Location-based services for elderly and disabled people

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Abstract

Many techniques have been developed to perform indoor location. Each strategy has its own advantages and drawbacks, with the application demanding location information the main determinant of the system to be used. In this paper, a system is presented that serves location to innovative services for elderly and disabled people, ranging from alarm and monitoring to support for navigation and leisure. The system uses ZigBee and ultrasound to fulfill the application requirements, differing in this respect from all other existing systems. ZUPS (ZigBee and ultrasound positioning system) provides wide multicell coverage, easy extension, robustness even in crowded scenarios, different levels of precision depending on the user’s profile and service requirements (from a few centimeters to meters), limited infrastructure requirements, simple calibration, and cost-effectiveness. The system has been evaluated from the technical, functional, and usability standpoints, with satisfactory results, and its suitability has also been demonstrated in a residence for people with disabilities located in Zaragoza, Spain.

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1. Introduction

Location-based services (LBS) are a mainstay of ubiquitous computing and context awareness. Today, LBS are becoming a reality in a wide range of applications, although there are significant differences between indoor and outdoor systems.

Navigation support systems based on geographical positioning systems (GPS) are now used by the general public, and global system for mobile communications (GSM) operators offer valuable services to the subscriber based on his/her location. These services include, not only emergency support as required by the United States and the European Union [1,2], but also commercial services such as locations of the closest restaurants and stores and even navigation. It is possible to offer such services because global localization techniques are highly standardized. However, this is not the case with local positioning, where technologies are closely bound up with the desired services they will support.

The local position measurement (LPM) system from Abatec Electronics AG is a local range-positioning system based on microwaves, which achieves high accuracy and refresh rate, but is suitable only for outdoor use [3,4]. This technology supports an outdoor sports monitoring service. Ultra-wideband (UWB) technology offers similar performance, but is also suitable for indoor scenarios. Ubisense [5,6] offers an indoor positioning system with up to 15-cm 3D accuracy as well as a variety of services for logistics, workplace, and military applications. Another fashionable technology for deploying LBS is WiFi, because location systems can reuse existing network infrastructures. WiFi location systems are usually based on field mapping and achieve a maximum accuracy of about one meter. An example of such a system is that offered by Ekahau [7], which also offers health care, manufacturing, and supply-chain solutions.

However, these technologies usually require complex hardware that sometimes is not feasible. For smart-dust-like
scenarios, where the sensors are too simple to integrate any specific radiofrequency hardware, the Lighthouse system [8] offers a positioning approach in which three rotating light beams are used to perform 3D localization with no need for complex hardware on the sensor side. LBS for these scenarios are focused on associating sensor information with its location. Another way to avoid the need for hardware on the target side is to use artificial vision, which is widely used in industry for mobile robot positioning.

Many other positioning technologies could be used to provide LBS – radiofrequency, ultrasonic, inertial, infrared, magnetic fields – each one with different drawbacks and advantages [9–14]. In short, on the one hand, use of a particular positioning technology often conditions the services that can be offered, and on the other hand, some services or scenarios also condition the technology needed. To date, there is no positioning technology that could be suitable for every service and scenario.

In this paper, a ZigBee and ultrasound-based positioning system (ZUPS) is described, which can be classified as a local positioning system with high positioning accuracy and low cost. Its implementation is analyzed with reference to a particular case (a residence for disabled people located in Zaragoza, Spain) to support LBS such as alarms, guidance support, and leisure. Section 3 describes the fundamentals of ZUPS. Section 4 focuses on implementation issues such as installation, power consumption, ethical issues, and evaluation. Finally, conclusions are presented.

2. Location-based services

The main service developed in this work using ZUPS is intended to warn when an alarm or risky situation occurs, an objective given a high priority by experts in caring for the elderly and people with disabilities. However, ZUPS can also provide support for other services, such as guidance and spatial orientation training inside a large building or a leisure and mobility training system. This particular implementation was carried out in a three-story residence for people with disabilities in Zaragoza, Spain. The ground level includes a yard and common areas (offices, occupational workshops, cafeteria, gymnasium, etc.), and the other two floors are dedicated to private rooms for the residents.

2.1. Alarm system

A common strategy nowadays for providing security for people who are considered at risk consists of limiting their mobility by restricting their access or even making them stay in specific areas. The objective of the service described in this paper is to improve security and support users’ freedom to move by enlarging their permitted area. The approach combines two ideas. The first involves trying to make people conscious of appropriate behavior in different situations: risk areas or situations where they should not stay (e.g., the kitchen), others where they should be accompanied by a caretaker (e.g., the nursing room), and others where they can move freely. The second idea involves monitoring location to detect abnormal or risky patterns like wandering in the middle of the night. For intensive monitoring, ZUPS, described in the next section, is used to identify users and to monitor when and where each user is going. This type of monitoring is user-dependent, determined by his/her wishes, characteristics, and type of dependency. When the system has determined someone’s position, the following situations can be detected:

- Risk due to staying in a room that presents a risk for that person without his/her caretaker (kitchen, medical treatment room, etc.).
- Inappropriate presence or walking patterns (nocturnal presence in the dining room and not in the bed).
- Duration of stay greater than the specified maximum (staying in the bath longer than half an hour may indicate that the person has experienced an accident, is sleeping, or simply has some degree of disorientation).
- Absence or contact loss (the user is leaving or has left the building).
- Conducts that denote anxiety, escapism, or other problems of interest (small-scale repetitive itineraries).
- Lack of movement for too long in an unusual place (no movement for 5 min in the middle of a corridor).

An accelerometer and a button are integrated into the device that the users wear; thus it is possible to detect falls and make emergency calls. Upon the detection of any kind of call or alarm (including information on where it has happened), a warning can be triggered to the most appropriate person to respond to it. The choice of the person to be notified depends on the type of situation detected, the institution’s policy, and the user. For example, if fast assistance is required – e.g., because of a fall or an escape attempt – the system will warn the nearest caretaker. In other cases, the person may have a favorite caregiver or, because of his/her characteristics, may need the assistance of more than one person at a time. In the best case, if the user’s autonomy is good, the system could simply warn him/her of the situation detected. In all cases, the system analyzes both the situation and the predetermined personal preferences to provide notification of the situation in the best possible way.

2.2. Guidance system (navigation training)

The location system will also be used to support and train users to find their way inside buildings. A guiding system (GUIA) [15], intended for people with disabilities, is under development and will be aware of user abilities and building status. The system uses a complete building map together with any special or common landmarks it has available. Common landmarks are those found in any public building that are meant to provide guidance, like signs and directories. Special landmarks are those that are not
specifically intended to provide guidance, but are still appropriate as references, such as vending machines or doors of different colors. Other system inputs are the user’s target place (or places), his/her disabilities (blindness, reduced mobility, etc.), special building circumstances (like human traffic information or repairs underway), and the user’s current position and head orientation.

With these data, GUIA calculates a route which the user can comfortably follow, taking into account possible limitations in each part of the path given the specific user’s capabilities. As the user moves through the building, the system sends guiding messages according to his/her needs (so far, voice and text messages have been implemented) until he/she reaches the target.

In the current implementation case, most users are familiar with the residence, and therefore GUIA is useful mainly as an educational guide to help people become acquainted with the building, although good results have been obtained in previous trials in Madrid even with people that have lived in the residence for some time. The system has also been evaluated with elderly people in unknown buildings, with satisfactory results [16].

2.3. Leisure and mobility training system

Motivation of people living in residences is a key issue for their quality of life, especially for elderly people. In the analyses of rehabilitation activities in several scenarios and of past successful or failed experiments, motivation was highlighted as a crucial factor in the efficacy of rehabilitation or maintenance efforts. After some work sessions with health and social workers with experience in residences, a new location-based service was invented: an interactive game. By simply adding a buzzer to the location device, it becomes a gadget that emits different sounds depending on its location. This device can be used to create games oriented mainly toward finding objects and people, performing trials, and answering questions.

This service is currently under development. Even so, based on opinions of experts in caregiving, it is expected to offer various benefits. The most immediate one is likely to be an improvement in motivation because of the enjoyment produced by a cooperative-competitive activity. Moreover, this activity requires people to move around, which is intrinsically desirable. Another benefit is increasing the likelihood of acceptance of the technology; because the game-playing gadget is also the location device used in the alarm service, the unwillingness of people to carry it should be reduced.

3. Description of the location system

When implementing a location-based service, selecting the best positioning system is of key importance. In many cases, the infrastructure needed or the performance of the technology (range, accuracy, etc.) severely conditions the service characteristics. Many technologies exist that are able to provide location information; nevertheless, few of them have a significant impact on final applications [17] and none is perfect for every service [18]. The application designer should prioritize the requirements to choose the most appropriate technology. The most obvious considerations are accuracy, range, refresh frequency, and cost. Nevertheless, less obvious issues such as infrastructure, calibration, number of mobile devices located simultaneously, or robustness and immunity to occlusions can compromise the final implementation if ignored [19].

The positioning system developed in this work combines a number of interesting features – not covered by any of the existing systems – that fulfill the service requirements of the residence. The basics of the positioning technology are not novel: the system uses ZigBee (radiofrequency) and ultrasound to measure distances between mobile devices (tags) and beacons with known locations. Of course, this is not the longed-for “tracker-on-a-chip”, but its features make it especially suitable for large indoor applications requiring accurate indoor localization. It overcomes one of the biggest drawbacks of other ultrasound-based systems like Active Bat [12], Cricket [13], or Constellation [14]: the extent of the infrastructure needed. Even in adverse environments with ultrasound occlusions, it achieves centimeter-scale accuracy while reducing the infrastructure requirements by a factor of ten compared with the other ultrasound-based systems.

The system presented in this paper is the fourth version created on the basis of the first prototype developed 9 years ago. The experience accumulated since then is applied in this implementation, and each of the issues found to be essential in this system is presented in the following subsections. An overview of the system architecture is shown in Fig. 1.

3.1. Communication

The location system has evident needs for communication (positioning data and management commands) and synchronization (beacons and tags must coordinate themselves to emit and listen to ultrasonic chirps at known instants). The beacons are fixed within the building, and therefore they can communicate through cable (as the third version of the system did). The tags carried by the users, because they are mobile, require wireless technology. In this version, it was decided to use wireless technology only, mainly because it greatly simplifies installation, which is one of the main concerns when deploying a location system in a large-scale installation.

The choice of communication technology is critically important. Considerations include requirements from the user point of view that condition usability (long battery life, reduced size, and cost efficiency) and other technological concerns that influence system quality (fail-safe operation, ease of network deployment, scalability, adequate data rate, and security). Communication systems based on a star architecture are not useful in this context because they have
to choose between having reduced coverage or using long-range radio at the cost of reduced battery life. WiFi fulfills these functional requirements, but it has high power consumption and requires moderately large processing capabilities. The second version of the system, single-cell localization, uses Bluetooth [20], but its extension to multicell positioning poses network management difficulties.

Finally, because this system has requirements similar to those of wireless sensor networks, it was decided to use ZigBee. The strategic reasons favoring adoption of this solution were its interoperability with other potential ambient intelligence applications like home control and automation and the future projection of the protocol, with consequent cost reduction. Its adequate data rate (250 kbps), security (128-bit AES encryption), low latency (30 ms to join and 15 ms to access the network), ease of management (transparent to the user), and energy efficiency were the technical reasons for its selection.

The development environment from Ember [21] was used to develop a ZigBee-compliant network using a mesh topology [22]. Nodes in the network perform three different roles. The coordinator is the one initiating the network and also the sink where all the data will go. Beacons act as routers which maintain a routing table to address data packets and exchange data with the mobile devices. Both coordinator and router are full-function devices (FFD) supporting the complete ZigBee stack. Tags operate as reduced-function devices (RFD), supporting only a part of the standard to allow connectivity. They have the lowest power consumption, but cannot relay messages to other devices.

The ZigBee standard defines several network topologies: star, cluster tree, and mesh, differentiated by the hierarchy of links between neighbors [22]. Here a mesh topology was chosen because it fulfills the needs of the application: mobile devices, routing flexibility, and robustness in case of router failure. The mesh of beacons forms a backbone to which tags are connected in a star configuration. Beacons have a neighbor relationship with each other and temporary parent–child associations with tags. Tags will be mobile and should maximize their sleep time to save energy. As a result, they need to change their parents while moving and disappear from the network while sleeping. In summary, each tag maintains a temporary foster beacon-parent that forwards messages on its behalf and buffers incoming data while the tag is sleeping. Tags periodically poll their beacon-parents (even when they have nothing to send) to get any buffered data and to inform the beacon-parent that they are still there. If there is no poll response in 10 s, the parent assumes that the tag has moved on and removes the mobile node from its child table. When a mobile node moves and changes its parent, the corresponding beacon informs the rest of the network about its new responsibilities.

3.2. Network synchronization

Measuring the time-of-flight, or TOF, of an ultrasound signal is a coordinated task which requires beacon and tags to be synchronized. Synchronization is a key issue in wireless sensor networks [23]. As a result, many synchronization techniques exist, most of them based on exchanging messages to establish a global network time (GNT) [24]. Those methods working at the MAC (medium access control) layer, such as the TPSN (timing-sync protocol for sensor networks) [25] or the flooding-time synchronization protocol (FTSP) [26], can timestamp messages precisely when they are sent or received, achieving the highest accuracy. Unfortunately, when wireless standards such as ZigBee or Bluetooth are used, they are managed through an application program interface (API) which prevents access to lower layers, making these methods not applicable.

According to the time analysis performed by Maróti et al., the most problematic delays when transmitting messages over a wireless link are those arising from the send, receive, and access processes [26]. Using broadcast messages to establish a common time reference gets rid of the transmitter-side non-deterministic error sources. It assumes that all devices listening to the broadcast get the message at the same time. This eliminates the time uncertainty introduced by the send and access processes and sets a temporal reference which can be shared by all nodes [24]. Moreover, this procedure can be easily implemented in the application layer, as the authors have demonstrated with Bluetooth [27].
A wrong estimate of distance leads to computing an erroneous location. The authors of this paper have developed a multi-hop broadcast synchronization (MBS) method which expands the reference broadcast approach [23] to create a GNT which fully optimizes the exchange of messages. Fig. 2 shows an example network illustrating how the MBS protocol works.

Nodes in the MBS protocol perform two different tasks. Propagators transmit the GNT broadcast synchronization messages. Time-stampers notify the propagators of the arrival timestamp of the previous broadcast message, which will be sent by the propagator in the next synchronization message. In Fig. 2, nodes N3, N6, N9, and N11 are propagators, while nodes N1, N5, and N7 are time-stampers which must be synchronized when notifying the corresponding propagator node. To overcome this requirement when initiating the process, N1 will be the node whose local clock will be the GNT, i.e., N1 is the global time provider (GTP).

Network synchronization in Fig. 2 is achieved in two hops. In the first hop, nodes in the dashed ring will be synchronized by N6 to N1’s clock (using broadcast messages). Then N3, using N7 as time-stamper, plus N9 and N11 will synchronize the nodes in the dotted rings, propagating the GNT. N6 must also be synchronized, and because it is the only propagator connected to the GNT, it will be synchronized in the second hop by one of the other propagators.

The accuracy achieved depends on how many hops have been performed; each additional hop uses a time-stamper with more cumulated error in its time estimation. Table 1 shows the averaged and maximum synchronization error with 95% probability in a four-level network. Working at the ZigBee application layer, it is possible to have a global network time with enough accuracy and stability for precise location. Moreover, the number of messages needed is drastically reduced compared to any of the other multi-hop protocols based on the reference broadcast approach [24,28]. Indeed, it is of the same order of magnitude as in FTSP, the most efficient synchronization method [26].

### 3.3. Distance ranging

The procedure for obtaining distance between beacons and tags is well known and similar to that used to know how far away a storm is by counting the time from seeing lightning to hearing thunder. Thanks to synchronization, beacons and tags know the instant when each chirp is emitted. To measure the ultrasonic time-of-flight with the lowest error, it is important to determine what device should emit each chirp: a beacon or a tag. Cricket [13] and Constellation [14] use a transmissive beacon strategy (TBS), while Active Bat [12] uses a receptive beacon strategy (RBS); each has its advantages and drawbacks.

In TBS, each beacon sequentially emits ultrasound chirps, and all tags in range listen and measure TOFs. RBS works in the inverse manner: beacons listen to the chirps emitted by each tag that wants to be located. The time to perform a location cycle in TBS is proportional to the number of beacons, while in RBS, it depends on the number of tags to be located (Fig. 3a). Location of moving tags is also influenced by the strategy used. In TBS each chirp reaches the tag at a different position, and the location algorithm generates larger errors with faster tag speed (Fig. 3b).

The propagation of ultrasound is highly influenced by the architecture used. Obstacles (people, furniture, etc.) are usually close to tags. Thus, because an ultrasonic signal’s range is greater the further away the obstacles are from the emitter, TBS performs better in field deployments. In addition, because more power is necessary to emit a chirp than to hear it, it is better that tags, which are battery-powered, listen, and beacons, which can be powered from the grid, emit.

Briefly, RBS is the most appropriate architecture when a small number of mobile devices must be simultaneously, intensively, and precisely tracked. If many slow-moving battery-powered tags must be located in a real installation with a limited number of beacons, TBS performs better.

From the discussion to this point, it is clear, because the authors have decided to use TBS, that beacons and tags know when chirps are emitted (because they are synchronized) and tags can measure TOF precisely using their internal timers...but what happens during the transit of the ultrasonic signal? It was found to be critically important to characterize all non-deterministic influences that may randomly degrade the range. An exhaustive analysis of all the potential situations in a real deployment is infeasible; nevertheless, it is possible to categorize them into four types depending on the real conditions that cause them [29], as shown in Fig. 4. Type I error means that there is no signal blockage, but that small errors may have arisen

### Table 1

<table>
<thead>
<tr>
<th>Synchronization hop</th>
<th>Synchronization error (μs)</th>
<th>Distance error (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Hop (Avg./Max.)</td>
<td>11.9/28.7</td>
<td>3.9/9.5</td>
</tr>
<tr>
<td>2. Hop (Avg./Max.)</td>
<td>19.3/49.9</td>
<td>6.4/16.5</td>
</tr>
<tr>
<td>3. Hop (Avg./Max.)</td>
<td>28.5/68.6</td>
<td>9.4/22.6</td>
</tr>
<tr>
<td>4. Hop (Avg./Max.)</td>
<td>41.6/104</td>
<td>13.7/34.3</td>
</tr>
</tbody>
</table>

A wrong estimate of distance leads to computing an erroneous location.
because of synchronization misalignment, temperature drift, or hardware delays, usually following a Gaussian distribution. Types II and III errors are due to slight and moderate degrees of obstruction of the signal by people or objects around the tag. These errors are commonly called non-line-of-sight (NLOS) errors, and because the distribution of obstacles does not follow any particular pattern, these errors can be correctly modeled by a uniform distance-dependent distribution with a maximum value varying from 5% to 100% of the distance. A Type IV error means a complete signal blockage, in which case measured data, if any, will be aberrant.

This analysis was very helpful in designing the deployment of the beacons and to decide on the best positioning algorithm to use.

### 3.4. Location algorithm

Once the distance from a tag to each of the beacons is known, its location can be calculated. Many strategies have been developed to solve this problem, including neural networks, iterative methods, algebraic techniques, and statistical procedures. All these approaches are susceptible to the errors described previously. An exhaustive study of this problem has already been carried out [29], and only the conclusions that are most applicable to real scenarios are presented here.

If there are no significant errors in the initial data, almost all the algorithms will achieve a high degree of accuracy. However, if most of the distance estimates are corrupted, any algorithm will fail because there is no valid relationship between the initial data and the output. The commonest situation involves initial data containing a mix of correct and erroneous data. In such a case, enough data are available to calculate the position accurately (three distances in three dimensions), but erroneous data prevent a direct solution. This is a common situation in indoor positioning systems: beacons are distributed around a room, and some of them – it is unknown which ones – have a direct view of the tag, while others are hidden by the environment.

The least-median-of-squares (LMedS) algorithm was found to be the best in situations in which it is not possible to use any prior information to solve the multilateration

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**Fig. 3.** TBS vs. RBS. (a) If there are more tags than beacons, TBS will take less time than RBS to emit all the chirps. In the opposite case, if there are fewer tags than beacons, TBS will take more time than RBS. (b) Mobile tag. In TBS, the tag receives each chirp at different positions, so there will be an error when computing the tag location. In RBS, the tag emits the chirp, and distances are referenced to a unique position.

**Fig. 4.** TOF taxonomy. B4 and B5 have a direct path to the tag, and ranging errors are mainly due to sensing issues. The paths from B1, B2, and B3 are hindered by people and a large obstacle and present the greatest errors in ranging estimation.
problem. The LMedS algorithm, far from simultaneously using all available data, is based on the compilation of sets of input measurements that are used to calculate a space of solutions and estimate the residuals of all the measurements. The so-called “robust solution” is the one whose residuals have the minimum median. The details of this algorithm are presented in [29].

Fig. 5 plots the results of the LMedS algorithm compared to those from a least-squares algorithm, which is the method that is most commonly used to solve non-linear systems that converge to a global minimum. The case of a $10 \times 10 \times 5$ m installation with eight beacons is considered, with one to four measurements affected by severe NLOS error (Types III and IV). This example shows how the LMedS algorithm can manage NLOS errors effectively. Although the least-squares algorithm fails even with NLOS errors of 10%, LMedS is able to handle up to three out of eight measurements with severe NLOS errors (which is quite improbable in a real situation).

The most important conclusion of this analysis is that the system must be designed to ensure that sufficient correct data are available to calculate the location of the tag accurately, regardless of the environment. Therefore, the best way of ensuring accurate positioning is to collect redundant data and use a good algorithm that is able to filter out erroneous measurements. This is usually accomplished by installing more beacons than are strictly necessary, but how many are required? The clearest evidence of the importance of the algorithm can be found in the relationship between accuracy and the density of beacons required in the current system vs. the density required in other systems. Active Bat is the ultrasonic-based system with the least required infrastructure; it requires 750 sensors in a 930-m$^2$ office building [30]. The method developed here achieves similar accuracy – within several centimeters even under adverse conditions – using LMedS and TBS, but requiring only 55 beacons in a 1200-m$^2$ installation (Fig. 6). Four ultra-wideband sensors are needed to perform location in a deployment over 400 m$^2$ [5]. Thus, because the scenario used here has a long corridor and thick walls, about 20 ultra-wideband sensors would be needed to provide similar accuracy, but at a much higher cost.

3.5. Multicell management

Depending on the service, accuracy requirements may vary. For example, for an alarm system, it is enough to...
detect the room where a person is. However, for a guidance service, high accuracy is needed to provide correct guidance messages, and the same applies for finding things and people in the leisure and mobility training services. As has already been noted, multilateration may perform accurately with four to eight beacons in each room (the exact number depends on the size of the room and the number of obstacles). With just one beacon in each room, it will be possible to determine the proximity of tags in a way similar to the Active Badge infrared system [31], Bluetooth [32], or Cell of Origin in GSM.

The current scenario, a residence for people with disabilities, is a large area where some rooms need just proximity location while corridors and other spaces demand high accuracy (Fig. 6). A large number of beacons will need to be both synchronized and coordinated. The current research has developed a global multicell management schema that combines proximity (rough location) and multilateration (fine location) in a simple and efficient way.

Ultrasound signals share the same physical channel (overlapping near beacons which are emitting chirps) and cannot pass through walls. These particular features allow splitting of the coverage area into several small areas, i.e., location cells. These cells are defined by one or more beacons whose chirps reach a tag anywhere in the cell.

It is possible to take advantage of the previously described synchronization to schedule beacons and their corresponding location cells. Time is divided into slots in which the beacons will emit chirps, with enough duration to avoid ultrasound overlapping. Each beacon will emit chirps only in some slots, which are determined by a binary sequence code – a “one” in the code means to emit in that slot, while a “zero” means no emission. By logically OR-ing the codes of all the beacons belonging to the location cell, the cell code is formed (see Fig. 7). That cell code is used to identify the cell and must be unique. If at least three beacons belonging to a cell have exclusive slots where only they can emit ultrasound signals, some tags listening in that cell could measure three valid TOFs and perform multilateration. Then that cell will be a multilateration cell (M-cell); otherwise the cell will be a proximity cell (P-cell).

At the start of a location process, every beacon in every cell will emit chirps according to its code. Each tag will receive chirps in some time slots, from which it can deduce the code and identify the cell. Once the cell where each tag is located has been identified, if it is an M-cell, the beacons belonging to it (and their coordinates) are known, and the tag has already measured the TOFs of the chirps; therefore, the location of the tag can be estimated. There is no need for extra cell activations, and all tags can be located in the same cycle.

Another key issue is robustness against errors. In fine localization, the LMedS algorithm is robust to the presence of errors, but multilateration depends also on correctly identifying the cell where the tag is. Therefore, cell identification must also be robust against errors. The management schema is based on recognizing an ultrasound code which identifies a cell, so the receiving hardware should be immune to false ultrasound signals. Some possible ways to increase robustness are to use multi-frequency chirps or to implement a signature to differentiate signals from noise, but that requires increasing hardware complexity. Because the system use a binary code to identify the cell, which is “transmitted” in some way through the air by the ultrasound signal, it should be possible to use techniques such as parity or Hamming codes to mitigate data communication errors. If a binary code is used to identify a certain cell, a Hamming code can be applied to it, and

![Multicell management schema](image)

**Fig. 7. Multicell management schema.** (a) The cell has a slot code that defines chirp emissions. Each beacon has an effective code, which defines its emission, and the logical OR of all beacon codes gives the cell code. (b) Chirp emissions of several cells are defined by its codes. The tag will listen that chirps and can identify the cell where it is.
then the ultrasound emission in that cell can be set according to the new code. The tag will listen to the ultrasound signal with the Hamming code, decode it, and finally identify the cell.

4. System implementation

4.1. Architecture implementation

The beacons, implement ZigBee full-function devices, functioning in this context as routers, and together form a mesh network. The tags implement ZigBee reduced-function devices and can move freely, connecting to the network through beacons. There is also a ZigBee coordinator that initiates network formation and acts as a gateway. Because the ultrasonic range is lower than the ZigBee range, wireless communication does not impose any restriction other than power consumption. Routers are the most power-demanding devices because they cannot go to sleep, but because the beacons are fixed and powered from the grid, this is not a concern. Emitting ultrasound signals is also energy-demanding, but because TBS is implemented whenever beacons chirp, once again this is not a problem. Tags are mobile and battery-powered, so concerns about power consumption are critical for them. Each tag’s microcontroller stays in sleep mode when not communicating or locating. It wakes up periodically to measure acceleration and every 10 s to poll its parent and exchange one data packet. Each location process takes 12 cycles, or 600 ms, and polling the parent takes 20 ms. The average current consumption depends on how often the tag is located. Tags use a rechargeable LiIon battery having 600 mAh at 3.7 V capacity, and Table 2 shows the current consumption of each tag’s component in active and sleep modes. If a tag is located once every 10 s, it will last for 75 days, assuming 24-h operation. If it is continuously located, i.e., every 600 ms, its energy supply will last about 110 h. Fig. 8 shows a picture of the mobile device.

The system has been developed using Microsoft’s.Net Framework architecture and consists of several layers. In the lowest layer, communication with the ZigBee network gateway has been implemented. Above that, a virtual representation of the ZigBee devices and ZigBee network is constructed, allowing definition of the network and exchange of messages. Above the ZigBee layer resides the location core, which links the ZigBee devices with beacon and tag objects and takes care of localization tasks. Finally, the alarm service itself is based on the location core and the ZigBee layer.

4.2. System deployment and calibration

The first concern for practical implementation of the system is the number of devices involved, where to place them, and how to define the location cells. For each cell, two localization methods are considered: proximity and multilateration. Cells that perform localization by proximity usually require only one beacon (e.g., P02 in Fig. 6), although sometimes two beacons are used to ensure good ultrasonic coverage (e.g., P27 in Fig. 6). Where fine localization is needed, M-cells are defined (e.g., M## in Fig. 6). Because the pattern of obstacles in these cells is unpredictable, they are assigned from five to eight beacons to ensure that the system can cope with any ultrasonic blockages. Emission power and reception gain were tuned to ensure a maximum ultrasonic range of 15 m, corresponding to a 50-ms slot duration.

Fig. 6 shows the residence’s ground floor covering an area of 2000 m², which requires 88 beacons and is divided into 27 P-cells and 32 M-cells. Cell boundaries are chosen according to the “visibility” of beacons; places that receive chirps from the same beacons define a cell holding these beacons, and the codes of these beacons define the effective code of the cell. In large open spaces, such as the residence corridor in Fig. 6, cells usually are small zones where a tag can receive the chirps from only certain beacons, and these beacons also belong to several cells (the sole beacon inside cell M05 also belongs to cells M03, M06, M07, M08, and M09). Once the set of beacons in a cell is defined, a recursive algorithm assigns codes to beacons to ensure that the code of each cell is unique.

From the authors’ experience [19], beacon locations near the ceiling are preferred to maximize ultrasound coverage and avoid obstacles. Calibration of the system is an important issue, especially for the coordinates of the beacons forming M-cells. Direct measurement of the 3D distances to dozens of beacons placed several meters above the floor from a reference point with centimeter-scale precision is complex and laborious using 1D positioning systems such as measuring tapes. To deal with this problem effectively, the procedure described in [33] was used. Tags were placed in several positions and their coordinates measured (the tag coordinates were much easier to determine than the beacon coordinates because they are at ground level). Then the tag measures the signal transit times to all beacons in range, and the location of the beacons is computed by solving the inverse multilateration problem. Because the accuracy of the beacon locations will determine system performance, it is crucial that measurements of signal transit times be error-free in calibration mode. This procedure eliminates errors by multiple repetitions of the measurements and verifies agreement between distances measured by signal transit times and distances between measured tag positions and

<table>
<thead>
<tr>
<th>Tag component</th>
<th>Current in active mode (mA)</th>
<th>Current in sleep mode (μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microcontroller</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Wireless transceiver</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>(RX and TX)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultrasound hardware</td>
<td>4</td>
<td>0 (when not used, is disconnected)</td>
</tr>
</tbody>
</table>
calculated beacon coordinates. In deployments of this technology, it has been found that in calibration mode, these distances agree to within 1 cm if there are no signal blockages. In P-cells, beacon locations are not relevant, and therefore it is unnecessary to locate them precisely.

4.3. Privacy and ethical issues

A privacy and ethical analysis concerning location determination was undertaken for the third version of the location system [34]. Existing information on the topic was collected, supporting the definition of internal design guidelines such as obtaining consent for location, the exact nature of which will vary depending on the user profile, data storage, and data security. Recent studies on the ethics of LBS [35,36] posed unanswered questions about these LBS and also revealed the need for a suitable legal and ethical framework to address these concerns. Briefly, privacy requirements are associated with the information gathered from the users, and ethical issues are related to use or misuse of that information. Technology in general allows more and more collection of information from users, and sometimes this is done simply because the technology allows it.

The system presented here does not store any information which is not strictly necessary for the operation of the system itself. Of course, some information about each user must be stored, such as restricted areas, preferences, or the identification of the device he/she carries, but no information about users’ activity logs or habits is retained. Even the database support which existed in the third version of the system has been removed and replaced by XML files. Moreover, the alarm service reveals where a particular user or caretaker is only when an alarm sounds, so their privacy is maintained.

4.4. Evaluation

On the technical side, the system performed as expected. Locational accuracy was checked by estimating the location of a mobile device placed at 750 validation points throughout a test area of $8 \times 10 \times 5$ m with six beacons near the ceiling. Each location has a direct view of at least four beacons; a 99% confidence interval of <5 cm was obtained for the two-dimensional positioning error, increasing to <10 cm in three dimensions (3D). When analyzing the simultaneous position of two tags, the relative errors were <2 cm in 3D, which indicates that most of this error is due to calibration. Evaluation of tracking would have been possible only with a system with better performance than the current system. Nevertheless, people moving at a walking pace were satisfactorily tracked by visually checking their position. For the alarm service, fall detection was also verified to perform successfully by means of 340 falling tests with volunteers.

The entire service evaluation involves real users of the residence, and only a long-term study will provide the required information [37]. This evaluation is currently underway; meanwhile, as in other studies [38–40], the system has been evaluated through interviews with professionals in close contact with the final users of the service: social workers, occupational therapists, and educators. This procedure conforms to the ISO/IEC 9126-1 quality standard. Of the many items discussed in the standard, certain ones were selected because of their relevance to the users: functionality (suitability, accuracy, interoperability, and security), usability (learnability, understandability, operability, and attractiveness), and quality in use (effectiveness, safety, and satisfaction).

The evaluation began with a demonstration of how the system works. Feedback and suggestions were then collected by means of personal interviews and questionnaires on functionality, usability, and quality in use. The results agreed with the present study on the usefulness and design of the system, but pointed out certain issues related to the usability and learnability of the mobile device. For example, it would be convenient to have some colored LEDs to indicate the state of the device, or to provide a way to lock it.

5. Conclusions

An LBS can be based on a wide variety of positioning technologies, but often technology imposes hard constraints on what services an LBS can provide. This paper
has presented a novel indoor positioning system supporting alarm, guidance, and leisure services at a residence for people with disabilities. The system combines ultrasonic and ZigBee to perform localization simultaneously by two methods (proximity and multilateration), giving a rough or fine location as needed.

The system minimizes the infrastructure required while maintaining centimeter-scale accuracy and robustness to ultrasonic occlusions, thanks to the location strategy (TBS), the positioning algorithm (LMedS), and the ultrasonic hardware that provides a range up to 15 m. The multicell management schema is also key to coordinating a large number of wireless devices. This schema allows autonomous operation of the positioning system without the need for an external management entity.

Because this system needs 90% fewer beacons than other existing ultrasound-based systems, configuration and expansion are much simpler. The system uses off-the-shelf hardware, and therefore costs are greatly reduced compared with other technologies offering similar performance, such as ultra-wideband. Moreover, the use of ZigBee provides a transparent network management approach, in the context of which a novel synchronization method – a mainstay of the autonomous operation of the system – has been developed. Because ZigBee is also a standard, interoperability of the system with many others (such as environmental control systems) is ensured.

This research has also revealed issues related to implementation over a large area, demonstrated how this system can be used for many location-based services having similar requirements, and described how ethical concerns about gathering location information from the users were addressed. The correct technical operation of the system has been proved, and its service usefulness and suitability have been confirmed by experts in contact with the end users.

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