TELEMATICS TECHNOLOGIES – INDOOR POSITIONING: TRACKING AND NAVIGATION FOR GOODS AND PEOPLE (AUTO174)

*Comment: The original title was **Positioning: In-House Positionig.** we would prefer the technical term **Indoor Positioning**, as it is more widely used in the community.*

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Keywords: Positioning, Navigation, Indoor, Triangulation, Lateration, Angulation, Time-of-Arrival, Time-Difference-of-Arrival, Roundtrip-Time-of-Flight, Dead Reckoning, Pattern Matching

***Abstract* –** Indoor positioning has become very popular in recent years. Application scenarios range from pedestrian navigation over asset tracking to automated industrial production, and with the variety of use cases, also the diversity of indoor positioning methods, technologies and systems grows. This article explains how indoor positioning works, describes the basic methods such as lateration, dead reckoning and scene analysis, motivates the need of indoor environmental models and gives a comprehensive overview on existing and future indoor positioning and tracking systems classified according to the positioning technology in the rough context of automotive telematics and production. One aspect is the design principle and usability of certain methods and technologies for the complex problem of indoor positioning, while considering different parameters such as accuracy, coverage and cost.

I. INTRODUCTION

Classically, the aim of positioning is mainly to give orientation and navigational aids. Since the rise of the Global Positioning System (GPS) as a cheap positioning technology, many applications have been designed, which 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: Provide a high quality orientation service inside buildings. From this perspective, it would of course be optimal to have a seamless positioning system which works inside and outside buildings equally well based on the same technology. However, such a system does not yet exist.

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. But 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 for 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 (Zinnen, Wojek and Schiele, 2009) explains how to use high quality ultra wideband positioning to do some type of bodymodel-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 3D localization tags mounted to the quality checker himself.

The main barrier to a wide adoption of such systems lies, of course, in the area of privacy: 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, 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 elder people to live in their own homes for a longer time using digital surveillance where nowadays living in a nursing home is mandatory. Positioning and activity recognition are then used to detect situations where the residents needs help immediately.

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

II. 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 which 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.

i. Modeling of Indoor Locations

While for outdoor positioning, navigation and guidance very simple maps containing a graph of roads interconnected by junctions 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, e.g., the edges of a navigation graph, but 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 which are described in detail in Section III: 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, but nowadays especially signal-strength patterns of existing wireless infrastructure are often used to infer positions with some method of machine intelligence which we want to include in the term Scene Analysis.

Based on 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 be able to model symbolic coordinates such as room names. 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).

As a consequence, indoor environmental models typically model location in a hybrid form and allow for translating between symbolic and geometric coordinates. Furthermore, positioning is possibly based on symbolic coordinates and hence based on areas rather than points. To be able to calculate shortest ways, 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 be used to define overlapping locations, but a set-based model neither directly supports distance nor reachability queries. Hierarchical models directly model containment of symbolic locations, e.g., 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 which 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.

ii. DIFFERENT ASPECTS OF POSITIONING SYSTEMS

Before different methods and systems are explained in detail, we want to focus on some aspects which 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, e.g., given by conveyor, the possible movement is completely known. Of course, this should influence the choice of positioning system. A simple, cheap 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 between 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 which have to provide a coarse location to a multitude of objects will not use expensive sensors mounted to the objects. They should rely on infrastructure-based positioning, optimally on existing infrastructure as it 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 point of view, 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 which scale with the area of localization. A modern, highly accurate indoor positioning system based on ultra wideband technology typically uses four or more sensors per room which all need dedicated power and communication cables and induce costs, of course. The use of existing infrastructure such as WLAN, however, does not induce 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 with 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, which 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, 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 weight 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 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.

III. 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 which 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.

i. 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.

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 due to measurement errors. It is common practice to use Gaussian least square 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 square 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 which 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.

ANGULATION

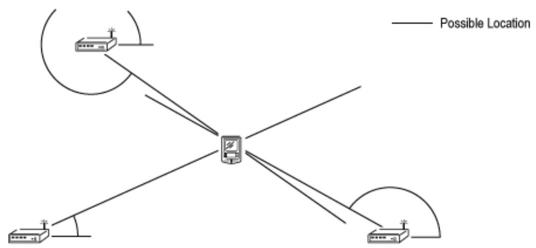

Figure 1: Location Determination by Angulation

For position determination by angulation (see Figure 1), angles between given reference positions are measured by for example 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 square 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.

Inside buildings, it is difficult to infer a distance between two points. As a consequence, 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 which 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.

TIME-OF-ARRIVAL

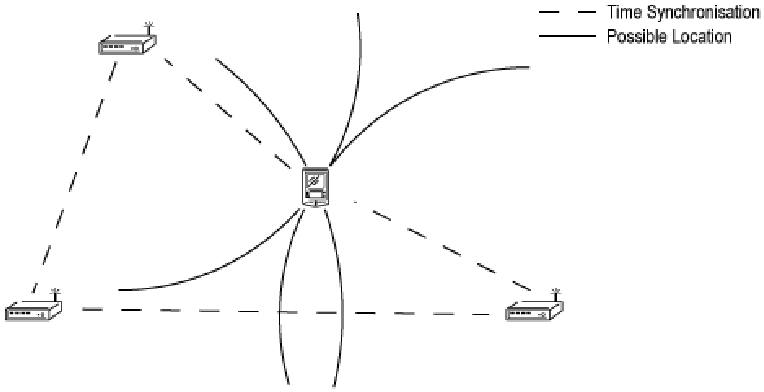

Figure 2: Time-Of-Arrival Positioning

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 a 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 due to 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 location. The position is then given by the intersection of those circles (see Figure 2). This is in effect the same method as used by GPS.

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 the receptions of those pilot signals. This gives a good basis for hyperbolic multilateration. The most important advantage over classical Time-of-Arrival 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 hyperbola for more pairs of reference locations.

ROUNDTRIP-TIME-OF-FLIGHT

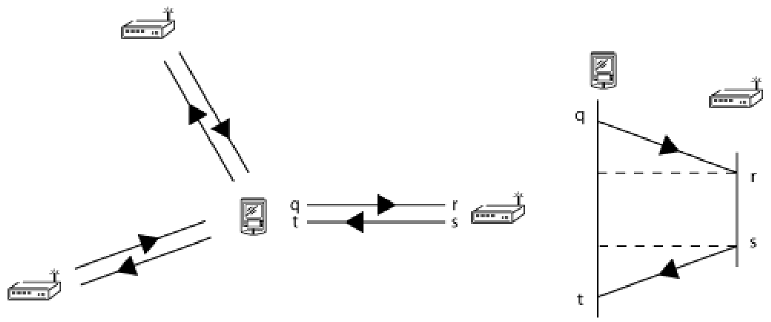

Figure 3: Roundtrip-Time-Of-Flight Positioning

In scenarios of Roundtrip-Time-of-Flight, (typically) the mobile entity initiates a measurement by sending a signal which 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 of the initial signal and reception of the reflected signal. Half of this time, possibly reduced by a processing time for active reflectors, gives the time which 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.

ANGEL-OF-ARRIVAL/ANGLE-OF-EMISSION

For angulation two main types of angle determination can be distinguished: The first one is associated to 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 Angle-of-Emission or Theta-Coding in which a signal is sent out, which contains 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.

ii. 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 are adding up leading to unrealistic movement state (e.g., non-zero 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.

iii. 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 which detect presence or as a symbolic coordinate.

iv. Scene Analysis

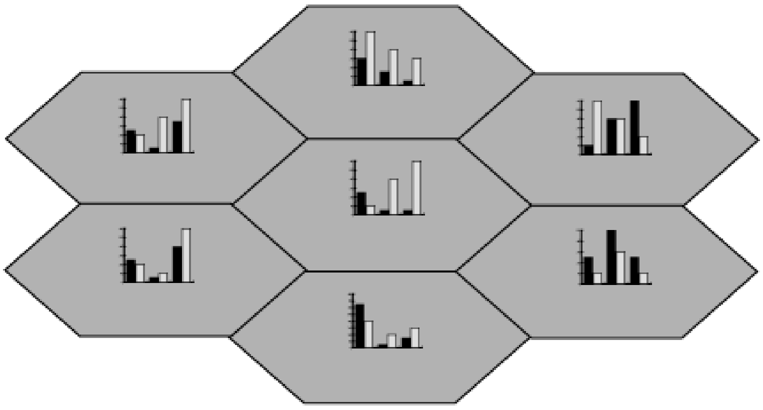

Figure 4: Scene Analysis and Position Fingerprinting

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 which 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.

IV. Technologies for Indoor Positioning

With the high number of positioning methods, it is no surprise that there also exists a multitude of technologies which 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, the corresponding methods which are used to infer positions, accuracy levels, and application scenarios.

i. High Sensitive GNSS, Pseudolites

Signals of Global Navigation Satellite Systems (GNSS), e.g., 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, e.g., 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 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 a very high accuracy of few centimeters or even millimeters (Cobb, 1997), they do not work well in non-line-of-sight conditions. Due to the 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 which transmit GPS like signals in another frequency spectrum (e.g., the license free ISM 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 instead (Rizos et al., 2010).

Despite the complex signal propagation in buildings, there are approaches to provide indoor positioning with high sensitive GPS or GNSS receivers. Even if the signals are weak and might have been reflected, they can be detected with the help of high 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.

ii. 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 shall reflect 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 for 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. Using 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 which 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 most well-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 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 section of its own, because the techniques are quite different from active light-based positioning systems.

iii. 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 which 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 the 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 to 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, e.g., generated by the well-known SIFT (Scale Invariant Feature Transform) algorithm (Lowe, 2004), offer a 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 as 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 which 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 which use optical commercial mice (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. Since 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, since 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.

iv. RADIO-BASED SYSTEMS

Many systems for indoor positioning are based on radio signals. However, there are many different methods and technologies, how radio information is utilized to deduce the position of a target. There are approaches based on timing, e.g., 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 such as GSM or CDMA, personal area networks such as Bluetooth, WLAN, RFID or ultra wideband. Even radio or television signals can be used for indoor positioning.

Utilizing radio signal for positioning is not a new idea, since 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 due to 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.

Due 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 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 of 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 to automatically calculate 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 towards 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 ultra wide band 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 3D positioning with centimeter-level accuracy (Steggles and Gschwind, 2005). Due to limitations in transmit power, most wideband-based systems typically are restricted to approximate line-of-sight conditions, i.e., do not provide coverage through walls. Since ultra wideband-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, radio frequency identification, 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 to such a reader, the system is able to receive a short range signal from the targets RFID tag and can therefore deduce that it is near to the position stored for that reader. While the main use case 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, e.g., 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 since there often is no fixed Bluetooth infrastructure, it is seldom used for positioning.

V. 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 which can be used to deduce the altitude of the sensor, and odometers measuring wheel rotation to calculate the travelled distance. Some of these sensors provide absolute values such as the direction of a compass or the altitude of a barometer, 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 only report changes of position. Thus, Inertial Measurement Units (IMU) 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, 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, i.e., the estimated position, speed, and orientation of the target. This vector is altered in the prediction phase according to a system model which 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 compass or gyroscope for the direction of movement (Woodman and Harle, 2008). However, there is also ongoing research for robot localization and simultaneous localization and mapping techniques.

vi. 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 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.

A lot of 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.

vii. PRESSURE-BASED SYSTEMS

Finally, there exist some very specialized indoor positioning systems which measure the pressure created by a target moving over the ground. One system, 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.

V. CONCLUSION

With this article, we have given a recent overview over the topic of indoor positioning with a strong focus on the task of positioning. Positioning is that 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, 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 common sense how navigational information for indoor environments can be modeled.

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auto177: data acquisition and fusion

Glossary

Angle-of-Arrival
Angle-of-Arrival is 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
Angle-of-Emission is 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
Dead Reckoning is a method for position determination based on a previously known position and measuring the change in position, e.g. by measuring speed and direction of movement.

Infrastructure-based Positioning
Infrastructure-based Positioning describes positioning systems, which measure signals from and computes the position of a target without the need of a communication channel.

Proximity Detection
Proximity Detection is 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
Roundtrip-Time-of-Flight is a method for determining the distance between an entity and a target which relies on the total traveled time of a signal whose propagation speed is known from the entity to the target and back.

Scene Analysis
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
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
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
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
Time-Difference-of-Arrival is a method of determining the distance between entities which

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

Time-of-Arrival is a method of determining the distance between entities which 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

Triangulation stands for localization techniques which make use of triangular geometry including lateration, angulation and their combinations.