Advanced Engineering Informatics 25 (2011) 32–40

Contents lists available at ScienceDirect

Advanced Engineering Informatics

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

A comprehensive multi-factor analysis on RFID localization capability

Junyi Zhou, Jing Shi *

Department of Industrial & Manufacturing Engineering, North Dakota State University, Dept 2485, PO Box 6050, Fargo, ND 58108, USA

ARTICLE INFO

Article history:
Received 6 November 2009
Received in revised form 11 March 2010
Accepted 7 May 2010
Available online 8 June 2010

Keywords:
Radio frequency identification (RFID)
Localization
Accuracy
Cramer-Rao lower bound (CRLB)
Landmark layout

ABSTRACT

The concept of using radio frequency identification (RFID) devices to obtain the location information of objects is novel, and it has great potentials for supply chain applications. The capability of RFID localization, reflected by localization accuracy, is a fundamental issue. This paper presents a comprehensive analysis on how the accuracy is affected by multiple factors, which include region geometry, target distribution, ranging-error distribution, and landmark layout. The performance metrics are the expected mean squared error (MSE) and the expected Cramer-Rao lower bound (CRLB) over the entire localization region. The optimal landmark layouts were first obtained for all the combinations of other factors, and then the impact of individual factors on the localization accuracy was analyzed and discussed. By combining the theoretical analysis and Monte Carlo simulation, it was discovered that (1) the optimal landmark layouts follow simple empirical deployment rules; (2) the performance generally improves as the target distribution is more centering in the region; (3) the performance for rectangular geometries decreases as the aspect-ratio increases; (4) a higher landmark number can improve localization accuracy, but the beneficial result becomes negligible if more than 8 landmarks are used. Moreover, it was demonstrated that the results from a preliminary RFID localization experiment are in agreement with the findings from the simulation.

1. Introduction

Localization using radio frequency signals (RF-based localization) has attracted considerable amount of interest in recent years [1,2]. Along with wireless sensor network (WSN) and wireless local area network (WLAN), radio frequency identification (RFID) has been recognized to be a viable and economical technology for RF-based localization. RFID technology has been widely adopted for item tracking in supply chain applications in recent years. For instance, RFID plays a key role in providing product tracking information in the international project PROMISE, which aims to integrate and smooth the electronic information flow throughout supply chains for the entire product life cycle [3]; RFID can be applied to improve the life-cycle data management of engineered-to-order components by providing automated component identification and distributed data storage [4]; RFID is also considered an effective and efficient way to track materials and equipment in construction supply chains [5,6].

However, for many applications, it is desirable to obtain the accurate location information of the objects instead of only the general existence or non-existence information within the range of RFID tracking. For instance, inaccurate inventory is a major challenge for inventory management, and it results in significant cost for many companies. The investigation by Kang and Gershiwin [7] indicates that the overall inventory accuracy of a global retailer is only 51%. A main cause of inventory inaccuracy is the misplaced items. A study shows that in a store of a leading retailer in US, 16% of the items are not placed in the correct places [8]. RFID localization can reduce the chance of misplacement, and if misplacement happens, it can help the operator to find the misplaced items quickly. In this way, RFID localization can effectively reduce the inventory inaccuracy and improve inventory management. For positioning purpose, RFID can be certainly integrated with GPS (Global Positioning System) to improve the accuracy of a vehicle positioning system [9]. Nevertheless, localization by RFID itself should be an inexpensive and valuable drop-in function for many RFID applications in that it needs little extra infrastructure investment. For instance, GPS is mostly suitable for outdoors applications and the devices are more expensive than RFID tags. Therefore, RFID localization not only is very attractive for the existing RFID applications, but also can stimulate the development of new applications for RFID technology, such as accurately monitoring individual patient flow in a hospital.

Using RFID technology for localization purpose is relatively new [2], but the principle does not deviate from the general RF-based localization. For a localization system, accuracy, which measures the localization capacity, is one of the key performance metrics. In literature, much attention has been shed on analyzing and improving localization accuracy of RF-based localization, which

* Corresponding author. Tel.: +1 701 231 7119; fax: +1 701 231 7195.
E-mail address: jing.shi@ndsu.edu (J. Shi).

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doi:10.1016/j.aei.2010.05.006

has brought a plethora of publications on related topics such as new localization algorithms, localization error bounds, and landmark (also referred as reference nodes, beacons, etc.) placement. The most relevant studies are summarized as follows.

Localization algorithms can be divided into two categories: range-based and range-free. The former is based on the assumption that the pairwise distances between RF nodes can be measured by certain techniques. The latter, on the contrary, makes no assumption about the availability or validity of such information. Algorithms using RF path loss model [10], time of arrival (TOA) [11], angle of arrival (AOA) [12], are the typical ones in the former category, while algorithms using proximity [13] or nearest-neighbor [14] fall into the latter category. Range-based algorithms can localize the target with high accuracy provided the distance measurement has low noise. However, they usually require extensive effort in calibration, and they are susceptible to environmental noises. On the other hand, range-free algorithms are generally more robust against environmental noises, and hence are suitable for harsh environments. The localization algorithm used in this study is based on the principle of multilateration, which is a widely used range-based algorithm.

Given the configuration of an RF-based localization system, the localization accuracy provided by different localization algorithms may vary. As a result, the lower bound of localization error becomes important in that it sets the limit for the capacity of an RF-based localization system. The majority of relevant literature focuses on the analysis of Cramer-Rao lower bound (CRLB), which specifies the lower bound for the variance of an unbiased location estimator. For example, the general formulas of CRLB for localization systems using RSSI (received signal strength indicator), TOA, and AOA were derived based on the measurement error models [15]; and similarly, CRLB was derived for the proposed maximum likelihood localization algorithm [16]. However, little research can be found in literature regarding how the system configuration factors affect CRLB. The factors include the geometry of localization region, distribution of target position, placement of landmarks, and distribution of ranging error.

There are some studies in literature that address the effect of landmark placement on localization accuracy in simplistic ways. Chen et al. [17] compared the localization accuracies of a square layout and a collinear layout with four landmarks in a rectangular geometry. It showed that the square layout performs significantly better than the collinear one. However, the optimality of other landmark layouts has not been addressed. In Refs. [18] and [19], the quality of a layout was measured by the geometric dilution of precision (GDOP), and the optimal and poorest layouts were obtained for specific target points. However, the findings may not hold for the situation where the target is random, and hence the expectation of accuracy needs to be evaluated. Based on a hop-based range-free localization algorithm, Benbadis et al. [20] showed that the localization error, evaluated by average zone size and maximum zone size, is minimized when the landmarks are evenly distributed on the boundary of a circular localization region. In this case, the zone size is measured by the number of hops, and this is not applicable to the typical RFID localization that is based on RSSI data. Zhou et al. [21] studied the expected localization accuracy, in the form of Euclidean distance, in circular regions. It was found that for the simplified cases, the quality of landmark layout can be well captured by the polygonal area formed by the landmarks.

This paper presents a comprehensive study on how multiple system configuration factors affect the performance of RFID localization. The region geometries included are rectangles with various aspect-ratios, circle, and regular polygons with different numbers of edges. There are four target distributions: one uniform distribution and three normal distributions representing low to high level of centering. Also, there are four ranging-error distributions: one normal distribution with constant variance and three normal distributions with distance-proportional variance. For each combination of region geometry, target distribution, and ranging-error distribution, the optimal layout is obtained after comparing a large number of landmark layouts.

2. Research problem

A two-dimensional RF-based localization system is considered here, in which the target location is estimated from the ranging measurements, i.e., the estimated distances, between the target and a number of landmarks. The system resembles a typical RFID localization application, where the RFID tag attached to an object acts as the target, and the readers act as the landmarks.

Let the actual location of the target be (x, y), which is to be estimated, and the estimated location of the target be $(\hat{x}, \hat{y})$. The Euclidean localization error is $e_{xy} = [(x-\hat{x})^2 + (y-\hat{y})^2]^{1/2}$. As mentioned before, one performance metric (P1) used in this study is the expected mean square error (MSE) in the localization region. For an unbiased location estimator, the MSE at (x, y) is $E[(e_{xy})^2] = E[(x-\hat{x})^2 + (y-\hat{y})^2] = V(\hat{x}) + V(\hat{y})$, where $E(\cdot)$ and $V(\cdot)$ are the expectation and variance operators, respectively. Suppose the target is randomly distributed in region Ω with a probability density function (PDF), p_{xy}. Then we have

$$\mathrm{P1} = \int\int_{\Omega} [V(\hat{x}) + V(\hat{y})] p_{xy}\, dx\, dy. \tag{1}$$

The other performance metric (P2) in this study is the expected CRLB in the region. For a two-dimensional localization system, let C_{xy} denote the CRLB at (x, y). Then we have

$$\mathrm{P2} = \int\int_{\Omega} C_{xy} p_{xy}\, dx\, dy. \tag{2}$$

C_{xy} has two components C_x and C_y, which are the lower bounds of localization error in coordinates x and y, respectively. By the definition of CRLB, we have $C_x \leqslant V(\hat{x})$ and $C_y \leqslant V(\hat{y})$. As a result, we have $\mathrm{P1} \geqslant \mathrm{P2}$. In other words, the expected CRLB is a lower bound of expected MSE in the region. In this sense, the metric P2 measures the capacity of the localization system, and it is not related to the localization algorithm used.

For the performance metrics defined by Eqs. (1) and (2), respectively, the following observations can be made. First, the integral depends on the geometry of region Ω. In practice, this indicates that the facility shape has an effect on the localization performance. Second, p_{xy}, the PDF of the target distribution, is also a factor that affects the localization performance. In practice, this means we need to take into account the frequency that an object or event appears everywhere in the region. Third, the estimated location $(\hat{x}, \hat{y})$ is obtained from the ranging measurements, and hence the variances $V(\hat{x})$ and $V(\hat{y})$ are dependent on the ranging-error distribution. Meanwhile, as shown later in the formulation of CRLB, C_{xy} also depends on the ranging-error distribution. In practice, this indicates that we should consider the characteristics of a ranging technique. Finally, the landmarks are the nodes where the RF signals are measured and the ranging measurements are obtained, so their placement is one important factor affecting the localization performance. In a typical RFID localization application, this means that the RFID readers should be placed in proper positions to obtain high localization performance. Therefore, in this paper, we aim to investigate how these four factors of system configuration affect the localization performance.