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STREAMLINING AN INDOOR POSITIONING ARCHITECTURE BASED ON FIELD TESTING IN PIPE SPOOL FABRICATION SHOP

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ABSTRACT

This paper describes the implementation of an indoor positioning architecture based on radio frequency profiling using received signal strength (RSS) measurements for localizing and tracking resources in construction-related applications. The profiling-based approach is coupled with commonly used noise filtering algorithms in order to cope with the application of material tracking in a pipe spool fabrication shop. With 95% likelihood, consistent positioning accuracy of 1-2 meters away from the actual position of a tracked tag can be obtained in the fabrication shop−which is deemed sufficient for materials and labor hours tracking in support of shop production control. In particular, through simulation experiments using data collected from a pipe fabrication shop we investigated the sensitivity of the resulting localization accuracy with respect to the quantity and layout of the reference points, aimed at streamlining system updating and simplifying solution implementation.

1 INTRODUCTION

The advent of innovative technologies has enabled the construction industry to effectively improve project performance and overall productivity while significantly saving time and cost. Positioning and tracking of critical construction resources including materials, equipment and laborers with sufficient accuracy and reliability is crucial to fulfilling construction project objectives. Automated positioning and tracking systems provide construction managers with timely and accurate access to updated status information of crews and materials. As the construction project size and complexity grow, determining the locations of construction resources on a real-time basis presents distinct challenges to technological innovations. Today's wireless sensor technologies and automated data acquisition tools provide the potential to improve construction productivity and safety management (Ergen et al. 2007;Wu et al. 2010; Shin et al. 2011; Jang et al. 2012; Razavi and Moslehi 2012; Maalek and Sadeghpour 2013; Li et al. 2014). Increasing interest in location awareness systems and services in the construction industry have led to widespread applications of radio frequency (RF) technologies, including the global positioning system (GPS) (Caldas et al. 2006; Montaser et al. 2011), and the radio frequency identification (RFID) (Goodrum et al. 2006; Song et al. 2006a, 2006b; Chae and Yoshida 2010; Li and Gerber 2011)

While the problem of determining location information in outdoor environments has been well supported by the Global Positioning System (GPS), location tracking inside buildings can hardly achieve sufficient localization accuracy and reliability as needed by particular construction applications (Shen and Lu 2012). An option is to determine the location of a tracked tag based on indoor ground-deployed wireless infrastructure, i.e., via indoor radiolocation techniques. The majority of the studies in the area of indoor localization considers WiFi wireless access points as a convenient infrastructure. The WiFi nodes are usually a permanent or semi-permanent infrastructure. The coordinates of those nodes are assumed to be known and act as the reference by which the location of the tracked tags will be determined. The primary purpose of deploying the access points is to extend Local Area Networks (LANs) to wireless users, and thus localization is a secondary task carried out using the same infrastructure. The placement and the number of WiFi access points cannot be arbitrary and is restricted for a totally different purpose than localization, i.e., cost and connectivity considerations and to ensure adequate, continuous coverage for users. However, in construction sites, the placement and number of access points is very likely to be constrained or even dictated by external factors, e.g., placement of walls and obstacles etc and thus can make the application of WiFi access points for localization challenging. Therefore, we would rather not have to deal with restrictions of the number and placement of the access points used for localization.

Development of cost effective methods for positioning and tracking based on received signal strengths of radio frequencies is desired in order to harness the full potential of applying new technologies in construction. A great deal of research have been done in order to understand which access point based localization algorithm is best (Khoury and Kamat 2009; Cho et al. 2010; Luo et al. 2010; Maalek and Sadeghpour 2011; Saidi et al. 2011). Instead, in this paper we not only introduce a reliable localization method but also examine the impact of the number and placement of the stationary nodes (called pegs in this study) and reference points on localization.

To this end, this research evaluates the feasibilities of an RSS-based location tracking techniques, namely, the profiling-based method. To verify the positioning accuracy of this methods, a wireless sensor network system was prototyped for conducting positioning experiments. Further, in order to evaluate the achievable accuracy of this method in a real-world indoor environment, we coupled the profiling-based method with commonly used noise filtering algorithms and conducted field testing in a pipe fabrication shop. With 95% likelihood, consistent positioning accuracy of 1-2 meters away from the actual position of a tracked tag was obtained in the fabrication shop−which is deemed sufficient for materials and labor hours tracking in support of productivity analysis (Sacks et al 2005; Lu et al 2007).

In this study, low cost wireless transceivers were used to build the wireless sensor network. A large number of low cost wireless transceivers can be purchased for the cost of a single access point. For example, at present, a dozen or so nodes equipped with low cost low power RF transceiver and microcontroller (like EMSPCC11 from Olsonet Communications which costs less than 20$ per node) can be purchase for the cost of a single access point with the advanced version of the IEEE 802.11 standard (currently approximately USD $300.00). With more transceivers and their fixed placement (here pegs), we can feasibly have a greater granularity of localization information than what can be provided by only a few WiFi access points that can be acquired at the same expense.

In fact, in construction environments that are strongly influenced by multipath propagation, even the accuracy of angulation and lateration techniques is questionable (Lu et al. 2007; Shen and Lu 2012). Therefore we do not attempt to relate the signal strength measurements to the actual distance between pegs and tracked tags. Instead, we consider only signal strength pattern matching techniques and use location fingerprinting (profiling) techniques. In location fingerprinting, the RSS of the tag is compared against a pre-collected set of samples from known (profiled) reference points (Haque et al. 2009). Profiling can overcome the limitations of RSS ranging methods by which the multipath-affected environments makes the direct transformation of RSS into distances or angles highly unreliable.

On the other hand, a large number of profiled points will be surveyed in terms of RSS in order to offset the imprecise nature of the RF-range measurements. Therefore, it is important to identify the "leanest" system design by determining the smallest quantity of reference points that are sufficient for an acceptable positioning accuracy in order to streamline the time consuming and labour intensive task of profiling. Therefore, we explore the effect of the number of reference points and their arrangement on localization errors through simulation experiments using data collected from a pipe fabrication shop.

2 INDOOR POSITIONING APPLICATIONS IN CONSTRUCTION

Indoor positioning localization problem has received considerable attention in recent years, which led to the development of a wide range of technologies and methods. An example is Ekahau tracking system which relies on a WLAN (wireless local area network) positioning infrastructure, achieving a positioning accuracy of 2 m in the laboratory testing environment (Khoury and Kamat 2009). The Ultra Wide Band (UWB) technology has higher accuracy in localizing objects which is due to high immunity to interference and multipath. Teizer et al. (2008) presented algorithms and experiments utilizing UWB technology for positioning and tracking construction resources. As part of robotic capabilities evaluation, Khoury and Kamat (2009) performed indoor experiments using a UWB-based positioning system in the laboratory environment, which could obtain an accuracy of 10 to 50 cm. However, the UWB technology has a number of drawbacks including costly infrastructure , line of sight in communication and a dense network of fixed receivers, hindering its deployment in a highly dense and dynamic construction environment (Torrent and Caldas 2009). Real-Time Kinematic GPS (RTK GPS) can provide positioning accuracy of centimeters level. Nonetheless, the performance of a GPS-based localization system can be substantially compromised on the indoor dynamic construction site due to blockage and the multipath effect, which is caused by deflection and distortion of transmitter signals in highly dense areas or by temporary structures or facilities (Lu et al. 2007).

With the aim to deliver acceptable measurement accuracy for construction applications, radio frequency signals received from wireless sensor modules (ZigBee) and ultrasound were combined to implement positioning and tracking methodologies (Jang and Skibniewski 2009; Skibniewski and Jang 2009; Shin and Jang 2009). However, ultrasound positioning has inherent disadvantages including line-of-sight requirement, multipath, high cost and power consumption making it difficult to deploy the proposed methodology in complicated indoor construction environments (Wu et. al. 2010). Hybrid methodologies by integrating RFID and Zigbee-based sensor networks were also applied for asset tracking and material management (Cho et al. 2010; Cho et al. 2011). RFID tags were used to identify materials, while the Zigbee communication technology was used to wirelessly transfer the collected information. These studies have confirmed that wireless sensor networks (ZigBee being the most popular commercially solution) provide the effective infrastructure that enables inexpensive wireless communication network while rendering straightforward networking capability in construction applications.

3 RSS PROFILING-BASED POSITIONING ARCHITECTURE

The localization process of the proposed positioning technique can be viewed as a combination of RSS profiling and position computing. Technically, the location of fixed nodes (pegs) does need to be known. A tracked tag (the node to be localized) is the same type as a peg and periodically emits radio frequency packets. In the profiling stage, the network collects the radio frequency packets transmitted by the tag while it is placed at predetermined known locations called profiling points. The radio frequency packets transmitted by the tag are received by all the pegs within the monitored are and then sent as a report to a database that is maintained on the central server. The report consists of the peg ID, the tag ID, and RSS measured. A single sample of the RSS readings in the database is in the format of $< C; \Omega >$, where C stands for the known coordinates of the sampled point in the form of (x, y) and Ω represents the set of RSS values corresponding to all of the pegs at this sampled point.

The level of RSS measurement noise is dependent on the application environment and can hardly be predicted in a construction environment. To effectively reduce uncertainty and improve accuracy, the adaptive Kalman (Hu et al. 2003) filter is then used to correct for signal loss and exorbitant signal changes in both profiling and tracking phases. Generally, a Kalman filtering algorithm works in a two-step process: a prediction stage and a measurement updating stage. The Kalman filter operates recursively on a set of noisy, uncertain and inaccurate input observations which herein are the RSS samples stored in the database, producing an optimal estimate of the system state. In the proposed system, hence, signal data collected in profiling and tracking phases are pre-processed by Kalman filter algorithm prior to invoking the localization algorithm in order to reduce the noise effect.

In the localization stage, the location of the tracked tag is estimated based on the coordinate information of profiling points. In the initial stage of the localization phase, the server compares the tag's RSS measured by all the pegs against the RSS collected at each profiling point. Provided that Ψ is the set of RSS values obtained from the tracked tag, the distance between the tracking point and a specific profiling point is determined by Eq. 1.

$$D(\Omega, \Psi) = \sqrt{\sum_{i=1}^{n} (\Omega(i) - \Psi(i)^2} \quad (1)$$

where n is the total number of pegs in the monitored area. In the second step, an arbitrary number (k) of profiling samples ,that have smallest distance values away from the tracked tag, are selected. This set represents the best matched set of profiling points. In the last step, the coordinates of the selected samples are averaged to produce the estimated coordinates of the tag. The averaging formula biases the selected samples in such a way that the one with a smaller distance is weighed with a proportionally larger weight. Suppose $D_{\max}$ is the maximum distance among the best k selected samples and$S_d = \sum_{i=1}^{k} D_i$is the sum of all those distances, then the tag coordinates are estimated as:

$$x_{est} = \frac{\sum_{i=1}^{k} x_i \times (D_{max} - D_i)}{k \times D_{max} - S_d} \quad (2)$$

$$y_{est} = \frac{\sum_{i=1}^{k} y_i \times (D_{max} - D_i)}{k \times D_{max} - S_d} \quad (3)$$

where (x_i, y_i) are the coordinates of the profiling point i. The proposed profiling-based method compares the RSS differences between the tracking point against the relevant profiling points, rather than using the Euclidean distance between a tag and a peg, . It is also worth mentioning that the current profiling system design is most suitable to problems concerning positioning in a 2-D domain. However, it can be readily extended into 3-D domain applications by deploying pegs and profiling points throughout the physical space, where all the pegs and profiling points are located not necessarily on a single plane. For instance, once pegs have been established and reference points profiled at different floors, the system could determine the exact floor in which the tracked tag is located. As such, a particular area on a specific floor can be identified with a unique set of RSS data associated with relevant pegs.

4 SYSTEM VALIDATION IN A PIPE SPOOL FABRICATION SHOP

Experiments were conducted at a pipe fabrication shop near Edmonton, Alberta. The environmental conditions of the fabrication shop were generally hostile to apply RSS-based positioning methods with the presence of welding and cutting machines, metallic and many obstacles to signal processing. The shop configuration is frequently changed for handling different jobs. Figure 1 shows the test area selected for conducting the experiment. The objective of the study is to evaluate the feasibility and assess the performance of the proposed profiling-based positioning method inside the spool fabrication shop.

Eighteen pegs were fixed at known locations along the perimeter of a 20 m × 20 m test area, of which fourteen pegs were placed on tripods at the height of 1.30 m while other four were either placed on top of the tool boxes or secured to walls or beams at the approximate height of 2 m. A tag was attached to a small piece of pipe and moved along a square-shaped path (14 m × 14 m) within a defined work zone of the shop. Figure 2 demonstrates the experiment layout.

Figure 1: Experiment setting in pipe spool fabrication shop.

According to the inputs from the floor personnel, the proposed methodology would be cost effective if the accuracy and reliability of under 2 meters with 95% probability could be delivered in such a practical shop setting. As such, the layout and quantities of pegs and the grid of profiling points were initially designed to be sufficient in order to evaluate the best achievable performances of the proposed method and assess whether the proposed indoor positioning methodology can potentially serve shop management needs for tracking spool components and laborers within a typical work zone.

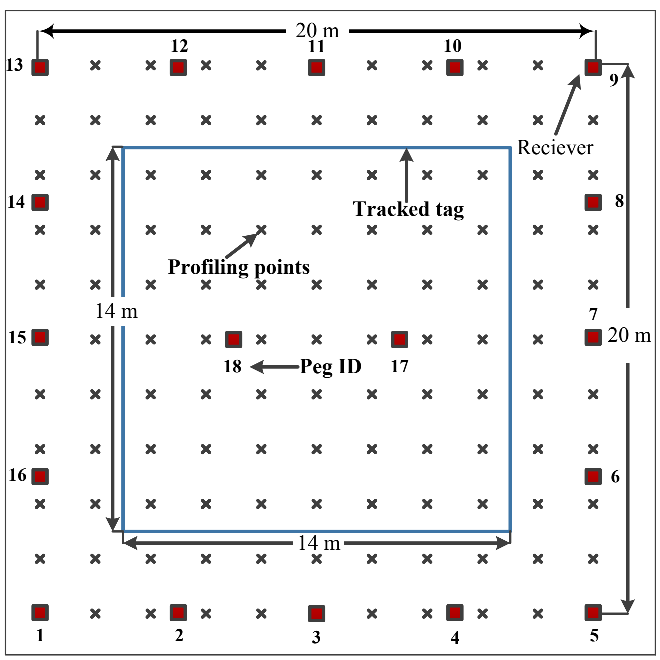


Figure 2: Experiment layout in the fabrication shop for RSS-profiling localization method.

The results indicate that the proposed RSS-profiling method is able to locate the tracking tag with an average accuracy of 1.52 m, the standard deviation of the errors being 0.73 m. The minimum location error was 0.13 m and the maximum was 3.47 m. The 95th percentile is 2.72 meters, which implies with 95% likelihood, the tag's position can be fixed within 2.72 m of its actual position in the shop.

In this present study, Kalman filter is further applied in an attempt to reduce the signal noise and compensate for any signal loss for the RSS profiling method. The final positing results from applying the RSS profiling based method coupled with the Kalman filtering algorithm demonstrate that the average localization error and the standard deviation can be reduced from 1.52 meters and 0.73 meters to 1.17 meters and 0.50 meters, respectively.

The position error statistics based on shop testing given in Table 1 contrast the effect of preprocessing RSS data by Kalman filtering. It can be observed that with Kalman filtering, satisfactory accuracy and reliability of tag positioning results can be obtained, with the average and the standard deviation being 1.17 m and 0.50 m, respectively. The 95th percentile is 1.90 meters, which implies with 95% likelihood, the tag's position can be fixed within 2 m of its actual position in the shop.

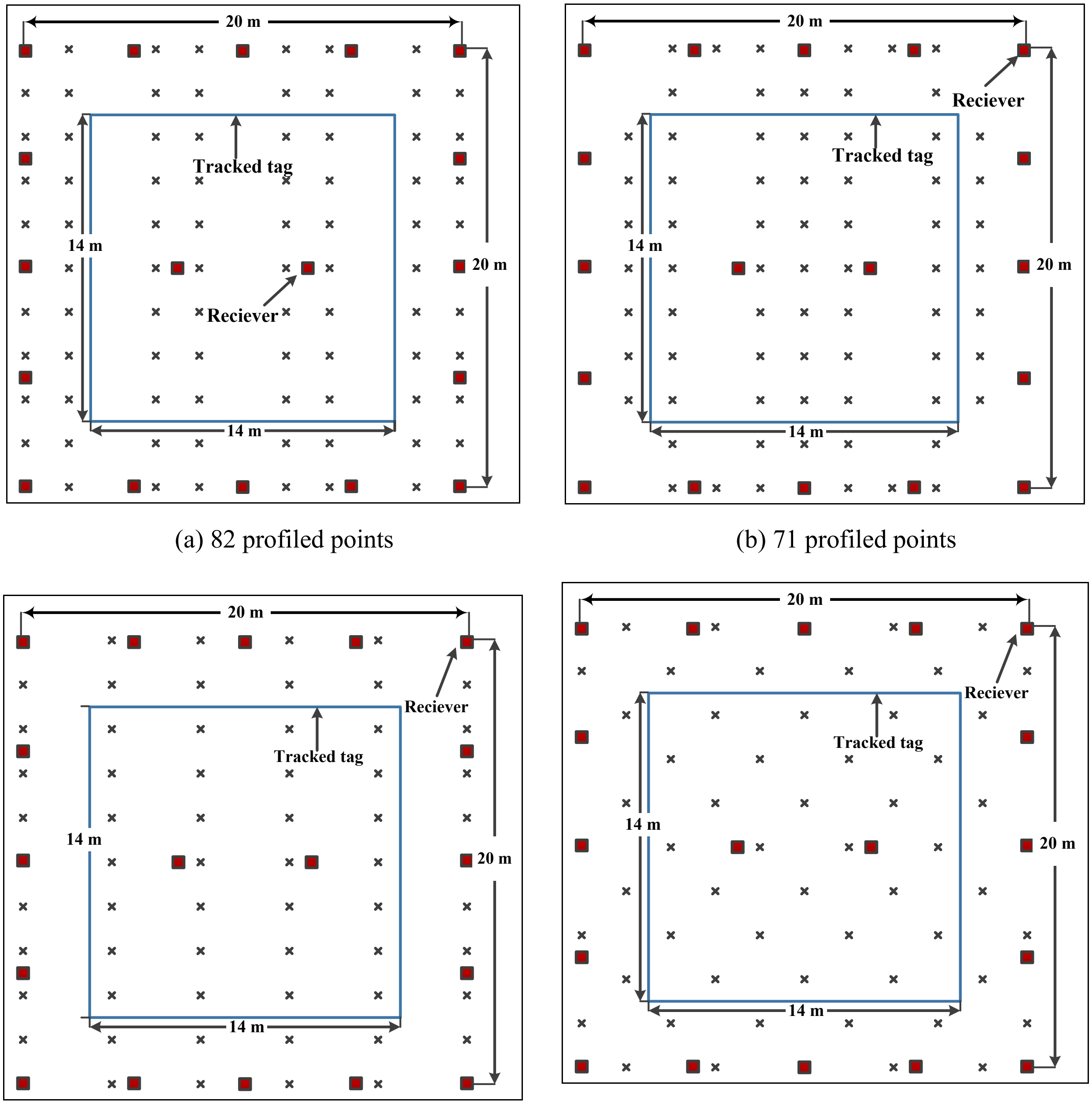
Table 1: Accuracy comparison on the profiling-based positioning technique with and without Kalman filter.

Positioning Techniques	Localization accuracy (m)				
	Min	Max	Average	Standard Deviation	95th Percentile
Profiling-based	0.13	3.47	1.52	0.73	2.72
With Kalman Filter	0.13	1.97	1.17	0.50	1.90

5 IMPACT OF PROFILE POINT SELECTION ON INDOOR LOCALIZATION

The proposed RSS-based positioning system can easily be applied to in-building localization using inexpensive devices and can provide localization error less than 2 meters. Profiling can help to decrease the adverse impact of the environment on the transformation of the RF signals into distances. For this purpose, it seems that we would need to measure a large number of profiled points to offset the imprecise nature of the RF measurements. Therefore, it is important to determine the smallest number of reference points that are sufficient for an acceptable positioning accuracy in order to reduce the time consuming and labour intensive task of profiling. In this section, we explore the effect of the number of reference points and their arrangement on localization errors.

For this purpose, we removed reference points from the first test database in a way such that the density of reference points remained roughly the same across the grid. Figure 3(a) shows the layout of reference points after removing 31 points. The resulting setup for positioning simulation utilizes measurements from 82 reference points. By further removing points in the same fashion, i.e., one at a time, we achieve the new layouts with 49 profiled points (Figure 3(g)).



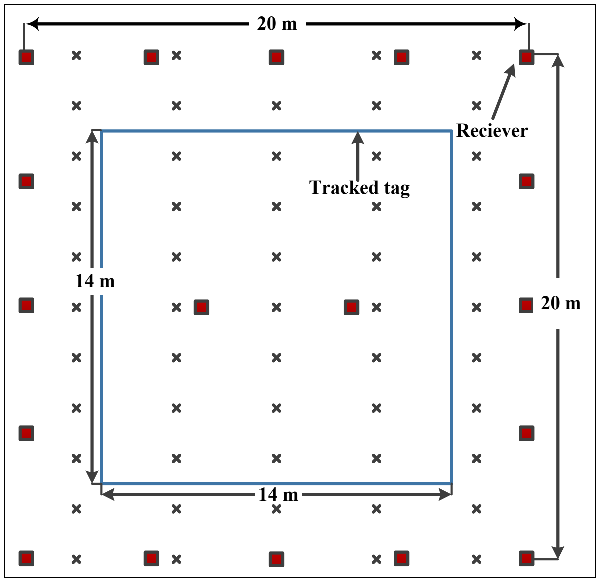
(a) 82 profiled points

(b) 71 profiled points

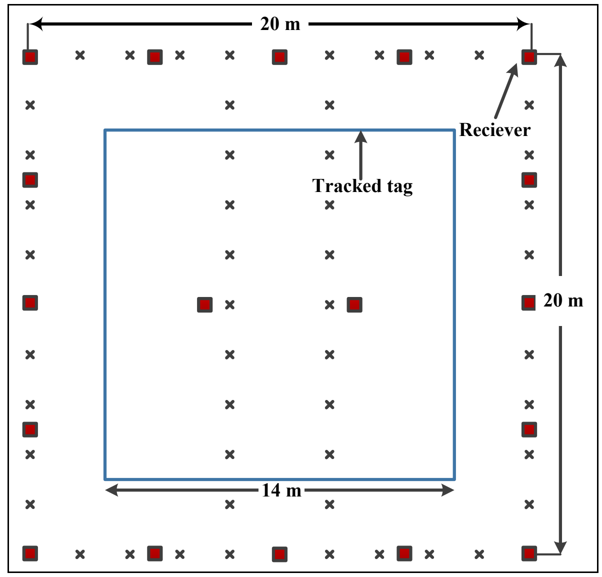
(c) 60 profiled points

(d) 54 profiled points

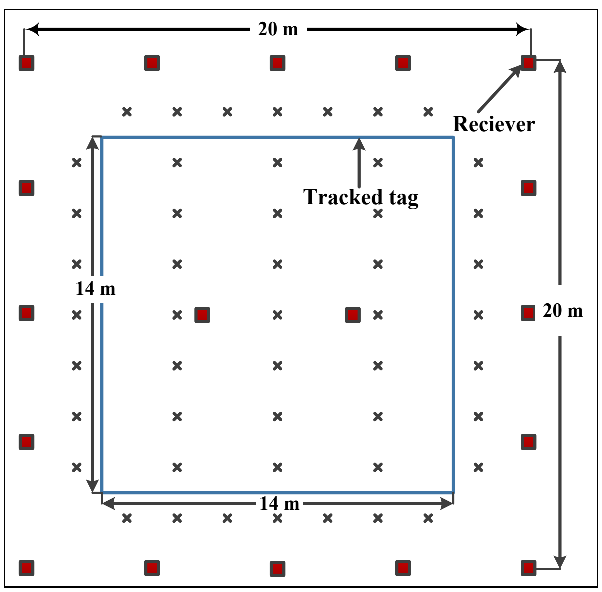
Figure 3: Layouts of profiled placements.



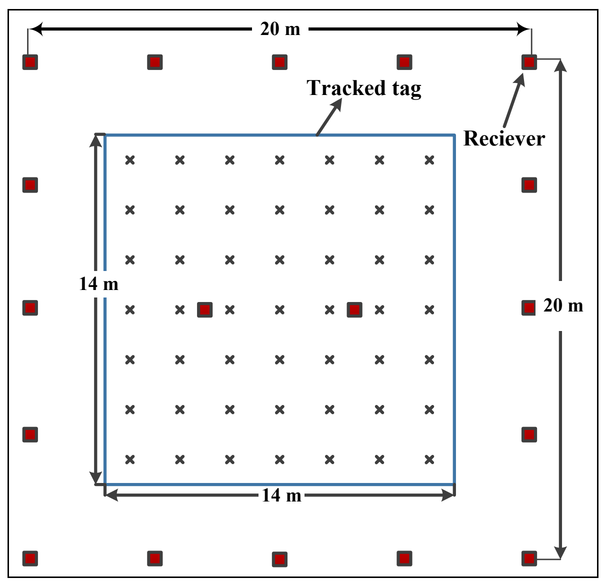
(e) 53 profiled points



(f) 50 profiled points



(g) 49 profiled points



(h) 49 profiled points

Figure 3: Layouts of profiled placements (continued).

The average error for the RSS-based positioning system with all the initial 113 reference points was 1.17 meters (Figure 2), but we could remove points in a regular fashion and eventually keep 49 points while the error was still less than 2 meters (Figure 3(g)). This indicates that it is possible to have a less complex deployment of reference points without degrading the performance significantly. The average error in location estimation for each of the layouts is shown in Figure 4. Overall, we have observed that the more the reference points the better the localization. Yet, the number of reference points alone is not sufficient, as their placement matters as well (see for example the case of Figure 3(g) vs. Figure 3(h). In both layouts, 49 profiling points were profiled for addressing the location estimation problem. However, the case of Figure 3(g) resulted in 1.57 m of localization accuracy, hence, the localization error for the case layout in Figure 3(h) is 2.11 m. We also observed that removing a large number of reference point from the surrounding area would result in losing information that are essential for localization and thus deteriorates the localization accuracy. For instance, Figure 3(c) with 60 profiling points, results in somewhat similar localization accuracy to Figure 3(b) with 71 profiling points (1.30 m vs. 1.31 m). Also, in Figure 3(c) and Figure 3(d), 60 and 54 profiling points were profiled respectively. However, despite upward trend, the case of Figure 3(d) with 54 profiling points resulted in smaller localization error (1.30 m vs. 1.28 m) since the reference points were more evenly distributed across the grid.

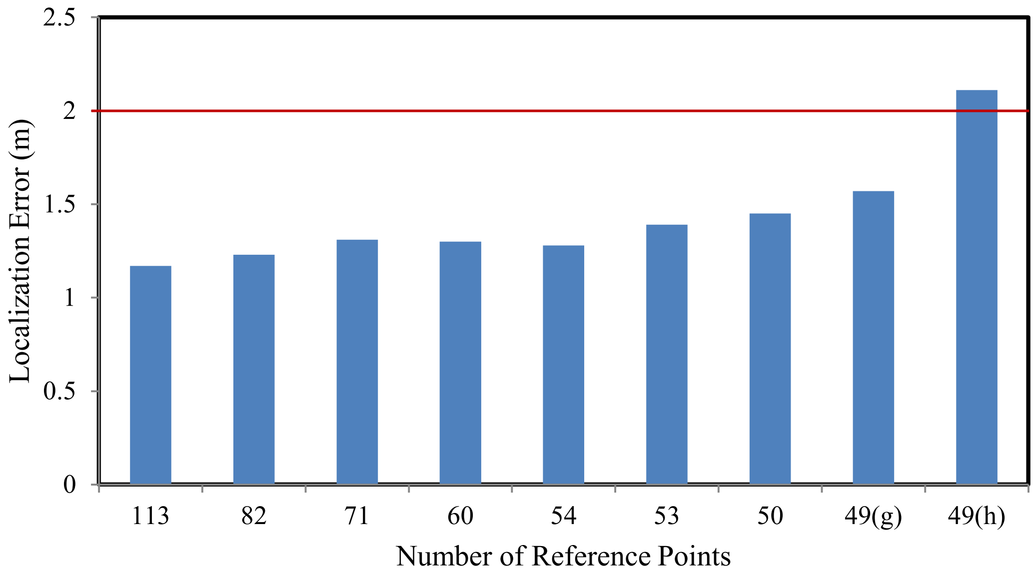


Figure 4: Localization error (95th percentile) for different number and layout of profiling points.

Therefore, it can be concluded that a smaller set of reference points can provide good localization, in particular if their layout has been carefully designed. The presented analyses of "what-if" scenarios for setting up the solution in the work zone of the pipe spool fabrication shop may guide real-world deployment of reference points (profiling points) so as to minimize the system's complexity while attaining the required accuracy of localization.

6 CONCLUSION

Over the past few decades, sensor technologies, mobile computing, and tracking methods have advanced, enabling cost-effective data collection and communication in construction field. Nevertheless, indoor localization remains a technical challenge. This study evaluated the feasibility of applying an RSS-based profiling method in indoor construction application settings so as to achieve the positioning accuracy of 1-2 meters with high reliability. This accuracy is generally accepted as the sufficient positioning performance for resource tracking and field productivity measurement in construction. The profiling-based method was coupled with commonly used noise filtering algorithms in order to cope with the dynamic application setting in a pipe spool fabrication shop. With 95% likelihood, consistent positioning accuracy of 1-2 meters away from the actual position of a tracked tag was obtained based on field testing in the pipe spool fabrication shop of a major contractor in Alberta,. The proposed methodology would potentially serve the needs of tracking components and labor-hours in handling and connecting those components inside the fabrication shop.

The proposed scheme can be easily applied to construction indoor localization applications using inexpensive devices. We also found that a smaller set of reference points can still provide good localization, in particular if their layout has been carefully designed. In the proposed RSS-based system, the decision about the number of pegs is flexible and they can be used as needed without any restrictions on numbers. However, the placement of the pegs might affect the location estimation. Therefore, examining the impact of the number and placement of the fixed nodes (pegs) on localization will be our ensuing research. In the follow up research, sensor node placement along with profiling point layout will be formally defined as an optimization problem. Analytical formulation for optimizing and streamlining the layout and quantity of profiling points and pegs will be attempted. The optimization solution can guide deployment of pegs and identification of reference points so as to minimize the system's complexity and application cost while achieving the required accuracy of localization.

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