Indoor Localization for Fire Safety

A brief overview of fundamentals, needs and requirements and applications

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Abstract
An indoor localization system for positioning evacuating people can be anticipated to increase the chances of a safe evacuation and effective rescue intervention in case of a tunnel fire. Such a system may utilize prevalent wireless technologies, e.g., Bluetooth, RFID and Wi-Fi, which today are used to survey incoming and outgoing traffic to a certain space or location, to estimate group sizes and to measure the duration of visits during normal operation of buildings. Examples also exist of where the same wireless technologies are used for safety purposes, for example to assess real-time location, tracking and monitoring of vehicles, personnel and equipment in mining environments. However, they are relatively few, and typically rely on a high degree of control over the people that are to be tracked, and their association with (connection to) the localization system used for the tracking.

In this report, the results of a brief overview of the literature within the field of indoor localization in general, and the application of indoor localization systems within the field of particularly fire safety, is summarized. This information forms the underlying basis for the planning and execution of a future field study, in which an indoor Wi-Fi localization system will be tested and evaluated in terms of if, and if so how, it can be used to position evacuating people in tunnels. Whereas such a system allows digital footprints to be collected within a wireless network infrastructure (also already existing ones), questions remains to be answered regarding aspects such as precision and accuracy, and furthermore, how these aspects are affected by other independent variables. In the end of this report, examples of research questions deemed necessary to answer in order to enable a sound evaluation of the system is presented. These need to be addressed in the future planning of the above-mentioned field study.

Keywords
Indoor positioning, wireless localization, first responders, rescue services, evacuation, health and safety

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Preface

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Contents

1. Introduction

In the end of 2019, a Swedish research project on the topic of indoor localization of people in road and rail tunnel fires was initiated after having been granted funding by Brandforsk. The purpose of the project is to explore if, and if so under which conditions, an indoor localization system utilizing smartphones Wi-Fi functionality can be used to position people in a tunnel. Both during normal operations, and during an incident, such as a fire emergency.

The main part of the project consists of a field study in a tunnel, in which localization data will be collected both by the above-mentioned indoor localization system and, for evaluation purposes, by a video-based system. This field study was scheduled to take place in December 2020, but was postponed due to the ongoing corona pandemic, and the at the time increased spread of covid-19 in Sweden.

Prior to the field study, a brief review of the literature within the field of indoor localization systems in general, and the application of such systems within the field of particularly fire safety, was conducted. The primary intention of the review work was to form a common ground and consensus about the different technologies and techniques available for indoor localization within the project group, and to identify what previously had been done in related areas to the project. Part of this information was also intended to be incorporated in a technical report about the field study.

As the field study was postponed, a decision was made to publish what at the time had been made available within the literature review. This internal report constitutes that publication. Applicable parts will be detailed and incorporated in the above-mentioned report about the field study (when it has been executed).

1.1. Background

Evacuation of people in case of, as well as rescue operations in, fire is more difficult in road and rail tunnels compared to in buildings above ground. The majority of the most common safety support systems in tunnels (such as fire alarm systems and automatic water sprinklers) are, furthermore, designed in such a way that they mainly can contribute with information about the fire. At the same time, information on whether there are people left in a road or rail tunnel during a fire, and if so where, are factors that can be expected to have a great effect on how a rescue operation develops, and in the long run, the rescue service's opportunities to assist evacuation. An indoor localization system for positioning evacuating people can therefore be anticipated to increase the chances of a safe evacuation and rescue intervention in the case of a tunnel fire.

Today, there are several, more or less developed, techniques for positioning and tracking people and their movement both outdoors and indoors under normal conditions [1]. The GPS technology is the most common in outdoor environments, but can only be used to a limited extent when positioning people indoors and then needs to be supplemented with other technologies [2]. However, in road and rail tunnels as well as other types of underground facilities, such as mines, with only a limited number of entrances/exits, the GPS technology is not a practically viable alternative for positioning people, even when supplemented by other technologies.

Therefore, technologies other than GPS are usually used to determine a person's position in different types of indoor environments. Which is most suitable to use in a particular application and environment depends, among other things, on the need for level of detail, precision, range, response time and reliability. Indoor localization systems utilizing Bluetooth, RFID and Wi-Fi are in this context examples of technical solutions with a relatively high degree of technology maturity regarding positioning of people under normal conditions. In contrast, the current state of knowledge about and experiences from indoor positioning of people during incidents, such as a fire, is limited [3].

In this report, information regarding indoor localization systems utilizing any of the above-mentioned wireless techniques are briefly summarized. In addition, the needs and requirements on these techniques when deployed to fulfil a safety function are discussed. Finally, experiences of applying these for safety purposes are briefly explored.

1.2. Aim and Objectives

The aim of this report is to summarize the information gathered during above-mentioned initial literature review. The objective is to document information related to the prevalent technologies, fundamental measurement and localization principles used in the field of indoor localization systems, particularly with an emphasis on GPS, RFID, WLAN and Wi-FI and Bluetooth. In addition, the objective is to document information related to the needs and requirements on these systems from a safety perspective, as well as experiences of when they have been applied for safety purposes.

1.3. Limitations and Delimitations

This report is not all-covering, and as such, no claim is made regarding the comprehensiveness of the content. The literature summarized in this report was collected and briefly examined partly to form a common ground and consensus about different indoor localization technologies and techniques within the project group, and how these have been applied to fulfil a safety function in the past (and can be applied in the future). In some parts, the examined literature is discussed in general terms (from a safety perspective) rather than being reproduced in detail. Although there is not a whole lot of publications available on indoor localization for fire safety, there is a tremendous amount of literature published on positioning of people in general, as well as the deployed techniques for this. The interested reader is referred to other publications for more information, and the publications referenced in this report may serve as a good starting point for such investigations.

In this paper, an emphasis is put on wireless tracking based on GPS, RFID, WLAN and Wi-Fi and Bluetooth. Together with visual systems (such as CCTV) and systems based on regular cell-phone traffic, these are the most prevalent ones when considering data collection of individuals and crowds. As such, other techniques, e.g., radar (to, for example, determine the range, angle or velocity of objects) and laser scanners (to, for example, count people) are not covered in this report.

2. Wireless Localization Fundamentals

In this section, the prevalent technologies, fundamental measurements and localization principles used in the field of indoor positioning systems is presented. From a layman perspective, the technologies can be interpreted as the physical infrastructure of any given indoor localization system. The distance measurement techniques can, furthermore, be seen as the fundamental techniques for collecting specific parameters and variables within such an infrastructure. The localization principles can, finally, be interpreted as the assessment methods to position a device, based on the parameters/variables collected within the infrastructure. A more comprehensive review of in total 13 different technologies (of which the below-mentioned are included), and the measuring principles of each of them, is presented by, among others, Mautz [4].

2.1. Technologies

There is currently not one solution or one single type of technology that can be used for all applicable situations where indoor localization is desirable. All existing technologies are associated with both advantages and disadvantages, and as such, the required performance parameters must be assessed and matched with the user requirements before deployment. In the following section, some of the most commonly used technologies to collect data on individuals and crowds is briefly presented in order to form a basis for understanding the later parts of this report. It is not uncommon that these technologies are combined to achieve better results in terms of tracking people in indoor environments [5, 6, 7]. Experiences of this are, for example, reported by van den Heuvel et al. [5] who combined the Bluetooth and Wi-Fi technology for tracking and infrared sensors for counting people. This was done in order to overcome issues related to penetration, more specifically, the detection percentage of the people being tracked. In other applications, the combination of the two technologies has, for example, been done to improve measurement accuracy [7].

2.1.1. Global Positioning System (GPS)

Global Positioning System[1] (GPS) is a satellite-based radio navigation system and is the default system used in outdoor settings. The system provides geolocation and time information to a GPS receiver anywhere on or near the Earth. Today GPS is used by people all around the world to, among other things, navigate when travelling [2] (in other words, for positioning of oneself).

To determine a user's location with GPS, access to four measurements or senders (satellites) are required. These determine the user's latitude, longitude, height and receiver clock offset from the satellite's internal system time. Less satellites can, however, be used if either the receiver time or height is accurately known.

GPS can provide service to an unlimited number of users as GPS does not require the user to transmit any data. The satellite broadcasts a signal with its position and the time of signal transmission, whereas the receiver computes its location. The receiver can, for example, be a smart phone or a dedicated GPS device.

Physical obstacles, such as mountains, buildings and other construction works, block GPS signals as they are generally weak signals. As such, GPS is by default not very efficient for positioning in indoor or in dense urban environments, and GPS does not work in underground facilities [6, 8]. However, assisted GPS (A-GPS) is a technique that combines GPS with a mobile network system or another indoor GPS sender. This allows localization when the signal from satellites is poor by utilizing a sender that simulates the signals from a GPS. The technique is often used in dense urban environments, and have, furthermore, been deployed in some indoor settings, such as road tunnels [9].

If GPS is to be used to locate people by a third party, the person who is going to be positioned must first consent to the sharing and separate analysis of the necessary data for positioning [10]. For market applications in smart phones, this means that the user of, for example, Google Maps, must give consent for location data to be collected.

2.1.2. Radio Frequency Identification (RFID)

Radio Frequency Identification (RFID) is a localization technology which uses radio waves to identify objects or items. It is commonly used for access control to buildings and tracking goods [11]. An RFID system typically consist of a reader and a tag, in which (somewhat simplified) the reader transmits a radio signal that in turn is received by the tag [6]. Depending on the RFID tag functionality, the tags can be divided into three categories, which determines what happens after the tag has received the signal:

1. passive,
2. active, and
3. semi-passive.

A *passive* tag relies on the RFID reader to transmit a signal, and as such, it must pass a choke point to be registered. The tag uses the energy from the reader to respond back to the reader as it has no internal power source. An *active* tag has an internal power source and can transmit a signal independent of a reader. It can, furthermore, be configurated to constantly transmit or to transmit a signal only when it is prompted. An active tag generally has a greater range than a passive tag due to its direct power source. A *semi-passive* tag is a battery-assisted tag that uses the benefit of both the passive and active tag. It uses energy from the reader to transmit a signal but uses an internal power source to power

[1] GPS is owned and operated by the United States government. GALILEO is the European Union (EU) and GLONASS is the Russian counterparts to GPS. These satellite-based navigation systems work and function essentially the same way as GPS [2].

additional sensors that monitor environmental conditions [11]. Passive tags have range of about 1-10 m, while active tags can have a range of 100 m depending on the environment [6]. In terms of positioning accuracy of RFID tags, this depends on the tag spacing but is typically 0.1 to 1 m [8].

2.1.3. Wireless Local Area Network (WLAN) and Wi-Fi

Wireless Local Area Network (WLAN) is a wireless communication system that is commonly used in local area networks to wirelessly link two or more devices. Most modern WLANs are based on the protocol IEEE 802.11 standards, and WLAN is commonly referred to as *Wireless Fidelity* (Wi-Fi). Wi-Fi is, among other things, typically used to provide Internet access to devices in a local area [11].

Any device equipped with Wi-Fi, such as a computer or a smart phone, has a unique Media Access Control (MAC) address. On a local Wi-Fi network, devices (e.g., a smart phone and an access point) exchange their MAC addresses to identify each other[2]. A device's MAC address can also be used for localization purposes. Location data is in those situations largely captured per device using that device's MAC address as a unique identifier, as it is meant to be permanent for each device. However, in later years, software developers (of, e.g., operating systems) have implemented functionalities that attempts to randomize a device's MAC address, making positioning and tracking more difficult [12, 13].

When employed for positioning, the advantage to Wi-Fi compered to technologies, such as GPS, is that it can work both outdoor and indoor, e.g., in the built environment. Furthermore, the technology can be used for indoor localization by employing an already existing infrastructure (used, for example, to provide Internet access to users in a building) making the technology cost efficient. In addition, the effect of non-line-of-sight on Wi-Fi-signals is typically small [14].

In indoor localization applications, depending on the set up, Wi-Fi typically has an accuracy of 1-50 m, and a range of 20-100 m [4, 8, 15, 16, 17]. In reality, impairments in wireless transmission can be expected due to, for example, attenuation distortion, noise and refraction, which affects this numbers. Tunnels may, for example, extend the transmission range, whereas building and people are known to hinder transmissions [15].

2.1.4. Bluetooth (BT)

Bluetooth (BT) is a short range and low-power wireless technology that uses 2.4 GHz radio frequency for communication [6, 10]. The advantage of the technology is, among other things, it's relatively high level of security, low cost, low power requirements, and small hardware size. This is also why it is typically equipped in most mobile phones and laptops [4]. Bluetooth is used primarily to interconnect a variety of personal devices such as smart phones with headphones, laptops with keyboards, etc. [18], but can also be used in applications related to indoor localization. Typically, Bluetooth is in such cases often used as a complement to Wi-Fi in indoor localization systems (e.g., as an additional capability to collect device information due to MAC address randomization, or to increase accuracy), and not as a stand-alone system for positioning [7, 19].

Bluetooth range depends on what power class the specific radio device uses. Power class 3 is usually found in smart phones, which corresponds to a range of about 10 m [6]. Depending on the application, Bluetooth have an accuracy of 10 m [4].

2.2. Distance Measurement Techniques

There are several measurement techniques available to localize people (and other objects) in the built environment, independent of the technology deployed. The following basic principles are common for

[2] The frequency with which, for example, a mobile device communicates with an access point, cannot be controlled and is dependent on a number of aspects, such as: a) the manufacturer of the mobile device, b) association with the local network, and c) whether the mobile device is asleep or standby [15, 51]. Association with the local network and standby mode can be expected to increase the frequency/occurrences a mobile device sends a probe request.

distance and angular observations of localization systems built on the technologies covered in chapter 2.1. In most cases, several measuring points are needed in order to find a specific position or to locate a device, e.g., by triangulation, where determining distance is vital. The measurement techniques for distance measurement can be divided into two categories (see Figure 1):

1. wireless distance measurements, and
2. measurements of physical quantities.

A localization system can also use a hybrid of these measurement techniques.

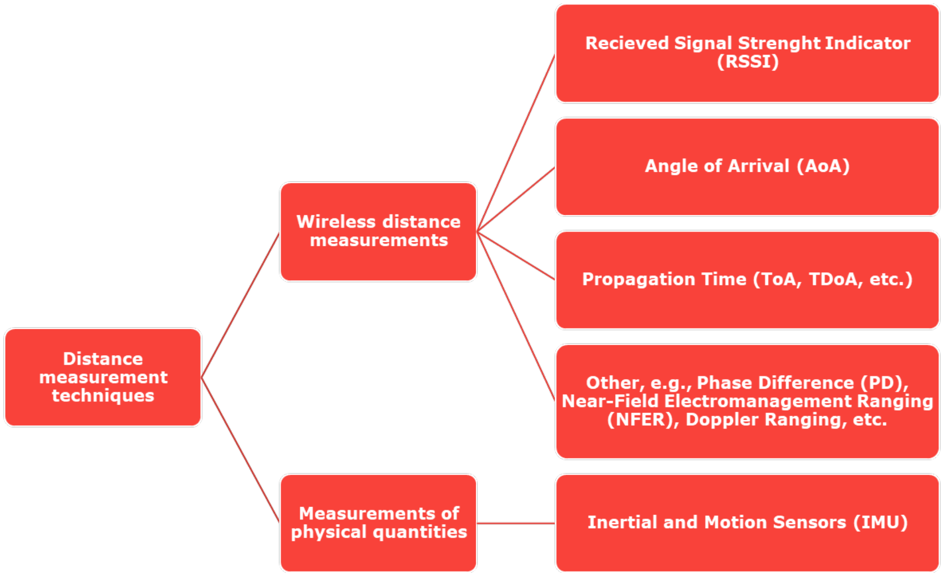

Figure 1. Classification of distance measurement techniques typically deployed by the technologies covered in chapter 2.1.

2.2.1. Wireless Distance Measurements

To obtain the distance or location information from a wireless system, such as GPS, Wi-Fi or RFID, there is a variety of different wireless distance measurement techniques that can be used. These can be divided into different categories depending on their transmission properties. The most commonly used types are [8]:

- Received Signal Strength Indicator (RSSI)
- Angle of Arrival (AoA)
- Time of Flight (ToF), Time of Arrival (ToA), Time-Difference of Arrival (TDoA), etc.

Received Signal Strength Indicator (RSSI) is a measure of the magnitude of the signal power or the relative received signal strength in a wireless environment [8]. To compute the distance between nodes, a localization system needs to have prior knowledge about the RSSI [19]. In a linear system this is simple as the stronger the RSSI is, the shorter the distance between nodes. However, in an indoor environment, the relationship between the nodes may be non-linear. In these cases, different analytical and/or empirical models or algorithms are typically used to estimate the distance [8].

Angle of Arrival (AoA) uses the propagation angle of a wireless signal and triangulation techniques to determine the intersection of the transmission paths [8]. To achieve a good localization accuracy with AoA, line-of-sight is required between transmitter and receiver. Angle of Arrival does, however, not require temporal synchronization between the transmitter and the receiver [19].

Time of Flight (ToF) and *Time of Arrival* (ToA) measures the time a signal takes to travel from a transmitter to a receiver to estimate the distance between the two [8]. A well-known application of this is radar [11]. This technique is mainly suitable when line of sight is available [11]. The major drawback with this measurement technique is the need of a high temporal synchronization between the transmitter and the receiver. For example, a synchronization error of one nanosecond between the sender and receiver, results in an error of 0.3 meters in the localization [19].

Time-Difference of Arrival (TDoA) works similar to ToF and ToA with the addition that it takes additional transmitters into consideration [8]. As such, TDoA have similar disadvantages as the ToF and ToA techniques. GPS is an example of a technology that uses this type of measurement technique, requiring information from at least four satellites [8].

2.2.2. Measurement of Physical Quantities

With the help of sensors capable of measuring physical phenomena, such as acceleration, velocity and orientation of movement, the computation of travel distance and orientation of movement can be calculated [19]. Generally, smart phones today have sensors such as accelerometers and gyroscopes, that can be used for these types of measurements [20]. This distance measurement typically employed in these applications is fully autonomous and do not require any external devices or transmitters. The main drawback with this technique is that the error control associated with each measurement as it presents a cumulative behaviour [19].

2.3. Localization Techniques and Principles

By processing some or several of the wireless distance measurements made by the techniques presented in chapter 2.2, a location or position can be determined. There are multiple techniques and principles that can be used to process the measurements. These principles can be divided into two categories (see Figure 2):

1. autonomous methods, and
2. training-dependent (or empirical) methods.

These methods can, furthermore, be combined in one application, e.g., an indoor localization system.

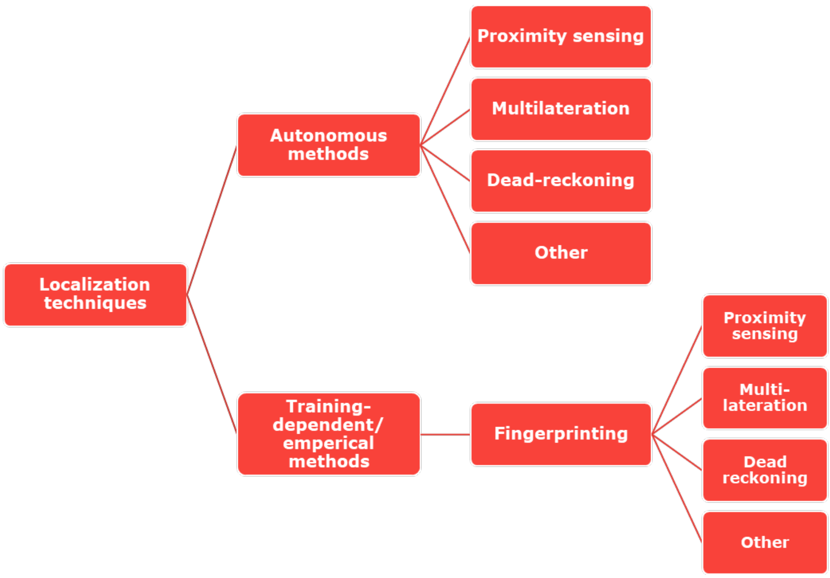

Figure 2. Categorization of localization methods. Note that the autonomous method can be used after an initial fingerprinting.

As presented in Figure 2 some of the commonly used techniques are [8]:

- proximity sensing,
- multilateration,
- dead-reckoning, and
- fingerprinting.

Proximity sensing is one of the simpler localization principles and is based on the identification of a signal in cellular-style networks, which is translated into a location region based on the network coverage [3, 8]. Proximity based location systems are usually based on a dense network of antennas distributed throughout a site, whose location is previously known. If a node, such as a mobile phone, is detected, or detects two antennas, its position is defined or approximated by the antenna that receives the strongest signal. As such, this method does not allow for continuous monitoring of a particular position [19].

Multilateration is a technique that assesses the location either by distance, angles or a combination of both. Examples of multilateration principles are trilateration and triangulation [8]. Triangulation estimates the location of a device based on angle measurements (AoA), see Figure 3. Trilateration, on the other hand, uses the signal strength or timing of information to form coverage circles and intersection. Thus, with information of at least three intersection points, the location of a device is assessed, see Figure 3. As such, trilateration employs distance measurements techniques such as ToA, TDoA and RSSI [19].

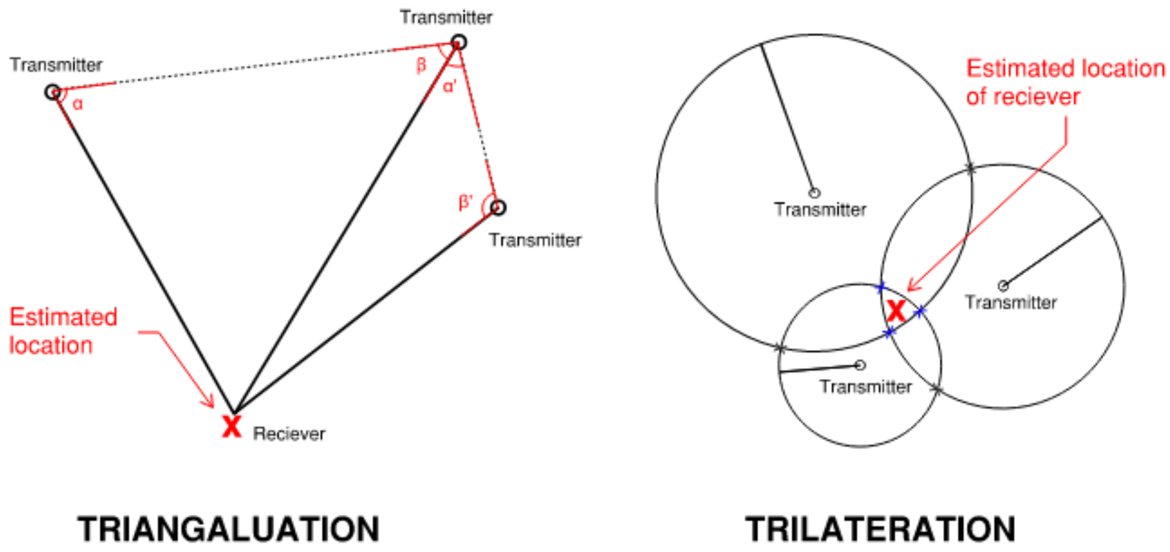

Figure 3. Illustration of the multilateration principles triangulation (left) and trilateration (right).

Dead-reckoning is a localization technique that calculates the current position based on the previous position [3]. The position is updated based on information from different inertial and/or motion sensors (physical quantities) such as speedometers, accelerometers and gyroscopes [8]. As such, this method is infrastructure independent [17, 21]. Dead-reckoning is often used together with way-point corrections or with map knowledge to ensure higher accuracy as otherwise the position error will grow exponentially. In these cases, waypoints are often based on the proximity sensing technique and are RFID based [21].

Fingerprinting, or pattern matching method, is an empirical method that estimates the location of a mobile node. The method involves a calibration (offline) phase and a location estimation (online) phase [6]. The calibration phase consists of measuring the network signal characteristic, i.e., the fingerprints, at certain points to create a network map of the environment [6, 8]. In other words, a target area is divided into a grid and the signals at each grid is captured, which forms a map of the signals [3]. Fingerprinting based on RSSI values is the prevalent method using Wi-Fi for positioning [4], therefore, this technique is elaborated on further in chapter 2.3.1. As shown in Figure 2, fingerprinting methods can and often use some or several of the other common measurement techniques after the initial mapping phase. The fingerprinting method is popular as it relies on existing infrastructure. Hence, it is a cost-effective solution [19].

It is to be noted that many localization systems use multiple measuring principles, which then requires the use of various positioning techniques, so called hybrid systems [4]. In Table 1 a short summary of advantages and disadvantages of the different methods is presented.

Table 1. Advantages and disadvantages of the different localization techniques and principles mentioned in this chapter.

Localization techniques	**Advantages**	**Disadvantages**
Proximity sensing	The technique is robust [3] as well as simple and easy to set up and integrate with other localization techniques, especially dead-reckoning [19].	Requires a high number of antennas to be accurate [3, 19]. Does not allow for continuous monitoring of a particular position [19].
Multilateration	A position can be estimated in real-time based on reference points with known locations, such as radio antennas [3].	Requires at least three reference points with known locations [3]. Generally, requires line-of-sight and need of a high temporal synchronization between the transmitter and the receiver [19].
Dead-reckoning	Infrastructure independent [3, 17, 21].	Positioning error increases with time [21].
Fingerprinting	Can use existing infrastructure [8, 19]. Is robust even in noisy measurements, is accurate, has the capability to track several mobile nodes in real-time, has low computational and communication overhead and is overall cost-effective [3, 19].	Requires pre calibration/mapping [8].

2.3.1. Fingerprinting Techniques

Several techniques can be employed for fingerprinting, and they generally fall into any of the following two categories [8]:

1. static location estimation algorithms, and
2. filtering approach.

Static location estimation algorithms mean that fingerprints are individually used in the calculation of a location with an algorithm. These algorithms are generally either deterministic or probabilistic [8]. *Filtering approach* means that a network map, sometimes called a radio-map, captures the relationship among different calibration points/nodes. This makes the approach more robust against measurement-wide variations [8]. The filtering approach is the most common fingerprinting approach.

Calibration Phase

All filtering techniques require an initial *calibration phase*, an offline phase where a network map is created. A fingerprint is a characteristic or a set of characteristics, which makes an environment unique [19]. The fingerprinting map is created by recording the RSSI values of the signal as a function of their location within an area, as well as some factors, such as the orientation of the measurement, that can strongly influence the readings. During the calibration phase, between tens to a thousand of samples can be taken to characterize each location. To reduce computational demand, if needed or required, the samples can be stored as approximations with the most common being statistical properties such as mean, variance, median and a histogram. Depending on which fingerprinting method that is used, different approximation methods are used [8].

Filtering Approach

In a filtering approach, all the previous measurements in addition to the current one is considered when calculating a location estimate. The filtering method tries to capture patterns in the signal variation in the calibration phase (offline phase) and use it to better match measured points in the location estimate phase (online phase) [8].

The two common filtering approaches are the Bayesian Filter and the Kalman Filter. The Kalman filter is one of the most well-known filters and it is an implementation of the Bayesian filter [8]. It represents an iterative method for integrating multiple measurement sources to produce a more consistent and accurate location. The method can be used in any system that relies on distance and bearing measurements between nodes or other indirect psychical measurement [19]. The Kalman filter has several advantages such as good accuracy, robustness even in noisy measurements, the capability to track several mobile nodes in real-time and low computational and communication overhead [19].

2.4. Summary

In Table 2, a summary is provided including information about the above-mentioned technologies for wireless localization, the distance measurement techniques employed within these, and also the employed localization technique to assess the position. Detailed information regarding accuracy for the below mentioned (and other) indoor localization technologies are provided by, among others, Mautz [4], who also lists different user and technical parameters that can be used to define the characteristics of any indoor localization system. An example of how this has been applied, at least partly, to classify an indoor localization system proposed for a tunnel environment is provided by Pereira [8].

Table 2. Summary of the in this report mentioned technologies for positioning, employed distance measurement techniques and their capabilities in terms of accuracy.

Technology	Distance measuring technique	Localization techniques and principles	Prerequisites for system/hardware	Typical coverage/range	Approximate and typical accuracy
GPS	ToA/TDoA	Trilateration (multilateration)	Four satellites or transmitters and a receiver that can calculate position [2]. Typically requires consent and a third-party app for external positioning [10].	Global/worldwide [4]	10-13 m [2, 8]
RFID	RSSI	Proximity sensing, fingerprinting	Requires tags and transmitters [5].	1-50 m [8, 16], passive tags 1-10 m [6], active tags up to 100 m [6]	0.1-1 m (depends on tag spacing) [8]
Wi-Fi	RSSI, AoA, ToA, TDoA	Fingerprinting, multilateration, dead reckoning, proximity sensing	Network based and existing infrastructure in buildings as well as smartphones can be used for positioning [10]. Most applications using Wi-Fi need to be pre-calibrated [19].	20-50 m [8, 4, 16]	1-50 m [4, 17]
Bluetooth	RSSI, AoA, ToA, TDoA	Proximity sensing, fingerprinting	Generally, cannot use existing infrastructure as it is usually non-compatible and therefore often and requires specific Bluetooth beacons [3].	10-100 m [6]	10 m [4]
Inertial and Motion Sensors	Physical quantities	Dead reckoning	Sensors able to measure inertial and motion [16]. Smartphones meet this requirement. No need for calibration or existing infrastructure [16, 21].	N/A	Accuracy degrade with time of measurement [16, 21].

3. Needs and Requirements Related to Indoor Localization

An important step when designing and implementing an indoor localization system is to study the user requirements and the specific desired application description. If an indoor localization system is to be used to track firefighters during an intervention, it is likely that the user needs are different compared to if a similar system are to be used to keep track of dangerous goods in, for example, a mining industry. Furthermore, if an indoor localization system is to be deployed to position people during a fire, accuracy demands may be different between a building and a tunnel.

In the following chapters, an overview of the key indoor localization requirements and conditions related to first responders, occupants and work health and safety is presented. Focus for the user requirements have been on accuracy and usability. Reflections are made in relation to findings in past studies.

3.1. Positioning of and for Rescue Services and First Responders

Indoor localization related to rescue services for firefighting can be divided into the following three categories:

1. Positioning of fire fighters,
2. Positioning of occupants exposed to the fire, and
3. Positioning of the fire and the fire induced consequences, such as the spread of smoke.

Depending on which category is being considered, different needs and requirements can be expected.

3.1.1. Positioning of Fire Fighters

Positioning of firefighters simply means monitoring and tracking individual fire fighters during interventions. This may provide value, either for the individual firefighter (to keep track of where oneself is in a building), or the commander leading the rescue service (to keep track of and organize the operation). For an individual firefighter navigation is essential to, for example, reach safety quickly if conditions become critical, and for an incident commander, it is from a health and safety point of view, as well as a mission planning view, important to be able to keep track of firefighters' locations.

As a response to this, best practices for navigation in, for example, poor visibility, have been developed and used for a long time. The methods are generally simple and practical, and facilitating low-tech equipment. Among other things, these techniques consist of following a water hose, and returning firefighters sketching the building layout to assist the commander and other firefighters [22]. Furthermore, fire rescue services today mainly rely on radio communication to organise a rescue operation, but also for individual positioning of intervening fire fighters [17]. In Sweden, the rescue services do, for example, use a radio communication system termed RAKEL, which is the main communication system for speech and short messages [9]. The existing positioning practices for firefighters are typically considered to be robust, but it has been noted the noise from the fire and/or fans can interfere with radio conversation [22, 23].

Despite the above-mentioned strategies to position fire fighters during intervention, it has been demonstrated that first responders in the USA are twice as likely to die inside structures today as they were 20 years ago. The leading cause of death is becoming lost or being trapped or disorientated due to the higher prevalence of complex buildings [22, 24]. Due to the limitations of the above-mentioned systems and practices, an indoor localization system for positioning of fire fighters during rescue operations may have the potential to increase the safety of individual fire fighters, as well as to assist with mission planning, coordination and situational awareness for the incident commander [19]. To determine the user requirements for emergency responders for such a positioning system, an assessment can be made of the following parameters (used, when applicable, also in later chapters):

1. accuracy,
2. information accessibility (usability), and
3. the system's adaptability, architecture and autonomy.

First responders of mission critical scenarios as well as researchers and developers and other end users have, for example, in relation to the above aspects expressed that they want an indoor localization system for them to: a) have a precision of localization of about 1 m, b) be functional within all types of buildings, c) be restricted to equipment that is brought on-site by the relief units themselves, d) require no site-specific training, e) have a stability against structural changes, and f) be of moderate costs [21].

Other aspects highly relevant for a positioning system to be used for indoor localization of first responders relate to reliability, e.g., to ensure functionality when exposed to fire induced consequences. However, this and other aspects related to the hardware design are not elaborated on in any detail in the following sections.

Accuracy

The application of an indoor localization system in a complex building with many compartments typically requires high accuracy in terms of positioning of individual fire fighters. A survey by Li et al. [24] did, for example, determine that accuracy was deemed as the most important requirement for first responders followed by ease of deploying the solution on scene. Room-level accuracy was also indicated as more important than meter level accuracy.

For the use of a similar system in a tunnel, however, the same level of accuracy may not necessarily be required due to the fairly simple geometry of such building works. The demand on accuracy with regard to localization of individual firefighters could, for example, instead be interpreted as a function or in relation to the closest access point to the fire exposed tunnel, such as a cross passage. As an example, if the distance between cross passages is 300 m in a road or rail tunnel, the minimum requirement for indoor localization of individual fire fighters would at least be 150 m.

In relation to the above, the following should also be noted:

- In an interview with the Swedish fire rescue services in Stockholm, they communicated no need to position individual fire fighters in a tunnel, but only to position their vehicles on a map with an accuracy between 20-50 meters [9].
- During tests of rescue services tunnel response capability, with only the use of standard-issue equipment, the maximum safe work distances in a tunnel with low visibility has been showed to be around 100 to 120 m [25].
- It may take 15-30 minutes for experienced fire fighters to create a water hose system (to ensure water during the intervention in a tunnel) of 150 m length [23].

Based on the above, it is concluded that even though high accuracy may typically be desirable, it is not strictly necessary for all applications. Thus, if an indoor localization system is to be used position individual fire fighters in a tunnel, an accuracy level between 20-150 m may be a reasonable aim.

Information Accessibility

The location of an individual firefighter is not of much value if the information is not clearly presented in such a way that it can be understood by the intended user. Survey results, furthermore, indicate that the position of individual firefighters need to be computed and assessed in real time [22].

If an indoor localization system is intended to be used by an individual firefighter, higher requirements for the interface is required to ensure that firefighter can use any required devices in the dark with protective gear. Such devices must also be robust to withstand rough handling and high temperatures. It is also necessary to guarantee that the indoor localization system does not interfere with any other normal firefighter activities [22].

If a localization system instead is intended to be used by an incident commander, there is a lower requirement for the device to be robust (with regard to the above-mentioned aspects). Instead, there is a higher requirement for the location of several firefighters to be presented in a user-friendly graphical user interface that can provide situational awareness [22].

System's Adaptability, Architecture and Autonomy

Firefighters may move in unusual patterns, which means that if an indoor localization system utilises body-worn motion sensors, these can end up at odd angles [22]. Therefore, the movement pattern of firefighters must be taken into consideration if physical measurements are to be used to determine their location. The system should also be scalable to ensure that it can track and monitor all firefighters in an emergency [19]. Other aspects to consider are potential power outages and minimising the likelihood of failure of the entire positioning system if a fire impacts one signal.

3.1.2. Locating Victims Exposed to the Fire

One of the major problems during rescue interventions, particularly in underground facilities, is the lack of information regarding whether there are people left in the vicinity of the fire, their location and if they are threatened by untenable conditions [23, 26]. From a life safety point of view, rescue services have developed best practices for search and rescue operations, e.g., to find occupants in such an emergency. These methods are generally simple and slow as the firefighter needs to systemically search through an area. Particularly if visibility is low and the occupants are non-responsive. As such, a system to position people in need of assistance could assist the rescue services to faster locate occupants left in a building or a tunnel.

Accuracy

The application of an indoor localization system in a complex building with many compartments typically requires high accuracy in terms of positioning of individual occupants [19]. However, as for the indoor positioning of individual fire fighters, the need for high accuracy in tunnels may not be as high. In contrast, it may be more important to be able to conclude whether there are occupants left within a section of a tunnel to ensure that no occupants are missed in a search and rescue operation. Based on this, it is concluded that even though high accuracy may typically be desirable, it is not strictly necessary for all applications for the same reasons as stated above (in relation to indoor localization of individual fire fighters).

Information Accessibility

The information provided to firefighters and/or incident commander should, preferably, meet the same requirements as for positioning of individual firefighters.

System's Adaptability, Architecture and Autonomy

An indoor localization system to track people in need of assistance should be scalable to ensure that it can track and monitor all occupants [19], and in other respects be designed with the needs and requirements mentioned in relation to indoor localization of individual fire fighters. Such a system should, furthermore, not malfunction due to the conditions during a fire [27], which puts an emphasis on aspects such as power supply, fire protection of cables, etc., to the indoor technology facilitated for the positioning. In addition, legal barriers concerning the normal privacy of the occupants in distress need to be addressed [27].

3.1.3. Positioning of the Fire and the Fire Induced Consequences

Monitoring and positioning fires in, for example a building or a tunnel, is vital for fire emergency management [28]. In buildings, this is traditional done with help from an addressable fire alarm system. An addressable fire alarm system means that each fire detector has an address or location that is connected back to a central control panel. Hence, this allows, e.g., an incident commander to assess which device that has activated, and, thus, to locate the fire within the building.

In tunnel environments, monitoring fires and the fire induced consequences (such as where it is burning, what is burning and how the fire develops) is also an existing implementation. In many cases, particularly in urban areas, such information can be provided to rescue services by an operator at a traffic control centre. The operator then utilizes information and signals from, for example, a fire alarm system, a sprinkler system or a CCTV system, and communicates it to an incident commander.

In relation to indoor localization systems for people, it is generally considered that the current monitoring of the fire fulfils the user requirements required by rescue services. As this system is readily available today, and given the limitations and delimitations this review, it is not discussed further in this report. It is, however, acknowledged that this type of information may be coupled with other information regarding indoor localization of individual fire fighters as well as occupants in need of assistance during a fire.

3.2. Indoor Localization of and for Occupants

A distinction can be made between two categories of indoor localization studies (related to fire):

- Positioning of occupants for the occupants themselves (e.g., to support the ability to escape in case of fire, decision-making, etc.)
- Positioning of occupants for a third party, for example, for crowd monitoring and tracking.

3.2.1. Positioning for Occupants

Positioning of occupants for the occupants themselves means that individual occupants can make use of information about where they are in a building (or other building works) in order to, for example, enable fast and correct decision making regarding how to act and where to evacuate. Such information can be expected to improve the possibilities to self-evacuate, which is the governing principle in most buildings and tunnels and means that occupants are supposed to evacuate by their own means without the assistance from, for example, rescue services [23, 29]. Today, navigation and orientation in case of fire is typically made by help from way-guidance signs, which most often are non-interactive[3]. As such, they could direct occupants towards, instead of away, from a fire, or might not provide the occupant with the fastest evacuation route.

An indoor localization system may, in this respect, provide occupants exposed to a building or tunnel fire with additional information before and during an emergency [10]. This would allow occupants to easier and quicker find the nearest exit, optimal evacuation routes and potentially avoid obstacles and untenable conditions. The same system could, furthermore, also be used in normal navigation to assist occupants find what they are looking for, such as the shortest route from a central spot in a train station to a specific platform.

Accuracy

Generally, occupants can observe and assess the environment they are in and, therefore, for many applications, the accuracy of the localization is not necessarily critical. As such, location at cm level is not needed for pedestrian navigation [4] in general, instead studies in buildings have shown that room-level accuracy is sufficient [20]. The required accuracy for occupants is, however, environmentally dependent. Occupants in a tunnel may, for example, be expected to be unfamiliar with the surrounding environment and may, furthermore, experience difficulties navigating in it as well as uncertainties related to using to them unknown escape routes leading from the tunnel. On the other hand, tunnels are generally not very complex from a route selection perspective, and there are typically less options available compared to a traditional building. Hence, from an accuracy point of view of an indoor localization system to be used in fire emergencies, it may be feasible to provide information regarding an occupant's position in relation to the closest escape routes or exits. On the other hand, a higher level of accuracy may be of value, as it may would enable occupants to relate their position to indoor "landmarks", resulting in higher reliability and sense of safety.

In the reviewed literature, no recommendations or conclusions are provided about the accuracy of indoor localization of people in tunnels. Based on the above discussion, it seems reasonable that if such an indoor localization system is employed to provide individuals with the ability to position themselves, an accuracy in the interval of 20-150 m seems reasonable with regard to the typical placement of escape routes in such building works. This is based on the distances that occupants may need to travel to reach an escape route, as well as to allow occupants to receive feedback and see that they are making progress.

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[3] It is, however, acknowledged that research efforts in recent years have focused on the effectiveness of so called dynamic signage systems [49, 50, 52]. However, this is not yet a common safety installation buildings or tunnels.

Information Accessibility

When the user of an indoor localization system is an individual occupant, existing smartphones[4] without any alterations could be used as part of the positioning infrastructure [4]. Applications that are mainly used in normal operations, but can be utilised in an emergency as well, is deemed to be the most feasible solution for most such indoor localization systems. These applications will be used during normal operations but could then be utilised in an emergency as well. This would also allow occupants to become familiar with the system, prior to an incident.

As the lack of intuitive way-guidance can cause users to become trapped in a facility [28], localization data and information should be presented intuitively in an easy and user-friendly way. The information can, for example, be presented by alert messages and/or within an application on a user's phone [30]. Via such an application a user can receive alert information from connected sensors deployed in the built environment, and information regarding the position of, for example, obstacles caused by a fire [31].

However, in a tunnel context, it may not be feasible to depend on occupants having downloaded an application to their smartphone to be used in case of an emergency. Particularly as indoor localization and positioning needs are typically low during normal operations when the tunnel is used only for travelling between different places (in a car or train carriage). As such, it is questionable if occupants can or should be assumed to have taken such prior actions. As an alternative, systems as the OASIS Common Alert Protocol can be used for alert messages. A hybrid alternative could be to utilize very popular and commonly used standard applications, such as Google maps, that are already installed on most smart phones [30].

Indoor localization systems intended to be used by occupants of a building (or a tunnel) emergency may be designed to provide the user with the following information [3, 32]:

- notification of an emergency and when it occurred,
- which way the user is facing, and
- exit guidance (such as which way the closest exit is).

An example of how such information could be presented to a user is illustrated in Figure 4 [32].

[4] Particularly as smartphones today are highly adopted in our daily lives [10]. As an example, in 2017 in Sweden, 98 % of the population above 12 years old had a mobile phone and 85 % had access to a smartphone [53].

Figure 4. Visual example of the type of information that may be provided to and be of value for occupants in a tunnel emergency [32].

System's Adaptability, Architecture and Autonomy

As most smartphones today have GPS/A-GPS, Wi-Fi and Bluetooth integrated, these technologies can and should preferably be utilized when positioning occupants [27]. In other respects, the same requirements as for positioning of individual firefighters can be deemed to be applicable.

3.2.2. Positioning of Occupants

Third party positioning of occupants can be (and has been) made with the purpose to monitor a crowd where, for example, high occupant loads may be expected. It typically regards the tracking of numbers (crowd density estimations), location, flows and behaviour of people [10, 33]. Such information can be valuable to direct people and traffic, but also to gather information that can be used to base decision making on in case of an emergency such as fire. It may, for example, be used to direct and instruct rescue services during intervention, or as a basis for decisions on which mitigating actions to take in case of fire. In addition, monitoring individuals or groups of people may be expected to deliver valuable information that can be used in research studies on, for example, pedestrian dynamics.

In the context of research on human behaviour in case of fire and pedestrian dynamics, there is a need for reliable methods to position occupants during data collection in order to derive and develop valid correlations between, for example, individual movement speeds and occupant loads. Historically, and presently, this has mainly been collected via observations, either manually or with the help of video cameras. Indoor localization systems could enable mapping and tracking positions and behaviours of individuals as well as crowds, potentially more efficient and with a greater level of detail than in the past. In the longer perspective, this could provide the research field with more up-to-date data reflecting current population demographics, which is deemed necessary as most evacuation models today use data that is more than 40 years old (since then the population characteristics have changed dramatically [34]).

Accuracy

The required accuracy for third party positioning of occupants depends on the specific application and environment. In most practical applications, location at cm level is not needed for pedestrian tracking [4]. With regard to crowd management for safety and security reasons, a high accuracy is not strictly necessary for induvial occupants, instead it may be of greater importance that a localization system is able to accurately detect crowd turbulence, which can be early warning signs for unsafe and critical crowd conditions [10]. Furthermore, it may be sufficient to be able to position people in a tunnel fire in sections made up by two escape routes. However, in a research application context, high accuracy is typically desired to be able to track each individual occupant with a high degree of precision in order to relate this information to other independent parameters and variables. If the purpose, for example, is be to derive flow rate capacities for different escape route elements (doors, stairs, etc.), an accuracy corresponding to 1 m seems reasonable, whereas studies to derive individual movement speeds in relation to, e.g., occupant loads, would require an even higher accuracy.

3.3. Work Health and Safety

Historically, the outcome of past incidents in underground facilities has demonstrated that health and safety is a critical aspect for the industry involved in, for example, mining [16]. Therefore, there has been a focus on the development on safety management systems for these environments, which provides information on, among other things, worker's locations [14]. There are also many aspects of tunnel construction that are more closely aligned with mining than with surface infrastructure in the built environment [25].

Most current deployed localization systems in underground facilities are applied in underground mines. In mines, the positioning system typically consist of access and entry systems which are used to identify occupants entering and leaving at some key points [35]. Installing localization systems in underground facilities is enforced by law by most countries [35], including Sweden and China [14]. Such system are typically installed due to design requirements to mitigate the risks related to fire, collapse or emissions of toxic or flammable gases, in order to enable assessments of how many occupants are currently underground and in what areas (in the acute phase of the incident) [36].

Typically, and historically, the localization systems used in the mining industry have consisted of stamp cards or tags [36]. However, today such indoor localization systems typically build on the RFID technology [14, 16, 25]. A drawback of this technology is the low accuracy and range provided by these systems [14], which may cause problems in a rescue intervention. Therefore, it has been suggested that more accurate and also real time localization systems may be more efficient from a safe work environment perspective [14, 35]. Such solutions are now beginning to show up on the market (see chapter 4.1.3).

According to Lin et al [14], the indoor localization system requirements for the use in work health and safety applications should include the following:

1. the individual position of workers in real-time, and
2. a bi-directional alarm and warning system, so that workers can send an emergency alarm and a control system can issue a warning alarm to workers in case of an emergency.

These and other aspects are also pointed out as challenges related to underground positioning by Thyrbom et al [35].

Accuracy

Thyrbom et al [35] suggest the accuracy for workers in underground mines need to be high (without further specifying the term). However, in operational road and rail tunnels that are less complex, less accuracy is required. In accordance to the Swedish Transport Administration (Trafikverket), an accuracy of between 10-30 m for maintenance work in a tunnel is desired [9]. Thus, and as have been stated previously, quality aspects of an indoor localization system (such as accuracy), is dependent on the purpose and application of the system. Typically, the more complex environment, the greater need for accuracy.

Information Accessibility

In relation to the previously mentioned applications for indoor localization, requirements related to information accessibility, i.e., usability, may be expected to be lower in a work health and safety perspective. This is because workers can be trained in advance to use the system.

3.4. Summary

A summary of user requirements is presented in Table 3. The desired horizontal accuracy in relation to the coverage for each application is presented in detail by Mautz [4].

Table 3. A summary of user needs and requirements for different indoor localization system applications as discussed above.

Category	User	Positioning of	User requirements	Required/desired horizontal accuracy
Rescue services and first responders	Rescue services	Firefighters	• Real-time position • Take into consideration firefighter's movement pattern • User-friendly interface • Scalable and robust	20-150 m
		Occupants	• Real-time positioning • User-friendly interface • Scalable and robust	20-150 m
Occupants	Occupants	Occupants	• Real-time position • User-friendly interface • Should utilise user's smartphones • No activation, alteration or prior installation of program to user's smartphone	20-150 m
	Crowd management and researchers	Occupants	• Real-time position	Depends on application, typically higher for research
Work health and safety	Workers and managers	Workers	• Real-time position • Bi-directional alarm and warning system	10-30 m

4. Indoor Localization Applications

As previously mentioned, there is currently not one solution or one single type of technology that can be used for all applicable situations where indoor localization is desirable. Whereas the application of GPS has become the default technology to be used for positioning in outdoor environments, there is no corresponding system for indoor settings to be used in the built environment, neither for normal nor emergency situations.

In a compilation from 2012 by Mautz [4], it was concluded that only a few applications intended for use during normal operation (e.g., not emergency situations) had reached the market as a ready product. Today, however, more and more applications are being used in a wide variety of applications. Some of the current application of indoor localization systems are developed or have been utilized for/in:

- Navigation and visitor flow in shopping malls [11], offices, trade shows, public buildings, etc. [4]
- Location detection of products [4] and logistics [17]
- Topical information in cinemas, concerts or events [4]
- Public transportation systems and terminals [5, 7]
- Estimation of population densities [6]
- Mapping movement of pedestrians and cyclist in a city [11, 13]
- Emergency alarm buttons [11]
- Mapping spread of infection (Covid-19) [37]

Many studies regarding indoor localization systems, covering a wide range of applications, have been reported. Furthermore, there are additional examples of studies directed on issues related to tracking quality, see for example the publication by Danalet et al. [38]. However, according to a report by Adler et al. [39] from 2014, most studies on localization of occupants in non-emergency scenarios with wireless networks, such as Wi-Fi, do not report any actual experiments, but only computer simulations. Furthermore, their results show that there are significant differences between published simulation results and actual experiments in real-world indoor localization scenarios.

As this is an emerging field, more and more studies on indoor localizations systems (and optimizations of them) are being published. It is also to be noted that the field of indoor localization systems to be used in emergency situations is an even newer field and the current state of knowledge is limited [3]. Those publications that has been made available and studied within the current review are presented in an overview below in relation to rescue services, occupants and work health and safety.

4.1. Positioning of and for Rescue Services and First Responders

4.1.1. Positioning of Fire Fighters

The majority of the published studies with a safety focus present indoor localization systems to be used by firefighters [3, 19, 22], i.e., positioning information to be utilized by individual firefighters or fire rescue commanders.

In a comprehensive survey, Ferreira et al. [19] compiled and compared 31 different localization systems and studies for emergency responders. These consisted of 12 radio signal-based systems (i.e., Wi-Fi, Bluetooth and RFID), 13 inertial and motion sensor systems and 6 hybrid systems. All if the studied systems positioned either firefighters or other first responders and most of them where designed for the use of either only the emergency responder or the emergency responder and the incident commander. Most of the radio-based systems used a combination of wireless technologies and measurement techniques, with Wi-Fi utilizing RSSI being the most common. Many of the reviewed localization systems had been exposed to very limited testing, and the radio signals had low reliability of the position information and coverage as the signals were affected by, for example, radio propagation phenomena's, such as multipath fading, scattering, diffraction and reflection. It is, however, to be noted that the studied systems typically assessed accuracies at less than 10 m. Compared to only using radio-based systems, the hybrid systems outperformed the others in terms of accuracy and reliability. The use of both radio-based signals and inertial sensors generally complemented each other. The inertial and motion sensor measurements in the hybrid systems did, however, have issues with recognizing the movement of firefighters. It is, furthermore, to be noted that the localization systems reviewed by Ferreira et al. [19] had to a large degree been evaluated under controlled or semi-controlled environments where emergency responders used predefined routes and movements. In a real scenario, many unpredictable situations may occur and as such, it is hard to conclude how efficient the different systems would be in real applications.

Similarly, in a survey from 2015 by Bastos et al. [3], 30 different indoor localization systems were reviewed, typically developed and designed to be used by firefighters. Bastos et al. [3] concluded that there is a predominance of system that use radio signals, especially RFID with the most commonly adopted localization technique being lateration. Bastos et al. [3] also concluded that direct comparison of the performance of the different reviewed localization systems is difficult, as each study typically employ different methodologies to evaluate the corresponding system.

Fuchs et al. [21] argue that dead-reckoning systems deliver an advantage in terms of positioning fire fighters during mission critical scenarios. The reason is its autonomous operation independence from an existing infrastructure, which may compensate for deficiencies of radio-based techniques. However, in order to avoid problems such as so called drift over time (increasing positioning error over time), Fuchs et al. [21] also conclude that the localization technique should be complemented by other techniques.

It is noted that most existing indoor localization systems do not consider the challenging conditions that first responders typically work in. Other research related to rescue operations in tunnels have, for example, demonstrated that fire induced consequences (or consequences caused by fire safety installations, such as fans) may obstruct communication possibilities during intervention [23]. Similarly, conditions such as high temperatures, thick smoke, noise, etc., may hinder the propagation of signals [22]. As few experiments with the same conditions as an in an emergency has been performed, it is hard to know the exact impact this would have on different localization systems.

Although many studies have been carried out on the topic of indoor localization systems for firefighters, few to none of the proposed systems meet all user requirements for such applications. According to Ferreira et al. [19], the main reason for this is the lack of corporation between the development teams and the fire brigades, and state:

This lack of cooperation implies that the majority of the developed systems are unable to adapt to the dynamic scenarios faced by emergency responders during their on-duty missions, resulting in a poor performance of the system in terms of accuracy and precision.

In addition to this statement, the major issues and challenges in the design and performance assessment are by Ferreira et al. [19] argued to be related to: 1) high system cost, 2) test scenarios, 3) recognition of typical movement patterns of emergency responders, and 4) poor availability of signals from wireless technologies. Consequences in relation to these aspects were, among other studies, highlighted in 2009 when firefighters in Massachusetts evaluated six location systems that the manufactures believed where ready for the market. The firefighters performed a series of test interventions while using these systems. The results of the evaluation showed that none of the solutions helped the firefighters complete the interventions faster than with already adapted methodologies [40]. One localization system did, for example, fail to detect sharp turns. Another worked only when firefighters walked or ran but not when they crawled. A third caused a rescue team to redirect into a wrong building.

Regarding indoor localization systems for the use in road or rail tunnels, even fewer studies have been able to identify. Among these is a Swedish initiative [41], driven by the health and safety regulations regarding rescue interventions in smoke, particularly related to underground environments with long intervention routes [42]. This research project found that the most promising technology was a radio communication positioning system, which in practice means that first responders create a so-called ad hoc network by distributing communication units along the intervention route during a rescue operation. The positioning can then be made by wireless communication between these units and equipment that the first responders carry on themselves.

In addition to what has been mentioned above, the following can generally be concluded for the current indoor localization systems for firefighters:

- Indoor localization systems should, preferably, be developed in corporation with the fire brigade,
- Indoor localization systems need to be tested and evaluated in real scenarios and environments in which they are to be used, and
- Indoor localization systems making use of hybrid technologies and measurement techniques, and that facilitate information from both wireless and inertial/motion measurements, are generally more robust, reliable and accurate.

4.1.2. Locating Victims Exposed to the Fire

As discussed in the previous section, the majority of the available studies on indoor localization for fire rescue services focus on positioning of first responders [3, 19]. A few studies have, however, included proposals to locate occupants in distress (victims), but in only one reviewed case study [3, 19], this was elaborated on in further detail [3, 43].

Li and Becerik-Gerber [43] proposed an application for the use of first responders that could locate and position both occupants and first responders by utilizing smartphones and tethering technology to establish an ad-hoc Wi-Fi-network among the smartphones. The coverage of the system was limited by the short communication range of smartphones, which is about 30 m, and that each device had to be connected to at least two other devices for the localization algorithm to work. The system was only tested in line-of-sight-conditions but provided fairly fast and accurate positioning. Occupants did, however, need to have an application pre-installed on their phones and the system was dependent on the battery of the smart phones.

In addition to the above-mentioned study, Pereira [8] studied an indoor localization system for tunnel occupants with the use of GSM and Wi-Fi networks. With RSSI fingerprinting, the system provided an accuracy around 30-50 m within the tunnel. The system was not tested for emergency use but could be used by a third-party such as first responders for locating occupants in case of fire. In the study, several localization techniques were evaluated, and it was concluded that by combining different technologies, the system provided higher flexibility and robustness.

Ma and Wu [28] developed an indoor localization system for firefighters and occupants that need to be rescued. However, in the evaluation of the system, no result was presented for occupants that needed to be rescued, but only information on the localization of firefighters and occupants for their own use. The result from this study regarding positioning of occupants is presented in the following chapter.

4.1. Indoor Localization of and for Occupants

There are quite many applications for tracking and monitoring occupants, providing information to be used both by the occupants themselves, and particularly for third parties. As an example, navigation and visitor flow in shopping malls [11] and indoor navigation in transport transfer buildings [6, 44] have become fairly common. However, the majority of the applications and studies are typically aimed at operation during normal conditions, and few studies have analysed the applicability of indoor localization systems to be used during an emergency [3]. Two types of systems or functions can be distinguished; those intended for the occupants to use and those collecting data on the occupants and their movement.

4.1.1. Positioning for Occupants

Most indoor localization systems to be used by occupants are mass-market applications for indoor positioning and not intended for emergency use. These applications usually consist of systems that allow an occupant to navigate in shopping malls, train stations or large public buildings. Most commonly these systems use Wi-Fi fingerprinting methods, as this technology and technique allows already existing system infrastructure to be used [4]. The systems can provide an acceptable localization at m level, and the systems are not too complicated to implement [20]. Many applications also utilize information from the occupants' smartphones, as most phones today are equipped with motion sensors such as accelerometers, gyroscope and magnetometer [20].

For localization systems for occupants to be used during normal operation, experiments on Wi-Fi Time-of-Arrival (ToA) measurements show poor quality due to multipath and low resolution of the clocks. Using RSSI have also proven unreliable due to an irregular dependency between attenuation and distance in indoor environments [4].

With regard to indoor localization systems for occupants in emergency situations, there are fewer applications available. In a survey from 2015, Bastos et al. [3] reviewed 30 studies where only four of the studies included localization systems for occupants (victims) in an emergency. These systems all utilized wireless distance measurements, and the majority of them employed the RFID technology with the most adopted localization technique being lateration with RSSI.

Other studies, such as the one by Depari et al. [31], Nui [27], and Mirahadi et al. [45], have developed or theoretically evaluated applications or system that can be used during emergency evacuation. However, neither of them has been evaluated in case studies or experiments, and as such, no direct conclusions can be drawn. Similar examples of studies, such as the one conducted by Xu et al. [20], have only examined systems that have been tested in laboratory environments, with only one occupant being positioned in the study, and not under emergency conditions.

Ma and Wu [28] developed a system for firefighters and evacuees. The system combined Wi-Fi fingerprinting with information from a smoke detection system and building cameras and deployed this information in a joint BIM model. An experiment within a three-storey office building was set up with one test group using the system, and another control group not. The result showed that the test group generally acted more rationally in their decision making and that their evacuation time was reduced by 48 % compared to the control group.

In relation to applications specific for occupants in road or rail tunnels, no studies or developed applications have been found in the literature. A so called '*tunnel app*' for the use with a smart phone have been suggested in previous research [32], where information regarding what direction to walk in and distances to the closes escape routes could be displayed (see Figure 4).

As the current studies and applications for use in emergency scenarios only have been exposed to limited experimenting and tests in controlled environments, the following conclusions derived from mass-market applications may be deemed applicable and valid also for emergency situations:

- Most commonly deployed systems use Wi-Fi fingerprinting methods as this allows an existing infrastructure to be used,
- Any indoor localization system needs to be tested and evaluated in realistic scenarios in non-line-of sight environments before being deployed.

4.1.2. Positioning of Occupants

In the context of emergencies, the majority of the published studies present systems typically for crowd monitoring by a third party. Currently, most research that focus on crowd monitoring systems present specific indoor localization solutions that are implemented prior to gathering locations and prior to the occurrence of an emergency [10].

In a review of intelligent evacuation management systems from 2016 by Ibrahim et al. [10], 17 crowd monitoring case studies and techniques were evaluated. All case studies were based on indoor localization systems, but where tested outdoor with line-of-sight and no signal blockages. Generally, challenges in tracking were, for computer vision techniques, related to the presence of many occupants on site. Hence, crowd monitoring via nonvideo based technologies such as GPS, Bluetooth, and RFID were hypothesized to yield better outcomes in terms of crowd monitoring. The studies having examined the latter systems had utilized the occupants' smartphones. The primary limiting factor related to this approach is that it requires the user's consent to collect the data. For tracking crowds, the review also found that when using RFID tags, the technology was too application specific as well as none reliable and expansive for its intended use [10].

A number of other studies have also focused on the tracking and monitoring of occupants and crowds [6, 11, 13], but not during emergencies. Tyni and Wikberg [13] did, for example, conclude that collecting data with Wi-Fi-sensors is relatively simple. However, compiling the data, and mapping occupants with the messy data collected pose a more challenging task. As such, additional calibration may be needed to ensure quality of the post processed output.

It is to be noted that the actual research work is limited in terms of emergency evacuation scenarios, and especially large-scale ones [10]. As shown in a report by Hansen [46], additional research into crowd movement is required for parameters such as culture, gender, emotional state, cooperative behaviour, wall distance or obstacle avoidance, bottlenecks or openings, headway, acceleration time, torso rotation, body size, health status and stair gradient. By utilizing localizations systems for occupants in emergency scenarios, data about these parameters could be collected which would allow for better models and predictions of crowd movement in emergency scenarios.

4.1.3. Work Health and Safety

Indoor localization systems for work health and safety in underground facilities mainly consist of application in either operational mines, or the construction of new underground facilities such as road and rail tunnels. Most indoor localization systems in mines are focused on aspects such as access and entry and employs the RFID technology. However, other systems are also tested and used. As an example, a Wi-Fi RSSI system was developed and deployed during construction of a power station in Xiloudu, China [14]. The system achieved real-time tracking and was generally reliable and accurate.

A hybrid position system prototype was, furthermore, developed and tested in coal mine in China using RFID with RSS and inertial sensors. The system utilised the Kalman Filter fingerprinting algorithm [16], and the study results suggests that the method developed is efficient and satisfied the requirements of the particular projects it was tested within, with a positioning accuracy reported to be less than 10 m (however, no detailed results from the test was made available).

An example of a market ready indoor localization system is provided by Mobilaris. The system utilize LTE, Wi-Fi, UWB, RFID and other proprietary technologies for real-time location, tracking and monitoring of vehicles, personnel and equipment in mining environments [47], and claim that they are able to produce real-time information of the locations of people with approximately 50 meters precision by using Wi-Fi [48].

4.2. Summary

The field of indoor localization systems aimed to be used during emergencies seem to constitute a fairly new and unexplored field, and as such, the current state of knowledge is limited, with few experiences and little best practices to employ. A number of applications for indoor localization in general have reached the market as a ready product. However, with regard to indoor localization systems for emergency situations such as fire (utilising wireless technologies and techniques for distance measurements, etc.), few applications are known to be in use.

Generally, most studies and applications, regardless of who the user is, aim to be as accurate as possible and do not necessarily reflect over what accuracy is needed for the specific application. As there is no benchmark for indoor localization applications, their performance is not evaluated against any standardized tests. Furthermore, as indoor localization systems generally have either not been tested outside labs or only in controlled environments with line-of-sight and predefined routes or movement, this makes generalizable conclusions in relation to the potential application for tunnels difficult to make.

Indoor localization utilizing wireless technologies is challenging due the fact that there are walls and objects around the confined spaces where transmission occur [4]. In most applications, however, this still have not been reviewed. Based on the reviewed literature and the results and conclusions drawn in the related studies, it is fairly clear that more case studies or experiments, in the environment for which the localization system is to be used for safety purposes, need to be performed.

A general conclusion that can be made is that indoor localization systems that utilises multiple technologies and location measurement techniques generally seem to be more robust and accurate. Wi-Fi fingerprinting is typically deployed, although it may not necessarily provide the best accuracy (compared to all available solutions), and this is likely a consequence of the fact that this allows any existing infrastructure to be used. Hence, these types of systems are cost efficient and fairly easy to implement

5. Future work

Utilizing wireless technologies to track people (either outdoor or indoor) is today typically used to survey incoming and outgoing traffic to a certain space or location, to estimate group sizes and to measure the duration of visits. Using the same technologies to track people in indoor environments in case of emergencies may provide valuable information about what is going on in a certain situation, and enable, e.g., an incident commander or an operator at a traffic control centre to make better informed decisions about mitigating measures. In this respect, Wi-Fi is deemed as a promising technique to do so, primarily due to the following reasons (cited from Petre et al. [15]):

[..] First, many people carry WiFi-enabled devices making it an ideal instrument for tracking people. Second, and very important, is that the owner of a device need not do anything to allow tracking except enabling the WiFi capabilities on her smartphone. In practice, smartphones virtually always have their WiFi enabled. [..]

Hence, the Wi-Fi technology allows digital footprints to be collected within an already existing network infrastructure.

As the technology maturity regarding indoor localization of people during incidents is relatively low, it is deemed necessary to initially evaluate aspects such as precision and accuracy when exploring such a system's performance and capabilities. Particularly as the techniques for localization mentioned above typically have been deployed on a larger scale, e.g., to assess movement paths rather than exact positions, and not seldom in outdoor settings, or have been applied in settings with full control over the people that are to be tracked (such as in mines). Examples of research questions on which an empirical study can be based are, therefore:

1. Where are people located in a tunnel at a given time (as measured/tracked by the Wi-Fi localization system)?
2. How do the in bullet 1 measured positions correlated to direct observations (e.g., made by help from a video surveillance system)?
3. What percentage of those actually being in a tunnel are registered/positioned by the Wi-Fi localization system?
4. How does the presence of obstacles affect the tracking?

These questions should, furthermore, be investigated during variations in (at least) the following independent variables: a) local population densities, b) association with (connection to) the wireless network, c) movement patterns, and d) access point installation density. The reason is that these variables can be expected to affect the performance of the positioning. It is first when these questions have been explored, that statements may be made regarding whether the technique can be used to improve fire safety, and/or to be used in more research-oriented activities (e.g., to collect data on pedestrian dynamics). Such statements could, furthermore, be based on the list of dimensions defining an indoor localization system proposed by Mautz [4].

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