LOCATING SENSOR NODES ON CONSTRUCTION PROJECTS

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ABSTRACT

Localization of randomly distributed wireless sensor nodes is a significant and fundamental problem in a broad range of emerging civil engineering applications. Densely deployed in physical environments, they are envisioned to form ad hoc communication networks and provide sensed data without relying on a fixed communications infrastructure. To establish ad hoc communication networks among wireless sensor nodes, it is useful and sometimes necessary to determine sensors' positions in static and dynamic sensor arrays. As well, the location of sensor nodes becomes of immediate use if construction resources, such as materials and components, are to be tracked. Tracking the location of construction resources enables effortless progress monitoring and supports real-time construction state sensing. This paper compares several models for localizing RFID nodes on construction job sites. They range from those based on triangulation with reference to transmission space maps, to roving RFID reader and tag systems using multiple proximity constraints, to approaches for processing uncertainty and imprecision in proximity measurements. They are compared qualitatively on the basis of cost, flexibility, scalability, computational complexity, ability to manage uncertainty and imprecision, and ability to handle dynamic sensor arrays. Results of field experiments and simulations are also presented where applicable.

KEY WORDS

RFID, construction, materials management, locating, sensing and sensor networks

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INTRODUCTION

Requirements in system state or health monitoring and advances in Micro Electro-Mechanical Systems (MEMS), and computing and communication technologies have led to the development of massively and randomly distributed wireless sensor networks consisting of thousands of nodes. Each node may integrate sensing, computing, communications and even actuation. Deployment of such nodes often involves random scattering through a region of interest, such as a mass of curing concrete, a flow of effluent, or a herd of endangered animals, while communications with a central location may be lost due to limited battery power and hence communication range. As such, network connections among nodes (and even computational clusters) are often based on distance from node to node. Therefore, network topology is random. Random topology necessitates ad hoc communication protocols. To establish such ad hoc networks, the nodes must first be located.

Some research done in emerging developments in ad-hoc networking in civil engineering include ad hoc space architecture for collaboration to support disaster relief efforts involving critical physical infrastructure (Aldunate, 2005), support for mobile computing applications on construction sites (Reinhardt, 2005) and support for real-time construction state sensing and effortless progress tracking (Furlani, 1999, Sacks, 2003). A very early application was structural health monitoring using wireless sensor networks (Glaser, 2005). Also related to ad hoc sensor networks are developments in RFID (radio frequency identification) which are penetrating markets even more rapidly (Jaselskis, 2003). RFID systems are being used to track goods in warehouses, luggage through airports, and vehicles within Intelligent Transportation Systems. In most implementations, tags are read as they pass through portals equipped with readers or antennas and deployed at key locations.

In more dynamic environments and where location in a fixed coordinate system is required, such as construction sites, readers may be deployed on moving probes, such as key workers and materials handling equipment, rather than fixed portals. In such environments, communication ranges are anisotropic, time-varying, and dependent on surroundings. Locating tagged items effectively on construction sites can potentially facilitate tremendous increases in productivity and quality through efficiencies in coordination and allocation of resources (Tommelein, 1998, Kini, 1999, Peyret, 2002, Vorster, 2002, Jaselskis, 2003, Sacks, 2003). Any method to locate tags (nodes) must be scalable to tens of thousands of tags and be robust.

In the following sections, background and different models of localization are introduced, key performance characteristics are identified and then qualitative comparisons are made based on these characteristics. The paper concludes with some comments on the impacts of RFID based locating on construction productivity and project management. Recommendations are made for future research as well.

BACKGROUND

Wireless Sensor Networks (WSNs) distinguish themselves from other traditional wireless or wired networks through sensor and actuator based interaction with the environment. (He et. al, 2003) Such networks have been proposed for various applications including search and rescue, disaster relief, target tracking, and smart environments. The inherent characteristics of these sensor networks make a node's location an important part of their state. For such networks, location is being used: (1) to identify the location at which sensor readings originate, which has a feasible application in material management (for example, automatically tracking the location of construction laborers and equipment) (2) in novel communication protocols that route to geographical areas instead of ID's, and (3) when providing other location based services (such as sensing coverage and location directory service to provide medical information about a nearby patient in a smart hospital) (He et. al, 2003).

Materials management is a distinct management system that can make significant contributions to the cost effectiveness of construction 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, and suggested that an additional 4 to 6% savings would probably be produced by 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 materials management on labor productivity, reporting ineffective use of work-hours equivalent to 18% loss in labor productivity.

As an alternative to direct data collection relying on human observers, recent research efforts have 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, Sacks et al., 2005). However, related research efforts have focused on construction agents and 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. RFID technology suits identification purposes in tracking hundreds of materials in harsh environments. Its potential applications in the construction industry have been explored (Jaselskis et al., 1995), and several pilot tests 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., 2004). Though RFID technology presents several advantages over barcoding, its primary use in current applications is still limited to portal based identification purposes. This limitation had driven the commercial development of the Real Time Location Systems (RTLS) for indoor asset tracking applications.

Unlike conventional RFID systems, the RFID-based RTLS such as Pinpoint's 3D-iD provides both identification and location of tagged objects by virtue of a pre-configured wired network of fixed RFID readers. However, the RFID-based RTLS requires the 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 RTLS have been resolved by leveraging the IEEE standard Wi-Fi networks. Being based on the non-proprietary networks, the Wi-Fi based RTLS successfully overcame the substantial cost barrier to scalable location tracking systems, i.e., the infrastructural setup of separate networks. Good examples include solutions from AeroScout (www.aeroscout.com) and Ekahau (www.ekahau.com). However, the Wi-Fi RTLS still relies on existence of 802.11 access points in the building, which is not guaranteed for a facility being built, and may require extensive calibration to map the Wi-Fi signals to locations throughout the building. Due to its evolving and unpredictable nature, a construction site cannot afford location tracking systems relying on 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. 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 materials' tracking system.

LOCALIZATION MODELS

Triangulation, proximity and manual mapping are the principal techniques that can be employed together or individually for localization. For each model we describe its basic underlying concepts and research which has been done based on the model.

A few basic issues also play important roles in driving the applicability of each model for different location sensing applications. Cost is one of the most determinative issues. For the tags themselves, communication range, battery life (if the tag is active), ruggedness of packaging, data storage capacity, sensing capabilities (such as temperature or shock) are all significant technical issues. Communication ranges which are anisotropic, time-varying and dependent on tag surroundings can cause uncertainties and imprecision. The presence of moving or moved tags may cause conflicts and uncertainty in read data especially in the case of proximity methods. For RFID tags the signal from one reader can interfere with the signal from another where coverage overlaps. This is called reader collision, and while some techniques exist (such as time division multiple access) to avoid the problem, they add another layer of complexity. In addition to these issues, it is necessary to understand why attaching a GPS receiver to each item of interest is not feasible in most situations.

Global Positioning Systems (GPS) are becoming ubiquitous. Based on systems of satellites and triangulation techniques, GPS provides worldwide, all weather, 24-hour navigation and timing information. The accuracy of the derived position varies with the type of instrument used for collecting data, the method used in the surveying, the post-processing done and the method of the post-processing. Accuracy varies from a few millimeters to several meters (Asian GPS Conference 2002). However, due to low satellite signal strength, GPS is simply not designed to work indoors or underground, where much construction work and maintenance is conducted (Hightower et al., 2000). Additionally, the cost of GPS receivers prohibits wide scale deployment on a site, and GPS must be integrated with a wireless communication technology to report its location to a host, resulting in high expansion costs and more complex device architecture than an RFID tag. GPS has been suggested as a means to obtain location information in tracking labor inputs (Navon & Goldschmidt, 2002). For outdoor applications in which device density is low, and cost is not a major concern, GPS is a viable option (Patwari et al., 2001). However, tagging a GPS receiver to each object being tracked is expensive, and is not a viable option for large scale location sensing systems where tens of thousands of items need to be tracked within a few square kilometers.

MANUAL SEARCHING AND MAPPING WITH POSITIVE IDENTIFICATION

In this model a unit of a positioning system such as a GPS unit and a handheld computer with a GIS (geographic information system) are integrated into the specific application to assess the potential of data collection and positioning technologies, to improve the tracking and locating of materials on construction job sites. In a variation of this demonstrated approach, assume that items have RFID tags with flashing LEDs that light up when being interrogated so they can be located and then marked with the GPS rod and then recorded in the GIS.

A field trial was conducted to obtain experimental data for this model (Caldas et al., 2004). A GPS unit and a handheld computer were used in current fabricated pipe spools' receiving, storing, and issuing processes in lay down yards of a particular industrial project.

The GPS system determined its own location at any given time. The GPS reader was a combination of GPS backpack-mounted receiver and antenna. Position was defined in terms of three coordinates (X, Y, and Z). The handheld computer collected the positions determined by the GPS receiver. The computer was wired to the GPS receiver in order to collect the measured positions

The experiments conducted in the field trial referenced above measured search times required by field workers. Time measurements were taken for a baseline case in which crews used current industry work processes to locate spools. The study then measured times for other crews to locate the same pipe spools using GPS technology. The field measurements demonstrated an improvement in average search time of about 85%.

PROXIMITY MODELS

Proximity is the basis of another model for localization that does not attempt to actually measure the object's distance to reference points, but rather determines whether an object is near one or more known locations. The presence of an object within a certain range is usually determined by monitoring physical phenomena with limited range, e.g., physical contact to a magnetic scanner, or communication connectivity to access points in a wireless cellular network. The method of constraints, accumulation arrays, Dempster-Shafer theory and fuzzy logic are some approaches that can be employed individually or in combination for proximity based models.

Continuous versus Discrete Paradigms

In proximity models, for reduction in computational complexity, a discrete representation in 2D is employed instead of a more realistic continuous model. In the discrete view, a rover (any reader carrier) moves around in a square region Q with sides of length s which is partitioned into n^2 congruent squares called "cells" of area $(s/n)^2$. 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 Figure 1). 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 (Figure 1). This paradigm is applied in the proximity approaches in particular. A more robust approach is to encompass the actual read range with the discrete read range; for functional modeling purposes the first approach can be of advantage.

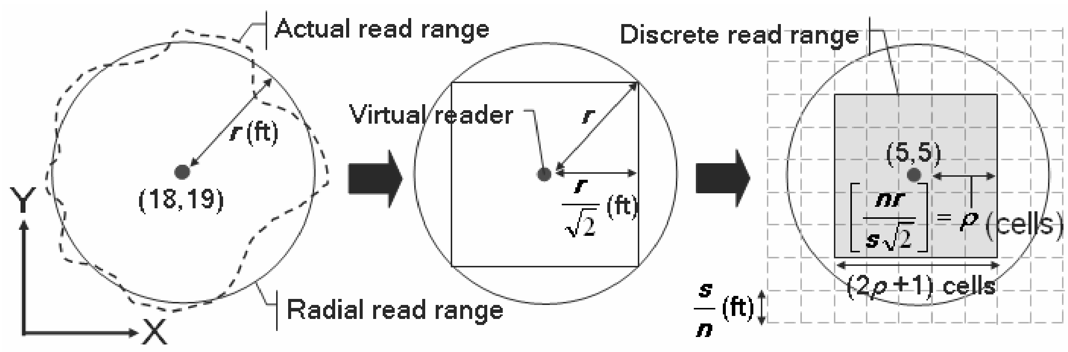

Figure 1. Modeling the RF communication region under the occupancy cell framework

Method of Constraints

Simic and Sastry (2002) presented a distributed algorithm for locating nodes in a discrete model of a random ad hoc communication network and presented a bounding model for algorithm complexity. Song et al. (2005) adapted this discrete framework, based on the concept that a field supervisor or piece of materials handling equipment is equipped with an RFID reader and a GPS receiver, and serves as a "rover" (a platform for effortless reading). The position of the reader at any time is known since the rover is equipped with a GPS receiver, and many reads can be generated by temporal sampling of a single rover moving around the site. If the reader reads an RFID tag fixed at an unknown location, then RF communications connectivity exists between the reader and the tag, contributing exactly one proximity constraint to the problem of estimating the tag location. As the rover comes into the communication range with the tag time and again, more reads form such proximity constraints for the tag. Combining these proximity constraints restricts the feasible region for the unknown position of the tag to the region in which the squares centered at the reads intersect with one another.

Song et al. (2005) also implemented the Simic and Sastry's algorithm in large scale field experiments, including as parameters: (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 based on random reader paths.

Analyzing 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. Particularly, for 68% of the experiments the size of the valid estimate averaged less than 50 cells, which can be thought of as a 7 x 7 cell area (see the upper curve in Fig. 3). 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. 3). Note that each cumulative frequency curve in Fig. 3 reaches 93% and the rest 7% is accounted for by "all invalid" instances in which the location estimate of all tags was invalid. Though this approach was proven adequate (3-4 m accuracy) for static distributions of tags, it is not easily extended to tracking moving or moved tags. Methods to improve both accuracy and ability to deal with conflicting data are being developed.

Figure 2. Field experiment for the method of constraints

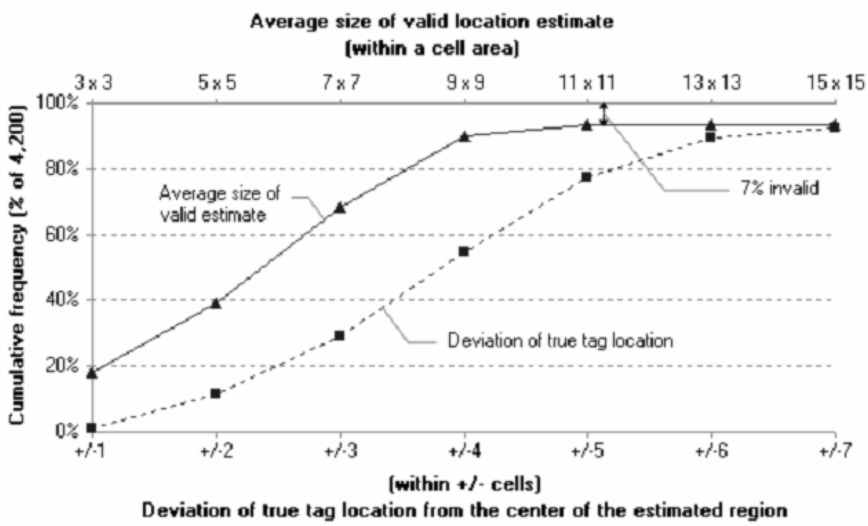

Figure 3. The overall performance of RFID proximity localization experienced in the field

Method of Accumulation Arrays

Using accumulation arrays for discrete modeling of the working space is a conceptual variation for proximity localization based on the concept in Song et al. (2005). However, unlike the method of constraints, reads would simply be accumulated cell by cell for each tag (See Figure. 4). To handle moving and moved tags, cells for each tag would begin to erode after a fixed number of reads while cell value magnitudes are related to probability of tag location. This model has not been implemented yet, and its obvious drawbacks are its potentially slow response to moves, and its large data structure requirement. However, its appeal is potential simplicity and therefore potential robustness for field application. It is a model that may be worth investigating.

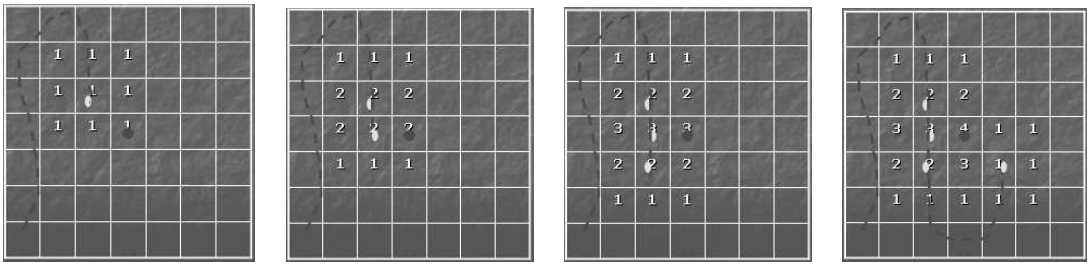

Figure 4. Accumulation of cell magnitute after each read in Accumulation Array method

Dempster-Shafer Method

The Dempster-Shafer method is another approach to proximity modeling which is based on Dempster-Shafer theory (Dempster, 1968, Shafer, 1976, Smets, 1994). The Dempster-Shafer Theory also known as the theory of belief functions, is a generalization of the Bayesian theory of subjective probability, whereas the Bayesian theory requires probabilities for each question of interest, belief functions allow us to base degree of belief for one question on probabilities for a related question (Shafer, 1992).

Caron et al. (2005) modeled each read by a basic belief assignment which is fused to the past measurements, and implemented the Dempster-Shafer formulation in a simulation environment for application to materials tracking in construction. In this environment when a reader reads a tag, it gets information about the position of this tag. This information, due to underlying imprecision and uncertainty, is modeled by a basic belief assignment under the belief theory framework. In this formulation, the probability of a tag lying in each cell is calculated using the pignistic transformation of this fused belief function, every time the fusion of a new read is made for the tag. Figure 5 shows the evolution of the pignistic probability of each cell as a function of new reads, and as the tag itself moves.

Caron et al. (2005) also showed that since this framework explicitly models conflicts among reads, it is well suited to indicate that a tag has moved. Conflicts may be caused by moving tags, sub/over-estimated tags and not working readers. When a conflict occurs at each virtual reading, the past fused data will be discounted in order to favor the last reading and to ignore the oldest readings. If the conflict is higher that a predefined threshold, past fused data could be rejected and the new fused data would be the latest one.

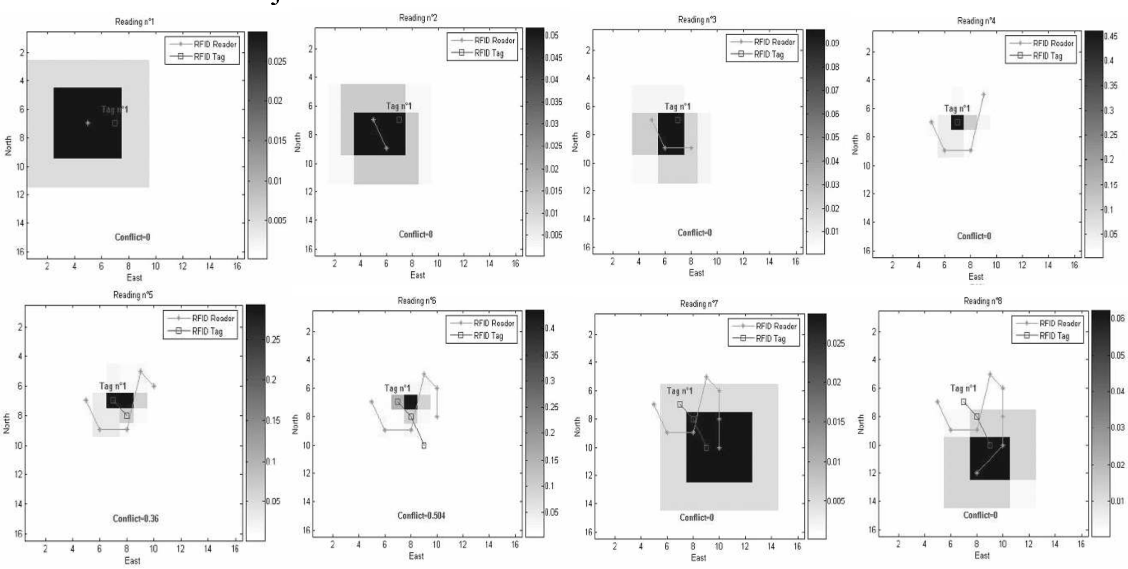

Figure 5. Evolution of the pignistic probability of each cell as a function of new reads

Generally, use of the Dempster-Shafer formulation increases integrity of localization of wireless communication nodes, because it can robustly deal with uncertainty and imprecision of anisotropic and time-varying communication regions. It also gracefully manages the issue of moved tags, presenting a scalable and robust approach to handling both static and dynamic sensor arrays. A key drawback of the formulation is that it increases complexity, although it is still computationally manageable.

Fuzzy Logic Method

This method of using proximity measurements in locating nodes would employ fuzzy logic instead of Dempster-Shafer theory in order to decrease the complexity associated with the Dempster-Shafer algorithm. While the fuzzy logic method builds on the insights gained through the Dempster-Shafer approach, it could consider the model to be continuous in some control variables such as moving tags or readers which are discretized in the other algorithms described earlier. This conceptual method is under development. It is being encoded and new field experiments are beginning in 2006.

TRIANGULATION BASED ON TRANSMISSION SPACE

As mentioned in the introduction, triangulation computes the position of an object by inferring its distance from multiple reference points with known locations, and is divisible into lateration and angulation, depending on whether ranges or angles relative to reference points are being inferred. As figure 6 shows, while two dimensional (2D) angulation requires two angle measurements and one length measurement such as the distance between the reference points, lateration requires three distance measurements between the object being located and three reference points (Hightower & Borriello, 2001). Lateration can be further classified into the time-of-flight and received signal strength methods, where the ranges to reference points are inferred from time of flight and signal strength of the communication medium, respectively.

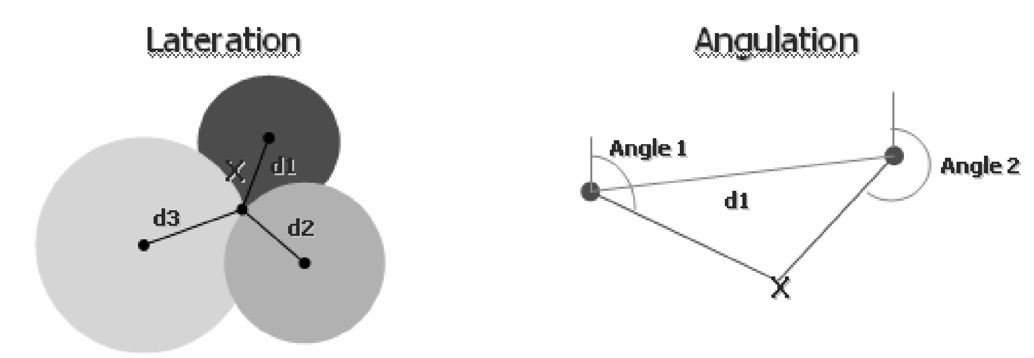

Figure 6. Lateration and Angulation

Approaches to locating RFID nodes based on triangulation or on relaxation algorithms (Bulusu, 2000, Doherty, 2001, Hightower, 2001, Boyd, 2004) are limited because of the cost of required node electronics (no current high volume demand exists). Again, as mentioned earlier, the anisotropic, dynamic transmission space on a construction site is not feasible to map at the temporal or spatial resolution required. For example, the Wi-Fi RTLS (real time location systems), such as commercial solutions from AeroScout, Ekahau and the PanGo Network, require extensive calibration to map the Wi-Fi signals to locations throughout the building while the existence of 802.11 access points is not guaranteed for a facility being built.

COMPARING THE MODELS

For comparing different models for locating RFID nodes, a hypothetical unified application platform is considered as a basis for fair judgment. The platform considered here is a 1000×1000 $m^{2.}$ construction site for an industrial project with an overall cost of $50,000,000 and a duration of 24 months. Tens of thousands of items need to be tracked. Each piece of equipment to be tracked, costs between $100 and $100,000.

For the hypothetical application platform, the following performance characteristics are considered in comparing the localization models:

- Cost – the total cost of all pieces of equipment, shipping, installation and maintenance of that equipment, training, etc.

- Flexibility – the ability to alter RFID localization system configurations, based on future circumstances.
- Scalability – the ability to extend the current system topology and architecture to many tags and readers interacting in different ways.
- Computational complexity – the number of steps or arithmetic operations required to estimate the location of tags. By reducing system-level computational complexity, the response time increases, which may become a critical parameter for some real-time applications.
- Handling uncertainty and imprecision – qualitative reading errors exist because of the technology itself, imprecision in read range is a given, and uncertainty exists because tags move, but we detect this indirectly with automated approaches, so the ability to handle these phenomena is another important characteristic of the system.
- Handling dynamic sensor arrays – for dynamic environments where tagged objects are constantly moving, the ability to manage and graphically represent information about the tags in a useful way is important.

Based on the performance characteristics described above, different localization models are compared (Table 1) as if they were used on the hypothetical application platform. Medium, High and Low in Table 1 refer to the levels of performance for each model with respect to each performance characteristic. However, it should also be noted that for different domain-related issues, there are always some cost-performance trade offs, such as rover/reader density vs. performance; granularity of space vs. performance; reading and re-computation frequency vs. cost, etc.

SUMMARY

This paper introduced and qualitatively compared different models for locating RFID nodes. Based on the research completed to date on each model, it is reasonable to conclude that RFID technology offers the opportunity to track the location of materials in construction applications at a near real time update rate and at an accuracy varying from one to a few meters. The potential impact of this technology on the construction industry includes: (1) improved real-time project and facility management and control via effortless productivity tracking and materials tracking, (2) time and cost savings to the construction industry, and (3) potential extension to safety applications.

Further research is however needed. The best approach overall is unknown and will be dependent on application domain specifications. It is also necessary to determine performance factor relationships among rover/tag spatial densities and velocities, distribution patterns, objects' geometric and material properties, site clutter, transmission ranges, and data structuring. Ultimately this technology needs to be integrated into decision support systems and knowledge management systems.

Table 1: Qualitative Comparison of Localization Models

Localization Model	Cost	Flexibility	Scalability	Computational complexity	Handling uncertainty and imprecision	Handling dynamic sensor arrays
Manual searching and mapping with positive identification	Low	High	Low	Low	High	Low/ Medium
Accumulation arrays	Medium	High	High	Low	Low(uncertainty) & Medium(imprecision)	Low/ Medium
Method of constraints	Medium	High	Medium	Medium	Low(uncertainty) & Medium(imprecision)	Low
Dempster-Shafer	Medium	High	Low/Medium	High	High	High
Fuzzy logic	Medium	High	Low/Medium	Medium	High	High
Triangulation based on transmission space	High	Low	Low	High	Medium	Medium

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