Tracking and Navigation for Goods and People

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1 INTRODUCTION

Classically, the aim of positioning is mainly to give orientation and navigational aids. As the rise of the global positioning system (GPS) as an inexpensive positioning technology, many applications have been designed that make daily life easier. Nowadays, the complexity of navigating a car in foreign environments has been completely moved into the digital world. The problem is reduced to having the right map, enough electrical power, and a concrete point of interest. This is one source of interest in indoor positioning services: namely, provide a high quality orientation service inside buildings. From this perspective, it would of course be optimal to have a seamless positioning system that works inside and outside buildings equally well based on the same technology. However, such a system does not yet exist.

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Sometimes, it seems that the aim for indoor navigation is a bit pointless, as often buildings are used by small, closed groups (except public buildings such as airports, shopping malls, etc.) and the problem is seldom orientation and localization. However, another reason for interest in indoor positioning comes from the areas of security management and control of production quality. High quality indoor positioning can allow activity recognition and can enable a production system to determine whether a given set of activities has been performed. As a very good example for the automotive domain, the paper by Zinnen, Wojek and Schiele (2009) explains how to use high quality ultrawide-band positioning to do some type of body-model-derived primitive selection to determine, in high dependability, whether a given set of quality checks has been done to a car. The only source of information in this case comes from the 3-D localization tags mounted to the quality checkers themselves.

The main barrier to a wide adoption of such systems lies, of course, in the area of privacy: that is, does the system give enough advantage over a classical checklist, such that the worker accepts that technology keeps himself under permanent surveillance?

A third area of application is, of course, the tracking of goods and people inside buildings. For goods, it can be very important to have a clear understanding of where and when the goods have been moved inside a warehouse. The tracking of people can be important and accepted in high-risk environments, where at any point in time a rapid evacuation might become essential. A common application domain where human beings need permanent surveillance inside buildings is the domain of ambient-assisted living. The aim of ambient-assisted living is to allow elderly people to live in their own homes for a longer time using digital surveillance where nowadays living in a nursing home is

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mandatory. Positioning and activity recognition are then used to detect situations where the residents need help immediately.

From this diversity of application domains and scenarios, many different positioning and navigation techniques have been developed, all of which have their strengths and weaknesses. In the following, we explain, in Section 2, the fundamentals of positioning systems and their relation to map information and different notions of position. Section 3 discusses the algorithms that can be used to infer location from observations at a high level of abstraction. In Section 4, we give a broad overview of the existing positioning systems. This section is organized along the physical sizes used for position determination and how the algorithms of Section 3 have been adopted to specific environments and systems. Section 5 concludes this article with a hint on research perspectives.

2 FUNDAMENTALS OF POSITIONING SYSTEMS

Position is possibly the most important source of context for mobile context-aware systems. However, position does not make sense without environmental information that can be used to infer some interpretation of location. This is essentially important for indoor positioning, as the determination of positions inside buildings is error-prone and hence the interpretation of positioning results becomes more complex.

2.1 Modeling of indoor locations

While for outdoor positioning, navigation, and guidance very simple maps containing a graph of roads interconnected by junctions would suffice, the problem of navigation cannot be solved by having a graph of "possible ways" inside a building. Imagine a large hallway with infinite possibilities of pedestrian movement, not only restricted to one-dimensional lines, for example, the edges of a navigation graph, but also free movement in a two-dimensional area. Providing step-by-step guidance or utilizing map matching with techniques known from outdoor car navigation is not possible. In addition, the determined positions are often not accurate enough to map the location to one single edge in a navigation graph.

As a solution to these problems, it is common practice to use more advanced environmental models than interconnected networks of points. These models are often tailored to the quality of the positioning system, the available map data, and the service demands of the intended location-based service.

Following Hightower and Boriello (2001), these models can be best understood from a classification of positioning algorithms. The authors define three types of such positioning algorithms that are described in detail in Section 3: triangulation, in which distances and angles are used to infer a position; proximity, in which the nearness to some known points is measured; and scene analysis, in which a set of observations, which vary with location, is used to infer a location of a mobile device. In the cited work, the authors limit scene analysis to a view from a particular point inside the navigation space; however, nowadays especially signal-strength patterns of existing wireless infrastructure are often used to infer positions with some method of machine intelligence that we want to include in the term "scene analysis."

On the basis of these three types of position inference, the type of position is completely different: triangulation approaches typically lead to numeric coordinates in some reference coordinate systems; proximity detection typically limits the possible set of locations to a smaller area; and scene analysis typically calculates some kind of probability distribution of location.

Hence, environmental models should be able to deal with these types of location. In consequence, environmental models inside buildings should be able to model geometric coordinates of course, but also to model symbolic coordinates such as room names. This is because, often, a scene analysis method reaches poor performance unless it is used with symbolic coordinates between which the measurements change significantly. Think for example of images taken with a camera. Two images of some object inside a room, which have been taken from different points, are still very similar, while the same movement distance between two other points might lead to fundamentally different images, because the semantic location has changed (e.g., leaving a room typically changes the complete appearance of the scene).

Consequently, indoor environmental models typically model location in a hybrid form and allow translating between symbolic and geometric coordinates. Furthermore, positioning is possibly based on symbolic coordinates, and hence on areas rather than points. To be able to calculate shortest ways, an environmental model must provide a sensible meaning of distance, spatial containment, and reachability even for symbolic places.

While the need of geometric coordinates leads to a spatial representation of the model in form of a coordinate system, where the building and relevant objects are assigned two- or three-dimensional coordinates, there are several ways to maintain symbolic coordinates. Becker and Dürr (2005) differentiate between set-based, hierarchical, and graph-based approaches. The set-based model consists of subsets of the set of all symbolic coordinates. The subsets can

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be used to define overlapping locations, but a set-based model directly supports neither distance nor reachability queries. Hierarchical models directly model containment of symbolic locations, for example, the containment of rooms in floors, but provide no information about topological interconnections between locations. In the graph-based approach, symbolic locations are modeled as the nodes of a graph that are connected by an edge if a direct real-world connection exists. This means that two rooms (being symbolic locations) are usually connected by an edge if there is a door in between. Graph-based models explicitly describe the reachability and enable the calculation of distances, but have no means to describe spatial containment. In conclusion, an indoor environmental model should not only be hybrid in form of symbolic and geometric coordinates but also have a graph-based and a hierarchical (or set-based) representation of symbolic coordinates.

2.2 Different aspects of positioning systems

Before different methods and systems are explained in detail, we want to focus on some aspects that can be important in choosing the right systems and for which, in contrast to the situation outside buildings where most systems rely on a single source of location such as GPS, different positioning systems are favorable.

The first general consideration is about mobility: if the targets to be localized are humans, they can move freely. If the target is a machine, its movement can be limited: a car cannot move sideways. If the mobility of the target is passive, for example, given by conveyor, the possible movement is completely known. Of course, this should influence the choice of the positioning system. A simple and inexpensive radio frequency identification (RFID) detector gives a pretty exact location in time and space for a conveyor-based production system using proximity. RFID for localization of people would lead to very expensive systems, as the functionality of RFID is limited to a very small area and hence a sensor network of RFID readers would have to be deployed and maintained at high costs.

Another important general consideration is among the scaling parameter. Often, there is a correlation among cost, accuracy, and coverage. If the positioning system has to provide a highly accurate position to a single mobile entity, an expensive inertial sensor unit can be the best choice. On the other hand, systems that have to provide a coarse location to a multitude of objects will not use expensive sensors mounted on to the objects. They should rely on infrastructure-based positioning, optimally on existing infrastructure, as is the case with wireless local area network (WLAN) localization.

Cost calculations and their scaling with respect to accuracy, coverage, and the number of targets can be very important for the right choice of indoor positioning systems. From this viewpoint, one typically differentiates between terminal-based positioning, where the sensing and position calculation is carried out by the mobile entity itself, infrastructure-based positioning, where the position of a mobile item is determined by some infrastructure possibly without any communication with the mobile entity, and terminal-assisted positioning, where the position of a mobile entity is calculated by some infrastructure, but the sensing of the parameters for position estimation is done by the mobile entity.

The use of dedicated infrastructure in general leads to installation and maintenance costs that scale with the area of localization. A modern highly accurate indoor positioning system based on ultrawideband technology typically uses four or more sensors per room, all of which need dedicated power and communication cables and induce costs, of course. The use of existing infrastructure such as WLAN, however, does not incur any (additional) costs. However, indoor localization using WLAN is much less accurate than indoor localization using dedicated wideband signals.

For terminal-based positioning systems, costs basically scale with accuracy, electric power demands, and the number of items to be localized. Every mobile item has to be able to calculate its own position and basically needs a computation unit and a sensing unit. If not only the mobile entity itself is interested in the position, one additionally needs a communication unit. Nevertheless, the effort has one advantage: terminal-based positioning offers privacy, which might be a desirable goal for the sensitive location information of a human user.

For terminal-assisted positioning systems, costs basically scale with all these parameters: the area of coverage where the infrastructure has to be installed and maintained, the number of mobile objects that have to be localized, and the desired accuracy and precision of location. However, in some cases, no additional costs occur at all. Think of using existing mobile phones, which already have a WLAN interface, along with an existing WLAN infrastructure and an Internet-based localization service, which takes signal strength information and returns location. In this situation, no additional cost is generated, and truly ubiquitous and cheap indoor localization becomes possible, although limited in accuracy, as WLAN was never designed to be used for localization.

Thus, when thinking of installing an indoor positioning system, one has to carefully consider the design principles and weigh the cost against the desired accuracy and coverage. Another basis for the right choice of system is given in form of the positioning methods used, because

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they also have an impact on the deployment, the infrastructural needs, and even the required physical properties of the site. Some systems, for example, only work in line-of-sight conditions between the positioning infrastructure and the target.

3 POSITIONING METHODS

Localization and tracking of people and goods inside buildings is much more difficult as compared to positioning outside buildings. The main reason is that radio-based methods have difficulties dealing with attenuation and multipath effects. Hence, many methods that are dedicated to deal with these circumstances and are able to even exploit these propagation complexities have been developed.

As described in the previous paragraph, a simple way to organize positioning methodology (following Hightower and Boriello (2001)) is into the three categories of triangulation, proximity detection, and scene analysis. We want to follow this organization, but add a fourth type of position determination called *dead reckoning*, in which an initial position is updated according to measurements concerning the acceleration, movement, and heading of a mobile entity.

3.1 Triangulation

The methods of triangulation are defined to be using the geometry of a plane triangle to deduce position information. One such method is lateration, in which distances between known points and a mobile entity are measured. Another such method is angulation, in which angles between different reference positions and a mobile entity are measured. Combinations are also possible: for example, the measurement of an angle and a distance from a known point resulting in a position.

3.1.1 Lateration

The most common method of triangulation is multilateration in which multiple distance measurements from multiple reference points with known locations are being used to find the position. For undisturbed measurements, a single distance estimation limits the locus of the object to be tracked to a circle centered at the given reference position with a radius given by the distance measurement. As a result, at least three reference positions (which must not be collinear) are needed to be able to uniquely identify the location of the target. In practice, such circles will not intersect in a common point because of measurement errors. It is common practice to use Gaussian least-squares regression on a linearization of the circle equation given by a Taylor series expansion. As a characteristic of such extensions, this results in a correction vector for an initial position, which could, for example, have been chosen as the middle point of all reference points. This correction vector is then used to update an initial position until this process converges to the position of minimal least-squares residuum.

A special form of lateration is given by hyperbolic lateration, where only the distance difference of a mobile entity to pairs of reference stations is known. As all points that have the same distance difference to two fixed points give the definition of a hyperbola, this is known as *hyperbolic lateration*. The method of dealing with disturbances is the same as for classical lateration; only the circle equations have to be replaced by the hyperbolic equations for the Taylor expansion.

3.1.2 Angulation

For position determination by angulation (Figure 1), the angles between given reference positions are measured, for example, by antenna arrays, and the location of the mobile entity is given by the intersection of rays starting at each reference location into the measured direction. For this intersection to take place, the orientation of the reference measurement units has to be known. Again, the method of Gaussian least-squares regression along with Taylor linearization leads to an iterative location determination algorithm. The measurement of angles at known reference locations is very dominant in practice, but it is important to mention the possibility of measuring all angles at the mobile entity. This typically leads to complexity in mobile entities, but the consistency between angles is automatic.

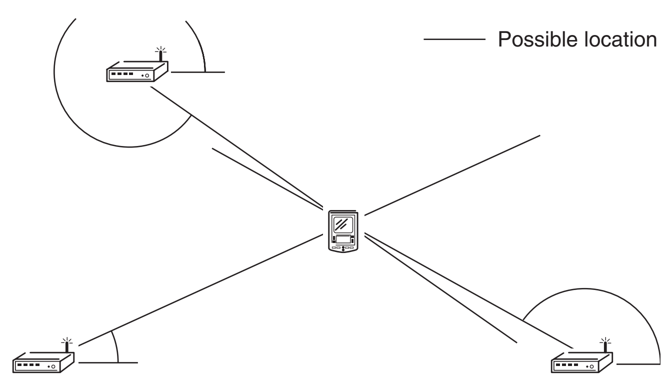

Figure 1. Location determination by angulation.

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Inside buildings, it is difficult to infer a distance between two points. Consequently, lateration in general leads to erroneous results inside buildings. Nevertheless, in areas where the propagation characteristics of signals are known (typically free space for sound, light, and radio waves), lateration is used. For the determination of distances, there are two main possibilities: either a measurement of signal strength that leads to a distance estimation based on expected path loss, or a measurement of time. For time measurements, the following three main methods can be distinguished: time of arrival, time difference of arrival, and roundtrip time of flight.

3.1.3 Time of arrival

In the case of time of arrival, pilot signals are sent at a known time at known locations. The time difference between sending and receiving of a pilot signal can often be used to infer the distance from the propagation speed of the signal (e.g., speed of light, speed of sound). These distances are called *pseudo-ranges*, as they can be quite different from the actual distance because of time synchronization errors, reflection, scattering, shadowing, and fading. All entities have to be time-synchronized, and one pseudorange estimation leads to a circle of possible locations. The position is then given by the intersection of those circles (Figure 2). This is in effect the same method as used by GPS.

3.1.4 Time difference of arrival

For the case of time difference of arrival, pilot signals are emitted at the reference locations at equal times, and the mobile entity records the time difference between receiving those pilot signals. This gives a good basis for hyperbolic multilateration. The most important advantage over the classical time-of-arrival method lies in the fact that the mobile entity needs no time synchronization with the infrastructure at the reference locations. As all points that have the same distance difference to two different positions lie on a hyperbola, each distance difference estimation leads to a hyperbola and the position is given by the intersection of these hyperbolas for more pairs of reference locations.

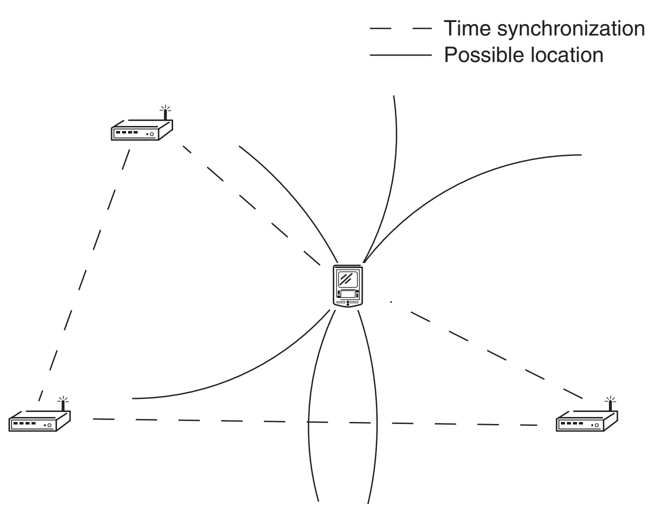

Figure 2. Time-of-arrival positioning.

3.1.5 Roundtrip time of flight

In scenarios of roundtrip time of flight, (typically) the mobile entity initiates a measurement by sending a signal that is mirrored back either by physical objects in space or even by active stations located at known reference locations. The mobile entity measures the time difference between sending the initial signal and receiving the reflected signal. Half of this time, possibly reduced by a processing time for active reflectors, gives the time that the signal needed to travel from the mobile entity to the reflector, which can be translated into a pseudo-range using the signal propagation speed (Figure 3).

3.1.6 Angle of arrival/angle of emission

For angulation, two main types of angle determination can be distinguished. The first one is associated with the term "angle of arrival," in which the angle of an incoming signal is determined, for example, by an antenna array. The second variant is called *the angle of emission* or *theta coding*, in which a signal is sent out, containing digital or analog information identifying the angle of emission. In both cases, the angle information is used along with the known reference locations to infer a position.

3.2 Dead reckoning

Dead reckoning is a method of calculating subsequent positions out of a fixed initial position. As such, dead reckoning is often based on the measurement of initial sensors giving acceleration and heading. All these sensors have in common that they measure a first or second derivative of the location (e.g., acceleration, acceleration in rotation, velocity). The location at a given time is then given as the integral of these accelerations. For discrete measurements, this integral is given by a sum. The most important problem of this type of positioning is the fact that measurement errors add up, leading to an unrealistic

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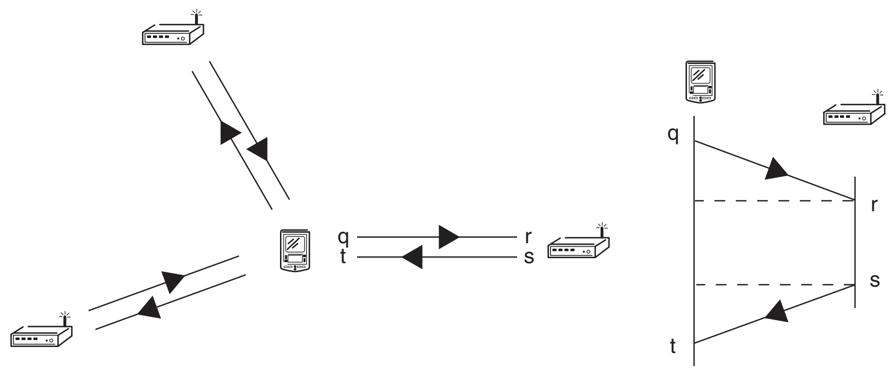

Figure 3. Roundtrip time-of-flight positioning.

movement state (e.g., nonzero speed for a stationary object) and location. Hence, dead reckoning is typically used as an intermediate method for the time between two subsequent position fixes of a slow positioning system or using high-quality, expensive sensors in a short timeframe.

3.3 Presence detection

Presence detection can be seen as a special form of lateration in which it is only known that the distance between a mobile entity and some reference point is below a fixed threshold (e.g., given by the area of coverage of a wireless network). In these cases, the position is often given as the mean of the positions of the stations that detect presence or as a symbolic coordinate.

3.4 Scene analysis

The technique of scene analysis uses methods of pattern matching and artificial intelligence to recall long-living environmental properties of given locations. A classical approach called *fingerprinting* is to divide the navigation space into cells that can be characterized by some statistics of measurable values such as the signal strength distribution of an existing wireless infrastructure. This type of positioning is often tied to a specific application and does not allow for a general description. You will find many different examples throughout the next section. In general, scene analysis is in some sense orthogonal to triangulation, as disturbances of propagation can be very characteristic for a specific place, and pattern-matching can be much more precise for highly perturbed signal propagation scenarios where the performance of geometric location determination techniques degrades. Scene analysis techniques are successfully used on almost any environmental feature that can be measured by mobile entities and varies with location (Figure 4).

4 TECHNOLOGIES FOR INDOOR POSITIONING

With the high number of positioning methods, it is no surprise that there also exist a multitude of technologies that can be used to infer the position of a target in indoor environments. Often, each technology supports multiple methods and each method can be applied with a variety of technologies. In the following, we give an overview of those technologies and the corresponding methods that are used to infer positions, accuracy levels, and application scenarios.

4.1 High sensitive GNSS, pseudolites

Signals of global navigation satellite systems (GNSSs), for example, GPS, suffer from attenuation effects and multipath mitigation in indoor areas. Therefore, those systems offer inaccurate or no position information at all, which can be compensated by senders on ground, for example, in or near the buildings, where position information is needed.

One kind of such senders, called *pseudolites*, emit GPS-like signals that can be used for lateration based on the time of arrival. Similar to satellite positioning systems, these senders need to be strongly time-synchronized and their position must be precisely known (Cobb, 1997). The signals can be used either together with existing GNSS to enhance the visibility of signals in degraded environments or to provide additional senders for more reliable and accurate positioning, or independent of any satellite system for the purpose of indoor positioning without reception of satellite signals. While pseudolites can offer very high accuracies of few centimeters or even millimeters (Cobb, 1997), they do not work well in non-line-of-sight conditions. Owing to their high accuracy, pseudolites can be used in automated industrial production.

A system similar to pseudolites is the Locata system. Locata offers a time-synchronized network of LocataLites,

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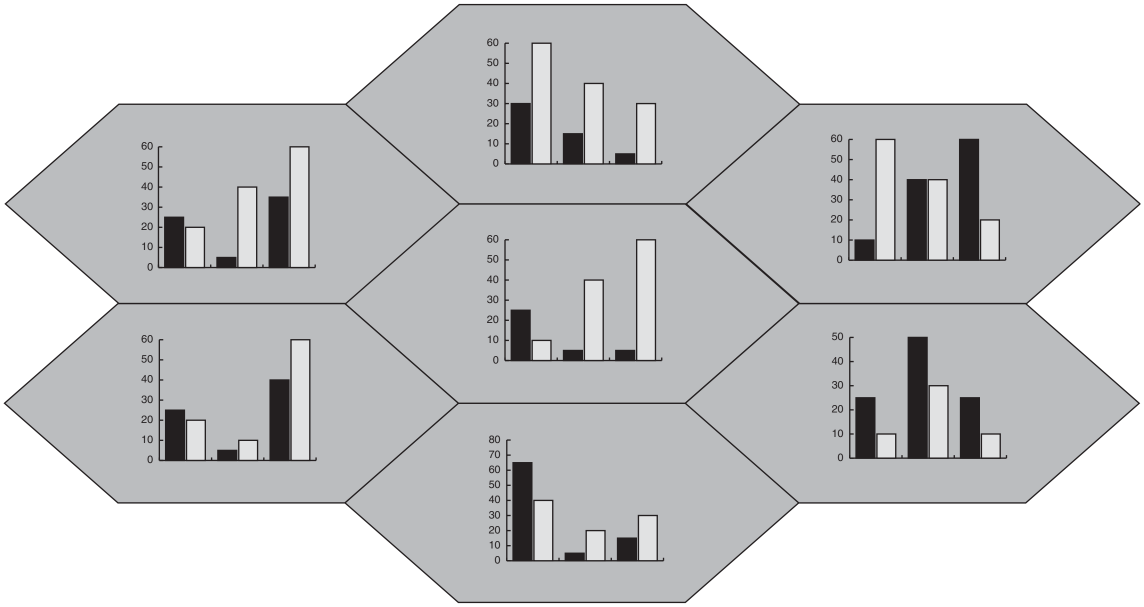

Figure 4. Scene analysis and position fingerprinting.

which transmit GPS like signals in another frequency spectrum [e.g., the license-free ISM (industrial, scientific, and medical) band at 2.4 GHz]. These signals can be used to calculate the position of a component called *Locata*. This component is able to receive standard GPS signals as well as signals from LocataLites and, therefore, is able to calculate its own position with centimeter-level accuracy even when no or too few GPS signals are available for position calculation, as long as enough LocataLites are visible (Rizos *et al*., 2010).

Despite the complex signal propagation in buildings, there are approaches to provide indoor positioning with highly sensitive GPS or GNSS receivers. Even if the signals are weak and might have been reflected, they can be detected with the help of highly sensitive receivers and utilized for position calculation. Experiments demonstrate the ability of such systems to offer positioning capabilities in indoor areas, but the accuracy is generally lower than in outdoor areas.

4.2 Light-based systems

A very promising technique for indoor localization is the use of special light. As light interacts with most indoor material in a much more deterministic way as compared to radio signals, it is possible to calculate distances to objects using the methodology of roundtrip time of flight. These systems are called *LiDAR* (light detection and ranging) systems. The term *LiDAR* reflects the fact that the basic working principle is the same as the one used by radar outside.

Travis, Simmons, and Bevly (2005) were able to detect depth information in a field of view spanning 180° with high frequency, allowing positioning and even continuous navigation using existing maps. The same system can also be used to generate three-dimensional map information using techniques of "simultaneous localization and mapping" (SLAM). Such systems can basically be enriched by the application of detectable landmarks and mirrors for the laser detection. With the use of a few such landmarks, variations in the depth image (due to existing or missing objects) do not harm the positioning process anymore. Tracking of special natural features inside buildings (such as edges, corners, and other regularities) is also possible by application of some image processing and analysis to a LiDAR-acquired depth image, possibly in combination with a camera image (Adams and Kerstens, 1998).

The same type of information can be generated by a much cheaper technology that does not rely on the measurement the roundtrip time of flight of a laser signal. By sending out a regular pattern of light, it is possible to calculate a depth image by observing the deformation of the pattern due to obstacles. The best-known example of this type of system is the Kinect, which is used by the Microsoft XBox to track movements of players. Unfortunately, the working range of such systems is bounded by the resolution of the camera used to detect the pattern.

Another class of light-based systems relies on presence detection by generating modulated light inside the

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navigation space. This modulated light can be generated by an infrastructure and detected by mobile devices allowing for self-contained positioning, or the mobile entity can send an identification code to a network of sensors (Want *et al.*, 1992).

Though the use of color image information detected by a digital camera is of course a kind of light-based systems, we describe camera-based systems in a separate section because the techniques are quite different from active light-based positioning systems.

4.3 Camera-based systems

Another technology often found in indoor positioning applications is a camera. The field of camera positioning can be subdivided according to two different approaches. In the first approach, cameras are attached to a moving object with an unknown position that should be determined. This is called *camera egomotion* in the following. The other approach relies on stationary cameras with known positions, which are used to estimate the position of targets moving through the cameras' views (Mautz and Tilch, 2011).

In camera egomotion, there are again different methods for position determination. One method relies on scene analysis, where distinctive features, objects, or landmarks are extracted from the camera view. In the case of natural features, they are compared with a database of previously recorded images, where the position of recording is known. Depending on the size of the database and the resolution of the images, the matching may take some time, but offers highly reliable position information. Werner, Kessel and Marouane (2011) were able to obtain submeter-level position accuracy with natural feature matching. Problems arise from different points of view concerning the database images and the image used for positioning, which leads to scaled and rotated variations of the captured scene. Therefore, scale- and rotation-invariant descriptions of scenes, for example, generated by the well-known SIFT (scale-invariant feature transform) algorithm (Lowe, 2004), offer high reliability. Instead of natural features, artificial distinctive markers such as barcodes can be distributed in the environment. When the position of the marker is known or can be stored inside the marker itself, the problem of scene analysis can be reduced to the detection of markers in an image. This problem is much easier to solve and faster to calculate than natural features, but the markers need to be set up carefully and are prone to partial occlusion by other objects.

Another method for position estimation often encountered in camera egomotion is the use of time-domain information from consecutive images, called *optical flow*. The technologies of SLAM, for example, calculate the movement of a camera projection between adjacent frames by solving a point-set configuration problem that comes from marker or natural feature comparison between frames. This type of system suffers from accumulation of measurement errors over time, as the next position is always calculated from the previous defective position. For recalibration, SLAM often relies on a technique called *loop closure*, where the mobile entity returns to an already mapped location. By identifying the scenery, errors in the trajectory can be corrected and the map quality heavily enhanced. However, this type of algorithm soon gets very complex, as it depends on the complete history, and the point-set configuration problem in itself is very hard and often only solved using a randomized Monte Carlo method.

There are some other systems that use commercial optical mouses (or similar techniques by taking a video of the ground) for dead reckoning (similar to optical flow). These systems are, for example, found in low-cost robot localization systems, where the sensor data of the mouse is used to compensate slip effects of the robot's wheels.

Stationary cameras detect targets moving through the captured scene. As the position of the camera and the position of objects in the field of view can be calibrated, it is easy to retrieve the position of a target. However, stationary cameras are faced with the task of identifying targets in the scene to assign the calculated position to the right target. Furthermore, it can be expensive to provide full coverage for the whole area of positioning and might imply privacy problems, as photos or videos of individuals could be recorded to calculate position estimates and map them to users. In addition, image segmentation needs to be performed carefully in the case of partial occlusion when multiple users are in front of the camera. Therefore, stationary cameras are often used for high accuracy positioning of robots or construction components in automated production scenarios.

4.4 Radio-based systems

Many systems for indoor positioning are based on radio signals. However, there are many different methods and technologies, and how radio information is utilized to deduce the position of a target. There are approaches based on timing, for example, time of arrival, time difference of arrival, and roundtrip time of flight, based on signal strength, either for lateration or for scene analysis (here often called *fingerprinting*), based on angulation, or even presence detection. A similar diversity can be observed concerning the radio technologies. There exist systems based on cellular networks for mobile communication

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such as GSM (global system for mobile communications) or CDMA (code division multiple access), personal area networks such as Bluetooth, WLAN, RFID, or ultrawideband. Even radio or television signals can be used for indoor positioning.

Utilizing radio signal for positioning is not a new idea, as in outdoor areas the common positioning technologies GPS and cellular positioning rely on radio signals. The latter also work in indoor areas, but suffer from increased inaccuracy because of the multipath propagation, fading, and attenuation. Furthermore, the physical characteristics of cellular communication enable the signals to easily penetrate walls, making it hard for fingerprinting techniques to distinguish between adjacent rooms.

Owing to the lower range (less transmit power) and the physical characteristics of the frequency band (higher frequency), WLAN-based techniques are often able to provide more accurate position estimates as compared to cellular positioning. When using fingerprinting (which is considered to be more accurate than timing approaches), the estimated position in indoor areas often lies within a few meters of the real position. Furthermore, many buildings have already an infrastructure of wireless access points installed. One of the first methods for WLAN positioning was based on fingerprinting (Bahl and Padmanabhan, 2000). However, fingerprinting requires a time-consuming calibration phase with the need for recalibration when structural changes alter the signal propagation characteristics. Much research has been done on the subject of calibration. There are approaches dealing with the simulation of propagation of WLAN signals, allowing automatic calculation of the expected signal strength [e.g., by using a building model, a propagation model, and counting walls between the known position of an access point and a certain reference position (Bahl and Padmanabhan, 2000)], automatic calibration techniques using crowd sourcing approaches, additional measurement stations, or mobile robots (Ocana *et al*., 2005). Another field of extensive research is dedicated to the algorithms for position estimation. Machine learning algorithms such as *k*-nearest neighbors, naïve Bayes or Bayesian networks, support vector machines, and neuronal networks have been proposed and extensively utilized for positioning (Liu *et al*., 2007). WLAN is often the basis of cheap pedestrian positioning systems in environments where a WLAN communication infrastructure already exists. However, a trend toward a combination of WLAN fingerprinting with additional positioning technologies such as inertial sensors exists.

While WLAN-based positioning techniques seldom acquire submeter-level accuracy, methods based on ultrawideband do. Those systems usually calculate the position based on short pulsed signal bursts from a target, which are received and evaluated in a time-synchronized infrastructure of receivers. One of the most successful commercial systems, Ubisense, combines time difference of arrival and angle of arrival for 3-D positioning with centimeter-level accuracy (Steggles and Gschwind, 2005). Owing to limitations in transmit power, most wideband-based systems typically are restricted to approximate line-of-sight conditions, that is, do not provide coverage through walls. As ultrawideband-based systems are comparatively expensive, they are often set up in industrial production scenarios in large factory halls, where the benefit compensates the expenses.

Another radio-based technology, RFID, is mainly used for presence detection in positioning scenarios. RFID readers are placed throughout the building, especially in corridors or at doors, and their position is stored according to a reference system. Whenever a target comes near such a reader, the system is able to receive a short-range signal from the target's RFID tag and can therefore deduce that it is near the position stored for that reader. While the main use of RFID is the identification, a coarse location of an identified item can also be retrieved when the location of the reader is known. This is often the case in industrial settings, for example, when RFID is used to locate and identify objects on a conveyer.

Finally, any other radio technology can be used to infer the position of a target using one of the described methods. The reason why WLAN is popular at the moment comes from the distribution of WLAN and the capability of mobile devices used for positioning. Some 20 years ago, a system would use infrared as a near-field communication and presence detection technology, while this can nowadays be achieved by near-field communication or Bluetooth. The latter could also substitute WLAN positioning, but as there often is no fixed Bluetooth infrastructure, it is seldom used for positioning.

4.5 Inertial navigation

Inertial sensors measure physical effects independent of any infrastructure. Examples are accelerometers sensing acceleration and gravity, gyroscopes measuring rotation, magnetic field sensors (i.e., compass) for orientation, barometers measuring the air pressure that can be used to deduce the altitude of the sensor, and odometers measuring wheel rotation to calculate the traveled distance. Some of these sensors provide absolute values such as the direction of a compass or the altitude of a barometer, whereas some offer relative changes such as the rotation of a gyroscope or the acceleration as a change of velocity. In general, inertial sensors do not provide a position directly, but can

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only report changes of position. Thus, inertial measurement units (IMUs) rely on dead reckoning techniques for position estimation and generally need to be supported with an initial position. However, the drift of IMUs leads to an accumulation of the position error over time.

For indoor positioning, inertial sensors are often combined with other positioning technologies to compensate for the drift, and to offer a better accuracy, coverage, or continuity. This integration is achieved by sensor fusion mechanisms such as Kalman (Kalman, 1960) or particle filters (Arulampalam *et al*., 2002). While the Kalman filter is an approach for modeling linear dynamic systems with a Gaussian distribution, particle filters are sequential Monte Carlo methods where a continuous probability distribution is approximated by a point cloud of particles. For indoor positioning, however, both work with a state vector and two phases called *prediction* and *update*. The state vector represents all relevant information of the observed system, that is, the estimated position, speed, and orientation of the target. This vector is altered in the prediction phase according to a system model that is often based on IMU data and then corrected using a measurement model based on absolute but noisy position measurements of some other technology. From a statistical point of view, the prediction and correction can be understood as the prior and the posterior distribution in a Bayesian approach.

In the field of indoor positioning, IMUs have been investigated mainly for pedestrian positioning, utilizing accelerometers as pedometer by counting steps or to measure the speed by integrating the acceleration in combination with a compass or gyroscope for the direction of movement (Woodman and Harle, 2008). However, there is also ongoing research for robot localization and SLAM techniques.

4.6 Audio-based systems

Using audio signals for indoor positioning is one of the early approaches for indoor positioning, but has continued as an active field of research up until now. The early systems such as ActiveBat (Ward, Jones and Hopper, 1997) used ultrasonic signals emitted by a moving target, which were captured by a dense infrastructure of receivers. Those approaches offered centimeter-level accuracy at high expenses, meaning that the infrastructure was expensive and therefore was only installed in small areas such as meeting rooms. The positioning method used for these systems is often multilateration based on time of arrival or time difference of arrival.

Many other approaches, such as microphone arrays capturing the main direction of pulsed audio signals or the utilization of the acoustic background spectrum in different rooms, have also been investigated in recent years. Microphone arrays are used together with angulation techniques, where either an infrastructure of senders with known positions emit pilot signals (beacons) and the target determines its position with the help of the microphone array (by exactly measuring the time of reception or signal strength of the signal at each microphone in the array), or the target transmits audio signals and the infrastructure of microphone arrays captures the signal and calculates the position of the target.

The technique based on the acoustic background spectrum was investigated for pedestrian indoor localization with smartphones in a university building (Tarzia *et al*., 2011). The authors were able to distinguish between several rooms at different times of day, although the chatter of multiple people impeded the use of their system.

4.7 Pressure-based systems

Finally, there exist some very specialized indoor positioning systems that measure the pressure created by a target moving over the ground. One system, the Smart Floor (Orr and Abowd, 2000), is based on a network of pressure sensors in the ground to detect location and identity of pedestrians using the user's footfall signature. The system was trained with a small number of 15 persons and was able to locate and identify more than 90% of the trained persons correctly. Smart Floor has its application area in a smart home environment, where only few different users need to be tracked and identified.

5 CONCLUSION

With this article, we have given a recent overview of the topic of indoor positioning with a strong focus on the task of positioning. Positioning is very complex inside buildings and applications range from navigation over production control to activity inference and business process automation.

Obviously, a position is meaningless without a sense of position, which is typically given by an indoor map. The topics of map creation, map modeling, and navigation semantics have been described very coarsely. A good source of information is Becker and Dürr (2005), which explains very clearly why indoor maps have to be different from outdoor maps and what they have to provide. We expect that standardization will make the generation and exchange of indoor maps favorable soon. Unfortunately, at this point in time, there is neither a standard nor a

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common sense how navigational information for indoor environments can be modeled.

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GLOSSARY

Angle of arrival	A method for determining the angle between two entities in which the angle of an incoming signal is measured, for example, by an antenna array
Angle of emission	A method for determining the angle between two entities in which the angle of an outgoing signal is coded into the signal and can be decoded by the receiver
Dead reckoning	A method for position determination based on a previously known position and measuring the change in position, for example, by measuring speed and direction of movement
Infrastructure-based positioning	Describes positioning systems that measure signals from and computes the position of a target without the need of a communication channel
Proximity detection	A method for localization based on the finite propagation distance of signals (i.e., the distance at which a signal still can be recognized), where the position can be assumed to be near the known position of the sender of the signal
Roundtrip time of flight	A method for determining the distance between an entity and a target that relies on the total traveled time of a signal whose propagation speed is known from the entity to the target and back
Scene analysis	In the context of indoor positioning, describes a method of localization by matching received signal pattern with known pattern, where the position of occurrence is known
Simultaneous localization and mapping	Stands for a technique where no initial map or reference data is available for positioning but is created on the fly and localization is performed with respect to the already generated incomplete map data
Terminal-assisted positioning	Describes positioning systems in which the mobile terminal measures signals and sends the gathered information to some fixed infrastructure, where its position is computed
Terminal-based positioning	Describes positioning systems in which a mobile terminal measures all signals and computes the position of itself without the need of a communication channel to any infrastructure
Time difference of arrival	A method of determining the distance between entities that relies on the time difference between two signals sent at the same time at different locations to identify the location of a mobile entity
Time of arrival	A method of determining the distance between entities that relies on the time of arrival of a signal to identify the time of flight of a specific signal whose propagation speed is known
Triangulation	Stands for localization techniques that make use of triangular geometry including lateration, angulation, and their combinations

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