Integration of RFID with other Technologies in Construction

Enrique Valero[a], Antonio Adán[b]

[a] *Heriot-Watt University, Energy, Geoscience, Infrastructure and Society School, Edinburgh EH14 4AS, United Kingdom*
[b] *Universidad de Castilla-La Mancha, 3D Visual Computing and Robotics Lab, Paseo de la Universidad, 4. 13071 Ciudad Real, Spain*

Abstract

Radio Frequency Identification (RFID) has been inserted in construction to make easier, and even automatic, a large variety of processes during the life-cycle of a building. However, RFID has some limitations and restrictions which can be highly reduced if it is combined with other sensors and technologies. This paper makes a review of the most popular technologies and applications which have been recently integrated with RFID in construction. The paper demonstrates that the integration makes the whole control system more accurate and efficient as well as increases the possibilities and applications of RFID in construction.

Keywords: RFID, construction, smart technologies, positioning

1. Introduction

One of the most extended and promising wireless non-contact systems is that of Radio-Frequency Identification (Shen et al., 2008) (Calis et al., 2011). This technology is based on exchanging information by means of electromagnetic signals (Domdouzis et al., 2007). Owing to its ability to identify and track objects, RFID is extensively used for diverse applications.

Different authors have proposed a wide variety of real and potential applications using RFID technology in the field of construction. The majority of these approaches aim to control different processes like concrete handling, cost coding for labor, equipment or materials tracking, and others (Jaselskis et al., 1995). In order to enumerate and compare the main contributions in the field of RFID in construction, different reviews have been presented since the 1990s. In 2006, the consortium ERABUILD presented a review of the state of RFID technology in the construction industry (CI) (Erabuild, 2006). The authors present some applications of RFID to date and propose some recommendations for further research into RFID in construction. Some specific RFID reviews addressed to a particular aspect or application also appear in the literature. A good example of those reviews can be found in (Ergen and Akinci, 2007). The paper of Ergen and Akinci presents a comparison of methods in which RFID is used to track pipe spools and precast components. And more recently, Lu et al. (2011) have presented a comparison of works related with the management of materials, men and machinery.

The objective of this paper is to present a new review which tackles the integration of RFID with other technologies in the field of construction. Nowadays, the combination of RFID sensors with other kinds of technologies is put into practice from the design of a building to the location of users and the mapping of the environment once the works are finished. This current and specific issue has not been dealt with in construction yet. In this document, we include the most recent works in this research field.

The paper is organized as follows. Section 2 discusses the possibilities and limitations of RFID and argues the suitability of combining RFID with other sensors in construction. Throughout the rest of the document, we show applications in which different technologies are combined, making easier the construction process. Section 3 presents the main works that use RFID and vision sensors. Section 4 deals with RFID and positioning systems. Section 5 is devoted to RFID and microcomputers. Integration of RFID and software is presented in Section 6. Finally, in Section 7 we discuss about conclusions and future works.

2. Possibilities and Limitations of RFID in the Construction Field

In this section we present different advantages and limitations of RFID in construction and justify the integration with other technologies throughout the lifecycle of buildings, which greatly improve the management of information before, during and after the construction of a building. Those properties are summarized in Table 1 at the end of this section.

Before the construction starts, some operations related to the production of materials and components are automatically registered and controlled by means of RFID tags. As Jaselskis et al. (1995) mention, this technology can be suitable for monitoring different stages of concrete production: from mixing to delivery in the jobsite.

During the construction process, thousands of materials and a crew of workers, equipped with tools and vehicles, are permanently changing their position in the jobsite. Controlling the location of resources (Su et al., 2014) and materials (Goodrum et al., 2006) - mainly in the organization of the storage area or the control of deliveries - helps to improve the productivity in building erection and to increase the safety of workers (Wu et al., 2013).

Finally, when a building is in use, an important number of maintenance and evaluation tasks are carried out. Diverse elements under inspection can be equipped with tags, aiming to monitor their condition or performance (Cheng et al., 2007). However, in terms of appearance, the presence of RFID tags on the surface of constructive elements or pieces of furniture is not desirable. An important advantage of RFID is that the user does not need to see the tag to identify the object and get the stored information. Tags can even be embedded in materials or structural components. In (Dziadak et al., 2009), authors discuss the location of buried assets by means of this technology. Besides, tags are small, light and their content is easy to manage.

As is noticeable in the recent literature, and is remarked in the previous paragraphs, RFID has contributed to automate an important variety of works, improving the efficiency in construction and reducing the associated costs. Nonetheless, several limitations have led researchers to investigate novel solutions based on the combination of RFID and other technologies. Some of those constraints are presented below.

As is known, accuracy is an important factor when it comes to position a user in a scene, but pose estimation through RFID systems is not really very accurate. In (Joho et al., 2009), authors propose an approach for robot localization based on RFID tags detection and RSSI, delivering errors over 0.3m for position and 0.2rad for orientation. Therefore, if a precise pose calculation is required, RFID needs to be combined with other technologies.

Recognition problems also arise if several tags must be detected at the same time. Then, RFID is unable to precisely identify and give the position of the tags, being impossible to know from which object the information comes.

Another disadvantage of the use of RFID technology in construction regards the interferences produced by certain materials. Metals and concrete - very common in the field of construction - can cause some problems during the information exchange process (Tzeng et al., 2008) (Mo and Zhang, 2007).

In fact, an additional surface must be inserted between the tag and the object in many cases (see (Jaselskis and El-Misalami, 2003)). In the same manner, reading problems can occur if tags are surrounded by metal, even if they are not adhered to a metallic surface.

As mentioned before, those restrictions can be improved or even overcome if other sensors and technologies take part in the control process. The reciprocal idea (being RFID used as an assisting technology) can also be thought. Thus, the efficiency of other sensors might greatly improve with the help of RFID sensors. Such direct and reverse ideas are tackled in the next sections. Most works developed in this framework during the last ten years are focused on the combination of technologies, mainly addressed to monitoring of construction sites. The easy communication between different devices facilitates the implementation of collaborative tasks and allows the operator to gather more information about works in progress or the maintenance of certain components.

Table 1: Advantages and limitations of RFID technologies for construction purposes.

Advantages	**Limitations**
✓Tags are light and easy to attach (Goodrum et al., 2006) (Su et al., 2014)	✗ Lack of accuracy in positioning (Joho et al., 2009)
✓Small and wearable tags (Wu et al., 2013)	✗ Interferences with materials (Tzeng et al., 2008) (Mo and Zhang, 2007)
✓Direct view of tags is not required (Dziadak et al., 2009)	
✓Facilitates maintenance and evaluation tasks (Cheng et al., 2007)	

3. RFID + Vision Systems

During the lifecycle of a facility, several recognition or maintenance operations are carried out in different scenarios with different degree of difficulty. In these cases, vision systems can be really useful. However, if the sensed objects are not well visualized, for example because of the light conditions or occlusion reasons, some object recognition tasks could become very complex. In such cases, vision sensors together with RFID technologies could make easier and more effective the object recognition process (see Table 2).

Cameras have been used for reality capture purposes for the last two centuries. The continuous development of these devices together with recent image processing algorithms have facilitated the use of cameras for control and surveillance tasks.

In the field of construction, amounts of components, such as workers, materials and tools, enter all the time to the job sites, but also an important quantity of residual soils need to be removed from this area. In general, these soils have to be deposed in special sites for reuse or recycling. In the paper by Huang and Tsai (2011), a couple of RFID readers equipped with cameras are installed at the disposal sites and RFID tags are adhered to the windscreen of the trucks in order to control the correct movement of the waste material.

In the previously mentioned reference, RFID and image information are processed separately. However, Fumio et al. (2008) show how the photography of a tracked component can be combined with RFID information in order to create graphics files with embedded RFID data. Thus, the system stores the authentic picture of each component.

More recently, the use of cameras for the generation of 3D models by means of photogrammetric techniques or the accurate 3D point clouds delivered by laser scanning devices have revolutionized the recording and the surveying of buildings. The combination of these vision systems with other technologies, such as RFID, improve greatly the 3D models and make richer the Building Information Modeling (BIM) increasingly used for the organization and management of construction sites, as presented in (Valero et al., 2015).

Photogrammetry and laser scanning technologies are used together with an RFID system in (El-Omari and Moselhi, 2011). RFID controls the quantities and location of labor force, materials and tools. Aiming to register the progress of a construction project, a scheduling and budget control model is generated. The laser scanner is used to create a 3D representation of the site.

A complete representation of the site under construction has also been carried out by means of laser scanners and photogrammetry in (Kiziltas et al., 2008). In this manner, possible defects in constructive components can be detected. The 3D models generated from the scanner are used to update the information stored in the plans and compare the as-planned and as-built models (Rebolj et al., 2008). To visualize the construction progress in real time, other authors (Wang et al., 2013) propose the integration of BIM models and augmented reality. They suggest the use of an RFID system to track different components.

Regarding buildings in their operation and commission stage, Valero et al.

(2015) use 3D laser sensors and RFID in inhabited scenarios to obtain a simple 3D model of the scene. The combination of RFID and computer vision technologies greatly facilitates the generation of semantic 3D models of the inhabited interior. In this case, different objects form part of the scenario. Authors are able to segment and recognize structural components of the building (walls, ceiling, floor ...) and pieces of furniture. Finally, the system generates a simplified 3D semantic model of the interior.

Table 2: RFID + Computer Vision systems.

Technology	**Applications**	**References**
RGB / Mono Camera	Residual soil control	(Huang and Tsai, 2011) (Fumio et al., 2008)
Video / Augmented Reality	Visualization in real time	(Wang et al., 2013)
Photogrammetry	Monitoring of materials and tools in construction	(El-Omari and Moselhi, 2011)
3D Range Sensors	Defects in construction	(Kiziltas et al., 2008) (Rebolj et al., 2008)
	BIM	(Valero et al., 2015)

4. RFID + Positioning Systems

At the turn of the millennium, RFID hardware and software were developed with the goal of estimating the position of humans and objects inside buildings. These RFID-based technologies have been developed and improved over the years with the aim of providing more accurate location values. Table 3 shows a summary of methods and applications related with positioning and RFID in the last years.

Early solutions are based on the analysis of the Received Signal Strength Indication (RSSI) in certain control points which cover an area of interest (Hightower et al., 2000)(Bahl and Padmanabhan, 2000). Thus, the tag readers, which receive the signal, can triangulate and calculate the position of users wearing tags. The range of these systems is a few tens of meters.

Aiming to improve the accuracy of the existing systems and to avoid the addition of more tag readers, the LANDMARC solution (Ni et al., 2003) proposes the installation of active tags organized in a grid array to locate a set of objects inside a facility. Over the years, several works have improved this 2D location system. Thus, the fusion of LANDMARC with general

Table 3: RFID + Positioning systems.

Technology	Applications	Environment	References
RFID Tag Readers	Human localization	Rooms, indoors	(Hightower et al., 2000)
		Indoors	(Bahl and Padmanabhan, 2000)
	Creation of tag maps with robots	Indoors	(Hahnel et al., 2004)
	Tracking of moving object	Indoors	(Milella et al., 2008)
Grid of Active RFID Tags	2D location of multiple objects	Indoors	(Ni et al., 2003)
		Indoors	(Yihua et al., 2008)
		Indoors	(De Amorim Silva and Da S. Goncalves, 2009)
	3D object localization	Indoors, outdoors	(Khan and Antiwal, 2009)
Programmable Beacon RFID Nodes	Localization of mobile objects	Indoors	(Lorincz and Welsh, 2007)
RFID + GPS / GIS	Material localization in GIS	Outdoors	(Caldas et al., 2004)
	Positioning of materials in industrial and construction processes	Outdoors	(Bulusu et al., 2000)
		-	(Doherty et al., 2001)
		Workshops, warehouses, outdoors	(Song et al., 2006)
		Outdoors	(Cai et al., 2014)
		Outdoors	(Soleimanifar et al., 2013)
	Location of moving objects in construction	Outdoors	(Liu et al., 2013)
RFID + Total Stations	3D building models generation	Buildings	(Sakamoto et al., 2012)
RFID + Ultrasonic Devices	Positioning system	Outdoors	(Skibniewski and Jang, 2007)
RFID + Laser Scanning	Mapping with robots	Indoors	(Valero et al., 2015)

Bayesian-based algorithms provides a new well-performed method (Yihua et al., 2008). De Amorim Silva and Da S. Goncalves (2009) improve the LANDMARC algorithm by means of another algorithm which provides a second estimation of the area in which an object could be located. Finally, Khan and Antiwal (2009) extend the earlier LANDMARC proposals in order to evaluate 3D positioning problems.

Note that all previous systems are centralized. This means that, to calculate the position of the user, they require a central server and also a power supply. Aiming to decentralize the process and avoid this dependence, a set of beacon nodes can be installed. These programming wireless devices replicate a signature linked to the RSSI and calculate the location of moving objects (Lorincz and Welsh, 2007).

Information about location or even pose of wireless sensors in a construction site can be really helpful in practice. This information facilitates the identification of materials located in the scene and estimate their position into it (Umetani et al., 2003)(Yagi et al., 2005). Nevertheless, aiming to obtain more accurate location measurements, RFID technology should be combined with other devices.

In the last years several strategies have been addressed to this objective (Caron et al., 2007). One of these approaches consists in integrating a GPS system with a Geographic Information System (GIS). A user manually looks for the tagged objects and records their coordinates (Caldas et al., 2004). Other techniques aim to estimate the position of materials in the jobsite by the proximity of an object with respect to other known locations (Doherty et al., 2001) or a set of reference points (Bulusu et al., 2000)(Song et al., 2006). However, GPS solutions present some limitations in certain environments, especially when it comes to interior of buildings. In order to avoid the limitations of RFID and GPS-based systems, the combination of ultrasound technologies and RFID can improve the positioning system (Skibniewski and Jang, 2007).

One of the more recent publications in this area is that of Liu et al. (2013), in which a combination of technologies RFID, GPS, PDA and GPRS is presented. Authors monitor watering operations during the construction of earth-rock dams. Trucks are equipped with RFID tags which provide the position of the vehicles. Other authors (Soleimanifar et al., 2013) propose an innovative system, consisting of an RFID reader and a GPS receiver onboard a vehicle. This system is able to identify and calculate the position of different tagged elements in a large construction site. Cai et al. (2014) introduce the boundary condition and the trilateration concept as a constraint and integrate GPS with RFID devices aiming to look for tagged objects in a real 3D scenario. This method improves the accuracy of outdoor RFID localization.

On the other hand, Sakamoto et al. (2012) present the combination of a total station and an RFID system. This proposal includes a 3D model of the building which facilitates the positioning of precast components in a facility under refurbishment.

One of the above-mentioned applications is the localization of humans and objects in inhabited interiors as well as the generation of a map of the environment. In the last years, many researchers have worked on solving Indoor Location Sensing (ILS) problems with the help of radio-frequency identification technologies. Some of those techniques and their results have previously been evaluated and compared in (Li and Becerik-Gerber, 2011) and (Manapure et al., 2004).

In certain occasions, the element whose position is calculated corresponds to a mobile robot. Recently, autonomous mobile robots are being introduced in construction, as shown in (Bock and Kreupl, 2004). In general, autonomous robots are used to carry materials from one place to another, so they need to know its position in the scene. Placing different tags in an inhabited environment and equipping the robot with an RFID antenna, the relative position of the mobile device can be calculated. Besides, if the robot is equipped with a laser scanner, a 2D/3D mapping process can be carried out. A recent publication in this research line is the one of Valero et al. (2015). This paper presents a Terrestrial Laser Scanning (TLS) data-processing pipeline aimed at producing semantic 3D models of furnished office and home interiors. The structure of rooms (floor, ceiling, and walls with window and door openings) is created using Boundary Representation (B-Rep) models. For the furniture, the approach integrates the RFID technology. The tags are attached to furniture and are sensed at the same time as laser scanning is conducted.

Finally, it is worth mentioning the proposals by Hahnel et al. (2004) and Joho et al. (2009). In the first one, the authors present an approach that generates a RFID tags map with mobile robots. This map is afterwards used to localize robots and persons in the environment. Once the map is generated, the robot can execute different tasks in the scene, like inspection and surveillance, acting as an autonomous security agent (Milella et al., 2008). In the second one, a novel sensor model is used to localize RFID tags and track a mobile agent in an RFID-equipped environment.

5. RFID + Microcomputers

Users are on many occasions required to interact with RFID systems. Therefore, they can be equipped with some sort of device to communicate with RFID targets located at large distances. In most of the cases, wireless devices, such as Personal Digital Assistants (PDAs), are used. The combination of these two different technologies is used over the lifecycle of a building.

Before starting the construction process, particularly during the fabrication of precast concrete components, RFID and PDAs technologies are successfully combined (Wang, 2008). The workers control the inspection tasks at the test labs and generate a portable data collection. Once the elements are manufactured, also their management is controlled. Thus, the information related to the inventory or the transport process can be sent and shared with the managers office or the works site (Yin et al., 2009).

Once the building is inhabited, there exist a variety of components which need maintenance tasks. These elements can be part of the structure of the building or equipment. The installation of RFID tags in these components allows the workers to update the information related to elements which need to be repaired or verified in the building. Therefore, a scheduling process can be developed in order to organize different maintenance tasks (Cong et al., 2011) (Ko, 2009).

Another aspect to take into account is that, in the last years, the construction of new buildings is decreasing in favor of the rehabilitation of inhabited facilities. Therefore, there exist buildings whose components can be reused or changeable. These are called Open Buildings (Kendall and Teicher, 2000). Cheng et al. (2007) propose the use of RFID and PDA systems to deal with the management of structural components in Open Buildings. This tool helps architects and engineers to reanalyze and redesign the buildings components.

RFID technologies are also useful to control and prevent disasters in buildings. In (Shiau et al., 2007), a PDA sends essential information of the scenario where a fire breaks out. This can save a precious time in rescue operations.

6. RFID and Software Integration

The increasingly use of specific software in the field of construction, and more especially computer-aided design (CAD) software, has made easier and more understandable the representation of reality. As is shown in Figure 1, during the last decades, the traditional blueprints have been replaced by more visual and colourful representations. These new 3D drawings include information about the evolution of works during the building process, resulting in 4D models (3D over time). Recently, more complex models (such as BIM) have revolutionized the building operations, delivering not only 3D models but also other information related to the very constructive process and the elements taking part in it (materials, human resources ...). In the following paragraphs, the contribution of RFID systems to the mentioned evolution is analyzed.

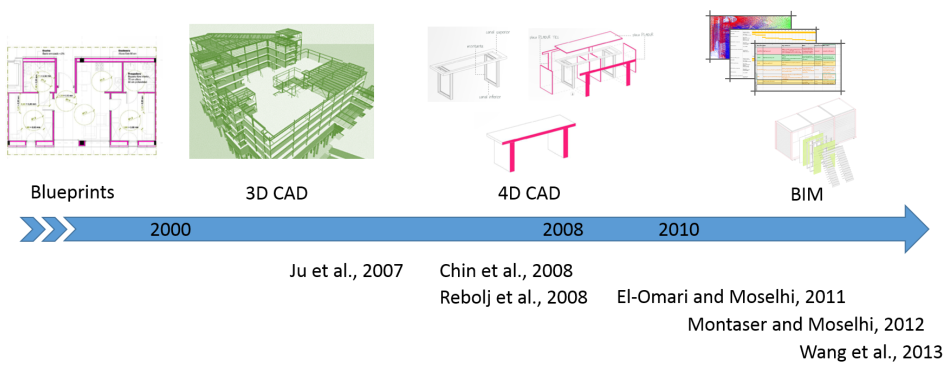

Figure 1: Evolution of representation of reality in construction.

In general, RFID barely stores a few data in tags. This information goes from some bytes up to several hundreds of KB for the most sophisticated devices. Aiming to use efficiently this information, software tools and particular developments are currently being integrated with the RFID systems. In this section, some examples of RFID and software integration are presented.

Usually, RFID information is extended with other kind of information to manage the construction sites in real time. A clear example of this idea is the creation of databases in which RFID data and CAD information are combined to create a real time monitoring system. One of the earliest integrated systems can be found in (Ju et al., 2007). In this work, information related to materials, which is stored into RFID tags, is added to 3D CAD models.

Well known software such as AutoCAD, Microstation and PHIDIAS, are also used to update the information and plans of the work (El-Omari and

Moselhi, 2011). The status of materials in the job sites by means of RFID technology is used in software that shows 4D CAD models of buildings under construction. Thus, both as-planned and as-built models can be compared. Chin et al. (08) propose this integrated model, developing an information system called RFID+4D PMS in which the progress of structural steel works is evaluated. In (Rebolj et al., 2008), several technologies are combined in order to generate 4D models of buildings under construction and detect project failures during the execution of the activities.

An RFID system can also deliver the position of the supervisor who, at the same time, is able to read and send information concerning materials or to make remarks about the constructive activity in the scenario. Users can even send pictures of the scene. The whole information is then inserted in a CAD model (Montaser and Moselhi, 2012). More recently, other authors (Wang et al., 2013) propose the integration of BIM models and Augmented Reality. In this case, RFID is used to visualize the construction progress in real-time and track different components.

Quality requirements in construction projects are important aspects consider. Note that detection of material defects or failures in construction is an essential issue because it entails an important economic impact. It is known that between the 5 and 10% of construction cost is due to the reconstruction of defective components, which are mostly detected during the constructive processes (Josephson and Hammarlund, 1999). Most of defects are related to human factors; among others things, the inefficient supervision of the constructive process. A solution to this problem has been proposed by Boukamp and Akinci (2007). The method consists in comparing different structural components from a 3D model of the planned building with as-built data provided by laser scanners and embedded sensors. These technologies are combined with scheduling and modeling software to register the acquired data, recognize constructive objects and finally, detect deviations and defects in these components (Akinci et al., 2006).

7. Conclusions

This article presents an extended review focused on the combination of RFID with other technologies in the field of construction. As is mentioned in Section 1, this review aims to improve previous reviews in different aspects. First, we explore the possibilities as well the limitations of RFID in construction. Second, we study the use of integrated RFID systems in processes which are carried out during the whole lifecycle of a building. And finally, we update the previous compilations of works, adding those in which RFID is integrated with other technologies.

After reviewing the state of art of radio-frequency identification in construction, we conclude that there exist several limitations and gaps which bring contractors to choose other available technologies. This point has been discussed in Section 2.

The combination of RFID with different technologies provides a powerful tool in the field of construction. The acquisition and management of diverse kinds of information by means of small, user-friendly and even wearable devices offer an interesting opportunity to continue making use of RFID in construction.

There is no doubt that RFID together with the technologies exposed in this paper, and others, can offer new solutions and requirements in the field of construction. Some of the future research lines are as follows.

- *Wireless devices.* One of the stronger and current research lines concerns the integration of RFID with personal digital assistants and other wireless devices (lets say microcomputers). Owing to the rising market and the lowering of prices of these gadgets, it is expected that such integrated systems will be inserted on a large scale in the construction field in the future.

- *Building renovation.* The recent impact of the housing bubble in some countries has led constructors to focus their activity on the recovery and maintenance of old buildings. As mentioned, the goal is to evaluate and maintain old buildings and to control certain properties linked to critical constructive elements, like beams or piping systems. Looking ahead, it is needed to take into account the concept of Open Buildings introduced in (Kendall and Teicher, 2000). This architecture philosophy proposes the usage of reusable and changeable building elements for enhancing the flexibility of buildings and reducing the resources consumption in the maintenance phase. This idea of renovating buildings instead of constructing new ones is more and more considered nowadays (Sakamoto et al., 2012). Here the integration of vision systems and chemical sensors might be interesting.

- *Building Information Models (BIM).* The addition of physical and functional parameters to the 3D models of facilities has substantially has improved the progressive evaluation of buildings, from its conception to its operation and maintenance. Recently, the RFID technology has been used to construct more precise and complete BIM models. Especially, it has been used for positioning tasks, such as the real-time location and tracking of users in BIM models (Guo et al., 2014) and (Costin et al., 2014).

- *Safety.* Another determining factor to be improved in construction is safety. Although there exist some works related with the assistance in fires, for example that of Shiau et al. (2007), this problem is not sufficiently tackled yet. It is important to remark here that infrared cameras together with RFID tags could quickly identify the origin and focus of the fire in a building.

- *Prevention.* An important aspect to be taken into account in the future is the control of delicate and out of sight constructive components. As is known, many elements in a facility are buried or embedded in walls. Think about pipes or electric circuits. These elements need to be periodically controlled by maintenance workers. Therefore, RFID tags could also be installed in these components so that the operator can easily do their work. A periodic revision could prevent and avoid great part of accidents what nowadays occurs in our buildings.

Ackonwledgements

This work was supported by the Spanish Economy and Competitiveness Ministry [DPI2013-43344-R project] and by Castilla-La Mancha Government [PEII-2014-017-P project].

References

Akinci, B., Boukamp, F., Gordon, C., Huber, D., Lyons, C., Park, K., 2006. A formalism for utilization of sensor systems and integrated project models for active construction quality control. Automation in Construction 15 (2), 124 – 138.

Bahl, P., Padmanabhan, V., 2000. Radar: an in-building rf-based user location and tracking system. In: INFOCOM 2000. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE. Vol. 2. pp. 775 –784 vol.2.

Bock, T., Kreupl, K., 2004. Procedure for the implementation of autonomous mobile robots on the construction site. In: Proceedings of the 21rd International Symposium on Automation and Robotics in Construction.

Boukamp, F., Akinci, B., 2007. Automated processing of construction specifications to support inspection and quality control. Automation in Construction 17 (1), 90 – 106.

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

Cai, H., Andoh, A. R., Su, X., Li, S., 2014. A boundary condition based algorithm for locating construction site objects using {RFID} and {GPS}. Advanced Engineering Informatics 28 (4), 455 – 468.
URL `ht`

Caldas, C., Haas, C., Torrent, D., Wood, C., Porter, R., 2004. Field trials of gps technology for locating fabricated pipe in laydown yards. Tech. rep., FIATECH, Austin, Texas.

Calis, G., Deora, S., Li, N., Becerik-Gerber, B., Krishnamachari, B., 2011. Assessment of wsn and rfid technologies for real-time occupancy information. In: Proceedings of the 28th International Symposium on Automation and Robotics in Construction. ISARC 2011.

Caron, F., Razavi, S., Song, J., Vanheeghe, P., Duflos, E., Caldas, C., Haas, C., 2007. Locating sensor nodes on construction projects. Autonomous Robots 22, 255–263, 10.1007/s10514-006-9720-1.

Cheng, M., Lien, L., Tsai, M., Chen, W., 2007. Open-building maintenance management using rfid technology. In: Proceedings of the 24th International Symposium on Automation and Robotics in Construction (ISARC 2007).

Chin, S., Yoon, S., Choi, C., Cho, C., 08. Rfid+4d cad for progress management of structural steel works in high-rise buildings. Journal of Computing in Civil Engineering 22:2.

Cong, Z., Mo, K., Menzel, K., 2011. Development of a rfid-based building maintenance system for facility management. In: Forum Bauinformatik 2011.

Costin, A., Pradhananga, N., Teizer, J., 2014. Passive rfid and bim for real-time visualization and location tracking. In: Proceedings of Construction Research Congress 2014. pp. 169–178.

De Amorim Silva, R., Da S. Goncalves, P., april 2009. Enhancing the efficiency of active rfid-based indoor location systems. In: Wireless Communications and Networking Conference, 2009. WCNC 2009. IEEE. pp. 1 –6.

Doherty, L., pister, K., El Ghaoui, L., 2001. Convex position estimation in wireless sensor networks. In: INFOCOM 2001. Twentieth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE. Vol. 3. pp. 1655 –1663 vol.3.

Domdouzis, K., Kumar, B., Anumba, C., 2007. Radio-frequency identification (rfid) applications: A brief introduction. Advanced Engineering Informatics 21 (4), 350 – 355.

Dziadak, K., Kumar, B., Sommerville, J., 2009. Model for the 3d location of buried assets based on rfid technology. Journal of Computing in Civil Engineering 23.

El-Omari, S., Moselhi, O., 2011. Integrating automated data acquisition technologies for progress reporting of construction projects. Automation in Construction 15:3, 292–302.

Erabuild, 2006. Review of the current state of radio frequency identification (rfid) technology, its use and potential future use in construction. Tech. rep., NAES, Tekes, formas and DTI.

Ergen, E., Akinci, B., sept. 2007. An overview of approaches for utilizing rfid in construction industry. In: RFID Eurasia, 2007 1st Annual. pp. 1 –5.

Fumio, H., Yasushi, Y., Shinichi, E., 2008. Development of digital photo system using rfid technology in plant construction management. In: Proceedings of the 25th International Symposium on Automation and Robotics in Construction (ISARC 2008).

Goodrum, P. M., McLaren, M. A., Durfee, A., 2006. The application of active radio frequency identification technology for tool tracking on construction job sites. Automation in Construction 15 (3), 292 – 302.

Guo, H., Liu, W., Zhang, W., Skitmor, M., 2014. A bim-rfid unsafe on-site behavior warning system. In: Proceedings of ICCREM 2014. pp. 330–339.

Hahnel, D., Burgard, W., Fox, D., Fishkin, K., Philipose, M., 2004. Mapping and localization with rfid technology. In: Robotics and Automation, 2004. Proceedings. ICRA '04. 2004 IEEE International Conference on. Vol. 1. pp. 1015–1020 Vol.1.

Hightower, J., Borriello, G., Want, R., February 2000. Spoton: An indoor 3d location sensing technology based on rf signal strength. Tech. rep., University of Washington.

Huang, R.-Y., Tsai, T.-Y., 2011. Development of an rfid system for tracking construction residual soil in taiwan. In: Proceedings of the 28th International Symposium on Automation and Robotics in Construction. ISARC 2011.

Jaselskis, E. J., Anderson, M. R., Jahren, C. T., Rodriguez, Y., Njos, S., 1995. Radio-frequency identification applications in construction industry. Journal of Construction Engineering and Management 121:2.

Jaselskis, E. J., El-Misalami, T., 2003. Implementing radio frequency identification in the construction process. Journal of Construction Engineering and Management 129.

Joho, D., Plagemann, C., Burgard, W., 2009. Modeling rfid signal strength and tag detection for localization and mapping. In: In Proc. IEEE Int. Conf. on Robotics and Automation (ICRA. pp. 3160–3165.

Josephson, P. E., Hammarlund, Y., 1999. The causes and costs of defects in construction a study of seven building projects. Automation in Construction 8 (6), 681–687.

Ju, H. T., Son, C. S., Kim, K. H., Kim, K. H., Kim, J. J., oct. 2007. A study on development of real time monitoring system for field integrated management - overall automation of steel construction -. In: International

Conference on Control, Automation and Systems, 2007. ICCAS '07. pp. 1937 –1941.

Kendall, S., Teicher, J., 2000. Residential Open Building. E & FB Spon, London and New York.

Khan, M., Antiwal, V., march 2009. Location estimation technique using extended 3-d landmarc algorithm for passive rfid tag. In: Advance Computing Conference, 2009. IACC 2009. IEEE International. pp. 249 –253.

Kiziltas, S., Akinci, B., Ergen, E., Tang, P., 2008. Technological assessment and process implications of field data capture technologies for construction and facility/infrastructure management. ITcon 13, Special Issue: Sensors in Construction and Infrastructure Management, 134–154.

Ko, C.-H., 2009. Rfid-based building maintenance system. Automation in Construction 18 (3), 275 – 284.
URL http://ww

Li, N., Becerik-Gerber, B., Aug. 2011. Performance-based evaluation of rfid-based indoor location sensing solutions for the built environment. Adv. Eng. Inform. 25 (3), 535–546.

Liu, D., Cui, B., Liu, Y., Zhong, D., 2013. Automatic control and real-time monitoring system for earthrock dam material truck watering. Automation in Construction 30 (0), 70 – 80.

Lorincz, K., Welsh, M., Aug. 2007. Motetrack: a robust, decentralized approach to rf-based location tracking. Personal Ubiquitous Comput. 11 (6), 489–503.

Lu, W., Huang, G. Q., Li, H., 2011. Scenarios for applying rfid technology in construction project management. Automation in Construction 20, 101–106.

Manapure, S., Darabi, H., Patel, V., Banerjee, P., 2004. A comparative study of radio frequency-based indoor location sensing systems. In: 2004 IEEE International Conference on Networking, Sensing and Control. Vol. 2. pp. 1265 – 1270.

Milella, A., Cicirelli, G., Distante, A., 2008. Rfid-assisted mobile robot system for mapping and surveillance of indoor environments. Industrial Robot: An International Journal 35, 143–152.

Mo, L., Zhang, H., 2007. Rfid antenna near the surface of metal. In: Proceedings of IEEE 2007 International Symposium on Microwave, Antenna, Propagation, and EMC Technologies For Wireless Communications.

Montaser, A., Moselhi, O., August 2012. Rfid indoor location identification for construction projects. In: Proceedings of the 29th International Symposium on Automation and Robotics in Construction, ISARC 2012. Eindhoven.

Ni, L., Liu, Y., Lau, Y. C., Patil, A., march 2003. Landmarc: indoor location sensing using active rfid. In: Pervasive Computing and Communications, 2003. (PerCom 2003). Proceedings of the First IEEE International Conference on. pp. 407 – 415.

Rebolj, D., Babič, N. u., Magdič, A., Podbreznik, P., Pšunder, M., Oct. 2008. Automated construction activity monitoring system. Adv. Eng. Inform. 22 (4), 493–503.

Sakamoto, S., Kano, N., Igarashi, T., Tomita, H., August 2012. Laser positioning system using rfid-tags. In: Proceedings of the 29th International Symposium on Automation and Robotics in Construction, ISARC 2012. Eindhoven.

Shen, X., Chen, W., Lu, M., 2008. Wireless sensor networks for resources tracking at building construction sites. Tsinghua Science & Technology 13, Supplement 1 (0), 78 – 83.

Shiau, Y., Tsai, J., Cheng, S., 2007. Fire control in buildings and the development of rfid applications systems. In: Proceedings of the 24th International Symposium on Automation and Robotics in Construction (ISARC 2007).

Skibniewski, M. J., Jang, W.-S., 2007. Localization technique for automated tracking of construction materials utilizing combined rf and ultrasound sensor interfaces. In: Proceedings of Proceeding of the 2007 ASCE International Workshop on Computing in Civil Engineering.

Soleimanifar, M., Beard, D., Sissons, P., Lu, M., Carnduff, M., 2013. The autonomous real-time system for ubiquitous construction resource tracking. In: Proceedings of the 30th International Symposium on Automation and Robotics in Construction.

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

Su, X., Li, S., Yuan, C., Cai, H., Kamat, V., 2014. Enhanced boundary conditionbased approach for construction location sensing using rfid and rtk gps. Journal of Construction Engineering and Management 140 (10), 04014048.

Tzeng, C.-T., Chiang, Y.-C., Chiang, C.-M., Lai, C.-M., 2008. Combination of radio frequency identification (rfid) and field verification tests of interior decorating materials. Automation in Construction 18 (1), 16 – 23.

Umetani, T., Mae, Y., Inoue, K., Arai, T., Yagi, J., 2003. Automated handling of construction components based on parts and packets unification. In: Proceedings of the 20th International Symposium on Automation and Robotics in Construction (ISARC 2003).

Valero, E., Adán, A., Bosché, F., 2015. Semantic 3d reconstruction of furnished interiors using laser scanning and rfid technology. Journal of Computing in Civil Engineering, 04015053.

Wang, L.-C., 2008. Enhancing construction quality inspection and management using rfid technology. Automation in Construction 17 (4), 467 – 479. URL `http://www.sciencedirect.com/science/article/pii/S0926580507001057`

Wang, X., Love, P. E., Kim, M. J., Park, C.-S., Sing, C.-P., Hou, L., 2013. A conceptual framework for integrating building information modeling with augmented reality. Automation in Construction 34 (0), 37 – 44.

Wu, W., Yang, H., Li, Q., Chew, D., 2013. An integrated information management model for proactive prevention of struck-by-falling-object accidents on construction sites. Automation in Construction 34 (0), 67 – 74.

Yagi, J., Arai, E., Arai, T., 2005. Parts and packets unification radio frequency identification (rfid) application for construction. Automation in Construction 14 (4), 477 – 490.

Yihua, H., Zongyuan, L., Guojun, L., dec. 2008. An improved bayesian-based rfid indoor location algorithm. In: Computer Science and Software Engineering, 2008 International Conference on. Vol. 3. pp. 511 –514.

Yin, S. Y., Tserng, H. P., Wang, J., Tsai, S., 2009. Developing a precast production management system using rfid technology. Automation in Construction 18 (5), 677 – 691.