MODELS FOR LOCATING RFID NODES

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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 the 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

INTRODUCTION

Requirements in system state or health monitoring and advances in Micro Electro-Mechanical Systems (MEMS), and computing and communication technologies have led to

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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.

Examples of 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, 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.

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.

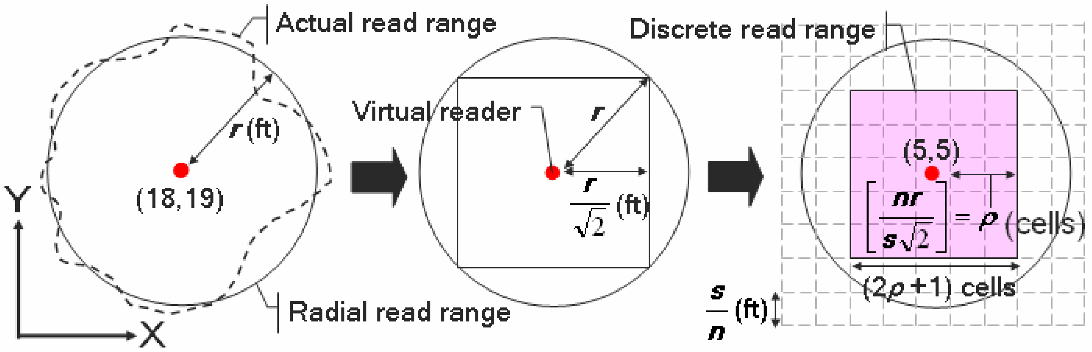

Figure 1. Modeling the RF communication region under the occupancy cell framework

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 read an RFID tag fixed at unknown location, then the 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 from 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. 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.

Method of Accumulation Arrays

Using accumulation arrays for discrete modeling of the working space is a conceptual approach 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. 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.

Dempster-Shafer Method

The Dempster-Shafer method (Dempster 1968, Shafer 1976, Smets 1994) is another approach to proximity modeling. 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 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 2 shows the evolution of the pignistic probability of each cell as a function of new reads. 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.

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.

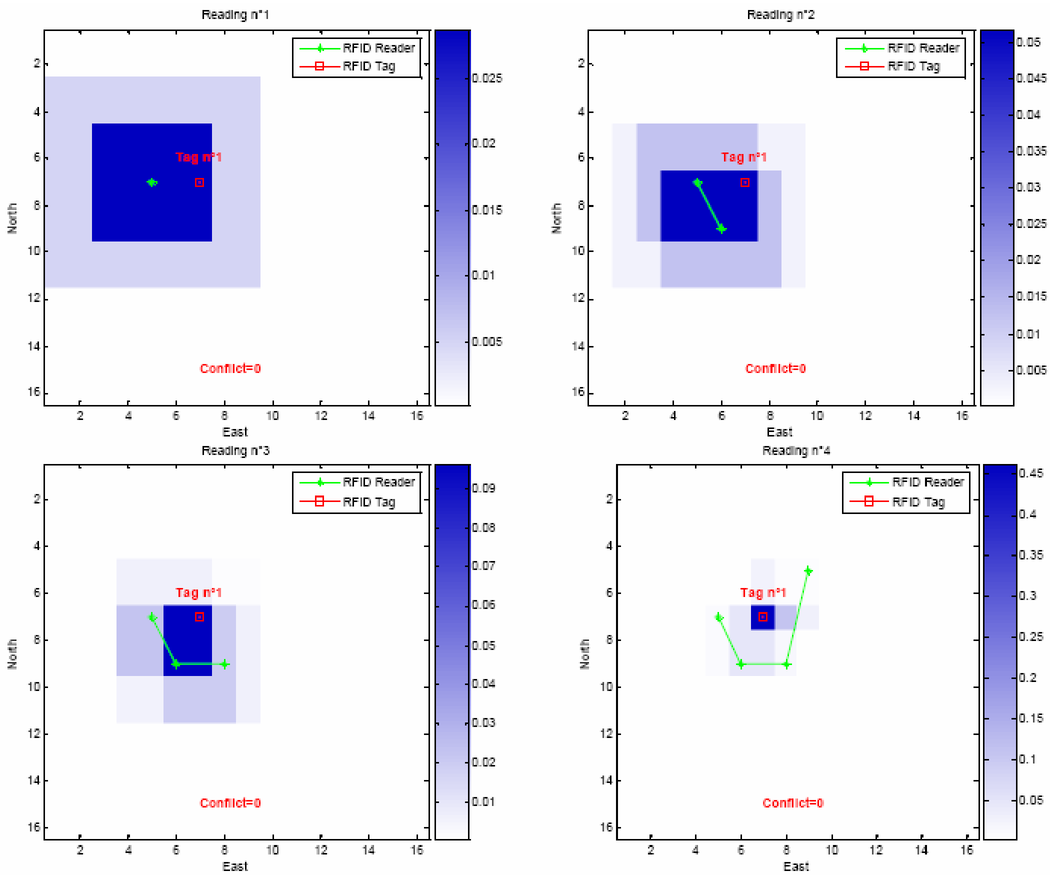

Figure 3. Evolution of the pignistic probability of each cell as a function of new reads

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 will be encoded and field experiments will be conducted in the next year.

TRIANGULATION BASED ON TRANSMISSION SPACE

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. 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.

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). Furthermore, 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 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 this process 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.

Table 1: Localization Models Comparison

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

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.

REFERENCES

Aldunate, R., Ochoa, S., Pena-Mora, F., and Nussbaum, M. (2006). "Robust Mobile Ad hoc Space for Collaboration to Support Disaster Relief Efforts Involving Critical Physical

Infrastructure." *J. Comp. in Civ. Engrg.*, ASCE, 20 (1) 13-27. Boyd, S., and Vandenberghe, L. (2004). *Convex Optimization*, Cambridge University Press, Cambridge, UK.

Bulusu, N., Heidemann, J., and Estrin, D. (2000). "GPS-less low-cost outdoor localization for very small devices." IEEE *Personal Communications*, 7 (5) 28-34.

Caldas, C.H., Haas, C.T., Torrent, D.G., Wood, C.R., and Porter, R.(2004). "Field trials of GPS technology for locating fabricated pipe in laydown yards." Smart Chips Project Report, FIATECH, Austin, TX.

Caron, F., Haas, C., Vanheeghe, P., and Duflos, E. (2005). "A Dempster-Shafer Formulation for Processing Uncertainty and Imprecision in Proximity Measurements." ASCE *Journal of Computing in Civil Engineering*, In Press.

Dempster, A.P. "A generalization of Bayesian inference", Journal of the Royal Statistical Society, 30, 1968.

Doherty, L., Pister, K., and Ghaoui, L. (2001). "Convex position estimation in wireless sensor networks." *Proc., INFOCOM*, IEEE, 1655-1663.

Furlani, K., and Stone, W. (1999). "Architecture for discrete construction component tracking." *Proc.*, *ISARC '99*, IAARC, Madrid, 289-294.

Glaser, S., Shoureshi, R., and Pescovitz, D. (2005). "Frontiers in sensors and sensing systems." *Smart Structures and Systems*, 1 (1) 103-120.

Hightower, J., Want, R., and Borriello, G. (2000). "SpotOn: An Indoor 3D Location Sensing Technology Based on RF Signal Strength." *Technical Report No. UW CSE 00-02-02*, Department of Computer Science and Eng., University of Washington, Seattle, WA.

Hightower, J., and Borriello, G. (2001). "Location Sensing Techniques." Technical Report, Computer Science and Engineering, University of Washington.

Jaselskis, E.J., and El-Misalami, T. (2003). "Implementing radio frequency identification in the construction process." ASCE *J. Constr. Engrg. Manag.*, 129 (6) 680-688.

Kini, D. U. (1999). "Materials management: The key to successful project management." *J. Manage. Eng.*, ASCE, 15 (1) 30-34.

Navon, R., and Goldschmidt, E. (2003). "Can labor inputs be measured and controlled automatically?" *J. Constr. Eng. Manage.*, ASCE, 129(4) 437-445.

Patwari, N., O'Dea, R.J., and Wang, Y. (2001). "Relative location in wireless networks." *Proc.*, *IEEE Vehicular Technology Conference*, Vol. 2, 1149-1153.

Peyret, F. and Tasky, R. (2002)."Asphalt quality parameters traceability using electronic tags and GPS." *Proc.*, *ISARC '02*, Washing ton, DC, 155-160.

Reinhardt, J., Garrett, J., and Akinci, B. (2005). "Framework for Providing Customized Data Representations for Effective and Efficient Interaction with Mobile Computing Solutions on Construction Sites," *J. Comp. in Civ. Engrg.*, ASCE, 19(2) 109-118.

Sacks, R., Navon, R., and Goldschmidt, E. (2003). "Building project model support for automated labor monitoring." *J. Comp. in Civ. Engrg.*, ASCE, 17(1) 19-27.

Shafer, G. (1976). "A Mathematical Theory of Evidence", Princeton University Press, Princeton.

Simic, S.N., and Sastry, S. (2002). "Distributed localization in wireless ad hoc networks." *Technical Report UCB/ERL M02/26*, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA.

Smets, P. and Kennes, R. (1994). “The Transferable Belief Model”, Artificial Intelligence, 66:191-234.

Song, J., Haas, C.T., and Caldas, C.H. (2005). “A Proximity-based Method for Locating RFID Tagged Objects.” Submitted for consideration for publication in *Special Issue of Journal of Advanced Engineering Informatics on RFID Applications in Engineering*.

Song, J., Haas, C., Caldas, C., Ergen, E., and Akinci, B. (2006). “Automating the task of tracking the delivery and receipt of fabricated pipe spools in industrial projects.” Automation in Construction, Elsevier, 15 (2) 166-177.

Song, J., Haas, C., Caldas, C., and Liapi, K. (2005).“Locating Materials on Construction Sites Using Proximity Techniques,” ASCE Construction Research Congress, San Diego, CA.

Tommelein, I.D. (1998). “Pull-Driven Scheduling for Pipe-Spool Installation: Simulation of a Lean Construction Technique,” *J. Constr. Engrg. Manag.*, ASCE, 124(4) 279-288.

Vorster, M.C., and Lucko, G. (2002). “Construction technology needs assessment update.” *Research Report 173-11*, Construction Industry Institute, Austin, TX.