Tracking the Location of Materials on Construction Job Sites

Jongchul Song[1]; Carl T. Haas[2]; and Carlos H. Caldas[3]

Abstract: Automated tracking of materials on construction projects has the potential to both improve project performance and enable effortless derivation of project performance indicators. This paper presents an approach by which materials tagged with radio frequency identification (RFID) tags can be automatically identified and tracked on construction sites, without adding to regular site operations. Essentially, this approach leverages automatic reading of tagged materials by field supervisors or materials handling equipment that are equipped with a RFID reader and a global positioning system receiver. To assess the technical feasibility of this approach, a mathematical model has been formulated such that the job site is represented as a grid and the location of materials within the grid is determined by combining proximity reads from a discrete range. Field experiments were conducted using an off-the-shelf RFID technology, and several metrics were developed to quantify the field performance and compare it with the theoretical positional accuracy derived from the discrete formulation.

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Introduction

Of the elements that comprise a constructed facility, construction materials and installed equipment may account for 50–60% of the total cost of a typical industrial project (Kini 1999). How materials and components are handled has a direct impact on project performance. On construction projects, hundreds of materials go through design, fabrication, interim processing, delivery, and storage prior to scheduled installation. Planning the installation of materials requires crew foremen to verify the availability of materials and other resource requirements (Choo et al. 1999). On industrial projects, when crew foremen make requisitions for certain materials, the constructor's laydown yard personnel locate, identify, and issue and/or stage them at the crew's work area. As prefabricated objects such as pipe spools and precast concrete elements are assembled and installed on site, the designed facility literally takes shape. Once materials and components are installed, an inspection is conducted to determine whether the installation complies with specifications, and performed work is documented to monitor and control project progress and plan successive work.

Tracking materials and components on construction projects implies primarily two different sets of requirements for positional accuracy; in both cases, identification is also required. When the delivery and receipt of materials to a construction site are tracked, it suffices to determine their location in the supply chain, e.g., a fabrication shop, or a constructor's laydown yard. However, after delivered to the site, the location of materials needs to be tracked with better positional accuracy. For example, though requisite materials may be known to be within a constructor' laydown yard, each item needs to be physically found in order to be issued to crew workers for installation. Such positional accuracy may also facilitate automatic determination of whether a certain material item is in close proximity to its appropriate handling equipment and by inference, whether it is being handled by the equipment. Tracking materials thus helps ascertain the basic construction activities being performed with the equipment.

Tracking the location of materials precisely is generally considered economically prohibitive, though it has become technically more viable with recent advances in automated data collection (ADC) technologies. The primary objective of the research presented here was to examine the feasibility of applications of radio frequency identification (RFID) technology to automating the tracking of materials and components on construction projects. This paper presents an approach by which an RFID technology is technically feasible in determining the two-dimensional (2D) location of materials, when combined with global positioning system (GPS) technology. The solution proposed here is to extend the use of current RFID technology to tracking the precise movement and location of materials on a construction site and in laydown yards, without modifications to current hardware and at a magnitude of less cost than pure GPS or other existing approaches.

Background and Literature Review

Materials management is a distinct management system that can make significant contributions to the cost effectiveness of con-

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[1] Postdoctoral Fellow, Dept. of Civil, Architectural, and Environmental Engineering, Univ. of Texas at Austin, 1 University Station C1752, Austin, TX 78712-0276. E-mail: uniastro@mail.utexas.edu

[2] Professor, Dept. of Civil Engineering, Univ. of Waterloo, 200 University Ave. West, Waterloo ON, Canada N2L 3G1. E-mail: chaas@civmail.uwaterloo.ca

[3] Assistant Professor, Dept. of Civil, Architectural, and Environmental Engineering, Univ. of Texas at Austin, 1 University Station C1752, Austin, TX 78712-0276 (corresponding author). E-mail: caldas@mail.utexas.edu

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struction projects (Business Roundtable 1982). Bell and Stukhart (1987) indicated that a very basic materials plan and approach would produce a minimum 6% savings in craft labor cost. They also suggested that an additional 4–6% savings would be produced by using integrated computer-aided systems that track bulk materials line items. They related this additional savings to the ability of the crafts to schedule their work around material availability. Thomas et al. (1989) studied the impact of poor materials management on labor productivity, reporting ineffective use of work hours equivalent to 18% loss in labor productivity.

The above studies suggest that the ability to provide timely and accurate information on materials availability for crew-level work planning presents the potential for improved labor performance. For this purpose, tracking the location of materials implies tracking the delivery and receipt of materials through locations in the supply chain. Concerned with tracking, locating, finding, and distributing the right material to the right location at the right time, field materials management has become more critical given the significantly increased use of prefabrication and preassembly over the past 15 years (Haas et al. 2000). In fact, field materials management has been identified as one of the areas with the greatest potential for improvement and the greatest positive development impact on engineering construction work processes (Vorster and Lucko 2002).

Yet the location of materials needs to be tracked with better positional accuracy than can be attained from the initial indication, for example, that a certain material has been received at and is within the constructor's laydown yard. Materials must be physically found in the laydown yard before being issued to crew workers who requisition them for installation on site. Accurate tracking of the location of materials will facilitate real-time, on-site measurement of project performance indicators, such as schedule progress and labor productivity. While field supervisors may spend 30–50% of their time recording and analyzing actual performance data (McCullouch 1997), this effort in relation to the lack of benefits from a project management information and control system often limits the effectiveness of the system (Futcher 2001; Kiziltas and Akinci 2005). As an alternative to direct data collection that relies on human observers, research efforts have thoroughly investigated the feasibility of: (1) automatically tracking the location of construction agents (laborers and equipment); (2) identifying and determining the status of the basic activity that the agent is engaged in; and (3) deriving project performance indicators (Navon and Goldschmidt 2003; Sacks et al. 2003, 2005). Automated measurement of project performance promotes successful implementation of the project management information and control system and ultimately enables project management to take corrective actions in a timely manner. However, related research efforts have focused principally on construction agents and have not fully examined the potential of tracking the location of materials on a construction site.

With recent advances in ADC technologies, tracking the location of construction resources has become technically more viable. For example, GPS can be used to precisely track the location of workers and machines over a great range of geographic and geometric scales. However, tagging hundreds of materials with simple GPS receivers costing around US$100 per unit would be prohibitively expensive, and still other means for identification would be required. This limits the scope of GPS applications for comprehensive materials tracking. Alternatively, a state-of-the-art GPS receiver could be used to acquire the precise coordinates for materials' location without tagging individual material items, as was found in a recent field test (Caldas et al. 2004). Although the effectiveness of the technology in locating pipe spools at large laydown yards was demonstrated with immediate payback for a typical industrial project, manual recording and periodic updates of the GPS coordinates are also required.

By contrast, RFID technology has been found suitable for identification purposes in tracking hundreds of materials in harsh environments. Its potential applications in the construction industry have already been explored (Jaselskis et al. 1995), and several pilot tests have demonstrated that the technology could be useful in receiving uniquely identified materials at job site laydown yards (Jaselskis and El-Misalami 2003). In addition, recent field trials indicate that the technology can be used to automatically track the delivery and receipt of prefabricated pipe spools as they are shipped and received through portal gates (Song et al. 2006). Although RFID technology presents several advantages over barcoding, its primary use in current applications is still limited to these portal based identification purposes. This limitation has driven the commercial development of the real-time location system (RTLS) for indoor asset tracking applications.

Unlike conventional RFID systems, the RFID-based RTLSs such as Pinpoint's 3D-iD provide both identification and location of tagged objects by virtue of a preconfigured wired network of fixed RFID readers. However, an RFID-based RTLS requires a significant infrastructural setup of proprietary networks and has difficulty interoperating with existing IEEE 802.11 wireless networks (Hightower and Borriello 2001). Most recently, these issues with the RFID-based RTLSs were resolved by leveraging the IEEE standard Wi-Fi networks. Being based on nonproprietary networks, the Wi-Fi based RTLSs successfully overcame the substantial cost barrier to scalable location tracking systems, i.e., the infrastructural setup of separate networks. Good examples of this Wi-Fi based RTLS include solutions from AeroScout (2005) and Ekahau (2005). However, a Wi-Fi RTLS still relies on the existence of 802.11 access points in the building, which cannot be guaranteed for a facility being built on the job site. Moreover, the mapping of Wi-Fi signals to locations throughout the building may require extensive calibration. Due to its evolving and unpredictable nature, a construction site cannot afford location tracking systems that rely on a fixed network infrastructure, whether proprietary or not, which should be configured carefully to cover the entire site and calibrated to its rf transmission space.

In summary, the research efforts discussed above justify in varying degree the need to track the location of materials on construction projects. Tracking the location of materials on construction projects should both improve labor performance and enable effortless derivation of project performance indicators. A central issue in using ADC technologies for automating the tracking of materials is that the existing approaches imply economically prohibitive deployment and require careful configuration and calibration. However, a combination of RFID and GPS technologies offers the opportunity to densely deploy low cost RFID tags with a few mobile RFID readers equipped with GPS to form the backbone of a construction material's tracking system.

RFID Proximity Localization Using Rovers

The concept proposed here is a field supervisor or piece of materials handling equipment that is equipped with an RFID reader and a GPS receiver, and serves as a "rover." The supervisor, for example, walks around the site on his or her normal business. The position of the reader at any time is known since the rover (supervisor or materials handling equipment) is equipped with a GPS

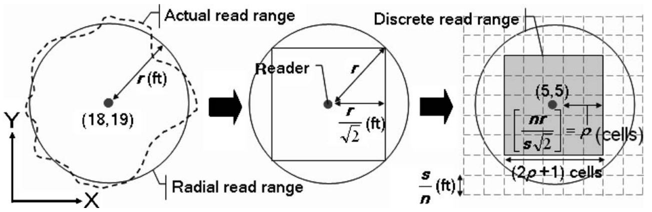


Fig. 1. Modeling RF communications region under occupancy cell framework

receiver, and many reads can be generated by temporal sampling of a single rover moving around the site. Suppose that the rover has generated a read at a known position with Cartesian coordinates (x_1,y_1) and in two dimension the reader has a radial read range with the radius r. If the reader at (x_1,y_1) read an RFID tag fixed at an unknown location (x_2,y_2), then the rf communications connectivity exists between the reader and the tag, contributing exactly one convex constraint $\sqrt{(x_1-x_2)^2+(y_1-y_2)^2}\leq r$ to the problem of estimating the tag location.

As the rover repeatedly comes into the range r from the tag, the accumulated reads form such convex constraints for the tag. Combining these proximity constraints restricts the feasible set of the unknown positions of the tag to the region in which the circles centered at the reads intersect with one another. Then, estimating the location of the tag comes down to selecting a point from the intersecting region. This is equivalent to solving an optimization problem under the convex constraints, and since there are no obvious objective functions to optimize, only feasible solutions are found (Doherty et al. 2001). Formulated as a convex optimization problem, the location estimation can be solved reliably and efficiently using interior-point methods (Boyd and Vandenberghe 2004).

However, unlike the well-known least-squares problems, general convex optimization problems have no analytical formula for the solution. Without analytical solutions, one could only say that "roving" applications of RFID in proximity localization will yield accurate location estimates if the rover generates infinitely many reads and proximity constraints for each tag. This asymptotic convergence suggests a governing tradeoff between accuracy, time, and resources for the approach proposed here.

Occupancy Cell Framework and Localization Procedure

A useful mathematical framework has been adapted from a model that Simic and Sastry (2002) envisioned with wireless sensor networks in which RFID tags would communicate with neighboring peer tags. In this framework, a square region Q with sides of length s in which the rover moves around is partitioned into n^2 congruent squares called "cells" of area $(s/n)^2$. Thus, the position of reads as well as tags is represented by a cell with grid coordinates, rather than a point with Cartesian coordinates, and one is only interested in finding the cell(s) that contains each RFID tag.

Under the occupancy cell framework, the rf communication region of a read is modeled as a square centered at the read and containing $(2\rho+1)^2$ cells, instead of a disk of radius r (see Fig. 1). This square region can be obtained by taking the read range as ρ cells

$$\rho = \left(\frac{nr}{s\sqrt{2}} \right) \tag{1}$$

where $(nr/s\sqrt{2})$ denotes the integer part of $nr/(s\sqrt{2})$. Then the rf communication region B_k of a read positioned at the cell R_k with grid coordinates (x_k,y_k) is defined by

$$B_k = (x_k-\rho, x_k+\rho) \times (y_k-\rho, y_k+\rho) \tag{2}$$

where $(a,b)\times(c,d)$ denotes the union of all cells with grid coordinates (i,j), $a\leq i\leq b$ and $c\leq j\leq d$, for integers $1\leq a<b\leq n$, $1\leq c<d\leq n$. For example, the read shown in Fig. 1 is positioned at the cell with grid coordinates (5, 5), and its communication region is represented by $(3,7)\times(3,7)$, which is equivalent to the shaded square.

Suppose that while the GPS-enabled rover moved around the site $Q=(1,n)\times(1,n)$, a tag at the cell T was read m times by a rover positioned at the cells R_k, $k=1,2,\ldots,m$. Then the cell T that contains the tag belongs to each rf communication region of the m reads, or $T\in B_k$, for all $1\leq k\leq m$

$$T \in Q \cap \bigcap_{k=1}^{m} B_k = Q \cap (x_+-\rho, x_-+\rho) \times (y_+-\rho, y_-+\rho) \tag{3}$$

where $x_+=\max(x_1,\ldots,x_m)$ and $x_-=\min(x_1,\ldots,x_m)$, and similarly for y_ks. Therefore, the estimate of the tag location T is given by

$$\begin{aligned} T \in & [\max(x_+-\rho,1),\min(x_-+\rho,n)] \\ & \times[\max(y_+-\rho,1),\min(y_-+\rho,n)] \end{aligned} \tag{4}$$

since $Q=(1,n)\times(1,n)$. For each tag, the size A_t of the location estimate is defined as the number of cells in the rectangle given by the right hand side of Eq. (4)

$$\begin{aligned} A_t = & [\min(x_-+\rho,n)-\max(x_+-\rho,1)+1] \\ & \times[\min(y_-+\rho,n)-\max(y_+-\rho,1)+1] \end{aligned} \tag{5}$$

Thus, for each tag, A_t defined by Eq. (5) indicates the size of the feasible region in which the tag may lie, and if $A_t=1$ cell, the location estimate given by Eq. (4) would be optimum. From this discrete formulation, a model is derived (presented later) of the theoretical performance which can be compared with the performance experienced in the field.

Field Experiments and Data Collection

To assess the technical feasibility of roving applications for determining the 2D location of materials, field experiments were conducted using an off-the-shelf RFID handheld reader and tags, based on the occupancy cell framework. A square region Q with sides of $s=36$ m (120 ft) was set up on the grass in an open field and partitioned into $n^2=30^2$ square cells with sides of 1.2 m (4 ft), with the boundary and grids delineated using stake flags and strings. Parameters considered for experiments included: (1) rf power transmitted from an RFID reader; (2) the number of tags placed; (3) patterns of tag placement; and (4) the number of reads generated.

Setting Parameters

Since the level of rf power transmitted from an RFID reader determines the range of rf communications between the reader and tags, it can be related to the read range for the underlying model of the communications region. For experiments conducted

Table 1. Assigned Discrete Read Range at Different Levels of RF Power

Power level	Transmission power (dB m)	Assigned discrete read range ρ (cells)	Corresponding radial read range *r* [*m* (ft)]
High	−5	7	12.2–13.7 (40–45)
Medium	−20	5	8.8–10.1 (29–33)

within the occupancy cell framework, two levels of rf transmission power were associated with a particular value of the discrete read range ρ, as shown in Table 1. Each of these values was assigned to a different level of rf power upon 200 trials of reading a total of 20 tags placed in the experiment field, rather than having been derived from Eq. (1) after the corresponding radial read range had been determined otherwise. For the medium level of rf power, 12 tags that lay within the square region defined by $\rho=5$ cells accounted for 96% of the total number of reads, while the other eight tags lay within the communication region as if the discrete read range had been $\rho=7$ cells.

In addition to the level of rf power, experimental variables included different configurations for the magnitude and density of tags. In the experiment field Q with an area of 36 m × 36 m, a total of 10 or 20 tags were placed, forming one of seven different patterns. Fig. 2 depicts one such placement pattern, called "even," which consists of 20 tags and represents an extreme in terms of tag density. Other patterns tried in experiments can be found in Song (2005). In particular, some of the tags were placed within the "interior" region such that they were distant from the boundary of Q by more than the discrete read range ρ and hence could be read from as many as $(2\rho+1)^2$ different cell locations in the overall region Q. Tags that fall within the dotted square in Fig. 2 are "interior" tags for the even pattern given the medium rf power level.

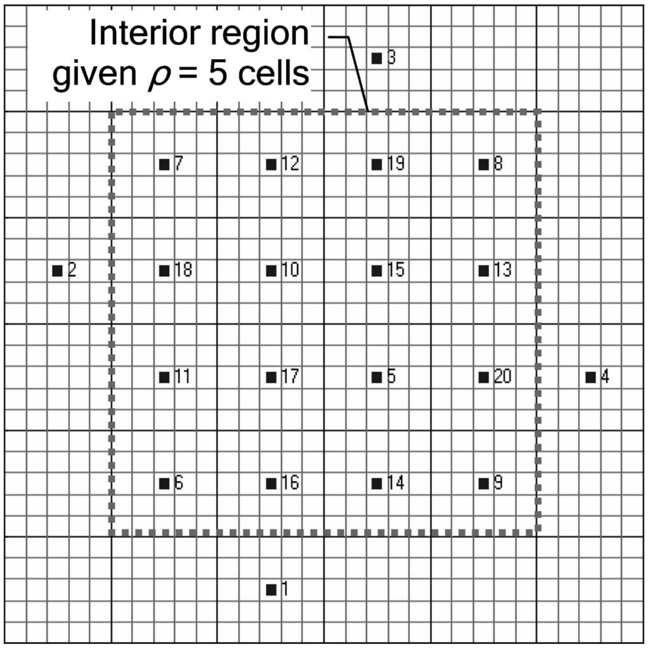


Fig. 2. Even placement pattern for 20 tags

Obtaining Proximity Information of Tags

Once the level of rf power was set and a total of 10 or 20 tags were placed in a particular pattern, the RFID handheld reader was carried around the region Q to generate reads and obtain the proximity information of the tags. Note that each combination of these parameter values characterizes the unique "test bed." For each test bed, the experimenter attempted only once to read tags in each of a total of 30^2 cells within the region Q. From this completely full read array, virtual rover paths and read rates were generated. Each successful attempt to read a tag contributed a piece of proximity information for the tag, indicating that it lay within the square region centered at the read and containing $(2\rho+1)^2$ cells. However, in each test bed some attempts were unsuccessful in acquiring an rf signal from any of the tags and did not yield proximity information for them, partly because all the tags lay far beyond the communication region of the reads.

Although the position of the RFID reader at any time would have been known if the experimenter carrying the reader had been equipped with a GPS receiver, experiments were dispensed with a GPS receiver since they were conducted using a fixed grid with known locations. By referring to the stake flags and physical grid lines in the experiment field, the experimenter located himself within one of the 30^2 cells to which an integer number between 1 and 900 had been assigned—handling of GPS positional error is described later. This numbering scheme was also used for naming the files that stored the ID numbers of the tags read in each cell.

Sampling Proximity Data at Different Intervals on Same Rover Path

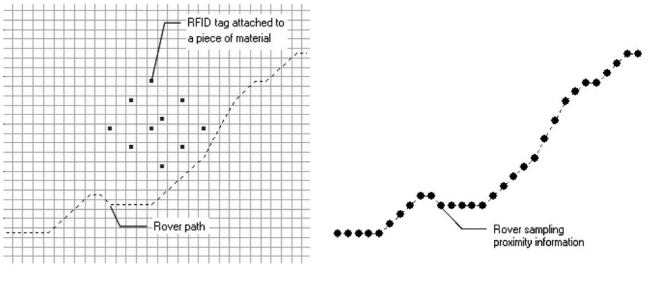
Out of a total of 900 reads generated from each test bed, a certain number of them were randomly selected iteratively such that they formed the unique set of proximity data contributed by the rover taking different virtual paths. The number of reads selected was also varied to determine its effect on the performance of RFID proximity localization. However, to keep the effect of a different number of reads from convoluting with that of a different rover path, it was necessary to simulate the situations in which the rover samples proximity data at different time intervals remained on a single path. Fig. 3 provides an illustration of this simulation. Suppose that the rover is taking one path on its normal business, as shown in Fig. 3(a). If every cell location along the path is taken into account, as in Fig. 3(b), proximity data drawn from a maximum of 30 reads are used to determine the location of tags. Selection of every fifth read, as in Fig. 3(c), simulates a slower read rate or a faster traveling rover. More intervals may be generated as shown in Fig. 3(d). These intervals might represent paces on site related, respectively, to strolling, jogging, and driving.

As a first step to implement the simulation illustrated above in a software environment, the number of reads made at the "strolling" pace was determined based on the analytical solution given by Simic and Sastry (2002). They proved that the K_ϵ number of reads necessary to localize a randomly picked interior tag within an $(1+\epsilon)$ cell area on average satisfies

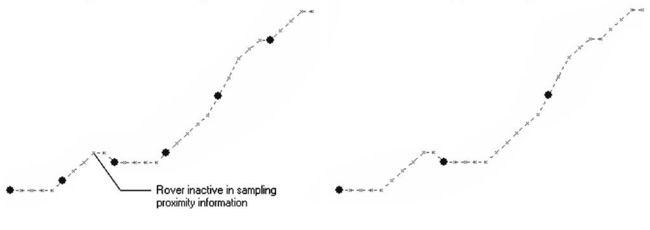
$$K_\epsilon(n,\rho) \geqslant n^2 \frac{\ln[8\rho(2\rho+1)] - \ln \epsilon}{2\rho+1} \tag{6}$$

assuming that reads are distributed evenly in the region Q. Given $n=30$, $\rho=5$ or 7 depending on the rf power level, and $\epsilon=4$, an integer value of K_ϵ satisfying Eq. (6) was determined.

Among the total of 900 reads generated in each test bed, the K_ϵ number of reads were randomly selected in 50 iterations to create



(a) Generic rover path (b) "strolling"



(c) "jogging" (d) "driving"

Fig. 3. Example of sampling proximity information at different intervals on single rover path

virtual rover paths. For each path, proximity data were sampled at two additional frequencies represented by fractions of K_ϵ reads, $0.2K_\epsilon$, and $0.1K_\epsilon$. For example, the $0.2K_\epsilon$ reads sample proximity data at every five cell locations along the path. For the test beds with medium rf power, this number of reads would be required to localize interior tags within a 169 cell area since given $\epsilon=4$, $0.2K_\epsilon=77$ is equivalent to $1.0K_\epsilon$ for $\epsilon=168$.

Using the visual basic for application (VBA) codes in Song (2005), a total of 150 sets of proximity constraints were simulated for each of 28 test beds developed in field experiments, and overall, 4,200 sets of proximity data were obtained. The overall data set can be classified into groups that are characterized by a single parameter, as shown in Table 2.

Terminology and Performance Metrics

To analyze the performance of RFID proximity localization resulting from the experiments, several metrics were developed and computed using the VBA codes in Song (2005). To begin, let K denote the maximum number of reads that can contribute to each of the 4,200 sets of proximity information, that is, $K=1.0K_\epsilon$, $0.2K_\epsilon$, or $0.1K_\epsilon$, depending on sampling frequency. Note that some of the K reads may not actually have produced pieces of proximity information.

Table 2. Summary of Data Set Classified by Parameters

Parameter	Possible setting/value	Sets of proximity information for each setting/value
Level of RF power	High, medium	2,100
Pattern of tag placement	Bilinear, cross, even, focused, linear, round, skewed	600
Number of tags	10, 20	2,100
Number of reads	$1.0K_\epsilon$, $0.2K_\epsilon$, $0.1K_\epsilon$	1,400

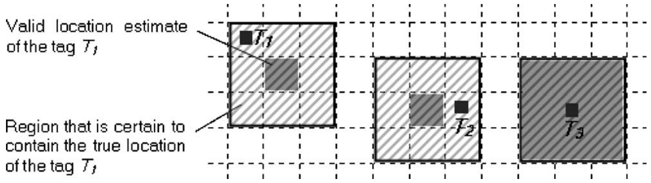


Fig. 4. Example of combining the size of valid location estimate with its bias

For each tag, the number of "successful" reads indicates how many of the total of K reads actually acquired an rf signal from the tag and hence provided proximity data for the tag. As expected, a successful read for a tag with grid coordinates (x,y) was possible with the reader positioned within the region $(x-\rho,x+\rho)\times(y-\rho,y+\rho)$. However, it also occurred when the reader was positioned beyond this region. Such a read is defined as an "off-side" read for the tag. Conversely, the reader positioned within the region may fail to acquire a signal from the tag, resulting in a "missed" read. In a sense, off-side and missed reads reflect imprecision and uncertainty in the rf communications region defined by the value of ρ assigned at an rf power level.

Due to this ambiguity, the location estimate of a tag given by formula (4) may not be "valid." A location estimate, represented by the region $(a,b)\times(c,d)$, is defined to be valid if the integers a, b, c, and d satisfy that $1\leq a\leq b\leq n$, $1\leq c\leq d\leq n$. Since the experiments were conducted in the region partitioned into $n^2=30^2$ cells, the size of a valid location estimate, given by formula (5), is an integer value between 1 and 900. Although a valid location estimate of smaller size is generally considered to be more precise, the goodness of the estimate should not be determined solely by its size; the estimated area may not contain the true cell location of the tag, due to the ambiguity in the modeled communications region. For an invalid estimate, definition of the size is not applicable, and an arbitrary nonpositive integer value was assigned for the sake of identification.

If the location estimate $(a,b)\times(c,d)$ for a tag with grid coordinates (x,y) satisfies that $a\leq x\leq b$ and $c\leq y\leq d$, then the estimate contains the true tag location and is defined to be "unbiased." By definition, an unbiased estimate is always a valid location estimate. In addition to distinguishing between biased and unbiased estimates, it is also necessary to define differences between biased estimates. Although biased estimates may be compared based on their size, the size does not indicate the extent to which each estimate deviates from the true tag location. The bias of a valid location estimate $(a,b)\times(c,d)$ is defined as the maximum number of cells that the tag's true cell location (x,y) is distant from the estimated region's boundary. Thus, the bias is calculated as $\max[\min(|x-a|,|x-b|),\min(|y-c|,|y-d|)]$, and if unbiased, it is given zero. Note that the bias takes only a nonnegative value and does not indicate the direction along the X- or Y- axis in which the true tag location is distant from the boundary of the estimated region.

For example, suppose that the location estimate of tags, given by formula (4), is the shaded regions shown in Fig. 4. For both tags T_1 and T_2, the bias of the location estimate is one cell while the location estimate for the tag T_3 is unbiased. When the region given by the valid estimate for a tag $(a,b)\times(c,d)$ is expanded by the bias β in each direction along X- and Y-axes, the smallest region is given such that it is certain to contain the true location of the tag. For each tag, this region is given by $(a-\beta,b+\beta)\times(c-\beta,d+\beta)$, which is represented in Fig. 4 by

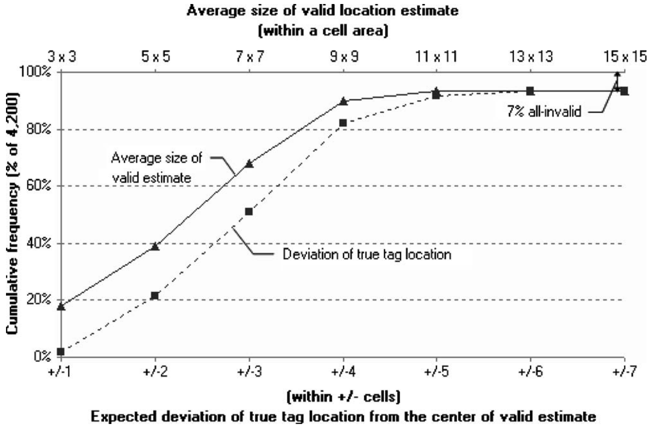


Fig. 5. Overall performance of RFID proximity localization experienced in field

hatched squares, and defined as the confidence region for the tag. In addition, the size of the confidence region is defined as the number of cells contained in the region, and it provides a means to directly compare one valid estimate with another by combining the size and bias of each one.

As such, the valid location estimate for a tag in Fig. 4 is as good as that of any other, all indicating that the true tag location is within ±1 cell from the center of the estimated region, or within a 3 × 3 cell area. Practically, the bias of a valid estimate is unknown unless the true tag location is known; all that the rover provides is the proximity information for each tag that may lead to a valid location estimate for the tag. However, given a particular configuration of experiment parameters, once it has been determined how frequently a tag's confidence region registers as being on average as large as nine cells, the tag's true location can be predicted at a certain level of confidence to be within ±1 cell from the center of its valid estimate obtained under the same configuration.

For each of the 4,200 sets of proximity information obtained through experiments, the metrics defined above were calculated for individual tags and then averaged out, resulting in corresponding summary measures with a few exceptions. First, if the set of proximity information led the location estimate for a tag to $(1,30)\times(1,30)$, this tag was not included in calculating average size and bias of valid estimates, or average size of confidence regions. This estimate, called a "default" estimate, resulted when none of the K reads successfully read the tag. Because it is already known that every tag lies within the experiment field $(1,30)\times(1,30)$, the default estimate is trivial although valid by definition, and its size 900 would only skew the summary measures. Other exceptions were made where average measures cannot be defined, e.g., when the location estimates of tags were all invalid.

Performance Analyses and Discussion

Analysis of the data collected shows that in 93% of the total of 4,200 instances, at least one tag was localized with a valid (but not default) estimate. In particular, for 68% of the experiments the size of the valid estimate averaged less than 50 cells, which can be thought of as a 7 × 7 cell area (see the upper curve in Fig. 5). Taking into account the effects of the bias as discussed earlier, the true location of a tag is expected in 51% of the total instances to be within ±3 cells from the center of the region given by the valid estimate for the tag (see the lower curve in Fig. 5). Note that each cumulative frequency curve in Fig. 5 reaches 93% and the remaining 7% is accounted for by "all-invalid" instances in which the location estimates of all tags were invalid.

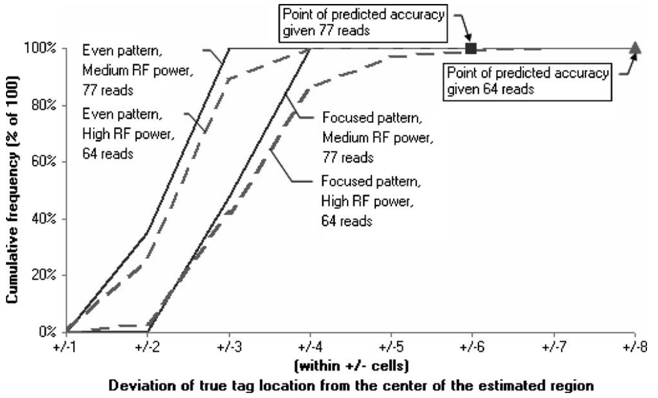


Fig. 6. Comparing positional accuracy experienced with theoretical

To assess the adequacy of RFID proximity localization, the results of these field experiments are compared with the accuracy predicted by Simic and Sastry (2002) under the occupancy cell model. Recall that the results of experiments are based on proximity information provided by the K number of reads generated along each virtual path. As described, using proximity measurements given by a total of $K=0.2K_{\epsilon}\approx 77$ reads with the discrete read range of 5 cells, interior tags should be localized within a 13 × 13 cell area on average, that is, with accuracy of ±6 cells. Similarly, with $\rho=7$ at the high rf power level, taking K as $0.2K_{\epsilon}$ given $\epsilon=4$ results in $0.2^{*}321\approx 64$ reads for which the true tag location is expected to be within a 17 × 17 cell area. Fig. 6 shows that the positional accuracy predicted for $K=0.2K_{\epsilon}$ reads has been accomplished for both extreme patterns—the cumulative frequency curves converge to points of predicted accuracy. This accomplishment is encouraging, considering the uncertainty and imprecision of the rf communications region that were experienced in experiments. It is also noted that at the same rf power level, location estimates for tags in the even pattern have met predicted accuracy more rapidly than those of the focused pattern.

Since the imprecision in the rf communications region originates from the assignment of a discrete read range at a particular rf power level, the estimate of tag locations may be improved by expanding the prescribed read range while remaining at the same power level. Fig. 7 shows the effects of expanding the read range by one cell at the high power level, on the test beds with the focused tag placement. Noting that the all-invalid instances have been decreased from 30 to 12%, the improvements can be attributed to reduced off-side reads at the high power level. Nonetheless, the high rf power is still outperformed by the medium rf power, suggesting that RFID tags with a short read range can be localized effectively with proximity techniques.

To summarize, in experiments on the performance of RFID proximity localization with short read range, the true tag location was estimated with the error ±3 cells, or ±3.6 m (side of 1 cell $=4$ ft ≈ 1.2 m), in approximately 68% of the experiments when the medium rf power is in use—94% of the time within ±4 cells. Assuming that the errors in location estimates using RFID are normally distributed, the estimate of the tag's location is subject to errors with 1 SD 3.6 m. To assess the overall error in tag location estimates, the impact of mapping the position of the

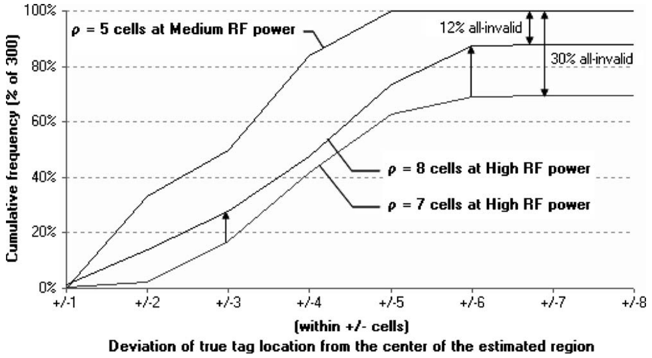


Fig. 7. Effects of expanding discrete read range for focused placement

rover to a cell location in reference to physical grids should be considered. For example, unlike in the field experiments, the position of the rover at a cell location may be known by a GPS receiver that is subject to errors in its estimation of 2D location with 1 SD 1 m. Thus, using short range RFID combined with GPS, the tag location estimate would have the overall error with a standard deviation of 3.7 m $\approx \sqrt{1^2+3.6^2}$.

The results of field experiments conducted using an off-the-shelf RFID system indicate that the approximate 2D location of materials can be inexpensively determined using the proximity localization techniques. The way in which this approach is formalized offers the following advantages:

1. It does not rely on a fixed communications network or require modifications to current RFID hardware to determine both identification and location of tagged materials, and it is compatible with constantly changing construction environments.
2. It leverages automatic passive reading with opportunity for active confirmation, and does not require line of sight for positive identification or manual updates of materials location. Thus, this approach is potentially much faster than existing approaches for surveying laydown yards and construction sites, and it provides the ability to rapidly find and distribute requisite materials for crew installation.
3. It works with multiple rovers, presenting the opportunity not only for key site personnel to carry the mobile RFID reader but also for other construction agents, such as materials handling and lifting equipment, to be mounted with mobile RFID readers equipped with GPS.
4. It potentially works with inexpensive passive RFID tags, providing multitiered capability for tracking items of varying criticality.

Ideally, this approach could be used to form the backbone of a location tracking system for other construction resources on site, such as craft workers, tools and auxiliary equipment, in addition to materials and components. This presents the potential to complement the existing approaches to identifying basic activities that construction agents are engaged in, which is a required step for the status determination of the activities and the derivation of project performance indicators.

Conclusions

This paper presented an approach by which RFID technology is demonstrated to be feasible in determining the 2D location of materials, without modifications to current hardware and potentially at a magnitude of less cost than pure GPS or other existing approaches. Analyses based on field experiments suggest that using this approach, tagged materials can be automatically identified and their locations simultaneously tracked in laydown yards and on construction sites, without adding to regular site operations. Essentially, this would be effortless and "ambient" tracking. This ability presents the potential for improvements to field materials management and for effortless derivation of performance indicators for project management's real-time control.

Although economic considerations were factored into the development of this approach, potential economic feasibility should be estimated to justify the up-front cost of implementation. Nonetheless, it is noted that roving applications of RFID technology in this approach form a unified platform to automate the tracking of materials and components in multiple stages of the project life cycle. In conjunction with its application to tracking the delivery and receipt of prefabricated materials through portal gates, roving applications will make the technology economically more attractive and drive implementation of the technology in realizing potential benefits. To implement roving applications in the real world, further research and development is also needed:

1. To characterize the performance trade-offs among parameters to determine optimal configurations for field deployment;
2. To develop methods for handling conflicting information generated by moved or moving tagged objects;
3. To expand the occupancy cell model to 3D localization and develop methods to determine the position of the rover when GPS may not function;
4. To develop protocols and architectures for integrating identification, proximity measurements, and GPS position data collected by multiple rovers into project information management systems; and
5. To formalize methods to complement existing approaches to identifying basic activities that construction resources are engaged in.

Finally, the occupancy cell model adapted to current ADC technologies can be used in developing localization algorithms for small devices that are envisioned in wireless sensor networks to mount additional sensing modalities such as heat, vibration, etc. Thus, in the future, embedded with the capability of recording and communicating their properties, transformations, movements, and progress, material objects will be able to embody the state of a constructed facility through its entire life cycle; the ambient intelligence they can provide will allow communicating facility state or "health" with project processes and with facility constructors, owners, and operators.

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