Indoor tracking for mission critical scenarios: A survey

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ABSTRACT

The availability of a reliable and precise tracking system for relief units operating in mission critical scenarios would drastically improve the situational awareness and thus facilitate the mission planning and accomplishment as well as increase the safety of human resources. Thus, the demand for such a system is very high both in the military and in the emergency and crisis intervention domain. While there are solutions like GPS for the localization in open areas, problems arise in urban scenarios and indoors due to insufficient or failed signal reception. For indoor use, multiple alternative localization concepts exist that are suited for different use cases and expose varying properties in precision, complexity and required preconditions. The deployment within mission critical scenarios implicates explicit restrictions and requirements so that only some of the techniques are adept or have the potential of being used here. This article identifies the commonly issued requirements to an indoor tracking in mission critical scenarios and introduces basic techniques for position estimation. Subsequently, existing indoor tracking systems specifically in the field of mission critical scenarios are reviewed with a focus on their capabilities in terms of reliability and accuracy. By doing so, an overview of current approaches in this field is given. Furthermore, the most adept techniques are classified with respect to the requirements within mission critical scenarios.

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1. Introduction

One of the key factors for mission success within emergency and crisis intervention as well as in military operations is the availability of a sound and detailed operational picture at any point in time, also denoted by the term situational awareness. An essential part is the visual presentation of the current locations of the units as well as their walked tracks. This information is crucial for mission planning, e.g. to support the central command in the decision where to send additional units. Furthermore, when facing an unknown environment the recorded tracks of the advancing units can be used to derive a map of passable paths at the mission site. For units that have lost their orientation, e.g. due to strong production of smoke, an existing or constructed site map in combination with the tracked position can serve as a guidance for finding an escape route.

The essential benefits of a precise and reliable tracking have led to a significant demand for such a system among first responders like firemen and also in the military domain. This has been documented in numerous papers such as [1–5] in the context of indoor tracking as well as in a user study conducted with firefighters [6]. Despite this potential, there is no product currently available on the market that allows for a precise and reliable indoor localization of relief units [7].
Most commercial devices for the emergency sector like [8,9] only provide rudimentary localization functionality like acoustic signalling allowing for the approximate determination of the direction the signal is emitted from. For the outdoor environment there exist satellite based localization solutions like the Global Positioning System (GPS) and the future European satellite navigation system Galileo that reach a precision of localization of up to a few meters. The enhanced Differential GPS (DGPS) can provide a localization accuracy of up to a few centimeters or even millimeters by using the additional data of another stationary GPS receiver that has to be located in the vicinity. A drawback of these satellite based systems is that their functionality depends on the proper reception of the satellite signals. Under difficult reception conditions like in street canyons or within buildings and even in dense vegetation the signal received is often not sufficient to calculate an accurate position. For these situations other techniques for localization are required in order to provide accurate position information. As the tracking of a person moving within a building is a common use case, many researchers have explored and evaluated possible techniques for this scenario which can be summarized by the key term indoor tracking.

In addition to the general advantage that the position tracking of relief units delivers in the context of mission critical networking there are synergies that arise between the tracking and the networking aspect. The functionality of a wireless mesh network that is able to forward the gathered tracking data from the deployed sensors to a central observation point using wireless mesh relays will be needed in most scenarios. Apart from the data transport, the mesh backbone nodes can also host (additional) tracking functionality that uses signal properties of the link layer to determine distances between sender and receiver. Vice versa, if the tracked moving objects themselves constitute network hops, the knowledge about their location can provide useful information for the routing and transport algorithms of the mesh network.

In summary, it can be stated that there is a strong demand for the precise and reliable localization and tracking of persons especially in indoor environments in the commercial and military sector as well as in the area of public safety [10]. This paper provides a survey of existing indoor tracking systems with a focus on mission critical scenarios. By reviewing the capabilities of the existing systems in terms of reliability and accuracy it is possible to focus on the most promising approaches for further research and to identify deficiencies that still need to be addressed.

The succeeding section defines the specific requirements to an indoor tracking system in the context of mission critical networking. Afterwards, Section 3 gives an introduction to the general techniques that can be used for position estimation. In Section 4 existing work and systems for indoor localization and tracking in mission critical scenarios are portrayed. Finally, a conclusion summarizes the results that were attained from the review of current systems. It identifies the major challenges and gives a recommendation for future approaches.

2. Requirements within mission critical scenarios

In 2008, the National Institute of Standards and Technology (NIST) conducted a study that pointed out the major requirements to a communication and localization system for the deployment within mission critical scenarios [1]. As one result it turned out that first responders claim a strong demand for an indoor localization system that meets the following specifications:

- Precision of localization of about 1 m.
- Functional within all types of buildings.
- Restricted to equipment that is brought on-site by the relief units themselves.
- No site-specific training required.
- Stability against structural changes.
- Moderate costs.

Similar requirements are also given in the report [11] of a workshop held at the Worcester Polytechnic Institute where researchers, developers and end users were summoned to specify the criteria for a localization system for emergency agents.

A further characteristic of the scenarios considered is the mobility and the number of sensor nodes to be tracked. In static sensor networks, a one-time determination of the position directly after the deployment is sufficient. The mobile sensors tracked here have to be repeatedly localized in order to allow for the tracking of the covered path and for updating the current position of a person. This implies that a suitable localization method must be dynamic and time efficient whereas long-term or multi-step procedures are not applicable. Furthermore, we may assume a rather limited number of mobile sensor nodes with a low connectivity in the use case of mission critical scenarios. For this reason, localization techniques that require a large number of nodes or neighbors are not suited in this context, either.

As the deployed sensors have to be attached to the body, restrictions concerning the size and weight of the devices will apply. This results in requirements to the applied techniques and algorithms that are common to most sensor networks using portable sensors: Mainly due to the limited energy capacity of the sensors a reasonable computing effort combined with energy efficiency must be ensured. This leads to the fundamental question where the actual position calculation should be executed [12]. It is possible to choose a decentralized approach where the computation is carried out in the sensors themselves resulting in a higher power consumption of the sensor nodes. Alternatively, the costly computations can be done by a centralized node which in turn leads to a higher communication overhead due to the raw sensor data that has to be transmitted. Besides these two approaches, hybrid methods are possible that combine both techniques in order to efficiently distribute the workload and to keep the communication overhead low.
3. General techniques for position estimation

This section introduces general methods for position estimation grouped into distinct categories and explains their basic functionality. The prerequisites for each technique and the corresponding pros and cons are pointed out.

A categorization of existing localization systems can be made based on the elementary technique that is used for the position estimation. The resulting categories are:

- Angulation (Measurement of angle).
- Lateration (Measurement of distance).
- Fingerprinting (Pattern matching).
- Inertial- and motion sensors.
- Connectivity/Neighborhood.

In the following, these five main categories are discussed in detail:

3.1. Angulation

In the concept of angulation, the location of an object is determined from the measured angles to fixed reference points. One or multiple sensors on the object to be located capture the direction from which a signal emitted by a reference point originates (Direction of Arrival — DoA). The reverse direction is possible as well, i.e. the reference points receive a signal that is emitted by the tracked object. The exact locations of the reference points are known a priori, so that the object’s position can be calculated from the angles to multiple reference points. For a successful localization, the angles to at least two reference points are needed as is illustrated in Fig. 1(a). The physical techniques for angular measurements are rather complex. The angulation using a radio signal for example requires custom-crafted directional antennas and is strongly affected by interferences and multi-path propagation within buildings [13].

3.2. Lateration

In contrast to the estimation of angles, the lateration determines the distances of an object to reference points with known positions. For a proper localization, the distances to at least three reference points are required as is shown in Fig. 1(b). The actual distance estimation itself can be realized by different techniques that are briefly discussed in the following:

3.2.1. Time of Arrival (ToA)

The distance estimation according to the time of arrival principle uses the time that a signal travels from a sender to a receiver. Based on the signal propagation speed the distance between sender and receiver can be calculated. This method allows for a very precise distance estimation assuming that the clocks of the sender and receiver are properly synchronized [14]. A system that uses this technique is the satellite-based GPS. A variant of the one-way time of arrival method is the measurement of the signal’s round trip time (RTT). Here, the sender starts a timer when starting the transmission of the signal, the receiver reflects the signal immediately back to the sender which stops its timer upon the reception of the reflected signal. The distance between sender and receiver is calculated as half the distance travelled by the signal. Measuring the RTT has the advantage that no clock synchronization of sender and receiver is required. However, both, sender and receiver must support this measurement procedure. Within buildings the signal propagation time can be influenced by reflection at walls and ceilings as the signal propagates on diverse paths with varying length (multi-path propagation). Due to the resulting time-delayed reception of multiple versions of the same signal an unambiguous determination of the signal’s propagation delay is significantly complicated.

3.2.2. Time Difference of Arrival (TDoA)

In the time difference of arrival approach, a sender simultaneously emits two signals with different propagation speeds. The receiver measures the time difference between the arrival of both signals and can thus calculate the distance. Besides this basic lateration between two points using TDoA, a multivariate version of TDoA is also possible: Here, the object to be localized emits only one signal that is received by multiple spatially distributed and time-synchronized receivers. Based on the difference in the signal’s propagation delay to the distinct receivers, a direct position estimation can be achieved [13].

The inverted direction is also possible: The object to be localized receives the signals from the distributed reference points and can calculate its own position from the known positions of the senders. Although the time difference of arrival technique allows for a very accurate distance estimation, it is only suited for rather short distances where the receiver is located in the line of sight of the sender [15].

3.2.3. Interferometry

The so-called procedure of interferometry deploys the emission of sine waves with multiple frequencies. The superposition of the different signals is recorded at the receiver by means of an array of multiple antennas. Using the measured phase shifts and known wavelengths, the distance to a sender can be determined [16]. This method is applied within the context of satellite-based radar and produces very exact estimates but at the cost of lengthy measurements and specialized expensive radio hardware.
3.2.4. Signal attenuation

Due to the physical fact that the signal strength of a radio signal decreases with increasing distance, the distance travelled from the sender can be deduced by measuring the received signal strength [17, 18]. As a precondition, the signal strength used by the sender must be known in order to determine the signal attenuation. Examples where this technique is put into practice are the localization of mobile phones and WLAN (Wireless LAN IEEE 802.11 [19]) localization. The advantage of using the signal attenuation is that no specialized hardware is required as the transmitter module measures the signal strength anyway. Imprecision in the distance estimation can occur though, caused by signal attenuation that is introduced by obstacles or reflection. This raises a major problem for indoor environments, as here no common signal propagation model can be applied in contrast to a free space environment. For this reason, in indoor setups the signal attenuation is usually only used as an attribute for the subsequently described fingerprinting technique where the signal strength is measured in advance at different locations of the site.

3.2.5. Hop-based

A further possibility to estimate distances within a multihop network is to count the number of hops on the communication path from a sender to a receiver [20]. Assuming an approximately equidistant distribution of the stations
the distance between sender and receiver can be deduced from the hop count. Obviously, this technique requires a high and possibly uniformly distributed node density as well as the absence of obstacles.

3.3. Fingerprinting

A different technique for localization called fingerprinting uses in-advance mapped properties of the environment for position estimation. For example, the received signal strength of a WLAN signal is measured at as many different locations as possible within the target area. This information is saved including its spatial mapping. A sensor that wants to locate itself measures its current signal strength pattern and compares it to the pre-generated signal map. The closest match in the map is then assumed as the actual position [21].

The disadvantage of this method is the high initial effort that is caused by the mapping of the attributes of the environment. Consequently, this technique is not suited for unknown sites as there is no information available on the property used for the pattern matching. For this reason, fingerprinting does not comply to the requirements stated in Section 2 for the intended use case in mission-critical scenarios. In particular, a site-specific training is required and the stability against structural changes is not given. Tracking systems that use this technique can therefore be excluded from further consideration for the use in mission critical networking.

3.4. Inertial- and motion sensors

Sensors that fall into the category of inertial and motion sensors allow for the measurement of the acceleration or the direction of a moving object. Examples for this kind of sensors are a magnetometer that determines the orientation relative to the earth’s magnetic field, a gyroscope measuring circular motions or multiaxial inertial accelerometers. An accelerometer measures the acceleration of an object on a given axis. The double integration over time yields the object’s velocity in the first step and in the second step the distance travelled from the origin. The concept is depicted in Fig. 1. Alternatively, it is possible to indirectly infer the distance to the starting point from other measures. An example here is a pedometer that deducts the step frequency by tracking the leg movements of a person. The distance travelled can then be calculated with either a fixed or a dynamically approximated stride length [22]. More precise is the derivation of the length of each step directly from the accelerometer by determining the mere horizontal acceleration. The precision achieved though strongly depends on the orientation of the sensor, its measurement resolution and the step types. For the measurement of an object’s orientation when the direction of movement changes it is necessary to additionally deploy a gyroscope or a magnetometer. The inertial and motion sensors are used within the so-called dead reckoning navigation. The term dead reckoning denotes the process of position estimation based on the continuous tracing of the measured direction and acceleration when starting from a known position.

A general prerequisite for tracking the current position of an observed object using inertial sensors is the knowledge of the initial position and orientation. Therefore, a localization is only possible relative to a known location within the coordinate system used. This directly leads to the main disadvantage of inertial sensors: Imprecise measurements of the acceleration and orientation that are inherent to the sensors result in a sustaining drift that sums up over time. Without an appropriate compensation, this drift results in a cubic error in the calculation of the travelled distance due to the double integration [3]. Thus, with increasing distance from the starting point the inaccuracy of the localization may drastically increase. For this reason, suitable methods are required for limiting this error.

The major advantage of inertial and motion sensors is that they do not require any setup of measurement devices or supporting sensors located at the site. Therefore, it is possible to conduct a position estimation in unknown terrain as the sensors are independent from any pre-installed infrastructure like transmitters, external satellites or other fixed reference points. Another advantage that may be relevant in security sensitive scenarios is that the sensors do not emit any signals for their measurements and can thus remain undetected. In the recent past, inertial and motion sensors are increasingly integrated as so-called inertial measurement unit (IMU) in end-user devices of the mass market like mobile phones and game controllers. This development drastically reduced the cost and size of these sensors and permits an inexpensive and straightforward deployment.

3.5. Connectivity/neighborhood

Another localization method that can be applied in specific setups is the analysis of connectivity, i.e. the number of attainable neighbors. Set that the number of reference points is sufficient and that they are spatially distributed the object to be located determines those reference points it can establish a signal connection to (neighbors). If the signal coverage areas of these reference points overlap in an adequate way the object can derive its location as the intersection of all its neighbors’ coverage areas. The precision of this technique depends on the number and distribution of the reference points as well as their signal range [23]. Another problem lies in the fact that the coverage areas of different neighbors are not necessarily equal and may even show certain dynamics. As a consequence, the localization gets inaccurate due to attenuation and reflection of the signal.

A special case is the localization merely based on reference points without any distance estimation. Here a localization can only be made when the tracked object directly passes a reference point, e.g. triggered by physical contact or by short
range signals as are used with radio frequency identification (RFID) tags [5]. As this method does not provide a continuous localization it is also named as waypoint navigation. For the position estimation between two waypoints the combination with one of the previously described techniques is often applied. The major advantage of the waypoint navigation is that at each direct passage of a waypoint the object’s current position is well approximated by the position of the waypoint. Positioning errors that result from inaccuracies in one of the other localization techniques can thus be corrected periodically. In particular, the positioning error of dead reckoning that results from the inherently inaccurate inertial and motion sensors can be limited by the inclusion of periodical waypoints.

In addition to the categories described so far a further classification of localization techniques can be done in infrastructure-dependent and autonomous methods. Infrastructure-dependent systems require existing or in-advance installed reference points with known locations. For the positioning process either a uni- or bidirectional signal transfer with the reference points must be ensured. Examples for infrastructure-dependent systems are GPS and WLAN lateration. Autonomous systems determine their position by measurements that are independent from an existing infrastructure. Example for autonomous systems are inertial- and motion sensors.

In mission critical scenarios an already existing infrastructure of reference points cannot be assumed. In particular, indoor scenarios are usually examples where the relief units could place the reference points successively while advancing into a building. The reference points can then be implemented within so-called beacons that also provide the communication functionality as nodes of an ad-hoc network. An additional benefit is that the track of placed beacons can serve as markers for the return path out of the building. As a result of these advantages, several of the existing approaches in the special context of mission critical scenarios use this method of successive beacon placement.

The conclusion that can be drawn from this overview of the general techniques for position estimation is that most localization methods use fixed reference points with known positions and determine the relative position of the target object to the reference points. Concerning the different techniques for distance estimation, the lateration methods based on signal propagation time (ToA, TDoA) can be ranked as most suitable in the presence of good signal conditions as they are comparably easy to realize, yield a high precision and can be implemented without additional hardware. In mission critical scenarios, an infrastructure of reference points is not necessarily given and especially in indoor environments the difficult signal conditions can complicate the process of signal based lateration. Therefore, the autonomous localization method of dead reckoning that uses inertial- and motion sensors is of great interest here. When using inertial systems it is also advisable to combine them with successively deployed waypoints in order to limit their inherent positioning error by periodically updating the track to correct positions.

4. Existing work on indoor localization

This section introduces existing work in the context of indoor localization. In order to focus on the use of mission critical scenarios primarily those concepts are considered that are generally suited to comply with the requirements listed in Section 2. The systems discussed are classified into solutions using signal related techniques for localization and those based on IMU sensing.

4.1. Signal-based systems

A survey paper from 2007 [24] analyses and compares general-purpose systems for indoor localization that rely on radio-based techniques. The systems considered deploy GPS, RFID, ultra-wideband (UWB), WLAN or Bluetooth [25] as well as cellular mobile networks. The analysed systems are compared with metrics that evaluate their positioning precision as well as complexity, scalability, robustness and cost. The highest precision is accomplished by UWB-based methods but these are in turn also rated as not robust and relatively expensive. As a general rule, most systems with a higher accuracy come at the cost of a higher complexity. Therefore, an adequate compromise has to be found for the respective application area. The development of improved localization algorithms and the combined use of signal-based methods together with inertial systems and waypoints are emphasized as important research areas. Furthermore, the advantageous placement of sensors or reference points may help to improve the localization accuracy can especially be relevant within mission critical scenarios.

The general limits of signal-strength based localization techniques for indoor use are studied in [21]. Even though only radio techniques are analysed that are based on the IEEE 802.11 standard, the authors claim that their results are valid for all technologies where the signal propagation is significantly affected by typical indoor conditions. The result of this analysis is that among all technologies considered the localization error reaches at best around 3 m with a 50% probability when considering the CDF of the localization error. For the 97th percentile the localization error lies at 9.15 m. Following these results, a reliable localization with an accuracy of below 1 m as specified in Section 2 is not possible using only signal strength based techniques.

In accordance to the previous analysis, the authors of [26] also state that there are existing localization techniques based on radio signals that reach a localization error of around 3 m under advantageous conditions in indoor environments. Furthermore, the concept of a cooperative positioning system called MagicMap [27] is introduced that allows for the combination of different radio based localization techniques. First results with a combination of WLAN, RFID and ZigBee led to an average improved localization accuracy of 33% compared to the use of only a single technique.
The possibility to use GPS even within buildings is analysed in [28]. The significantly worse signal quality of the GPS signal compared to the use outdoors is alleviated by the assistance of a cellular mobile network and the block correlation of multiple signals of different satellites. However, low-cost GPS receivers are not able to conduct these complex and time-intensive calculations. Therefore, more powerful chips have to be used. Although the general possibility for receiving a GPS signal within closed buildings could be shown with this method, the position deviation in three dimensions averaged to 25 m and is thus still far from room-level precision. The authors assume that further progress is possible with the use of differential GPS and improved chip processing power.

### 4.1.1. Systems using IEEE 802.11

In [1], so-called WLAN breadcrumbs are introduced whose original purpose is to span a multi-hop communication network for relief units that are entering a building. Aside from the communication aspect, it is described how to use these WLAN nodes as reference points for the indoor localization. The signal attenuation is used as an estimator for the distance to at least three nodes. As the signal attenuation is subject to reflection and multi-path propagation in an indoor environment as described above, a training phase is needed where the signal strength at different locations is mapped according to the fingerprinting method. Though the system is able to locate mobile objects in 80% of cases with a precision of 2 m, the necessity of a prior training phase for the localization functionality significantly limits the deployability for general mission critical scenarios.

Another tracking solution based on signal delay in a WLAN network has been developed for the localization of emergency agents in the course of the EU project LIAISON [29]. For the distance estimation the RTTs of 802.11 link layer packets are taken as the basis and statistically post-processed in order to reduce noise in the form of time variability. The tracking deploys a Kalman filter [30] including a prediction step. The position accuracy is given as 0.9 m with a 66% probability. Further research effort is seen for the multipath-propagation within buildings and the continuity of the localization during times when less than three access points are within signal range.

For the bridging of GPS outages, a further WLAN based system using signal delay is described in [31]. A software defined radio transmitter is used to receive both GPS and WLAN signals. In contrast to the previously described approach, specifically crafted test packets are sent by the reference stations to the node to be localized in order to determine the signal delay. As additional information, the test packets include the exact location of the reference station that emitted the packet. When the receiver obtains packets from a sufficient number of reference stations it can calculate its own position. In order to compensate for the multipath propagation, the test packets are sent on multiple frequency channels at the same time. By correlating the signals of all received frequencies the receiver can determine the shortest signal path. Tests showed a maximum position error of 5 m except for a few outliers.

Within the context of a comprehensive integrated system for the general support of first responders inside buildings (electronic Incident Command System, eICS), the concept of SmokeNet is introduced in [6]. The concept describes the integration of fire detection sensors into buildings that are additionally equipped with a transmitter for establishing a multihop sensor network for the data communication. As another possible feature of these sensors the localization of emergency agents is mentioned. It is proposed that the firefighters are equipped with a helmet-mounted display that is, apart from other functions, able to communicate with the sensors nodes. By iteratively reducing the signal strength until only one sensor node is detected, the position of a first responder can be approximated with the position of the detectable sensor node.

### 4.1.2. Systems using ultra-wideband

The French aerospace company Thales developed the Indoor Positioning System (IPS) that is described in [4]. The system determines the relative positions of relief units between each other and to emergency vehicles located outside the building by means of local radio signals. Therefore, emergency agents and vehicles are equipped with radio transmitters that set up an ad-hoc network. With RTT measurements of the signal delay, the distances between the transmitters are estimated. For the localization of the emergency vehicles, standard GPS is applied. Based on the combined positioning information the absolute coordinates of the persons can be calculated. In order to compensate for the multipath propagation of a conventional radio signal indoors, an ultra-wideband signal (UWB) is deployed. This kind of signal is spread over a large frequency range and thus utilizes the effect that normally only a few of the used frequencies are disturbed by interferences while others remain unaffected.

The Precision Personnel Locator (PPL) System [32] of the Worcester Polytechnic Institute (WPI) is a radio based system for the tracking of emergency agents within buildings and is independent from any previously installed infrastructure. For the distance estimation, an unmodulated wideband radio signal is used that has a structure similar to a signal modulated according to the orthogonal frequency division multiplex (OFDM) scheme. Due to the usage of multiple frequencies, the problem of multi-path propagation within buildings is reduced. The signal is emitted by portable devices that are carried by the emergency agents and is received by (at least) three reference points outside the building, e.g. mounted on firetrucks. The position is determined in three dimensions by estimating the distances using the time difference of arrival technique. Depending on the signal bandwidth used the system reaches a localization accuracy of below one meter even in difficult environments. It must be noted though, that the tests in [32] were conducted with 17 receivers as reference points that were equally distributed outside the building. This high coverage limits the negative effects of multi-path propagation which
Table 1
Error in the localization using a UWB signal through different media (cf. [1]).

<table>
<thead>
<tr>
<th>Material</th>
<th>Average error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheet rock</td>
<td>1</td>
</tr>
<tr>
<td>Plaster</td>
<td>2</td>
</tr>
<tr>
<td>Cinder block</td>
<td>4</td>
</tr>
<tr>
<td>Metal up to 15 m</td>
<td>10</td>
</tr>
</tbody>
</table>

should in turn have a significant positive impact on the achieved position accuracy. Test results with a smaller number of receivers are not presented. The use within mission critical scenarios though, would require the operation with only a few non-preinstalled reference points.

While the previously cited publication of the PPL system only considers the localization of static objects, the same system is examined for the tracking of mobile targets in [33]. As an extension, an additional Kalman filter is used in order to reduce the impact of outliers in the discrete position estimations. Further, the use of motion sensors for acquiring additional position information is analysed as the mere deployment of lateration is judged to be too imprecise in the presence of severe multi-path propagation conditions. However, the motion sensor in this analysis is mounted on a wheeled platform that serves as the tracked object and also hosts the emitter for the lateration. Therefore, no step detection is applied that would be necessary under realistic conditions. The fusion of the motion sensor data with the position estimates of the lateration yields an average error of 0.14 m.

In [1] measurements of the precision of a UWB signal for the distance estimation were conducted. In case of a line of sight to the object to be localized an average accuracy of 6 cm was achieved. In the presence of obstacles on the direct path to the object like walls or doors, the errors listed in Table 1 were determined with respect to the material to be traversed.

A commercial system that uses the UWB technique for tracking was developed by Ubisense [34]. The system mainly aims at being used for automated warehousing and process optimization. Tags that are attached to the tracked objects emit an UWB impulse that is received by a network of pre-installed UWB sensors. The system reaches a precision of 15 cm in three-dimensional space.

4.1.3. Conclusion for signal-based systems

The localization systems using a narrowband signal like in IEEE 802.11 confirmed the negative impact of multi-path propagation in complex indoor environments on the positioning accuracy. To compensate for the multi-path effect, signals spread over a larger frequency band can be deployed but even then the precision strongly depends on environmental conditions like the number and material of walls on the signal path. In general, the accuracy and reliability of all radio-based systems benefits from the number and spatial distribution of reference stations. In mission-critical scenarios these have to be deployed as quickly as possible which inherently constitutes a limiting factor for the count of reference stations. Some systems answer the deployment aspect with reference points whose transmitters are already mounted to the top of emergency vehicles. Although these are immediately ready for operation, the number of reference stations remains rather small and a favourable installation, e.g. encircling the mission-site cannot be generally assumed. In general, we assess an average localization precision of about 3 m during good conditions to be feasible for radio-based systems in realistic mission-critical scenarios.

4.2. Systems based on inertial measurement units (IMUs)

The following section reviews location systems that follow the approach of dead-reckoning by deploying inertial measurement units (IMUs) as described in Section 3.4.

4.2.1. Dead-reckoning without corrections

The distance travelled by persons in indoor environments may be traced without GPS reception by using step counters also called pedometers. A fundamental study of the utilization of pedometers in the context of tracking security personnel and first responders is presented in [3]. A basic problem when using pedometers is the choice of an appropriate step length for deducing a distance from the number of steps counted. Under the non-realistic assumption of a constant step length, the inertial pedometer considered in [3] exhibits a deviation of 5% of the travelled distance. Another pedometer that uses ultrasonic sensors attached to both ankles for measuring the actual step length reaches a lower average error of only 1.3%.

The drawback is that the ultrasonic sensors may only correctly register horizontal movements and are thus rated as unsuited for mission critical scenarios where the relief units often are confronted with rough terrain and have to traverse obstacles. Furthermore, it is stated that these sensors emit signals which makes them detectable and therefore inapt for security critical missions where stealth is required. In order to limit the inherent drift of inertial sensors that is caused by the two-fold integration over the time, the authors of [3] introduce the concept of Zero-Velocity Updates (ZUPTs): In the process of step counting, the time span during each stride phase when the foot touches the ground is detected and the velocity is set to zero for this interval. As a consequence of the ZUPTs, the impact of measurement inaccuracies in the velocity is limited to
one stride phase and cannot sum up over multiple steps. Thus, the measurement error merely linearly affects the calculated distance in the number of steps. The authors state to achieve an error of only 2% of travelled distance when considering marches of 10 to 15 min maximum. With longer timespans the drift of the applied gyroscope negatively affects the position accuracy. Fig. 2 illustrates the velocity correction using ZUPTs with measured acceleration data from the Openmoko Neo FreeRunner [35].

A similar approach to the localization of first responders is described in [36]. The system developed, called NavShoe, includes a very precise accelerometer and a gyroscope affixed to a person’s foot. For the position calculation ZUPTs are determined and additionally a Kalman filter is deployed which further improves the drift compensation. A test within a building where a path of 118 m was covered in 5 min yielded a position deviation of only 0.3%. Also the climbing of stairs could be detected and visualized.

We adopted the concept of the NavShoe system and show a result of our quaternion-based filter as an example for the effectiveness of ZUPTs. Fig. 3(a) shows the map of the first floor in a two-storied building. A person with a shoe-mounted IMU (MTi from XSens [37]) walked upstairs, along the first floor, and then again downstairs back to the starting point. The distance between the two stairways is 30 m. The whole walk of about 90 m took 2.5 min which is faster than Foxlin’s walk in [36] who made 118 m in 5 min. The estimated trace of the person is shown in black and the zero-velocity phases are marked as red dots.

After finishing the walk, the distance from the final position to the starting point was 0.38 m. Fig. 3(b) shows the person’s trace with ZUPTs in black and the trace without ZUPTs in blue. The stabilizing effect of the ZUPTs is clearly visible.

The geodesic laboratory of the Swiss Federal Institute of Technology developed a Pedestrian Navigation Module (PNM) described in [38]. The system also deploys motion sensors for dead reckoning in areas where no GPS signal is received. As target applications for the system the navigation of the blind and the tracking of emergency agents are mentioned. The step detection includes models for the automatic categorization of forward-, backward- and sideways motions. In this approach, the motion sensors are not attached to the foot but to a belt round the hip. Furthermore, the acceleration data is used to derive information on the step type like stair climbing or crawling. The models used can be tuned application-specific to match different use cases, such as navigation of the blind or tracking of soldiers. In order to compensate for magnetic interferences of the compass, the direction data is aligned with the data of a gyroscope. The measurement of the acceleration in z-axis is realized with a barometer. As an option, a training phase for the step detection can serve to train the specific step pattern of a person. This leads to an improved reliability of the step type categorization. For the determination of the stride length, the average step length of a person is derived from the body height or rather the leg length, based on a physiological model. The variation of the step length is assumed to be normally distributed over a succession of steps long enough. The positioning error is less than 5% of the distance travelled, in favorable conditions even 1% to 2%.

The Personal Navigation System (PeNa) introduced in [39] uses a sensor based on ultrasound for measuring the step length, a gyroscope and magnetometer as well as a laser scanner. For the orientation estimation, the data of the gyroscope and the magnetometer are fused with a Kalman filter. These results are used as an input for adjusting the scan range of the laser scanner that can achieve a more precise measurement of the direction. The gained results showed a good precision of the estimated distance but the deviation in the estimated direction accumulated up to 8°.
4.2.2. Dead-reckoning with waypoint corrections

Already active in the field of network-side support of relief units since 2002, is the Advanced Network Technologies Division (ANTD) of the National Institute of Standards and Technology (NIST). Within the scope of the project “Communication and Networking Technologies for Public Safety” [40] modern and interoperable networking and communication standards for the use in crisis intervention are being developed. For the task of indoor navigation of first responders a feasibility study [2] was conducted. The results of the study are summarized in the following:

In a first step, the applicability of a commercial motion sensor, the Dead Reckoning Module (DRM) from Honeywell [41], was analysed. The DRM contains a pedometer for step counting and in addition to a gyroscope also a magnetic compass for absolute direction sensing. Furthermore, a GPS receiver is integrated that can be used for the localization outside of buildings. The manufacturer claims a positioning accuracy of 2%–5% of travelled distance in pure dead reckoning mode, that is without the additional use of GPS. As an extension, the combined use of the module with waypoints of known position was studied. Every time a waypoint is crossed, the absolute position is corrected and thus, the drift of the motion sensors reset. The evaluation in [41] showed that the assumption of a constant step length led to an increasing offset of the calculated position without the use of waypoints. Furthermore, the magnetic compass was severely influenced by larger metal aggregations and magnetic fields within the building which led to significant errors in the direction estimation. The combination with waypoints already showed more useful results, as the degree of deviation was limited by the periodic position correction.

As the use of a constant step length as well as the error in the direction estimation were identified as problematic factors, two additional filters for compensation were developed. The first filter adjusts the step length at each waypoint by dividing the distance travelled from the previous waypoint by the counted steps. In a similar way, the second filter calibrates the direction under the assumption that the path from the previous waypoint was a straight line. Measurements including the filters and the waypoints led to a deviation from the true position of 10%–15% of the travelled distance within the scenario evaluated. Without the filters the precision was at 15%–20%. The number and magnitude of magnetic anomalies within the building is essential for the accuracy reached. It was shown that an average deviation of around one meter could be achieved when deploying waypoints with a spacing of 10–20 m. The authors come to the conclusion, that the usage of dead reckoning methods for the indoor tracking is suited, set that a periodic position correction is provided by means of waypoints. Adequate
filters can further improve the precision significantly. As a perspective, the authors propose the inclusion of an altimeter and an improved direction adjustment. Furthermore, the problem of irregular step patterns that are typical for relief units is described. These irregularities may arise from tumbling, kneeling or crawling. An intelligent mechanism for the detection of these situations is advised.

Based on this feasibility study, a realisation that deploys RFID tags as waypoints is given in [7]. In this approach, the person to be localized carries an RFID receiver which registers the RFID tags at a near passage. The advantage of the non-active RFID tags is that no power supply is needed for the waypoints. The disadvantage is the short detection range between 0.5 and 3 m of the tags, depending on the frequency used.

An interesting approach to take advantage of magnetic anomalies that are frequently present in indoor environments and normally compromise the accuracy of the magnetometer is proposed in [42]. In this paper, the manufacturers of the Honeywell DRM make use of the fact that the measured anomalies at a given location form a unique fingerprint for this position. Using a correlation technique, the fingerprint is detected when a user revisits the same location and the corresponding points in the calculated track can be mapped. Thus, bounds are put on the growth of position errors. The interesting aspect is, that the recorded fingerprints are conceptually similar to the use of waypoints with the difference that the magnetic anomalies are already present and do not need to be installed.

Within the scope of the EU-project LIAISON [43] a waypoint-based system for the indoor navigation of firefighters was developed [5]. Similar to the approach in [7], waypoints are marked with RFID tags. The difference here is that the tags do not have to be placed in advance but are set when proceeding into the building. At the present stage of work, the locations of the tags are assumed to be available within a database. The additional motion sensing is realized with three inertial sensors that are attached to different body parts. A gyroscope and a vertically aligned accelerometer are mounted to the shin. A further accelerometer at the thigh measures the forward motion. Finally, tri-axial gyroscopes, magnetometers and accelerometers attached to the upper part of the body provide information on the person’s orientation. The advantage of this array of sensors is that they can also register the actual body position like sitting, kneeling or recumbent. As mentioned before, this information is especially valuable in mission critical scenarios where irregular motion patterns are frequent. A further benefit is the possibility to report an alarm when a person lies motionless on the ground for a certain period. Instead of a pure step detection, each stride motion is classified into the categories forward motion, stair ascent, stair descent and backward stair descent. The step length is calculated directly from the measured acceleration. The orientation information from the chest sensors is processed with an adaptive extended Kalman filter. By fusing the data of all three different chest sensors the interferences of the magnetometer caused by magnetic fields can be compensated. A further extended Kalman filter is applied to merge the positioning data that arises from the passage of the waypoints with the information gained from the motion sensors. In [5] a comparison of the tracking results including the fused waypoint data to the tracking with motion sensors only is presented. While the track that is calculated with the motion sensor data only shows an increasing drift from the real path, the inclusion of waypoints leads to a relatively accurate convergence. With waypoints, 90% of the deviations remained below 5 m.

Another approach that was developed for the operation within disaster situations is described in [44]. Here, ultrasonic buoys are placed by the first responders themselves while advancing into the building. Additionally, inertial sensors are used that are mounted on the shoes of the relief units. In contrast to radio signals, ultrasound does not penetrate walls which allows for a granularity at room level. The dead reckoning is realized with the MTx from XSens [37] that includes a tri-axial accelerometer, a gyroscope and magnetometer. The distance estimation using detected steps is based on the previously described method using ZUPTs, thus limiting the estimation error to a linear factor of the travelled distance. The paper also identifies the influences of magnetic fields on the magnetometer that result in errors of the direction estimation as a major problem. The combined use of dead reckoning with the ultrasonic markers is only evaluated within a simulation that showed significant improvements in the localization accuracy as first results.

4.2.3. Dead-reckoning with map knowledge

The inclusion of context information like maps in the dead reckoning approach is analysed in [45]. Each change of position that is recognized by the inertial sensors is checked for plausibility with an existing floor map. It is assumed that persons do not cross walls and can change rooms only via doors that are also charted in the map. Passageways and stairs that are known from the map are used for position corrections by recognizing longer straightforward movements and stair climbing from the sensor data and mapping these on the respective map coordinates. A recalibration of the step length based on position corrections from the map knowledge is not yet included in the system presented but is proposed for further enhancement. The comparison with the floor map primarily helps in correcting orientation errors that are caused by the magnetometer when it is influenced by magnetic fields. The alignment with passageways and stairs also has positive effects on the position accuracy especially in tracks that extend over multiple floors. Overall, the average positioning error can be reduced to an average of 9%.

Another promising approach that combines the data of an IMU with map knowledge is described in [46]. A detailed three-dimensional building map is modeled as an input for a particle filter and fused to the inertial data from a foot-mounted XSens MTx [37]. To limit the drift error of the IMU, the already described zero velocity updates are used. The system could track a user moving in a large three-story building (over 8000 m²) to within 0.5 m in 75% of the time and to within 0.73 m in 95% of the time. This result shows that the inclusion of context information by means of an intelligent filter algorithm enables a very precise tracking using an IMU.
4.2.4. Conclusion for IMU-based systems

The large number of systems using inertial sensors underlines the advantages of dead reckoning in mission-critical scenarios as being independent from any infrastructure and thus being immediately ready for operation. The problem of signal multi-path propagation in an indoor environment is completely irrelevant for IMUs. The main problem constitute inaccuracies in the measurement of acceleration or orientation that lead to an increasing drift over time. In order to limit this drift error, waypoints should be used for position correction. Further mechanisms like sophisticated tracking filters, the data fusion of multiple sensors, and the inclusion of context information like map knowledge can lead to a significant improvement of localization accuracy. The use of dead reckoning for localization is definitely suited to reach at least room-level precision in mission-critical indoor scenarios.

4.3. System summary

In Table 2 the most relevant properties of the tracking systems described are summarized. The systems are either referenced by name or by an alternative characterization including a reference to the respective paper. In analogy to the previous presentation, signal-based systems are listed first followed by IMU-based systems. The column Sensors lists the sensor types used for each system. An inertial measurement unit denoted as IMU is assumed to contain a tri-axial accelerometer and gyroscope. Additional components like magnetic compasses are indicated. The following six columns mark the applied physical and algorithmic techniques for the localization procedure. The term sensor fusion in this context stands for the general combining of data from different sensors in order to gain a higher precision or reliability. An example is the use of a gyroscope to compensate for interference errors of an electrical compass. Checkmarks denoted in brackets mark the technique as optional. The Precision is either given as an average absolute positioning error in terms of granularity or as percentage of travelled distance (% otd). In some cases the positioning error is specified as a certain percentile of the cumulative distribution function, i.e. for example a positioning error of X m in Y% of cases. Deployability rates the time until a system is ready for operation at a mission site. Inertial sensors that can be integrated into the clothing and do not need a person or site specific training are immediately deployable. Systems that can be rapidly set up in the process of entering a building are marked as deployable. Systems that depend on a pre-installed on-site infrastructure or require extensive on-site training are noted as long-term deployable. The Complexity of a system is either rated as low, medium or high depending on the complexity of the sensor devices and the algorithmic complexity. Systems using map knowledge are rated as high in complexity due to the requirement of digitalized map information. Finally, in the column Cost the monetary costs for the deployment of each system is estimated in terms of low, medium or high. In this rough categorization we consider the costs of the used sensor hardware as well as the number of components needed. For example, a system using the more expensive hardware only in a few reference points will potentially be cheaper than a system requiring costly equipment attached to each tracked object.

5. Conclusion and future challenges

The high demand for a reliable and precise system for indoor tracking in the field of mission critical scenarios has been confirmed in several studies of existing working groups in this context. Also, the common requirements for such a system have been determined by questioning potential end users. As the major benefits of an indoor tracking system the more precise situational awareness and improved mission planning as well as the route exploration in unknown terrain and escape route navigation are mentioned. Especially the integration of an indoor tracking system into existing systems for outdoor tracking allows for the seamless situation tracking in a mixed scenario of buildings and open areas. Intermediate outages of the outdoor tracking system for example under bad signal conditions can thus also be compensated by the inertial and motion sensors of the indoor system. A general advantage is the enhanced localization accuracy and reliability resulting from the fusion of both systems.

For the localization within buildings most methods that are used for the position determination outdoors are not applicable. This is due to the fact that many techniques use radio signals for the distance estimation which behave significantly differently in indoor conditions. Within a building there is usually no line-of-sight between the sender and the receiver so that the signal reaches its destination only by reflection at walls and ceilings, over multiple paths and with unpredictable attenuation. For this reason, the deterministic computability of the distance out of signal attributes is not possible and leads to high errors. As a radio signal does not follow a defined propagation model indoors, using signal attenuation for position estimation is only feasible when preceded by an extensive fingerprinting phase of the received signal strength. Even then, an accuracy of below 1 m is not achieved. Signal delay is only an imprecise distance estimate in an indoor environment because of effects like reflection and multi-path propagation. Different approaches try to improve the accuracy by using wideband signals or statistical methods in order to alleviate the disturbances of multi-path propagation. The most promising concept seems to be the use of ultra-wideband signals (UWB). Overall, the lateration with signal delay and attenuation alone delivers unacceptable results for a reliable and precise indoor localization in difficult conditions.

The method of dead reckoning holds the decisive advantage to be independent from an existing infrastructure. It is not influenced by structural changes of the environment. The only disadvantage is the increasing error over time due to imprecise measurements. It turns out that a particular problem is the heading estimation using a magnetometer within buildings. Accumulations of metal or other magnetic fields constitute a major disturbing factor, resulting in a large
Table 2
Overview of the reviewed indoor tracking systems.

<table>
<thead>
<tr>
<th>System</th>
<th>Sensors</th>
<th>Lateration</th>
<th>Connectivity</th>
<th>Inertial + ZUPTs</th>
<th>Sensor fusion</th>
<th>Waypoints Precision</th>
<th>Deployability</th>
<th>Complexity</th>
<th>Cost</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal-Based</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indoor GPS [28]</td>
<td>GPS, cellular network</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>25 m</td>
<td>Immediate</td>
<td>High</td>
<td>High</td>
<td>Complex correlators</td>
</tr>
<tr>
<td>WLAN breadcrumbs [1]</td>
<td>WLAN nodes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fingerprinting requires in-advance training</td>
</tr>
<tr>
<td>WLAN (LIAISON) [29]</td>
<td>WLAN nodes</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Deployable</td>
<td>Low</td>
<td>Low</td>
<td>Kalman filter</td>
</tr>
<tr>
<td>WLAN SDR [31]</td>
<td>WLAN nodes (SDR)</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td>Deployable</td>
<td>Med.</td>
<td></td>
<td>OFDM signal</td>
</tr>
<tr>
<td><strong>IMU-Based</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inertial + ZUPTs [3]</td>
<td>Pedometer</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td>2% otd</td>
<td>Immediate</td>
<td>Low</td>
<td>Med.</td>
<td>Step detection, Results for 10–15 min. walks</td>
</tr>
<tr>
<td>NavShoe [36]</td>
<td>IMU</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Immediate</td>
<td>Med.</td>
<td></td>
<td>Step detection, Kalman filter, Only first test results</td>
</tr>
<tr>
<td>PNM [38]</td>
<td>IMU, compass, barometer</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Immediate</td>
<td>Med.</td>
<td></td>
<td>Step detection, step classification, (training)</td>
</tr>
<tr>
<td>PeNa [39]</td>
<td>Step length sensor, gyro, compass, laser scanner</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>8° direction</td>
<td>Deployable</td>
<td>High</td>
<td>High</td>
<td>Step detection</td>
<td></td>
</tr>
<tr>
<td>DRM [2,41]</td>
<td>IMU, compass</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Immediate</td>
<td>Med.</td>
<td></td>
<td>Step detection, correction filters, with waypoints precision of &lt; 1 m</td>
</tr>
<tr>
<td>Usonicbuoys + MTx [4,37]</td>
<td>Ultrasonic buoys, IMU, compass</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>90% in 5 m</td>
<td>Deployable</td>
<td>Med.</td>
<td></td>
<td>Step detection, Not evaluated yet</td>
<td></td>
</tr>
<tr>
<td>INS + Map [45]</td>
<td>IMU, compass</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Deployable</td>
<td>High</td>
<td>Med.</td>
<td>Step detection, map knowledge, Map must be available</td>
</tr>
<tr>
<td>INS + Map2 [46]</td>
<td>IMU, compass</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Deployable</td>
<td>High</td>
<td>Med.</td>
<td>Step detection, particle filter, Map must be available</td>
</tr>
</tbody>
</table>
orientation error that distorts further tracking. Gyroscopes have the advantage of not being influenced by these factors. At the same time, though, they are only capable of measuring the relative change in direction which is prone to measurement errors that accumulate over time. The most suitable approach here would be a clever combination of the data of both sensor types that in summary compensate for intermittent imprecisions of the respective other sensor.

There are multiple approaches to reduce the impact of imprecise sensor measurements with methods of sensor data fusion like Kalman or particle filters or by using a more sophisticated step detection. For being effective, it is essential to identify appropriate models as input parameters for these filters. The sensor data fusion methods require a model representing the probabilistic measurement inaccuracies of the sensor as well as a motion model of the object tracked. For more information on the concepts of sensor data fusion, we refer to [47,48]. Most systems that rely on pure dead reckoning reach a precision of 5%–10% of the travelled distance. The most effective way to limit the positioning error is to deploy periodic location corrections by means of waypoints. As the exact location of the waypoints is supposed to be known, the positioning error can be reset to almost zero each time a waypoint is crossed. Furthermore, recalibration of the motion sensors is possible by retrospectively comparing the currently measured value with the expected target value at each waypoint.

In most mission critical scenarios, the waypoints will have to be placed successively in the process of advancing into the mission site. In this context, we propose to conduct future research efforts in algorithms enabling an assisted placing of waypoints, thus supporting an optimal deployment. For example, a team leader could install a waypoint each time when the estimated precision of his current position is high enough to serve as a reference location for the new waypoint. Another possibility would be to setup a new waypoint each time the algorithm detects that one is leaving the signal range of other already installed waypoints so that a lateration will no longer be possible.

The described approach of using the fingerprints of magnetic anomalies as references, points the direction to interesting further extended use cases: Instead of only using the own recorded fingerprints that merely contribute to a better positioning precision when revisiting a location, all newly measured fingerprints could be relayed to the other units or to a central fusion point. Thus, a common map of fingerprints of the mission site is progressively created serving as global reference points. This is similar to the Simultaneous Localization and Mapping (SLAM) concept that is also extensively applied in robotics. With this method, one could not only use fingerprints of magnetic anomalies but also other measurable properties like for example WLAN signals. In general, we think that the distribution and clever integration of the collected sensor and tracking information of all units carries a high potential for improving the overall precision and reliability of all tracks. This is especially the case in indoor scenarios where the shapes of valid tracks are strongly limited by walls and other obstacles that normally cannot be traversed.

This study showed that the adept combination of multiple localization methods treated here forms a promising approach for the deployment in mission critical scenarios. Dead reckoning mechanisms deliver the advantage of autonomous operation independent from an existing infrastructure and may compensate for deficiencies of radio based techniques. In order to avoid a drift over time, dead reckoning over larger distances should be used only in combination with one of the described waypoint procedures. Furthermore, the waypoints can be embedded into devices that serve as relays for an ad-hoc network, thus also providing a structure for communication and the transport of sensor data. The position determination of these static waypoints can be realized with a signal based lateration technique which could optionally be used as a further addition in the person tracking process. The ultra-wideband technology appears to be most suited for the indoor lateration as it allows for a good precision even in the presence of obstacles. Still, further research is necessary in the field of UWB based tracking in order to find optimized placements of the transceiver stations for different scenarios that maximize the attained precision. For mission critical scenarios, this also includes to keep the number of required transceiver stations that have to be installed feasible.

Another aspect of high relevance is the development of refined positioning algorithms and data fusion filters that adequately combine the information of multiple sensors and implement a probabilistic integration of sensor data over time. In several of the covered works the application of tailored Kalman filters led to a significant improvement of the localization accuracy. Also particle filters are used, e.g. for the integration of known parameters of the environment like map knowledge. The choice of which filter to use may be restricted by the deployed sensor types, the available processing power and also depends on the given scenario. Furthermore, combinations of different fusion filters are possible that integrate multiple data sources into a more precise track. An application of this method is described in [49] where the cascaded use of a Kalman and a particle filter combined with map knowledge lead to a significant improvement in position confidence for a pure inertial tracking system. In summary, decisive benefits and improvements can be expected with the further adaptation of existing filter techniques and with the usage of sophisticated dynamic models. Due to the numerous hassles that aggravate a precise indoor location tracking especially under the conditions of mission critical scenarios, it seems to be inevitable to combine the data of several different localization methods that complement one another as much as possible. Here, the methods of sensor data fusion provide an adequate toolbox of filters for smartly combining the tracking data from multiple sources in order to attain an improved overall result.

References
