cases} B_{kr} = (M\mu/2\pi R^3)\cos(\theta_k) \\ B_{kt} = (M\mu/4\pi R^3)\sin(\theta_k) \end{cases} \tag{1}$$

where the subscripts r and t denote the radial and tangential components of the magnetic flux density $\mathbf{B}_k$, respectively; M is the magnitude of magnetic moment $\mathbf{M}$ of the current loop; and μ is the magnetic permeability of the medium. Eq. (1) holds for the magnetic field of a coil in the near-field. For A more general expression of a magnetic field induced along a closed curve, please refer to the Biot–Savart law [23].

The magnetic moment $\mathbf{M}$ is calculated by

$$\mathbf{M} = NIA\vec{\boldsymbol{F}} \tag{2}$$

where N and A are the number of coil turns and the area of the current coil, respectively. Although the excitation current $i(t)$ depends on the carrier frequency ω, the amplitude of the magnetic field is independent of ω. The unit vector $\vec{\boldsymbol{F}}$ denotes the axis of the coil which is perpendicular to the coil plane and follows the right-hand rule. We also note that the spatial phase variation of $\exp(jR/\lambda)$ can be ignored as long as the coil is in the near-field or quasi-static field that satisfies $\lambda/2\pi \gg R$, where λ is the wavelength. Therefore, the magnitude of the magnetic flux density $\mathbf{B}_k$ is expressed as

$$B_k = \sqrt{B_{kr}^2 + B_{kt}^2}. \tag{3}$$

At the sensor receiver, the magnitude B_k of the magnetic field of the kth transmitting coil is measured by three receiving coils as

$$B_k = \sqrt{B_{k1}^2 + B_{k2}^2 + B_{k3}^2} \tag{4}$$

where the subscripts 1, 2, and 3 represent three orthogonal coils at the receiver side [7]. By using (4), the magnitude of the magnetic flux density is measured invariant to the orientation of the sensor coils, which has the advantage of the sensor nodes having an arbitrary orientation.