JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT
2009
15(4): 325–336

DESIGN AND FIRST DEVELOPMENT OF AN AUTOMATED REAL-TIME SAFETY MANAGEMENT SYSTEM FOR CONSTRUCTION SITES

Alberto Giretti[1], Alessandro Carbonari[2], Berardo Naticchia[3], Mario De Grassi[4]

Dept of Architecture, Construction and Structures, Faculty of Engineering, Università Politecnica delle Marche, via Brecce Bianche, 60131 Ancona, Italy
E-mails: [1]a.giretti@univpm.it; [2]alessandro.carbonari@univpm.it; [3]b.naticchia@univpm.it; [4]m.degrassi@univpm.it

Received 09 Dec 2008; accepted 24 June 2009

Abstract. This paper reports a feasibility study which addressed the development of a new, advanced system mainly devoted to automatic real-time health and safety management on construction sites. The preliminary analyses and experiments described in this paper concern two of the most important functionalities which must be included in the system's final release. The first functionality consists in real-time position-tracking of workers involved on construction sites and the second – in a software tool for the prevention of non-authorized access to dangerous zones. This research step is part of a vaster, ongoing research project, addressing the development of a new generation of advanced construction management systems which allow real-time monitoring and coordination of tasks, automatic health and safety management, on-site delivery of technical information and the capture of "as-built" documentation. This paper focuses mainly on the development of a reliable methodology for real-time monitoring of the position of both workers and equipment in outdoor construction sites by applying Ultra Wide Band (UWB) based technologies. This positioning system was then interfaced with a software tool which performs virtual fencing of pre-selected, dangerous areas. Guidelines for the design of the receivers' topology will be addressed and the results of measurements recorded on a typical medium-sized block of flats, during different phases of the construction progress will be summed up. Finally, the preliminary experimental results obtained by the virtual fencing application tool will be presented and used to plan future research objectives.

Keywords: construction sites, health and safety management, real-time risk management, ultra wide band, position tracking, behavioural models.

1. Introduction

Building construction facilities are often nomadic and custom designed. Worker teams are engaged through local labour supply and workflow is frequently affected by weather conditions and the availability of local labour. Furthermore, building projects are very complex, involving thousands of parts and components; changes to design plans during the construction phase are not uncommon. Building parts and components are mostly made or assembled on site, standardization is rather low, often making adjustments during the construction phase, without any report of the adjustment on the original building plans. Consequently, the management of construction sites is complex and fatal accidents are not uncommon (Lee *et al.* 2009).

Moreover, considering that the coordinator for health and safety matters at the construction level cannot always preside ongoing construction activities, it can be inferred that the practical application of the prescriptions required by the Health and Safety Plan (according to European Council Directive 92/57/EEC) are left up to the workers. In addition, even the coordinator's continuous presence on the construction sites would not be sufficient in preventing accidents occurring on vast sites, as the coordinator is, in any case, incapable of performing ubiquitous control. This situation often leads to scarce application of health and safety requirements which could be the cause of dramatic accidents (Behzadan *et al.* 2008).

Presently, a set of new technologies could provide the necessary background for developing a new generation of real-time construction management systems, which can be seamlessly integrated into the actual arrangement of construction related activities (Abderrahim *et al.* 2005; Naticchia *et al.* 2005). They would automatically perform a number of strategic tasks, in fact supporting the work of those who are responsible for health and safety management. The idea underlying this approach is to track, in real time, the position of all the workers, equipping them with wearing tags, so small that they do not interfere with ongoing activities; this would provide the condition for continuously checking the workers' behaviour and for preventing possible dangerous situations. The system could then be enhanced towards further functionalities, such as the optimization of resource efficiency (Lee *et al.* 2006).

Given the aforementioned long-term purpose, this paper addresses the design and development of a proactive advanced system, fully described in paragraph 3 and composed mainly of 2 parts: the first performs real-

ISSN 1392–3730 print / ISSN 1822–3605 online
DOI: 10.3846/1392-3730.2009.15.325-336

time position tracking, while the second provides real-time prediction of risky events. If these occur or are about to occur, then the system will send one or more alerts to the operators involved or to the people responsible for the sites safety management.

The system conceived in this paper is aimed at supporting primarily the job performed by the health and safety coordinator. It could, for a number of specific tasks, also act as an alert system for these workers present on the site, who are requested to wear a special tag, capable of sending acoustical, vibrational or light-flashing warnings to their bearers, when dangerous situations are involved.

Position tracking is performed through the use of UWB (Ultra Wide Band) technology, shown to be capable of providing the required accuracy for path monitoring of humans and equipment within the site and also the core functionality of the entire system under development. Then, given the overall good results obtained by our experimental tests on position tracking, a first software tool for virtual fencing of dangerous areas was developed and tested, showing how the prevention of non-authorized access to dangerous areas can be achieved, a necessity also noted in previous literature (Teizer *et al.* 2007).

Such a system, in its final release, would support the semi-automatic management of real-time health and safety monitoring and the coordination of tasks, on-demand distribution of information (e.g. shop drawings), and the collection of "as built" documents.

Section 2 will propose an insight focusing on a number of excerpts, obtained from the vast amount of state of the art documents presently available, where the ones which are more focused on our type of research have been reported. The system under development within our research is briefly described in section 3, and then further detailed in sections 4 and 5: the first concerning the localization tests performed; the second regarding a preliminary software tool release, presently under further development, aimed at studying the feasibility of an algorithm for the automated virtual fencing of dangerous areas on construction sites.

2. State of the art

Despite the development and reliable application in manufacturing (Fuller *et al.* 2002; Brewer *et al.* 1999) of mobile computing for production management, it is almost completely lacking on construction sites. This is due to its outdoor, heterogeneous and highly evolving nature. Some preliminary results have been obtained on construction sites through the application of standard, outdoor position tracking technologies. Researchers have developed a mechatronic helmet, equipped with a GPS antenna and a bidirectional communication system for workers' safety control (Abderrahim *et al.* 2005).

Early research invested a great deal of effort in explaining the main advantages pursued with the adoption of mobile computing (Rebolj *et al.* 2001). The most important ones devoted to the field of construction management are: supply and delivery of records and progress updates directly at the jobsite; rapid communication and collaboration throughout the entire project life cycle, from financing and planning through to engineering and design, procurement, construction, and facility management; systems that provide construction teams with a project-specific extranet, whereby remote team members can communicate and access up-to-date documents. Mobile computing was shown capable of eliminating redundancy in project task operations, reducing response waiting time, limiting revision of job tasks, enabling fast access to construction standards.

Following such statements, the first applications and efforts have started giving back a number of practical, preliminary results. GPS positioning systems were tested to perform another management task: identifying and cross-referencing the construction entities visible in a user's field of view with shop drawings residing in construction databases (Khoury & Kamat 2007). They concluded positively in terms of feasibility, but realized the need for a more accurate position technology, different from GPS for indoor use.

There is a number of contributions, which accept position tracking technologies as a valuable means for construction management for many subtasks: an integrated RFID and GPS technology for the purpose of tracking highly customized prefabricated components and avoiding delays in construction (Ergen *et al.* 2007); embedding RFID tags in building components to store design data, which can be passed to the people in charge of maintenance during its operational phase (Cheng *et al.* 2007); controlling construction progress performance and material management through continuous monitoring (Gajamani & Varghese 2007; Song *et al.* 2007); efficiency improvement of tool tracking and availability increase by using RFID tags (Goodrum *et al.* 2006).

Another field of application is represented by the "FutureHome" EU funded project, which was developed for product and process analysis suited to manufactured and prefabricated construction solutions (EU Funded Project 2002). Other interesting applications are relative to a policy for integrating "as-built" information into IFC devices used in PDM systems (Akinci, Boukamp 2002).

Similar technologies and approaches to perform automated health and safety management on construction sites were adopted in this paper. This branch of research is not completely unexplored, even if more difficulties arise when tested, probably due to the suddenness tied to the manifestation of risky events and the more important critical quality that such applications entail.

Positioning systems were interfaced with software tools implementing practical functionalities. A policy for collision detection among construction equipments was tested: a board device (made up of a differential GPS receiver, a laptop and a radio used to transmit positions) communicated its position to a central server, which, in turn, received cautionary messages when necessary (Oloufa *et al.* 2002). The collision detection algorithm works by calculating the intersection point of the 2 vectors representing 2 moving vehicles, each vector is defined by a point and a direction. Notwithstanding the rather good results obtained in the preliminary experiments, localization accuracy and communication issues were considered, in any case, the 2 most critical issues to be improved. Hence, the works which assert the high accuracy achievable by the adoption of UWB technologies can constitute a valid alternative to those already tested (Purushothaman & Abraham 2007). In fact, Ultra Wide Band has been successfully tested as a means for real-time monitoring of construction site activities, highlighting its potential for both management and safety issues related to the complex environments of construction sites (Teizer *et al.* 2007): fieldwork tracking in an iron made construction showed a position accuracy significantly better than 1 m. This suggests that the technology can be very suitable for safety management, where precise localization is critical for avoiding workers' accessing hazardous zones, for performing collision avoidance, for preventing falls from height and a number of other accidents. Similar statements were also reported by the authors of a Project called "SightSafety", whose main aim was to exploit recent advances in ICT in order to develop innovative and proactive systems for automated collision detection avoidance; part of a more ambitious project regarding health and safety management on constructions sites (Riaz *et al.* 2006). In particular, the work focused on reducing accidents caused by vehicle/pedestrian collisions using advanced ICT solutions. The two tier software system developed by the authors is very interesting, the business logic was designed to recognize whether dangerous situations take place. Also stated is the fact that the greater the position accuracy, the better the system performs its tasks. This highlights the importance of using highly accurate location systems such as UWB, which could be quite valuable in performing health and safety management as well. The system's good performance is demonstrated by the vast interest it has attracted in a number of fields, such as homeland security (e.g. personnel ID, intrusion detection), automotive radar for collision and obstacle avoidance (Gresham 2004).

Efforts have already been made using UWB, in order to more effectively track and analyze the paths of construction resources; to increase productivity and safety overall in an automated way, e.g. signaling hazardous zones to workers (Teizer *et al.* 2008). It is also suggested for recording historical paths, in order to identify the safer ones according to the frequency with which workers use them and to signal when workers choose unsafe paths. This approach is very similar to the ones proposed in other fields of research, where algorithms for behavioural models are developed: they are used to forecast workers' behaviour, in order to perform risk avoidance in advance as compared to the moment when risky situations occur (Howden *et al.* 2003). Thus, alert messages may be sent before dangerous events come in play. Finally, recent research ascertains that further problems relative to sensor locating in very dense construction sites must be addressed (Caron *et al.* 2007). They are critical in order to insure proper communication among sensor nodes responsible for resource tracking, whose efficiency strongly depends on application domain specifications (e.g. geometry, environment, required accuracy etc.).

Our paper initially addresses the issues of UWB applications for the accurate tracking of workers on construction sites, built using typical south European technologies. Such experimental tests will prove to be very useful in providing guidelines for system setup. Subsequently, a first software application for fencing dangerous areas on construction sites is proposed, in order to partially address the feasibility of an overall software tool for automated real-time health and safety monitoring; besides, providing a demonstration application eventually useful for demonstrating the strong capabilities of UWB for construction sites.

3. The system

3.1. Software architecture

Fig. 1 shows the scheme of a 3-tier software architecture for real-time construction management. The lowest level implements the sensor, localization, communication and data management logics. The middle level "business logics" implements high level task oriented functionalities (e.g. when and how managing virtual fencing or collision avoidance tools, included in the lowest level, transferring those data to the high level application modules, according to the requests made by users).

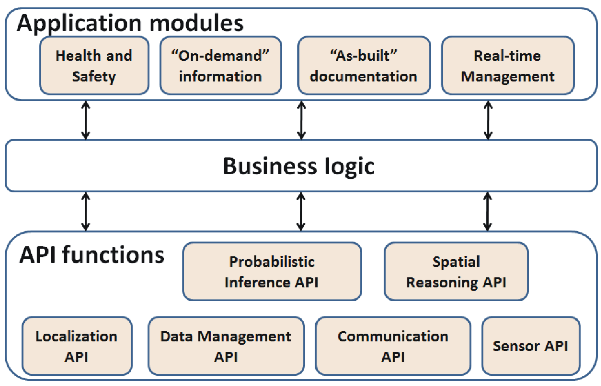


Fig. 1. Software architecture for real-time construction management

The application layer (highest level) customizes general business logic functionalities to specific application domain, such as health and safety management. In this paper, we will focus first on the development of the position tracking module, which is part of the localization API. Then, a preliminary user graphic interface for the visualization of the tracked tags will be developed.

Finally, the virtual fencing tool will be developed as part of the spatial reasoning API. It will be not limited to the identification of dangerous areas for people at work, but will also be devoted to foretelling when one or more workers are approaching dangerous areas, with the final aim of preventing their access. As later described, the algorithm underlying this tool is developed on the behavioural model theory, whose implementation can be carried out thanks to the high localization accuracy offered by UWB. We believe that further improvements of such a system, thanks to the collection of experimental data, will be possible in the tool future releases.

3.2. Ultra Wide-Band position tracking

Although recently exploited for practical wireless communication or accurate positioning, Ultra Wide Band's (UWB) origin stems from work in the early 1960s on time-domain electromagnetic (Bennett & Ross 1978). Early applications belong to the military field and, only at the end of the last century, the first commercial applications started to spread. Among the number of advantageous features offered by UWB (Fontana 2004), there is a number of very interesting ones, in terms of the applications we propose in this contribution:

- high localization accuracy (for both 2D and 3D), thanks to the reliability of the TDOA (time difference of arrival) algorithm implemented (Fontana *et al.* 2003);
- increased immunity to multipath cancellation, thanks to the use of very short UWB pulses, capable of discriminating between direct and time-orthogonal reflected waves;
- extremely low duty cycles, which translates into low average prime power requirements, ideal for battery-operated equipment;
- high peak-to-average power ratios, due to the short pulse system.

All the features listed are certainly advantageous for any application on construction sites. Let's consider, for instance, that standard systems always suffer for scattering (hence multipaths), when reinforced concrete is present; UWB instead is quite immune to this. Low power consumption allows tags to work autonomously for years, without recharging needs. Localization accuracy (better than 0.3 m) is really necessary for real-time health and safety management (e.g. workers tracking, collision avoidance etc.). Finally, thanks to the rather high peak powers, allowed for UWB by regulation, it can operate indoor over significantly longer ranges than other high rate communication systems (Fontana *et al.* 2003).

In its general form, a UWB system consists of a set of active tags (one of which is used as a calibration and called "reference tag"), UWB receivers and one or more central processing hubs. The hub interfaces with an external computer for user display and application software via Ethernet. UWB tags operate at a middle frequency of approximately 6.3 GHz and has an instantaneous – 10 dB bandwidth of 1.25 GHz. The system operates as follows: a set of 3 or more receivers are positioned at known coordinates about the periphery of the area to be monitored. Short-pulse RF emissions from tags are subsequently received by either all, or a subset, of these sensors and processed by the central hub's CPU. A typical tag emission consists of a short burst, included a set of data for ID purposes, repeated at a given frequency (limited between 1 and 60 Hz). Time differences of arrival (TDOA) of the tag burst at the various receives are measured and sent back to the central processing hub. Calibration (i.e. signal speed measuring) is performed at system start up by monitoring data from a reference tag, which has been placed at the known location. Every receiver obtains its power from the central processing hub via standard CAT-5 cables, which are also used to carry data back to the hub for subsequent processing. It's very interesting that there are no interferences at all between Wi-Fi wireless networks and ultra wide band signal transmission.

The UWB localization system tested in this paper consists of a set of active tags (0.3 W and 1 W powered tags), four UWB "mid-gain" type receivers and one central processing hub, manufactured by Multispectral™ Inc. In the used configuration, the tags work at 1 Hz, in order to exploit their lifespan as long as possible.

The main problem occurring in asset tracking system installation is that, in order to accurately determine tag position, a minimum number of receivers (three for 2-D measures, as in this case) must have a direct or attenuated line-of-sight transmission path. Hence, as walls and machinery may create signal attenuation or even complete signal blockage, receivers positioning must be previously and strategically designed. This problem can be solved using an "over-specified" or "over-determined" system, but trying to avoid ambiguities in position determination. This objective could be pursued by assigning different areas to different sets of receivers. However, accurate knowledge of UWB performances are needed for a correct application. This problem is particularly true for construction sites, hence our first tests in paragraph 4 are aimed at providing empirical guidelines for arranging UWB systems on typical sites at different stages of construction activities progress.

3.3. Predictive approach to risk

It is generally stated that, when coping with risky situations, it is necessary to adopt a predictive approach (Wang *et al.* 2004). An intelligent approach is always called for in order to check for risky events before they occur and to timely relay warning signals to workers, in order to prevent possible consequences, and a context aware system should be deployed over all the entire construction site (Oloufa *et al.* 2002). The system must also offer features specifically supporting the coordinator for health and safety matters, who will receive warning, when something on the site is not managed in a safe manner. The type of warning message and precaution adopted, will be evaluated according to the situation.

In addition, the high polling frequency of UWB technology (from 1 to 60 Hz) should be exploited to process real-time data and properly manage those situations by providing alerting signals in real-time. We think that 2 basic intelligent approaches are available for managing these situations, whose classification is valid also in the particular case of virtual fencing of dangerous areas considered for the purpose of this paper:

1. a deterministic approach, which predicts dangerous situations by checking the actual route followed by workers;

2. a probabilistic approach, which could be based on probabilistic models (e.g. Bayesian networks), to perform knowledge capture first and inference processing later, in order to first predict the route that every monitored worker is going to follow and then whether this path is expected to lead towards risky situations (Howden *et al.* 2003).

In this paper, we chose to analyze the first approach, even if the second approach will be studied later, within the next research step. Hence, in paragraph 5 we propose a first predictive software tool for managing risk in real-time. The laboratory test results are then later described.

4. The experimental campaign

Three tests were carried out to check the UWB localization system features on construction sites. The objective of the first one was simulating, how it performs when tracking equipment involved in excavation works. Hence, an open field area with no obstacles was chosen for simulating such a situation. The second and third tests were both set on the same construction site, but at two different stages of its progress: after the completion of the building's concrete frame and after the walls' erection. Such a wide set of experiments is deemed to be adequate for inferring, how the UWB system works during several construction stages, representative of the vast part of the entire process.

4.1. The construction site

The experimental tests were carried out on a site relative to a 5 storey block of flats (Fig. 2), built on a plan site with a reinforced concrete frame structure and light masonry walls. The entire building is surrounded by metallic scaffolding of the same height, equipped with protection against falls. The building interior can be accessed from the front, very close to the area where the site crane is located.

Fig. 2. Two main progress stages of the construction site

External hollow walls include 0.05 m polystyrene insulation (please refer to Fig. 3a), they have an external wall layer made of solid bricks and another internal one of cellular 0.08 m thick blocks.

Partitioning walls between apartments were made of 0.12 m thick concrete cellular blocks (Fig. 3b) and walls between rooms of the same apartments made of 0.08 m thick cellular blocks (Fig. 3c). A reinforced concrete block supporting the staircase and lift was built at the middle-back end of the building.

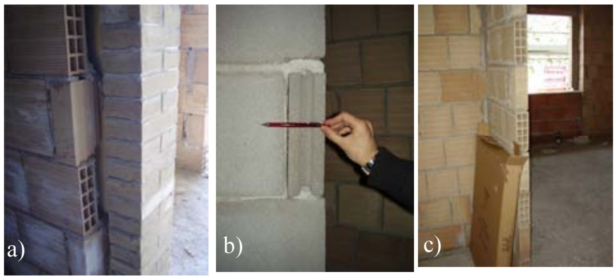


Fig. 3. External walls (a), concrete blocks (b), internal partitions (c)

4.2. First phase of the experimental campaign

The first test case concerns position tracking of workers and facilities (excavator, bulldozer etc.) moving within the excavation area. Hence, this phase was simulated making measurements in the parking area shown in Fig. 4a, where the receivers were placed at the 4 corners, according to the rhomboidal shaped scheme (Fig. 4b), where the maximum height and length measured (12.5×16.6) m.

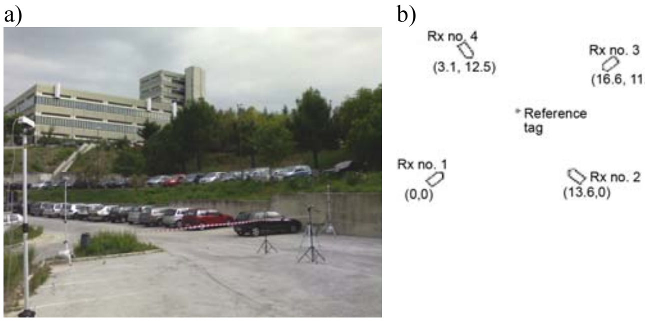


Fig. 4. Simulation of the excavation stage

Assuming that receiver no. 1 corresponds to the origin point (0,0) m, one reference node was placed at the (7.9, 6.3) m coordinates. Workers positions were monitored with an accuracy never lower than 0.3 m; the same held for facilities in the case tags were fixed to the ceilings. The only case, when accuracy is lower, is when tags are placed inside the facilities cabins: in this case, the accuracy decreases to about 1 m, because the system gives localization measures alternatively which are within the ray of 1 m from the exact known location of the machine: this is probably due to the scattering that UWB rays undergo before exiting the facility. Both 0.3 *W* and 1 *W* powered tags worked well in this case. Hence no problems were assumed to be found for tracking during excavation works; when there are no obstacles interfering with signal transmission. The same holds true for all tasks performed before the building erection and at the ground level.

4.3. Second phase of the experimental campaign

The second phase of the experiments was performed on the construction site, as shown in Fig. 2a (soon after the erection of the structure concrete frame). Fig. 5 shows the hub, PC and receivers positioning at the centre of the building, while Fig. 6 depicts a scheme of the experimental setup used for these tests: 4 receivers were placed at the corners of the site (at a height of 4 m) and one reference tag in the ground floor (whose position was taken as the point with (0,0) m coordinates).

a) b)

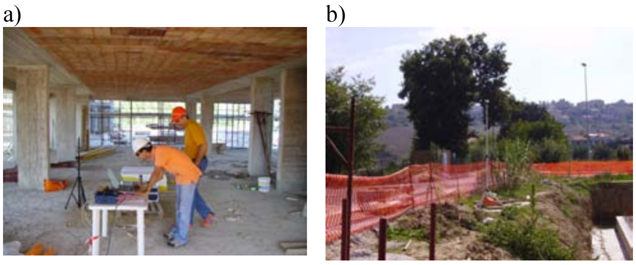


Fig. 5. Positioning of the hub and reference tag (a) and of one of the 4 receivers (b)

It should be noted that a metallic scaffold had already been installed along the building perimeter. The measurements of the entire area was approximately 38×35 m. Fig. 7 shows some of the successful measures, obtained using the 1 W power tag (as the 0.3 *W* was subject to blinking). A worker moving in the area was tracked.

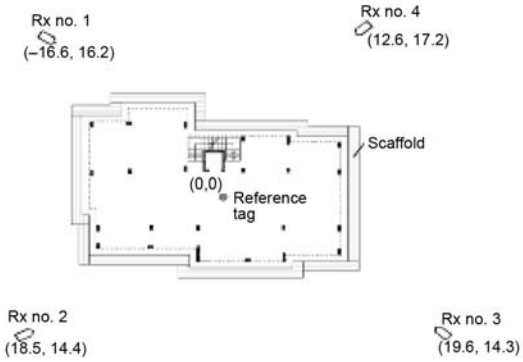


Fig. 6. Testing setup at the "concrete frame" stage

By comparing the worker's actual routes with the ones tracked by the system, it was found that the UWB system was capable of tracking the workers' position both on the building ground floor and when moving along the front scaffold. Other 2-D measures were made on the first floor and it resulted that the receivers were able to track the workers, as well. The same did not hold true for the second floor. From the analysis of Fig. 7, it can be derived that our UWB tracking system worked correctly also when the employee is standing in rather hidden locations, i.e. close to the reinforced concrete block housing the main staircase and near the site's boundaries. Some blinking was noticed around the staircase block only in very few cases: this suggested that more receivers should have been added for proper and continuous monitoring around that area.

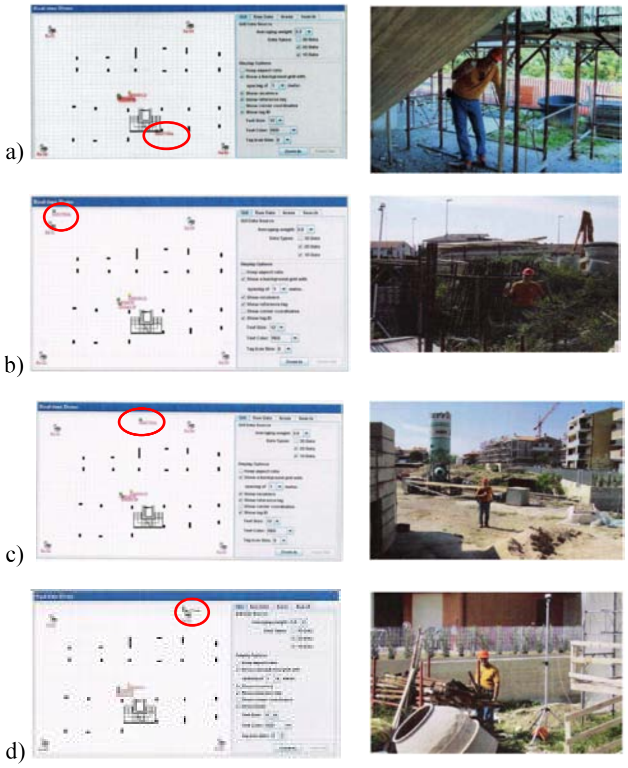


Fig. 7. Comparison between measured and actual positions of a worker's movements throughout the construction site

4.4. Third phase of the experimental campaign

The last set of experiments were performed with the building in its third progress phase: after the completion of the wall and with the scaffolding presence along its perimeter (Fig. 2b).

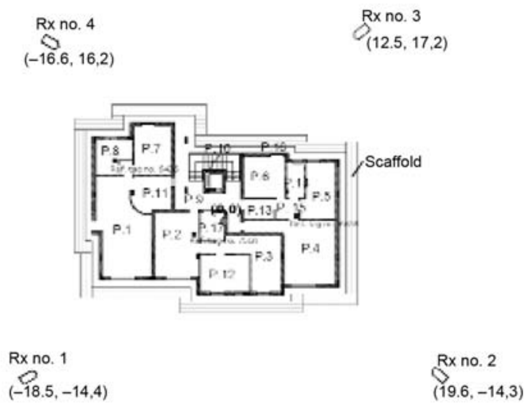


Fig. 8. Site layout at the "wall completion" stage

These tests were performed with the receivers located in two different ways: first, according to a sparse location (receivers located at a rather high distance from one another, like in Fig. 8), then according to an intensive lay out (the receivers were placed closer to one another, as in Fig. 10).

In the first case, it was noticed that the system setup (Fig. 8) did not allow real-time tracking of workers' positions, as one or more receivers did not receive the 1 W tag signals from a number of locations inside the building, hence indicating that the walls hindered the signals. The same figure depicts all the positions where power field tests were performed, in order to understand the main causes of possible, scarce, quality monitoring.

Table 1 lists, per each position (P) of Fig. 8, which of the receivers could communicate with moving tags and whether or not that position was correctly tracked. The last column reports an indicator value, referring to the type of errors detected.

Table 1. Position tracking results in the 3rd phase

Position	Receivers	Result	Errors
1	1,4	bad	M0
2	1	–	–
3	1,2	–	–
4	1,2,3	good	Ref750A (rare)
5	2,3,4	bad	M0
6	2,3,4	bad	M0, R0
7	1,3,4	blinking	M0
8	1,3,4	discrete	M0 (rare)
9	1,3,4	discrete	M0 (rare)
10	1,3,4	good	No
11	1,3,4	good	No
12	1,2	bad	M0
13	2,3	bad	M0
14	3,4	bad	M0
15	2,3	bad	M0
16	1,3,4	discrete	M0
17	1,3,4	bad	M0

All the results derived from Table 1 are summarized in Fig. 9, where green areas represent a good signal (at least 3 receivers perceived signals with at least discrete quality). They are the only areas where tracking could be performed, insufficient, in any case for the control of the entire building.

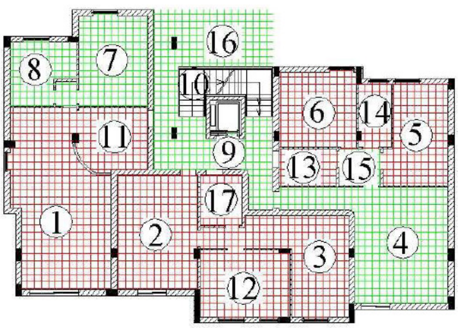


Fig. 9. Mapping of the signal quality (green stands for good and red stands for bad)

The second set of tests required the system setup to be deployed such as illustrated in Fig. 10, where a smaller area was covered by the same number of receivers. The results are listed in Table 2. It can be noticed that, with the exception of position no.1 (which contrasts with Table 1,

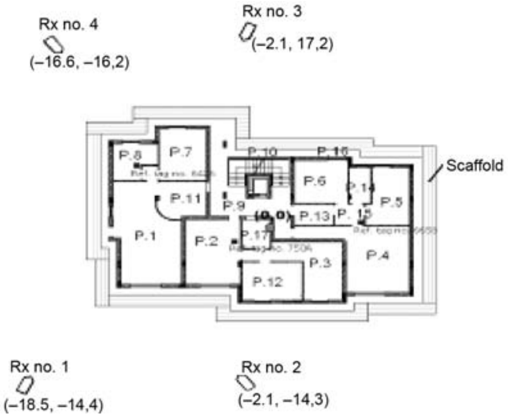
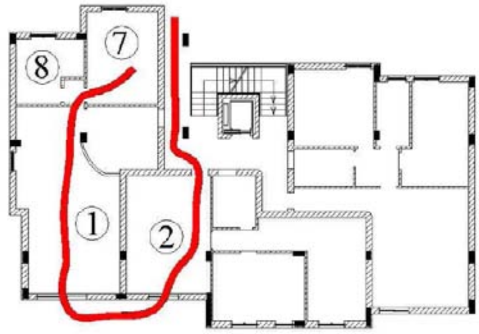


Fig. 10. System setup in the "intensive" configuration

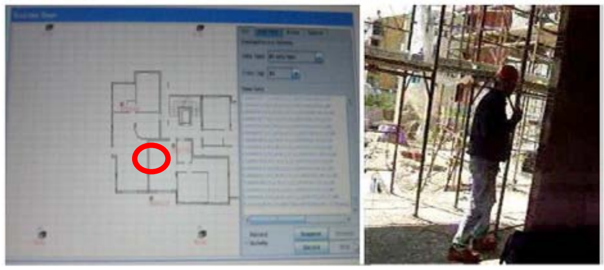
Table 2. Position tracking for the 2nd system setup

Position	Receivers	Tracking	Tracking
1	1,2	bad	M0
2	1,2,3	Discrete	M0 (rare)
7	1,3,4	Discrete	M0 (frequent)
8	1,3,4	Discrete	M0 (frequent)
11	1,3,4	Discrete	M0 (frequent)

a)



b)



c)

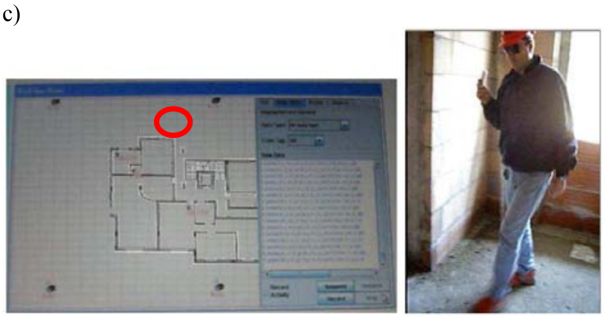


Fig. 11. Route for tracking (a) and 2 snapshots relative to that (b)

and is therefore not considered), the tag signal was always monitored by 3 receivers. Error M0 was often recorded meaning that the tag was not capable of pointing 3 receivers simultaneously.

Given that 3 receivers were always visible, we can infer that the frequency of the received signal could have been too low, due to obstacles. This problem can be tackled adding another receiver at the centre of the ground floor or in another convenient position.

In order to check whether the signal quality is sufficient for tracking people wondering about the building, the path shown in Fig. 11a was followed and Fig. 11b shows a number of snapshots of the walking worker. The results were that the tracking stopped once that he passed through room 1, where the signal quality proved to be very low, due to the low frequency of tags bursts which were received by fixed reference points.

4.5. Discussion on experimental results

By analyzing the experimental results described in the previous paragraphs, we can infer that UWB behaviour is rather constant during most part of the construction progress. In fact, the same system setup may be used from the start of the construction up until the erection of walls. At that stage, it becomes necessary to pass from a sparse (minimal) configuration towards a more intensive one (having a higher number of receivers per unit area).

In detail, during excavation works, tests confirmed an accuracy of about 0.3 m recorded for this kind of technology; also recorded by other authors (Fontana 2004). Determining the positioning of tags is necessary when facility tracking is required. These should be mounted outside the cabin, in order to provide the most accurate localization. A dramatic accuracy decrease must be taken into account (from 0.3 m to 1 m) if a tag is mounted inside a cabin. This effect is probably due to the reflection that UWB signals undergo before exiting the facility's cabin. Both the 0.3 *W* and the 1 *W* powered ones are suitable for this kind of monitoring.

As far as concerns the phase when the reinforced concrete frame structure was built, 4 receivers were sufficient for monitoring the workers' movements over the entire site on the ground floor (the entire roofed area is about 500 m^2) and while on the scaffolds. However, while the 1 W tag worked well, the other signal (0.3 W) was too weak. This was probably due to interference attributable to the scaffolding and to the reinforced concrete columns. A few errors in the localization (i.e. blinking) were noticed only in the areas close to the staircase and lift block, made up of reinforced concrete walls: in this case, we believe it is necessary to add more receivers in order to cover the area and thus avoid the blinking phenomena.

Table 1 and Fig. 9 are relative to the results recorded after the phase which saw the completion of the walls: we can infer that UWB behaviour changes dramatically after walls are built. It was noted that single layer walls made up of 0.08 m cellular blocks are quite transparent to UWB. On the other hand, both hollow walls with a double layer of blocks plus internal insulation, and concrete cellular blocks, sensibly weakened UWB signals. For example, signals traveled from position no. 9 to receiver no. 1, but they did not travel from position no. 6 to receiver no. 1: the signals were probably blocked by the hollow wall between positions no. 9 and 6. A similar statement holds true for the cellular concrete block wall between positions no. 11 and 2. When 3 receivers are in the line-of-sight, then localization works properly (e.g. in positions no. 4, 10, 11). On the other hand, if the received signal frequency is low (as in cases no. 5, 6, 16, 17), localization does not occur correctly even if 3 receivers are read. This occurs when the signal is weakened by the walls it passes through, hence it is likely that less than 3 receivers read the bursts simultaneously and thus the position cannot be computed. Therefore, in this case, the use of 4 receivers, chosen for the complexity of the environment, are not enough.

As a general statement concerning localization, we can conclude that UWB can pass through a maximum of 2 heavy walls but, in order to avoid the weakening of signals, a maximum of one heavy wall. On the other hand, UWB is transparent to thin and light walls, such as 0.08 m thick concrete cellular blocks. The sparse configuration of 4 receivers proved to be adequate for monitoring the site construction progress up until the stage involving the completion of the frame.

5. Automated safety management system

5.1. Predictive approach to risk management

As previously stated in paragraph 3, every health and safety real time management system needs a "Spatial Reasoning" API tool (referring to Fig. 1), charged with avoiding the occurrence of dangerous situations. This module is expected to very accurately exploit tracked data sent by an interfaced UWB localization system, and then apply the data in support of a number of functionalities.

Among the many functionalities offered by our Spatial Reasoning tool, we chose to develop an application for fencing dangerous areas, as it constitutes the basic tool to be used for discerning – even dynamically – whether or not different activities interact dangerously.

In particular, we adopted a "deterministic" approach to checking risks. This method should be interpreted as one which, initially evaluates the path followed by every worker (hence his behaviour), and then infers if the worker is going to face a hazardous situation. In this first stage, the system was tested in the laboratories of the DACS Department of the Università Politecnica delle Marche: a rectangular shaped area was drawn on the floor, simulating a dangerous and unaccessible area which could possibly be found on construction sites. The tests were useful for optimally setting all the parameters affecting such an application tool before its final testing in real workplaces.

5.2. Algorithm development

The main objective of the implemented algorithm is to check risks in advance, in order to alert operators at risk before harm can befall them. For this purpose, the first step is discerning and localizing hazardous areas. These can be areas where the presence of workers is not allowed (e.g. near unprotected scaffolding), and they can be selected directly from the site layout, during the design stage. The possibility that such areas are dynamically changing must also be considered: in case collision avoidance between 2 assets is performed, one object could be processed as the area not be entered, while the other as the operator moving about the construction site. Hence this first step is critical, as it is the basic tool for further applications. The main assumptions made for this first technologic development are that:

- the dangerous area is static and its location known beforehand;
- risks must be predicted before they occur.

The general approach followed in order to pursue this objective is surrounding every off limit area with a "warning" strip (in our drawings, the area is usually coloured in red, while the warning strip is yellow, as seen in the following Fig. 15). The width of the yellow strip must be sized according to tag frequency and to the average speed of the operators. This second parameter was assumed to be fixed at 0.5 m/s, while the first was sized through adequate testing (see paragraph 5.3).

In this manner, the algorithm is capable of checking the behaviour of operators who have already entered the yellow area to understand, if they are going to proceed approaching the red area or return, backing away from the areas defined as dangerous.

Fig. 12 better explains the logic of our algorithm. It first checks whether any operator has already entered the red dangerous area: if so a red alarm is sent, otherwise no alarms whatsoever. The algorithm then checks whether the operator has entered the yellow perimeter strip. If so, then his/her actual position is compared with the previous one (recorded in the previous time step) and a warning alarm is sent in the event that he/she has further approached the border line; if such is not the case, the entire procedure is repeated. It goes without say that tracking operators movements within the yellow strip is critical for this application. The most important parameters required in order to do so are: the width of the strip; tag frequency; speed calculation to check whether they are approaching or backing away from the border line.

5.3. Preliminary tests

Two experimental tests were carried out:

- the first to infer, how wide the yellow warning area should be;
- the second to validate the proposed algorithm and conclude about its reliability.

Both tests were performed in our laboratories. The first one was performed by positioning four UWB receivers, one (3.7×4) m large red area (Fig. 13a) and interfacing the UWB system hub with a software application tool (developed in Java^{TM} environment) implementing the algorithm in Fig. 12. Then one of our collaborators was equipped with a 1 Hz tag and was asked to repeatedly enter the red area following the 3 paths shown in Fig. 13a. Measures were repeated 8 times for each path and the results from these 24 measures were that the application tool is capable of sending warning signals (Fig. 14) within a maximum distance of 1.2 m beyond the border line, with an average distance gap of 0.7 m. Hence a warning strip slightly wider than 1.5 m should be planned when using 1 Hz tags. Fig. 14 shows one of the red alarm signals sent by the application software after a boy simulating a worker crossed beyond the boundary line.

In order to test the algorithm's reliability preliminarily, a 1.7 m thick warning strip around the red area (opportune for 1 Hz tags) was drawn on the laboratory floor (Fig. 15).

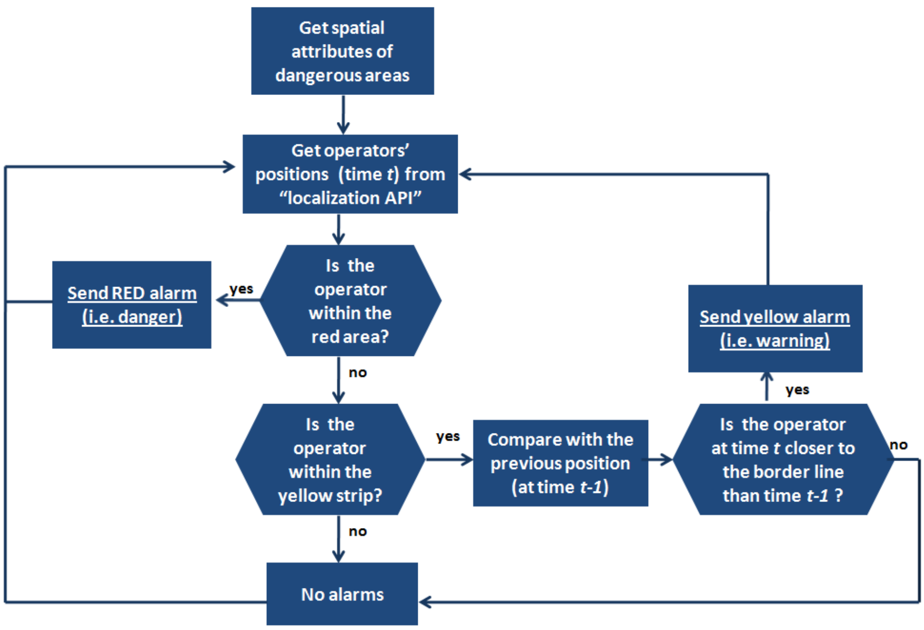


Fig. 12. The algorithm logic

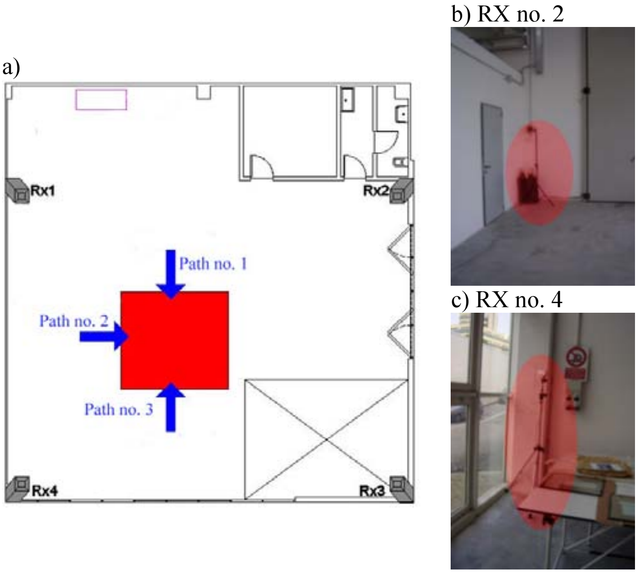


Fig. 13. Red area localization and track of the three paths used for the 1st experimental phase

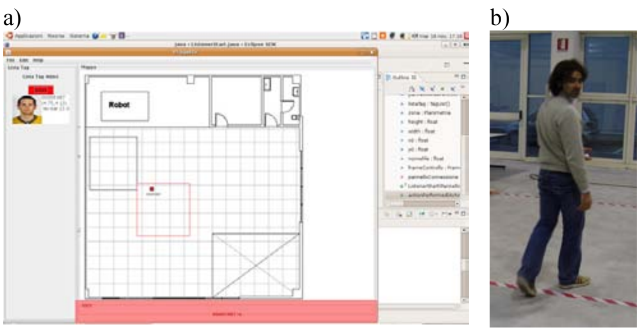


Fig. 14. One screenshot of the application sending a red alarm signal (red line at the bottom)

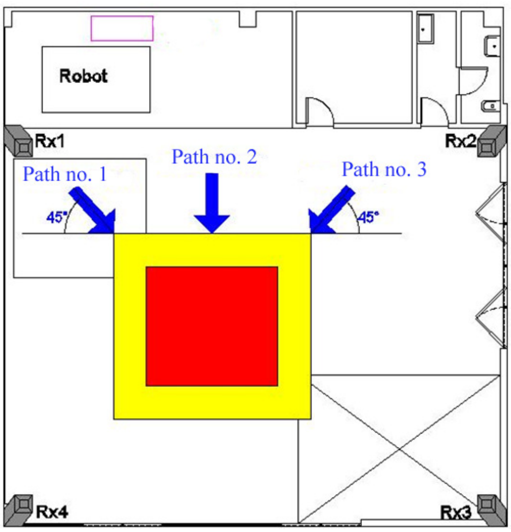


Fig. 15. Laboratory setup for testing algorithm reliability

Subsequently, the three paths depicted in Fig. 15 were traced by our collaborator and 10 measures were collected for each. Three types of possible errors for the system were discerned:

1. absence of alarms: the system does not send alarms, even if it should.
2. false red alarm: the system sends a red alarm even if the worker is within the warning strip;
3. false warning alarms: the system sends a warning even if the worker is not getting closer to the border line.

A different set of tests was performed for each path in Fig. 15. For path no. 1, no false alarms were recorded. For path no. 2 only one type 1 error was recorded (due to the low tag rate of 1 Hz, which did not allow monitoring the worker twice before accessing the red area). For path no. 3 three type 1 errors were recorded, which were then shown to be due to interfering objects very close to receiver no. 2. Fig. 16a shows the graphic interface sending a "yellow" warning alarm, attributed to a worker approaching the border line.

Instead, Fig. 16b shows the last test performed by having a collaborator walk parallel to the border line: every measure was affected by one or two type 3 errors due to the standard localization accuracy of UWB system, whose measures vary randomly around the real value within a 0.3 m distance. Hence, it was inferred that statistically filtering tracked measures so as to cancel random variation is always necessary.

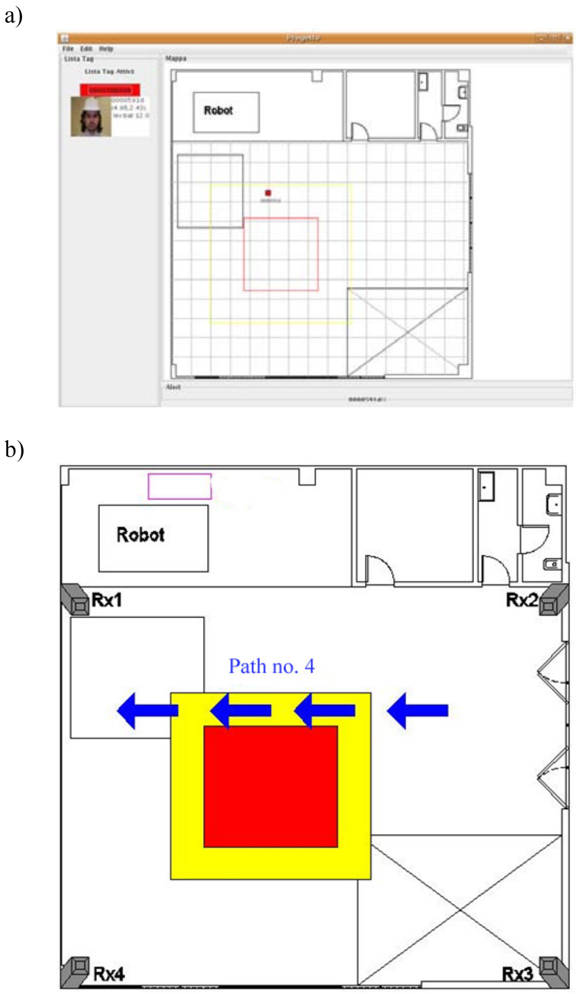


Fig. 16. One screenshot of the spatial reasoning API's virtual fencing tool for warning signals (a) and path no. 4 (b)

6. Conclusions

We can conclude that the UWB systems can be successfully applied for real-time management of constructions sites, if the installation is properly designed. The possibility for reliable tracking depends on the quality of tag signal reception at the receiver level, which was demonstrated unable to pass through more than 2 heavy walls. A minimal configuration of four UWB receivers for 2 levels of a typical 400 m^2 large block of flats will work properly until the erection stage of the construction progress. Subsequently, more receivers must be added, possibly even inside the building, whose interference with construction activities must be considered and solved. In the preliminary analyses carried out in this paper, the performances of a virtual fencing application were simulated as well. Tests performed in our laboratories showed that our deterministic algorithm is rather reliable for performing virtual fencing of dangerous areas, using a predictive approach. The few false alarms encountered can be nevertheless solved by adopting 2 amendments: filtering localization data, thus cancelling the random variation admitted by UWB system around the real position; using tags with higher frequency, which would allow reducing the warning strip width and increasing the algorithm reliability. Finally, other probabilistic techniques will be developed in order to strengthen the predictive capabilities of this application.

Acknowledgments

The authors wish to thank Lorenzo Parasecoli and the "Parasecoli Plinio & F." construction company for their technical and logistic support for testing on their construction sites.

References

Abderrahim, M.; Garcia, E.; Diez, R.; Balaguer, C. 2005. A mechatronics security system for the construction site, *Automation in Construction* 14(4): 460–466. doi:10.1016/j.autcon.2004.09.007

Akinci, B.; Boukamp, F. 2002. Representation and integration of as-built information to IFC based product and process models for automated assessment of as-built conditions, in *Proceedings of the 19th ISARC,* National Institute of Standards and Technology, Gaithersburg, Maryland. September 23–25, 2002, 543–549.

Behzadan, A. H.; Aziz, Z.; Anumba, C. J.; Kamat, V. R. 2008. Ubiquitous location tracking for context-specific information delivery on construction sites, *Automation in Construction* 17: 737–748. doi:10.1016/j.autcon.2008.02.002

Bennet, C. L.; Ross, G. F. 1978. Time-domain electromagnetics and its applications, *IEEE Proceedings* 66: 299–318. doi:10.1109/PROC.1978.10902

Brewer, A.; Sloan, N.; Landers, T. L. 1999. Intelligent tracking in manufacturing, *Journal of Intelligent Manufacturing* 10(3–4), September.

Caron, F.; Razavi, S. N.; Song, J.; Vanheege, P.; Duflos, E; Caldas, C.; Haas, C. 2007. Locating sensor nodes on construction projects, *Journal of Autonomous Robot* 22: 225–263.

Cheng, M. Y.; Lien, L. C.; Tsai, M. H.; Chen, W. N. 2007. Open-building maintenance management using RFID technology, in *Proceedings of the 24th International Symposium on Automation and Robotics in Construction – ISARC 2007*, September 19–21, 2007, Kochi, India.

Council Directive 92/57/EEC of 24 June 1992 on the "Implementation of minimum safety and health requirements at temporary or mobile construction sites" – 8th individual directive within the meaning of Article 16(1) of Directive 89/391/EEC, *Official Journal L 245*, 26/08/1992, 0006–0022.

Ergen, E.; Akinci, B.; Sacks, R. 2007. Tracking and locating components in a precast storage yard utilizing radio frequency identification technology and GPS, *Automation in Construction* 16(3): 354–367. doi:10.1016/j.autcon.2006.07.004

EU Funded Project 2002. FutureHome – Housing for Europe in the next century: Affordable, high quality homes for all, *5FP EU project under Brite-Euram program*, 1999–2002.

Fontana, R. J. 2004. Recent system applications of short-pulse ultra-wideband (UWB) technology, *IEEE Microwave Theory & Tech.* 52(9): 2087–2104.

Fontana, R. J.; Richley, E.; Barney, J. 2003. Commercialization of an ultra wideband precision asset location system, in *Proceedings of the IEEE Conference on Ultra Wideband Systems and Technologies,* November 2003, Reston, VA.

Fuller, S.; Ding, Z.; Sattineni, A. 2002. Case study: using the wearable computer in the construction industry, in *Proceedings of the 19th ISARC,* National Institute of Standards and Technology, Gaithersburg, Maryland. September 23–25, 2002, 551–556.

Gajamani, G. K.; Varghese, K. 2007. Automated project schedule and inventory monitoring using RFID, in *Proceedings of the 24th International Symposium on Automation and Robotics in Construction – ISARC 2007*, September 19–21, 2007, Kochi, India.

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. doi:10.1016/j.autcon.2005.06.004

Gresham, I. 2004. Ultrawide-band radar sensors for short-range vehicular applications, *IEEE Transactions of Microwave Theory and Techniques* 52(9): 2105–2122. doi:10.1109/TMTT.2004.834185

Howden, N.; Curmi, J.; Heinze, C.; Goss, S.; and Murphy, G. 2003. Operational knowledge representation: behaviour capture, modelling and verification, in *Proceedings of the Eighth International Conference on Simulation Technology and Training (SimTecT '03)*, Adelaide Australia, 2003.

Khoury, H. M.; Kamat, V. R. 2007. Automated georeferenced user position tracking for contextual information retrieval on construction sites, in *Proceedings of the 24th International Symposium on Automation and Robotics in Construction – ISARC 2007*, September 19–21, 2007, Kochi, India.

Lee, U.; Kim, J.; Cho, H.; Kang, K. 2009. Development of a mobile safety monitoring system for construction sites, *Automation in Construction* 18(3): 258–264. doi:10.1016/j.autcon.2008.08.002

Lee, S. H.; Peña-Mora, F.; Park, M. 2006. Dynamic planning and control methodology for strategic and operational construction project management, *Automation in Construction* 15(1): 84–97. doi:10.1016/j.autcon.2005.02.008

Naticchia, B.; Giretti, A.; Giretti, P. 2005. Systems for real time construction site management, in *Proceedings of the Joint 2006 CIB Symposium W065/W055/W086*, Rome, Italy, October 2006.

Oloufa, A. A.; Ikeda, M.; Oda, H. 2003. Situational awareness of construction equipment using GPS, wireless and web technologies, in *Proceedings of 19th ISARC*, National Institute of Standards and Technology, Gaithersburg, Maryland. September 23–25, 2002, 461–466.

Oloufa, A. A.; Ikeda, M.; Oda, H. 2002. GPS-Based wireless collision detection of construction equipment, *Automation in Construction* 12: 737–748. doi:10.1016/S0926-5805(03)00057-8

Purushothaman, S.; Abraham, P. K. 2007. Ultra Wide Band (UWB) based precise positioning system for robotics, in *Proceedings of the 24th International Symposium on Automation and Robotics in Construction – ISARC 2007*, September 19–21, 2007, Kochi, India.

Rebolj, D.; Magdič, A.; Čuš Babič, N. 2001. Mobile computing in construction. Advances in Concurrent Engineering, in *Proceedings of the 8th ISPE International Conference on Concurrent Engineering – Research and Applications*, West Coast Anaheim Hotel, California, USA, July 28 – August 1, 2001.

Riaz, Z.; Edwards, D. J.; Thorpe, A. 2006. SightSafety: a hybrid information and communication technology system for reducing vehicle/pedestrian collisions, *Automation in Construction* 15(6): 719–728. doi:10.1016/j.autcon.2005.09.004

Song, J. H.; Lee, N. S.; Yoon, S.; Kwon, S.; Chin, S.; Kim, Y. 2007. Material tracker for construction logistics, in *Proceedings of the 24th International Symposium on Automation and Robotics in Construction – ISARC 2007*, September 19–21, 2007, Kochi, India.

Teizer, J.; Lao, D.; Sofer, M. 2007. Rapid automated monitoring of construction site activities using Ultra-WideBand, in *Proceedings of the 24th International Symposium on Automation and Robotics in Construction – ISARC 2007*, September 19–21, 2007, Kochi, India.

Teizer, J.; Mantripragada, U.; Venugopal, M. 2008. Analyzing the travel patterns of construction workers, in *Proceedings of the 25th International Symposium on Automation and Robotics in Construction – ISARC 2008*, June 26–29, 2008, Vilnius, Lithuania.

Wang, A. P.; Chen, J. C.; Hsu, P. L. 2004. Intelligent CAN-based automotive collision avoidance warning system, in *Proceedings of the 2004 IEEE International Conference on Networking, Sensing & Control,* March 21–23 2004, Taipei, Taiwan.

AUTOMATIZUOTOS SAUGOS VALDYMO SISTEMOS STATYBOS AIKŠTELĖJE KŪRIMAS

A. Giretti, A. Carbonari, B. Naticchia, M. De Grassi

S a n t r a u k a

Straipsnyje aptartos naujos automatinės darbo ir saugos valdymo sistemos statybos aikštelėje kūrimo galimybės. Aprašytos preliminarios analizės ir eksperimentai – du pagrindiniai veiksniai, kurie turi būti įtraukti į galutinį sistemos variantą. Pirmasis veiksnys susijęs su statybos aikštelės darbininkų padėties realiu laiku nustatymu. Kompiuterine programa ribojamas jų patekimas į pavojingas neleistinas zonas. Šie tyrimai yra didelio besitęsiančio projekto dalis. Projektas susijęs su naujos kartos statybos valdymo sistemos kūrimu. Sistema leis kontroliuoti statybos eigą realiu laiku, užtikrinti automatinį darbų saugos valdymą, techninės informacijos ir dokumentacijos gavimą. Straipsnyje pagrindinis dėmesys sukoncentruotas į patikimos metodikos kūrimą. Taikant šią metodiką ir ultraplačiajuosčio bevielio ryšio (angl. *Ultra Wide Band* (UWB)) technologiją, galima bus nustatyti darbininkų ir įrangos padėtį atvirose statybos aikštelėse realiu laiku. Ši nustatymo sistema per grafinę terpę yra sujungta su programine įranga, kuri sukuria virtualų aptvarą iš anksto nurodytoms pavojingoms zonoms. Pateiktos imtuvo topologijos projektavimo rekomendacijos. Įvertinti tipinių vidutinio dydžio butų blokų užfiksuotų matavimų rezultatai skirtingais statybos etapais. Pateikti preliminarūs eksperimentiniai rezultatai, gauti įvedus virtualaus aptvėrimo koncepciją. Šie rezultatai bus panaudoti planuojant būsimų tyrimų tikslus.

Reikšminiai žodžiai: statybos aikštelės, darbų saugos valdymas, rizikos valdymas realiu laiku, ultraplačiajuostis bevielis ryšys, pozicijos nustatymas, elgsenos modeliai.

Alberto GIRETTI is assistant professor at the Department of Architecture Construction and Structures (DACS) of the Università Politecnica delle Marche – Engineering Faculty. He has an M.S. in electronic engineering and a PhD in Artificial Intelligent Systems. He has joined 15 national research projects and two European funded projects. His research interests include advanced techniques for building pathology diagnosis, advanced architectural design supporting tools, intelligent tutoring systems and automation in construction.

Alessandro CARBONARI is assistant professor at the Department of Architecture Construction and Structures (DACS) of the Università Politecnica delle Marche – Engineering Faculty. He has a PhD in Engineering for Sustainable Construction and he is official reviewer or editorial member of several international journals. He has enhanced his knowledge in the field of automation in construction, which is one of his main research interests, along with innovative technologies for sustainable construction, risk analysis models, project and construction management.

Berardo NATICCHIA is full professor at the Department of Architecture Construction and Structures (DACS) of the Università Politecnica delle Marche – Engineering Faculty. He has carried out research activities in several institutional programs, with particular concern in automation in construction. He has carried out activities relevant to Health & Safety Plan Certification and Safety Coordination of various important public works. He is expert of health and safety matters on construction sites and project management in construction.

Mario De GRASSI is full professor and Director of the Department of Architecture Construction and Structures (DACS) of the Università Politecnica delle Marche – Engineering Faculty. He has founded and directs the Building Technology Research laboratory, as well as the Artificial Intelligence in Design laboratory at the Polytechnic University of Marche. He has coordinated a number of national research projects and two European funded projects, in the fields of artificial intelligence tools for architectural design, intelligent tutorial systems and innovative energy saving building components for lightweight structures.