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Multi-sensor data fusion methods for indoor localization under collinear ambiguity

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ABSTRACT

Sensor node localization in mobile ad-hoc sensor networks is a challenging problem. Often, the anchor nodes tend to line up in a linear fashion in a mobile sensor network when nodes are deployed in an ad-hoc manner. This paper discusses novel node localization methods under the conditions of collinear ambiguity of the anchors. Additionally, the work presented herein also describes a methodology to fuse data available from multiple sensors for improved localization performance under conditions of collinear ambiguity. In this context, data is first acquired from multiple sensors sensing different modalities. The data acquired from each sensor is used to compute attenuation models for each sensor. Subsequently, a combined multi-sensor attenuation model is developed. The fusion methodology uses a joint error optimization approach on the multi-sensor data. The distance between each sensor node and anchor is itself computed using the differential power principle. These distances are used in the localization of sensor nodes under the condition of collinear ambiguity of anchors. Localization error analysis is also carried out in indoor conditions and compared with the Cramer–Rao lower bound. Experimental results on node localization using simulations and real field deployments indicate reasonable improvements in terms of localization accuracy when compared to methods likes MLAR and MGLR.

1. Introduction

Determining the location of a mobile node is an active area of contemporary research into ad-hoc wireless sensor networks. In addition to obtaining sampled information and time stamps from a particular sensor node in a network, the global position of node is also required in many applications like habitat monitoring, military surveillance and emergency response. A practical approach of sensor node localization using different signal modalities is useful for terrestrial applications. Signal modalities refer to the different types of signals such as radio signal [1], acoustic [2], light samples [3] and temperature wavefront [4]. A wireless node is equipped with different types of sensors to measure the radio, acoustic, light and temperature modalities together. Depending upon the availability of modality, either individual mode or combined fusion model can be incorporated into the localization system. Localization of sensor node is a challenging task using radio signal. The radio signal performs poorly in dense non-line-of-sight (NLOS) environment. There is a large fluctuation of radio signal at a particular location due to time-varying nature of wireless channel. The main challenge with acoustic signal is the reverberation in indoor environment. Visible light samples provide better indoor localization accuracy than the radio signal [3,5–7]. The limitation of visible light localization system is that it cannot work in outdoor broad sunlight, unless it is being used in the night with some light source. Other drawbacks include effect of shadow, reflection and a sensor node cannot measure

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light intensity accurately if it is on the other side of the wall. In this scenario, acoustic signal works better than the visible light. It may be noted that general visible light localization system utilizes 600–800 lumens LED in a very small network area e.g. 5 m × 5 m. Our experimental system may use general monochromatic light in a larger area say 25 m × 25 m.

The method presented in this work uses all the modalities together for localization of a sensor node and thereby improves its localization accuracy. In this work, we focus on optimal linear sensor data fusion [8]. The aim of the fusion technique is to minimize the mean square error while keeping the precision high. A fused signal model is developed by weighing them with the optimal weight for improved accuracy in this work. Additionally, it does not require any additional hardware such as antenna array or clock synchronization. Synchronization is required in case of localization with measurements like time of arrival (TOA) [9]. Whereas antenna array is used for angle of arrival (AOA) [10] based localization. Furthermore, incorporating all these modalities together makes the localization system more robust to NLOS communication inside a building. It is highly unlikely that all the modalities do not work well in the NLOS prone environment. Therefore, localization accuracy can be improved by using the combined fusion model. Note that, we can use individual modality also, if particular signal modality is much more prominent in a given scenario. Prior work on localization using multi-sensor data has focused on various fusion methods. A Bayes-maximum entropy method for fusion of ultrasound and visual sensor data has been illustrated in [11]. A data fusion technique of power and time measurements for mobile terminal location is described in [12]. In [13], an error tolerant multi-modal sensor fusion in embedded sensor networks for better information mapping has been discussed. The Kalman filter based indoor positioning system to compute location from multiple positioning systems is described in [14]. In [15], deployment of mobile agents in a distributed sensor network using multi-sensor data fusion method is proposed.

In this paper, the problem of node localization under collinear ambiguity using multi-sensor data fusion is proposed. Collinearity problem arises due to the linear (or straight path) motion of a mobile anchor broadcasting its location. The collinearity problem has been identified and stated in [16–18]. At-least three non-collinear anchor's locations are required for localization as described in [19]. In [20], the anchor broadcasts its position from non-collinear locations. Network localization by shadow edges requires absolute location of non-collinear vertices as discussed in [21]. [22] proposes static paths such as Circles and S-Curves, while [23] proposes Square, Archimedean Spiral and Wave paths which are planned to reduce the collinearity of anchors. Mobile beacon traverses in an intelligent manner in [24], such that it provides non-collinear reference locations. Hitherto, localization of nodes under collinear ambiguity of the anchors has not been explored. In our earlier work [25], a single mobile beacon based energy efficient localization algorithm has been proposed. However in [25], it is possible that mobile anchor tends to line up in a linear fashion between successive time instants. In this scenario, computation of location of node will not be possible. In this paper, multi-sensor node localization under the collinear ambiguity is described. The range between anchor and node is computed using attenuation models developed in a multi-sensor framework. The proposed method is compared with range based methods like MGLR (modified geometric link reconstruction) [26] and MLAR (modified linear algebraic reconstruction) [27].

Throughout this work, boldface letters represent a matrix or a vector. $\|.\|$ represents $\mathcal{L}_2$ norm, which is the Euclidean distance between two vectors. The transpose of a matrix is denoted by $(.)^T$. The nodes act as receivers whereas the anchors are emitters. The rest of the paper is organized as follows. Section 2 describes the node localization framework using multi-sensor data fusion. Node localization under collinear ambiguity is presented in Section 3. Section 4 discusses performance evaluation and the paper is concluded in Section 5.

2. Developing attenuation models for multi-sensor data

This section describes the development of attenuation model which gives relationships between received signal power and distance. These attenuation models are developed using measurements acquired from multiple sensors like radio, acoustic and visible light.

The Euclidean distance between transmitting and receiving sensor node is required for localization. Received signal [28] at sensor node can be described as

$$10n_e \log(d_{tr}) = P_t + 10\log\left[G_t G_r \left(\frac{\lambda}{4\pi}\right)^{n_e}\right] - P_r \tag{1}$$

where, n_e is the path loss exponent which depends on the wireless channel. P_r and P_t represent the received power at sensor node and transmitted power of the anchor in dB respectively. The transmission and reception antenna gain are denoted by G_t and G_r respectively. d_{tr} is the Euclidean distance between transmitting and receiving sensor node and λ is the carrier wavelength.

The correspondence between different signal modalities and distance is established by real sensor deployments using Crossbow motes as shown in Fig. 1. Three signal modalities, radio, acoustic and visible light samples are used in the experiments. Acoustic signals are collected using a sum of tone of frequency ranging from 100 Hz to 250 Hz spaced at 1 Hz intervals to mitigate the standing wave effect in the building, while a monochromatic source of wavelength 700 nm is used to collect light samples. The method of non-linear least squares is used to establish these relationships because this provides minimum root-mean-square error between actual and estimated distance vector.

At every one meter of radial distance, samples of different modalities are collected. One hundred such samples are recorded during an interval of one minute for estimate of coefficients. The relationship between radio signal and distance is