High-precision identification of contextual information in location-aware engineering applications

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A B S T R A C T
This paper presents research that investigated algorithms for high-precision identification of contextual information in location-aware engineering applications. The primary contribution of the presented work is the design and implementation of a dynamic user-viewpoint tracking scheme in which mobile users’ spatial context is defined not only by their position (i.e., location), but also by their three-dimensional head orientation (i.e., line of sight). This allows the identification of objects and artifacts visible in a mobile user’s field of view with much higher accuracy than was possible by tracking position alone. For outdoor applications, a georeferencing based algorithm has been developed using the Global Positioning System (GPS) and magnetic orientation tracking devices [5] to track a user’s dynamic viewpoint. For indoor applications, this study explored the applicability of wireless technologies, in particular Indoor GPS, for dynamic user position tracking in situations where GPS is unavailable. The objectives of this paper are to describe the details of the three-stage-algorithm that has been designed and implemented, and to demonstrate the extent to which positioning technologies such as GPS and Indoor GPS can be used together with high-precision orientation trackers to accurately interpret the fully-qualified spatial context of a mobile user in challenging environments such as those found on construction sites. The obtained results highlight the potential of using location-aware technologies for rapidly identifying and retrieving contextual information in engineering applications.

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1. Introduction

In an information-intensive industry such as construction, rapid and convenient access to project information is crucial in helping engineers, inspectors, and maintenance personnel make critical, real-time decisions. Field personnel typically spend a significant amount of time in manually accessing the information they need for important decision-making tasks. Such lost time amounts to lost productivity and thus money [4]. Conceptually, relevant information can be delivered to any decision maker in real-time by monitoring their physical and environmental context, and then reconciling the identified context parameters with the available pool of digital information.

Such context-aware computing is defined by Burrell and Gay [7] as the use of environmental characteristics such as a user’s location, time, identity, profile, and activity in order to provide information that is relevant to the current context. Context-aware computing can thus potentially enable mobile users (e.g., construction inspectors) to leverage knowledge about various context parameters such as their identity, current task, and location to ensure that they get highly specific information relevant to the decisions at hand [32].

The presented research introduces a dynamic user context-sensing framework that accurately tracks a mobile field user’s spatial context, and automatically retrieves prioritized project information of interest to that user, based on the sensed context. The developed framework consists of the following key components: (1) methods to accurately and continuously track a mobile user’s spatial parameters (i.e., position and orientation) in arbitrary environments; (2) algorithms to interpret a user’s fully-qualified spatial context based on the tracked spatial parameters; (3) algorithms to reconcile a user’s interpreted spatial context with the available pool of project information; and (4) methods to retrieve and interactively present the prioritized project information to the user.

The first framework component involves accurately tracking a user’s 3D position and orientation in any indoor and/or outdoor environment. The tracking scheme encompasses both outdoor positioning technologies and indoor wireless tracking techniques. For outdoor environments, a georeferencing based algorithm previously developed using the Global Positioning System (GPS) and magnetic orientation tracking devices [5] is used to continuously track a user’s dynamic viewpoint.

GPS is an attractive option because it does not rely on any pre-installed sensor infrastructure and instead depends on direct
satellite communication. However, GPS is unsuitable in situations where the user has a possibility of being indoors because the receivers need a clear line of sight to the satellites in order to track position. Therefore, for indoor environments, several wireless technologies such as Wireless Local Area Networks (WLAN) [10], Ultra-Wide Band (UWB) [26], Indoor GPS (iGPS) [25], and Radio Frequency Identification (RFID) [14] have been investigated and integrated within the designed framework as feasible indoor location tracking techniques [17].

This paper describes the algorithms in the second and third components of the developed framework, and demonstrates how a mobile user’s spatial context can be accurately interpreted with a level of precision that is sufficiently high to identify on-site contextual objects in location-aware engineering applications. Having identified contextual objects accurately, it is also shown how specific information of interest can then be retrieved and interactively presented to a mobile user. The designed algorithms have been validated by conducting several outdoor and indoor experiments, where a user was accurately tracked, followed by the interpretation of site object(s) in the user’s view, and retrieval and visualization of digital project information pertaining to the objects in context.

2. Related work

The relevance of context-awareness for mobile users has been demonstrated in many applications that have been summarized in Aziz et al. [4]. Prior applications of context-aware computing have included fieldwork [18,28], museums [12,19], route planning [24], libraries [1] and tourism [20].

Examples of other projects that have specifically focused on location based information delivery have included the GUIDE project [9] and the Mobile Shadow Project (MSP) [11]. In the MSP project, the authors used agents to map the physical context to the virtual context. In another project named Ambience [2], a different approach was used wherein the focus was on creating a digital environment that is aware of users’ presence, context, and sensitivity, and responds accordingly.

3. Research motivation

The inability to rapidly and conveniently access contextual information required for important decision-making tasks in the field has a significant negative impact during several phases in the life cycle of a constructed facility. From construction to inspection to maintenance, the incapacity of engineers, inspectors and other site personnel to quickly gain access to relevant information required to make critical decisions in real-time has considerable consequences in terms of safety and economy. For example, contractors and inspectors spend a significant amount of time manually searching for relevant project information as they go about making important decisions on-site on a day to day basis.

For all types of project information ranging from plans and shop drawings to specifications, schedules, installation guides, and change orders, rapid and convenient access to contextual data is critical. Time is valuable, and constructors’ and inspectors’ typically work with stacks of paperwork and unwieldy drawings on harsh and dynamic jobsites spending a significant amount of effort in identifying, accessing, and retrieving the information necessary for important decision-making tasks.

This repetitive, mundane, and seemingly innocuous activity consumes a significant amount of time, and thus money [4]. There is thus a clear and critical need for a new methodology that can allow high-precision identification and rapid, automated access to contextual information in a way that supports accurate, real-time decisions in construction, inspection and maintenance.

However, in all context-aware information delivery applications developed thus far (both indoor and outdoor), the spatial context is defined solely by the location (position) of the user. Another major attribute, the 3D head orientation, is ignored in the computations. A user’s three-dimensional head orientation fully describes the user’s line of sight (i.e., the direction in which the user is looking). Together with position, 3D orientation can define a user’s spatial context with much greater precision than is possible with position alone. For example, tracking only an engineer’s position on a construction site might help determine which floor of a building the engineer is located on [4].

However, this information is not sufficient to conclude which part or section of the room, or what particular component or object in that room the engineer is currently looking at or is interested in. While the position of the user is being tracked by a set of hardware devices and designed software implementation, head orientation data is an essential piece of information that also needs to be continuously monitored. Only by knowing both position and head orientation, a user’s fully-qualified spatial context can be interpreted.

A context-aware data delivery and information retrieval framework must retrieve and display graphical and textual data to the users based on their latest position, line of sight and the level of detail they request. As a result, tracking a user’s fully-qualified spatial context is a crucial task for applications designed to retrieve and deliver context-aware information with high-precision on a continuous basis. On-site accurate and effective information retrieval can be the key for higher productivity and faster service.

The primary contributions of the presented research are the algorithms that use a mobile user’s tracked spatial parameters (position and orientation) to accurately compute that user’s fully-qualified spatial context, and precisely identify the object(s) on-site that are of decision-making interest to that user at the particular time and location. The available digital information pertaining to the identified objects can then be retrieved and interactively presented to the user to realize a high-precision, context-aware information delivery framework.

4. Technical approach for high-precision context interpretation

In this research, the authors have developed a spatial context-aware methodology that focuses on automatically identifying and retrieving, with high-precision, contextual project information for on-site decision-making in field applications such as construction and inspection. Fig. 1 summarizes the mechanics of the proposed approach, using the case of building inspection for illustration. An inspector surveys a building for signs of visible damage following a disaster (e.g., earthquake). In this example, the inspector’s position and line of light are tracked using GPS and magnetic orientation trackers.

During the survey, based on the interpreted spatial context, relevant information about the building’s structural frame, construction details, and other information can be retrieved and presented. For example, as depicted in the lower left picture in Fig. 1, the building’s hidden structural frame can be superimposed on its façade to allow the study of critical connection locations that need detailed inspection. As the inspector approaches these connections, structural details on those connections can be automatically retrieved and displayed based on the interpreted and refined spatial context.

4.1. User spatial context tracking

Mobile computing has evolved over the last several years and has aimed at providing mobile users ubiquitous access to the right information at the right time. The position (i.e., location) of users is
an important component of mobile computing that can assist users with their desired goals, and make the workplace more intelligent. One of the most popular research areas in pervasive computing is the development of location-aware systems. Location-aware applications are systems in which computing devices provide the users with specific information depending on their location, and enable the design of applications that have the capability to identify a user’s location and modify their settings, interfaces, and functionality accordingly [29].

However, as noted above, in order to interpret a site engineer’s or inspector’s fully-qualified spatial context, another parameter in addition to the position is required. This parameter is the user’s three-dimensional head orientation, which is the direction in which the user is looking. It is defined by three angles named yaw, pitch, and roll that can be described using the same notation typically used to define the orientation of an aircraft in flight. As shown in Fig. 2, the yaw represents the rotation in the horizontal plane, pitch is the rotation in the vertical plane parallel to the forward direction, and roll is the rotation in the vertical plane perpendicular to the forward direction.

By capitalizing on the ability to accurately track mobile users (e.g., construction engineers, inspectors, etc.) in any indoor and/or outdoor environment, the presented research has designed and implemented a dynamic spatial context-sensing framework that can allow the accurate identification of construction entities and artifacts visible in a user’s field of view at any given time and location. In the framework’s first component, outdoor positioning techniques, together with wireless technologies and orientation tracking devices are integrated for tracking a user’s spatial context parameters.

For outdoor applications, positioning techniques have been investigated and validated in recent work reported in Behzadan and Kamat [5]. The outdoor positioning technologies were integrated within an outdoor AR platform (UM-AR-GPS-ROVER). The hardware configuration consists of a georeferencing based algorithm developed using the Global Positioning System (GPS) and magnetic orientation tracking devices to track a user’s dynamic viewpoint (Fig. 3).

The orientation tracker, a TCM5 magnetic device, includes a built-in compass, and employs solid-state magnetic field sensors which measure compass heading through a full 360° of rotation. The tracker employs proprietary hard and soft iron correction algorithms to calibrate out magnetic anomalies for repeatable, high-resolution measurement in challenging environments [30]. The tracking device was placed at the highest point inside the user’s helmet, directly above the top of the head, and parallel to the forward line of sight (Fig. 3).

The GPS measures the user’s position as longitude (x), latitude (y), and altitude (z). The magnetic tracker, on the other hand, mea-
sures the orientation of the user’s head (and thus line of sight) in the form of yaw (\(\alpha\)), pitch (\(\beta\)), and roll (\(\gamma\)) angles. These six measurements fully define the user’s outdoor location and line of sight at any given time.

However, GPS technology is not suitable for indoor applications because it becomes ineffective when there is no continuous straight signal path between the satellites and a receiver. Therefore, other feasible techniques of user position and orientation tracking in indoor enclosed environments had to be investigated. In contrast to the outdoor positioning technologies that are capable of identifying the location of an object or person in open areas, indoor positioning technologies typically set the constraint of a limited coverage range, such as a building or other confined spatial area. These technologies are therefore not dependent on any external network. They are dependent on a set of technologies used for transmitting wireless data in closed environments.

In recent work that addressed the first component (i.e., ubiquitous tracking) of the designed location-aware information retrieval framework, the authors investigated the effectiveness of three wireless technologies for dynamic indoor user position tracking. In particular, Wireless Local Area Networks (WLAN), Ultra-Wide Band (UWB), and Indoor GPS positioning systems were evaluated and compared. Experimental results demonstrated the ability of Indoor GPS, in particular, to estimate a mobile user's location with relatively low uncertainty (1–2 cm) [17]. Indoor GPS, along with magnetic orientation trackers, was thus adopted for further experimentation during the design and implementation of the subsequent components of the location-aware information retrieval framework described in this paper.

Indoor GPS takes into account the low power consumption and small size requirements of wireless access devices. The navigation signal is generated by a number of laser transmitters (Fig. 4). These are devices that generate a GPS-like navigation signal. The signal is designed to be similar to the GPS signal in order to allow pseudolite-compatible receivers to be built with minimal modifications to existing GPS receivers (Fig. 4). At least two transmitters have to be visible for navigation, unless additional means, such as altitude aiding are used [29]. A receiver in the measurement volume detects and processes the signals from each visible transmitter.

### 4.2. Computing the region of space visible to mobile user

By knowing the user’s position and orientation that is tracked by the first framework component (tracking module), the user’s line of sight can be accurately defined and the region of space that is in the field of view at that time can be computed. The region of real space visible to a mobile computing user can be conceptually thought of to be similar to an avatar’s viewpoint in a computer graphics application or virtual reality world. In a computer graphics world (e.g., visual simulation), the region of visible virtual space is called the viewing frustum or view frustum, and is typically shaped as a frustum of a rectangular pyramid [33].

Based on the concept of the viewing frustum, the authors mathematically derived the formulation for the region of space visible to a mobile computing user. This is graphically shown in Fig. 5. The planes that cut the frustum perpendicular to the viewing direction are called the near plane (P1–P2–P3–P4) and the far plane (P5–P6–P7–P8). Objects closer to the user than the near plane or beyond the far plane are assumed to be out of sight and context. Typically, the near plane is chosen close to the user’s viewpoint and the far plane is placed infinitely far away so all objects within the frustum are considered to be of interest regardless of their distance from the user. In Fig. 5, the user’s viewpoint is at position \((x, y, z)\) and the distances from the viewpoint to the near and far planes are \(n\) and \(f\), respectively.

As depicted in Fig. 6, the horizontal field of view (HFOV) is the angular extent of the user’s visible space when observed in plan view and the vertical field of view (VFOV) is similarly the angular extent of visible space in side view. The three rotation angles as shown in Fig. 2 are represented by symbols \(\alpha\), \(\beta\), and \(\gamma\), respectively. The yaw and the pitch are graphically represented in Fig. 6a and b, respectively.

Based on this scheme, interpreting the region of space visible to the user at a given time involves computing the coordinates \((x_n, y_n, z_n)\) of each of the frustum’s corner vertices (i.e., P1 through P8) as a function of the tracked spatial context parameters, i.e., the user’s position \((x, y, z)\) and the three-dimensional orientation of the line of sight \((\alpha, \beta,\) and \(\gamma)\). This was achieved by deriving trigonometric relationships between the vertex coordinates and the tracked parameters. Fig. 7 presents the equations derived to calculate the coordinates \((x_{P1}, y_{P1}, z_{P1})\) of vertex P1. Similar equations were derived for the other vertices. Thus, by computing the coordinates of all eight frustum vertices \((P1–P8)\), it was possible to accurately calculate the region of space that is in the user’s context at a particular time.

### 4.3. Identifying relevant contextual objects

In order to interpret which objects in the user’s surrounding environment are currently in context, the computed view frustum was represented as a geometric model (i.e., CAD object) on the computer. Then the coordinate system used to track the user’s nav-
igation is reconciled with the coordinate system used to model the user’s surroundings in CAD. A CAD design typically uses a local coordinate system without reference to any particular geo-referenced global coordinate system.

Methods to reconcile a pair of disparate coordinate systems have been successfully employed by the second author in research described in Behzadan and Kamat [5]. The viewing frustum model is then tested for geometric interference with CAD representations of objects in the user’s surroundings. The goal of intersection detection in computer graphics is to report any contacts between geometric objects when they occur [21]. In this context, the interference detection enables the determination of whether a corresponding real object is indeed in the user’s view at that particular time.

Using the method described above, several objects can be detected in the user’s view frustum at any given time. However, the user might be specifically interested in only one or few of the identified visible objects at that time. Such precision in interpreting which specific object(s) the user is interested in was achieved by adopting another geometric interference analysis technique known as raycasting [13].

Raycasting involves casting imaginary lines originating at the user’s viewpoint and heading along the line of sight. The objective is to test for intersection between the rays cast and geometric representations of the visible objects. This process is presented in Fig. 8, which depicts a user (i.e., inspector) looking at several objects such as columns, formwork, etc. These objects can all be identified as contextual using the intersection detection technique described above. In order to detect the most relevant object(s) at this particular time, seven rays (R1–R7) are cast and each of these rays intersects a different object. An object intersected by a ray that is closer to the line of sight (C12 in Fig. 8) is then considered to be of more relevance than an object intersected by a ray at a periphery of the frustum.

4.4. Retrieving information on specific objects in context

Once the specific objects of interest are identified using the algorithms described above, the captured spatial contextual information can be mapped to available data and services [3]. In this research, project databases and interoperable product models were used to store, access and retrieve project information (textual and graphical).

For example, the utility of the interoperable CIMSteel Integration Standards (CIS/2) product model was investigated and used. CIS/2 is a logical product model for structural steel building information [22]. CIS/2 has been implemented by many steel design, analysis, engineering, fabrication, and construction software packages to create a seamless and integrated flow and archival of information among all entities involved in the design and construction of steel framed structures.

The CIS/2 standard provides data structures for multiple levels of detail ranging from frames and assemblies to nuts and bolts. CIS/2 structures can be represented as analysis, design, or manufacturing models. In addition, any software application can seamlessly have CIS/2 import and/or export capabilities. For these reasons, the CIS/2 standard model presents a suitable data structure to represent cross-referenced building data for the evaluation of the developed automated information retrieval technique. In addition to CIS/2 product models, other project repositories such as MS Access databases were also successfully deployed on mobile computers as detailed in the validation section.

4.5. Interactive visualization of retrieved information

In order to interactively display information retrieved using the described methodology to the mobile user, a new class of display and interaction devices is needed. It is important that any information support provided to the user must not come at a safety and efficiency cost. For instance, any display technologies used must unobtrusively present information in a site engineer’s or inspector’s view without distracting the user from the core task at hand.

Several types of mobile computing devices have been investigated in this research. Examples include tablet PCs, PDAs, WLAN-enabled cell phones, and other wearable computers such as the Xybernaut Mobile Assistant [34]. In terms of display devices, several lightweight head-mounted displays have been explored for their suitability. Examples include wearable displays manufac-
tured by LitEye [23] and Inition [15]. Several models of displays are especially designed for rugged applications in harsh environments such as outdoor construction (Fig. 9), and can be used with lightweight wearable computers.

In addition to using interactive display devices, Augmented Reality (AR) has also been used to present the retrieved information to the mobile user. AR is the superimposition of computer-generated graphics over the user’s view of the real world [6, 5, 16]. With AR, it is possible to have complete control over the virtual elements that are superimposed on the real world, and how the user interacts with those elements. AR can involve additional advantages as well.

For instance, it can be less expensive since it uses the real world as a background (i.e., no need to model the real world). It can also facilitate the feeling of presence from the user’s perspective. Thus, users visualizing contextual information in AR can potentially increase their efficiency significantly by readily interacting with the mobile computers generating the augmented graphics in order to display the relevant subset of information in their views. For instance, automated retrieval of information within an AR environment can serve as an alerting mechanism that can compare the as-built and as-designed information and notify the user of any significant deviations such as activities behind schedule or materials not meeting the specifications.

5. Validation experiments and results

In order to verify and validate the concepts developed in this research, and to evaluate the accuracy of the studied positioning systems, several experiments have been conducted in both indoor and outdoor environments. These experiments and the obtained results are described in the following subsections.

5.1. GPS-based proof-of-concept experiment

In order to evaluate the effectiveness of the developed context interpretation algorithms and information retrieval methodology, and to demonstrate the developed ideas as a proof-of-concept, a validation experiment was conducted outside the G.G. Brown (GGB) laboratory building at the University of Michigan. This building houses several engineering departments including civil, mechanical, and chemical engineering. The goal of this experiment was to simulate an inspector surveying the building, and evaluate whether the different sections of the building in the user’s view can be automatically identified based on the tracked spatial context (i.e., global position and 3D orientation).

During the experiment, the user’s position and orientation were continuously obtained from the developed mobile computing backpack’s GPS and magnetic tracker, respectively [5]. The near and far plane distances were set to be 1 and 100 m, respectively.

\[
x_{p1} = \left[ \frac{\cos(HFOV)}{2} \times (n \cos \beta \cos \psi + x) \right] - \frac{\sin(HFOV)}{2} \times n (\cos \alpha \sin \gamma + \sin \alpha \sin \beta \cos \gamma) \times \frac{\cos(HFOV)}{2} \times \frac{\cos(VFOV)}{2}
\]

\[
y_{p1} = \left[ \frac{\cos(HFOV)}{2} \times (n \sin \beta + y) + \sin(HFOV) \times n \sin \alpha \cos \beta \times \frac{\cos(HFOV)}{2} \times \frac{\cos(VFOV)}{2}
\]

\[
z_{p1} = -\left[ \frac{\cos(HFOV)}{2} \times (n \cos \beta \sin \gamma - z) + \sin(HFOV) \times n (\cos \alpha \cos \gamma - \sin \alpha \sin \beta \sin \gamma) \times \frac{\cos(HFOV)}{2} \times \frac{\cos(VFOV)}{2}
\]

Fig. 6. Geometric relationship between line of sight and visible space for (a) yaw (x) and (b) pitch (β) rotations.

Fig. 7. Vertex coordinates of view frustum.
and both the HFOV and VFOV angles were chosen to be 45° (typical values for computer graphics applications). The GPS signals used the freely available Wide Area Augmentation System (WAAS) corrections for the tracked positions, resulting in a consistent positioning uncertainty of about 1.5 m.

Based on the tracked user position and orientation, the eight coordinates of the truncated pyramid (i.e., viewing frustum) were computed. The frustum was then aligned with a 3D VRML model of the GGB building and geometric interference tests were performed. Each time the user moved on the site, the intersection between the current frustum and sections of the building was computed and reported. It was observed that as the user was moving around the building, the computer was correctly interpreting which building segment was in the view at each time instant. Selected snapshots of both virtual and real camera views taken during the conducted experiment are shown in Fig. 10.

5.2. Indoor GPS – based user tracking experiment

Another set of validation experiments was conducted at the National Institute of Standards and Technology (NIST), specifically in the “maze” at the former NIKE missile base barracks building adjacent to the main campus (Fig. 11). The goal of these experiments was to simulate a mobile user such as a construction engineer or inspector surveying the building, and evaluate whether different building objects inside the maze can be automatically identified based on the user’s spatial context, followed by the retrieval and presentation of contextual information from project databases. In these experiments, the Indoor GPS positioning system was used to track the user’s location.

Four transmitters were deployed around the area of the maze as shown in Fig. 12, and one receiver and the orientation tracker were mounted on the mobile user navigating inside the maze. The user’s position and orientation were continuously obtained from the Indoor GPS and magnetic tracker. Given that the maze covers an area of 9 x 8 m, the near and far plane distances were considered to be 1 and 3 m, respectively, and both the HFOV and VFOV were chosen to be 45°.

The eight coordinates of the truncated pyramid were computed using the designed algorithm. The frustum was then aligned with a 3D VRML model of the maze and geometric interference tests were performed. Each time the user moved on the site, the intersection between the current frustum and objects inside the maze (i.e., building elements) was computed and reported (Fig. 13). Having identified specific objects (e.g., columns) in the user’s field of view, contextual information was then automatically retrieved from the project database (Fig. 14), in this case a MS Access database that included all the details pertaining to the structural elements located inside the maze. The results of the experiments indicated that the Indoor GPS tracking system consistently achieved a positioning uncertainty that fluctuated between 1 and 2 cm.

5.3. UWB-based user tracking experiment

This validation experiment using the UWB system for position tracking was also conducted at NIST, specifically at the steel structure on the main campus (Fig. 15). The goal of this experiment was to evaluate whether contextual information identified based on the user’s tracked spatial context can be retrieved from a CIS/2 product model.
Four Ultra-Wide Band (UWB) receivers and one reference tag were deployed around the area of the steel structure as shown in Fig. 16, and one UWB tag and the orientation tracker were mounted on the mobile user who was navigating around the steel structure. Similar to previous experiments, the user’s position and orientation were continuously obtained from the UWB system and magnetic tracker.

As the user moved on the site, geometric intersection tests between the computed frustum and virtual steel members were conducted and reported. Having identified specific steel members in the user’s field of view, contextual information was then automatically retrieved from the CIS/2 structural steel product model (Fig. 17). The results of all experiments using UWB-based positioning indicated that the UWB Tracking system overall achieved an accuracy that fluctuated between 10 and 50 cm.

5.4. WLAN-based user tracking experiment

In order to demonstrate the overall feasibility of the proposed framework, another validation experiment, using the WLAN-based Ekahau positioning system and magnetic orientation trackers, was conducted in the Structural Engineering Laboratory on the first floor of the GGB building at the University of Michigan. The WLAN indoor positioning testbed has an area of 40 ft by 25 ft and contains various structural elements including concrete walls and columns, steel columns and beams (Fig. 18).

Area calibration and data collection were part of the training phase required by the adopted WLAN fingerprinting approach. The signal strength measuring device (WLAN-enabled laptop in this case) was set at a predetermined reference point (RP) position and data was collected from each access point in the area and saved to the database. The user then advanced to the next RP and collected signal data again.

In these experiments, several RPs were chosen. The dots shown in Fig. 19 are different RPs located on the “tracking rails”. A fingerprint database, comprising of all RPs was generated. Within the database, a fingerprint consisted of measurements representing the received signal strengths obtained from each access point at that RP. Standard wireless access points deployed by the University of Michigan in the different buildings across campus as part of a wireless network were used.

Having created the fingerprint database, signal strength data was collected at each mobile user’s location while inspecting the different structural elements in the laboratory. The method of data collection was similar to that of the RPs during the training phase. Data collected was then compared against the saved fingerprints and the user’s position was determined. Based on this tracked position and orientation (obtained from a magnetic orientation tracker), as well as near and far plane distances (0.5 and 3 m, respectively) and both the HFOV and VFOV angles (20°), the eight coordinates of the truncated pyramid or viewing frustum were computed.
The frustum was then aligned with a 3D VRML model of objects in the laboratory, for example the concrete wall shown in Fig. 20. In this case, the user was looking at a wall and then “locked” the context by pressing a key to temporarily stop the processing of tracking information. This “frozen” spatial context state allowed the user to move his head freely and look at the computer screen without having his interpreted context change continually. Within the determined and frozen context above, the next step included performing interference detection tests.

First, the intersection between the user’s viewing frustum and objects was computed using general collision detection techniques, and then the raycasting technique was used to increase precision in object identification. For instance, a virtual ray was cast along the line of sight first (Fig. 20) to check for intersection and when it was detected and reported, contextual information was retrieved (Fig. 21).

Specific information on identified contextual object(s) for a specific activity can be prioritized based on the user’s function, and then retrieved. In this retrieval interface (Fig. 21), the user opted to retrieve different categories of information (construction schedule, 2D drawings, etc.) for the reinforcement placement and tying activity of the detected column C2. During the course of these experiments, it was found that the WLAN-based position tracking system overall achieved a positioning accuracy of approximately 1.5–2 m.

5.5. Position tracking systems comparative summary

The experiments described in the above subsections highlight the potential applicability of positioning technologies, mainly WLAN, UWB and Indoor GPS, for positioning in indoor environments. While these technologies share some common traits, they also have some significant differences based on an analysis of their...
technological aspects (e.g., line of sight requirement), as well as implementation details (calibration, equipment deployment, cost, etc.). The major differences are summarized in Table 1.

For instance, WLAN-based tracking systems are economical and equipment deployment mainly consists of placing access points in the tracked area. However, the area needs to be calibrated first (several sample points are required at different locations) which is an arduous and often challenging task, in particular in dynamic construction environments. Although the range of a typical 802.11 b WLAN node is 100 m, the technology does not provide the best accuracy (1.5–2 m) needed to locate mobile users and identify their spatial context with high-precision.

On the other hand, UWB and Indoor GPS require significant time and effort to deploy all required stations around the coverage areas, in particular on dynamic construction sites. Additionally, both technologies are relatively expensive. For instance, a full UWB system with four receivers (any antenna type), one processing hub, four cables (150') and eleven tags cost about $15,000. Individual receivers (any antenna type) are $2195 each. The hub costs around $5195 and individual 1 Hz tags are $40 each, and higher power tags range from $120 to $125 each.
An Indoor GPS system with four transmitters and one receiver costs up to $45,000 (transmitters cost $10,000 each). While the Indoor GPS technology range (60 m) is better than that of UWB (10 m), it depends on a clear line of sight and some calibration points are needed unlike UWB. However, both technologies offer centimeter level positioning accuracy with Indoor GPS positioning offering significantly higher precision.

6. Future research

In addition to improving the tracking component of the methodology, additional experiments are being conducted to illustrate how contextual information can be automatically retrieved from projects databases and, depending on the task at hand, can be interactively presented to mobile users (engineers, inspectors, etc.) in real-time on construction sites. In addition to construction and other engineering applications, the applicability of the developed methodology for providing information support in emergency response is also being studied.

Emergency response crews such as firefighters have been documented to lack the information technology support needed for collaboration, information sharing, and coordination [31,27,8], and can potentially draw significant benefits from the developed methodology. For instance, retrieved building information such as floor plans, exit locations, and locations of critical assets can be of significant help to first responders and engineers responding to a disaster.

An interesting problem that future research must address involves the dependence of a tracking technology on installed sensor networks inside buildings and other indoor locations. All indoor context-aware information delivery applications developed thus far rely on a pre-installed and calibrated network of wireless...
sensors (e.g., routers). However, this approach is unsuitable for applications in outdoor construction or disaster response. Engineers or first responders typically operate in a mixed outdoor and indoor environment. Therefore, the ability to track such users cannot rely on sensor infrastructure installed, for instance, in a building affected by a disaster itself.

GPS is an attractive option because it does not rely on any pre-installed sensor infrastructure and instead depends on direct satellite communication. Wireless technologies, on the other hand, can locate a user indoors, provided a network of wireless base stations is already installed at fixed known locations. However, both these options are not feasible on their own for tracking a user in a mixed indoor/outdoor environment. In order to address these issues, a hybrid outdoor and indoor positioning technique based on a combination of GPS and wireless positioning technologies is also being investigated by the authors.

7. Summary and conclusions

This paper presented the overall architecture of a spatial context-aware methodology for automatically identifying and retrieving, with high-precision, contextual project information to support decision makers such as engineers, inspectors, and maintenance crews on construction project sites. The authors have successfully designed and implemented a three-stage-algorithm to calculate the region of space visible to a mobile user based on the tracked location and head orientation, prioritize the context of visible objects in the user’s view using a raycasting and intersection approach, and retrieve and visualize the prioritized contextual information.

In order to demonstrate the feasibility of the proposed approach, a proof-of-concept experiment was first conducted in an outdoor environment. A user equipped with a GPS receiver and a
magnetic orientation tracker inspected the segments of the GGB laboratory building at the University of Michigan. The obtained results demonstrated that tracking a mobile user’s three-dimensional orientation in addition to the position is an effective way of increasing precision in the interpretation of the user’s fully-qualified spatial context.

Several other validation experiments were conducted in indoor locations at the National Institute of Standards and Technology and the University of Michigan using Indoor GPS, UWB, and WLAN-based systems for position tracking. The results of those experiments highlighted the potential of using terrestrial wireless technologies and magnetic trackers to accurately track the position and orientation of mobile users as they navigate in congested spaces such as those found on typical construction sites.

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References


