Department of Electrical and Computer Engineering

Part IV Research Report

Literature Review and
Statement of Research Intent

Project Number: 13

Localization and Mapping in a Firefighting environment

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Declaration of Originality

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ABSTRACT: Many localisation and mapping solutions have been developed for environments where the global positioning system fails to provide accurate data. Despite the multitude of technologies and techniques available, this is largely an unsolved problem as there is no universal solution that meets all application requirements. The target application for this study is firefighting. A positioning system that can perform both localisation and mapping is a crucial tool for improving the safety of firefighters and civilians, however, such systems are currently not commercially available. A literature review was conducted on sensor technologies, localisation and mapping techniques, and existing firefighter positioning systems in research. Core technologies that have been deemed suitable for the initial prototype include ultrasound, inertial measurement units, and lidar.

1. Introduction

1.1. Motivation

It is widely accepted that GPS is a robust technology for outdoor positioning, with meter or centimetre level accuracies, depending on the infrastructure used. However, many indoor environments are GPS-denied because the technology becomes unreliable due to signal attenuation and interference [1] [2]. Most indoor environments that firefighters work in are considered as GPS-denied. They work in challenging environments consisting of fire, smoke and darkness. Firefighters rely on all their senses to feel and navigate throughout an unfamiliar building. In these environments, firefighters can easily become disoriented due to the heat, loud noises, and severely reduced visibility, which has led to many fatalities [3].

The Devonport Volunteer Fire Brigade (DVFB) have also shown interest in the system and agreed to co-operate with data collection. DVFB explained that smoke-diving firefighting operations are similar across the globe as many procedures have been standardised. For indoor environments, firefighters operate in teams of two with breathing apparatus lasting around 30 minutes. While inside, activities include, walking, running, crawling, and climbing. After each team returns, if possible, the pair attempt to reconstruct a map either verbally or by drawing on a whiteboard and explain which areas they searched. Due to the stress the firefighters go through while inside the building, this map is often a very poor estimate of the ground truth. It was stated by the fire brigade that no advanced positioning technologies had made their way into New Zealand. Clearly, a reliable positioning system that performs both localisation and mapping is a crucial tool for improving the safety of firefighters and civilians.

1.2. Background

Indoor positioning systems (IPS) are a popular and multidisciplinary area of research with applications including social networking, healthcare, industrial automation and warfare. There are a multitude of technologies and techniques for solving GPS-denied localisation problems and most have been used extensively and are well established for their specific applications. The key challenge is that all technologies have their own weaknesses, for example, the use of RFID technology typically requires prior infrastructure deployment and inertial measurement units are prone to drift. Sensor fusion is unarguably the required technique for complex applications, where data from multiple sensors are combined to improve accuracy, reliability and better overall performance. However, the development of indoor positioning systems is largely still an unsolved problem in the sense that there are still many applications out there where is it is difficult to identify the optimal solution, such as firefighting. A perfect solution would require a balance between the many requirements such as cost, size infrastructure, accuracy, and reliability.

1.3. Structure

The report has been divided into two main sections, a literature review and statement of intent. The review begins by introducing IPS technologies and techniques, with a focus on firefighting. It then discusses previously conducted research, existing products, and their associated issues. The statement of intent critically analyses the reviewed literature, identifies the scope of this study, justifies its purpose and presents a brief proposal.

2. Literature Review

Over the years, various survey papers have been published on sensor technologies and techniques for IPS. As this is a rapidly changing field, it is important that surveys are conducted every few years. The most recent surveys to date present discussions on IPS requirements, applications, technologies, techniques, trends, and challenges [4–7]. The key differences between the surveys being their classification schemes and organisation of information. As explained in [5], many surveys merely present a flat-list of ideas; an example of this is Mautz's survey [6]. Furthermore, due to the way classification is done or how in-depth ideas are discussed, a few ideas may not be mentioned. From these surveys, it is evident that this is a broad field and without an application it is difficult to organise the information.

2.1. Requirements

The requirements for firefighting are stricter, to some degree, than general IPS applications. It is a safety critical system and providing false information could place lives in danger, however, the accuracy resolution does not need to be as strict as a positioning system for medical applications. In general, the major design considerations when selecting sensor technologies for IPSs are cost, size, accuracy, infrastructure, complexity and general feasibility. In [8] and [9], Rantakokko surveys the requirements and technologies specifically for first responders and firefighters. Rantakokko explains that positioning systems for firefighters should be reliable, fire-proof, night-proof, reasonably lightweight, small in size, power efficient, preferably infrastructure-less, and provide meter-level accuracy. An online, non-intrusive system with quick deployment is also required as firefighters need to focus on rescuing civilians, their oxygen intake, and own orientation. Similar requirements are also outlined in Fischer's survey [1].

2.2. Technologies

The majority of IPS technologies utilise the electromagnetic (EM) and acoustic spectrum. Examples include Wi-Fi, RFID, cameras, sonar, and lidar. Other technologies such as inertial measurement units (IMU), magnetometers and barometers are independent of those spectra. The following sections will briefly detail key categories of IPS technologies and their relation to firefighting. Note that as sensors can be exploited in many ways, a few belong in multiple categories. Though it is difficult to illustrate all subtleties, a brief summary of the technologies in relation to firefighting is shown in Table I.

2.2.1. Radio

Though technologies that use the radio frequency spectrum are by far the most popular, they may be unsuitable in a firefighting environment due to the additional infrastructure is required. Ideally, the positioning system should not rely on wireless routers or planted beacons in a burning building. However, in the future, the final system could exploit existing infrastructure to improve accuracy. Despite these disadvantages there are still existing prototypes that have used these technologies, such as for peer-to-peer localisation, as will be discussed in Section 2.4.

2.2.2. Passive sensors

In this review, passive sensors are those that do not actively send out signals and are purely measuring attributes of the environment. This includes technologies such as cameras, microphones, barometers and magnetometers that sense ambient light, sound, pressure and magnetic fields, respectively. In a loud, smoke-fire, and rapidly changing environment these technologies provide little help for positioning and mapping and are extremely sensitive to noise [6]. An exception is the IMU; although still affected by noise, it is still a popular technology that has potential in a firefighting environment. The two main components of an IMU are the gyroscope and accelerometer, which measure angular velocity and proper acceleration, respectively. In a perfect world, if an initial position is known, the IMU alone, regardless of the external environment, can provide location data with perfect accuracy. However, in practice this is not the case due to accumulation of error, as will be discussed in Section 2.3. Optical cameras are ineffective in these environments due to the dark and smoke-filled environment, however, the thermal imaging camera (TIC) has potential. By capturing infrared radiation, firefighters can identify heat signatures of humans, fires, and building features such as walls, through smoke and darkness [10].

2.2.3. Rangefinders

Another group of technologies are those with the ability to perform detection and ranging, which are typically used in surveying. A category has been given to rangefinders as an ideal firefighter positioning system should also be able to perform mapping, which requires rangefinders. This techniques uses signals that are reflected from a surface and returned to a receiver. The most common rangefinders include sonar, radar and lidar. Sonar utilises the acoustic spectrum while radar and lidar are based on radio and infrared waves (laser) from the electromagnetic spectrum, respectively. The advantage with all rangefinders is that additional infrastructure is not required, and both localisation and mapping can be performed at the same time.

Most commercially available sonar and radar systems are for long range marine and aviation applications, and are much too large in size to be suitable for firefighters. However, one-dimensional ultrasonic sensors are relatively small, low cost and are able to measure short distances, suitable for firefighting. In the past, lidar technology have been unsuitable due to its size, but recently the technology has become more compact and affordable, making it more suitable for firefighting. The multi-echo lidar is a special type of lidar that was designed for low visibility environments such as fog. It works by receiving multiple reflected signals and using filtering techniques to ignore false positives.

The main challenge for rangefinders is the effect of smoke and fire on wave penetration and propagation speed. Studies that evaluate the performance in these environments summarise that ultrasound and radar penetrate through smoke particles more easily due to their longer wavelength. The downside is that radar devices are too large to be mounted on firefighters and ultrasound is severely affected

TABLE 1
TECHNOLOGIES AGAINST KEY FIREFIGHTER REQUIREMENTS

Technologies	Size/Weight	Infrastructure Deployment	Smoke Proof	Localisation Resolution	Accumulates Error	Performs Mapping
Beacons/RFID Tags	Low	Yes	Yes	cm to m	No	No
Lidar	Medium	No	Varies	cm	No	Yes
Radar/Sonar	High	No	Varies	cm	No	Yes
Ultrasonic	Low	No	Varies	cm	No	Yes
IMU	Low	No	Yes	Varies	Yes	No
Optical Camera	Medium	No	No	cm	No	Yes
TIC	Medium	No	Yes	cm to m	No	Yes
Barometer	Low	No	No	-	N/A	No
Magnetometer	Low	No	Yes	-	N/A	No

by temperature gradients and the Doppler effect. The performance of lidar is largely unaffected by heat or fire, however it struggles with smoke particles [11] . In [12], it is shown that the multi-echo lidar can handle low levels of smoke but worsens with thicker smoke. Though these results imply that sonar and lidar might be redundant in fire and smoke, recent sensor fusion approaches have shown promising results, as will be presented in Section 2.4. Another challenge for these rangefinders is the need to consider the stochastic movements in orientation and position of the firefighters.

2.3. Measurement and Localisation Techniques

To add to the complexity, sensor technologies are not restricted to certain techniques for determining location. For the purposes of this review, a measurement technique refers to the way a sensor collects data while the localisation technique is the method to obtain location data. Often, they are closely related, but it is still important to understand the difference. Parameters that a technique uses depends on its application with key considerations being accuracy, infrastructure available and processing power.

2.3.1. Common techniques

Common measurement techniques include time of flight (ToF), angle of arrival (AoA), return time of flight (RToF), cell of origin and received signal strength indicators (RSSI), while common localisation techniques include proximity detection, trilateration, multilateration, triangulation, dead reckoning, map-matching and SLAM based algorithms [4], [5]. ToF methods exploit the propagation speed and time of signals to determine distance information. Similarly, RSSI models the distance but based on the strength of the signal received. Once distance measurements are found, trilateration or multilateration localisation techniques are used to perform simple geometry to determine location. In AoA, the angle that signals arrive are determined via the phase difference, which are then used to determine a location through triangulation. Another common technique is fingerprinting, where a database or map of a certain variable, such as RSSI, is created either by pre-measuring or mathematically modelling. The map can then be used as form of a look-up table to assist in determining location. Many measurement and localisation techniques require pre-installed infrastructure, thus, making them unsuitable for firefighting. Techniques specific to IMUs, ultrasonic sensors and lidars will now be discussed in further detail.

2.3.2. Techniques for IMU

Raw data from an IMU consists of angular velocity and proper acceleration, which for all intents and purposes means the effect of gravity is measured. The key reason why an IMU is useful is that the angular velocity and acceleration can provide orientation and position data through integration (or double integration) and rotation transformations. The typical usage of the IMU involves a process called dead reckoning, where the position of the next time-step depends on the previous position. In practice, accelerometers and gyroscopes have finite resolutions, biases, and electrical noise. These imperfections lead to an important phenomenon called drift, or integration drift, which is the accumulation of error as time progresses. Studies have shown that double integration alone can have errors showing quadratic growth and can provide accurate position data for only a few seconds [13], [14]. A common technique to mitigate the error is the zero-velocity update (ZUPT), where the velocity is reset to zero when the object is identified to be stationary [15]. This prevents the error from accumulating as fast. However, this does not stop error accumulation for when the object is moving. Another approach to using IMUs is step length estimation, where a model is developed to estimate the step length of the person or object [16]. For example, an IMU could be placed on the foot to detect steps and the number of steps would give an estimate of the position. This technique is still a form of dead reckoning, hence prone to drift and additional information is required to reset that drift. The issue with the addressed techniques for IMU is they generally require regular motions to detect steps or stationary instances.

2.3.3. Techniques for Ultrasonic and Lidar

Typically, the relative distance between two ultrasonic devices is obtained through time of flight methods. An emitter sends ultrasonic or laser pulses to a receiver and the propagation speed and time are used to determine the distance. Nodes or beacons can be placed around a room and the object of interest can be localized using trilateration or multilateration techniques. For a firefighting scenario, the environment cannot be prepared beforehand. Thus, an infrastructure-less approach is more suitable, such as measuring time for reflected pulses to return. The typical maximum range for ultrasonic rangefinders is around 10m, which should be sufficient to provide useful information in an indoor environment where firefighters traverse along walls this. Lidar operates in a similar fashion but handles much higher sampling frequencies and has more precise distance measurements.

Simultaneous localisation and mapping (SLAM) is used extensively to navigate robots in unknown environments. One definition of SLAM is the process where an object of interest builds a map of its spatial environment whilst simultaneously keeping track of its position in that map [17]. Though the definition of SLAM appears to directly reflect the firefighting problem, existing SLAM systems are generally applied to robots. The key advantage of robots is that their movement is more stable than firefighters, hence easier to model and resulting in less errors. Furthermore, robots typically have wheel odometry which can improve the initial position estimate.

A typical SLAM process consists of processing sensor data, feature (or landmark) extraction, data association, map building, and location estimation. Data association refers to the process of matching observed landmarks to currently tracked landmarks. The process then repeats in an iterative manner. Usually a rough estimate is given on the object's position from IMU or odometry data. The estimate is then improved by considering the feature estimates, or vice versa. The main challenges with SLAM are computational efficiency and robustness in harsh environments [18].

The most used SLAM algorithm is based on the Kalman filter, followed by the particle filter. The Kalman filter is a mathematical tool that iteratively estimates the state of variables when there is uncertainty in the input data. Given input data, the previous state, and their uncertainties (often quantified by variance), this technique estimates the next state of a variable and its uncertainty [19].

2.4. Existing Firefighter Positioning Systems

For any study, it is of great interest to understand existing solutions. As shown at the Microsoft Indoor Localization Competitions, there exist an abundance of indoor positioning systems [20] , but many exploit existing infrastructure such as Wi-Fi or pre-supplied information such as building layouts. It is true that a perfect firefighting positioning system should take advantage of existing infrastructure. However, many firefighting environments are unknown, hence the system's core should not rely on those technologies.

Currently, the thermal imaging camera is one of the most advanced technologies used by professional firefighters. This is mainly used to assist in seeing through smoke and not for positioning systems [10] . Many studies presented discuss only requirements, challenges, preliminary tests and concept designs. Discussed in the following sections are notable firefighter positioning systems, and their associated performance and flaws. Like Table I for sensor technologies, a summary of these systems is provided in Table II. More firefighting systems can be found in [21] and [22].

2.4.1. An IMU and UWB System

The Tactical lOcatoR (TOR) system is a real-time cooperative localisation system for firefighters developed by researchers from KTH Royal Institute of Technology [23]. It was adapted from their OpenShoe project, an open source project for embedded foot-mounted inertial systems [24]. The system uses custom-designed dual foot-mounted IMUs and UWB. A ZUPT approach for the IMUs is used to reduce errors, it further slows error accumulation by considering the upper limit of the distance between the foot-mounted sensors. The UWB technology is used to perform cooperative (peer-to-peer) localisation, exploiting the fact that firefighters operate in pairs and multiple teams may be in the building, essentially acting as moving beacons. Tests lasting up to ten minutes were conducted which involved walking, crawling and moving along staircases, with accuracies of around 2 meters. An important point to note is overhead, one of the many practical issues for a firefighter positioning system. In order to initialise the position and heading of firefighters, this system required firefighters to walk along a few lines. Furthermore, manual adjustment was required to fit the position data to a pre-supplied map. The study concluded that the position estimates had metre-level accuracy, however, mechanical robustness, tuning of sensor fusion algorithms and more scenario-dependent tests were required to improve the system.

TABLE 2
EXISTING IPS SYSTEMS FOR FIREFIGHTING

System	Technologies	Infrastructure Deployment	Tested with firefighter movements	Tested in smoke	Performs Mapping	Localisation Error
TOR [23]	IMU, UWB	No	Yes, up to 10 min tests	No	No	≃2m
Yuan [25]	IMU, RFID	No	Yes, up to 30 min tests	No	No	1 to 20 m
CMU [28]	IMU,UWB, long-range radio	Yes	N/A	N/A	No	N/A
Zakardissnehf [11]	Lidar, robot odometry	No	No	Yes	Yes	1 to 10 m
Chameleon [29]	TIC	No	No	Yes	Yes	≃4m
Baglietto [30]	IMU, Lidar	No	No	No	Yes	N/A

2.4.2. An IMU and RFID System

In 2017, another group of researchers designed an IMU-based positioning system with additional RFID technology to correct for drift [25]. Like the other systems, the IMUs were foot-mounted and the ZUPT approach was used. RFID tags are placed at the entrance of each room which help correct for any accumulated error. The group presents performance for both the IMU alone as well as with the RFID tags. For short tests, 1-2 meters of error was achieved for the IMU alone for various gaits. A long thirty-minute test was also conducted with mixed gaits which resulted in an average error of 20 meters. The group briefly claims that RFID improved performance, however no results are provided. A similar study was conducted with purely IMU at the University of Michigan where an IMU-only system was adapted for firefighting scenarios [26], [27]. Deployment and initialisation overhead were also reported in these studies.

2.4.3. Carnegie Mellon University

In 2017, professors from Carnegie Mellon University (CMU) received a three-year government grant for an infrastructure-free localisation system for firefighters [28]. The grant was one of the many awarded by the U.S. Commerce Department's National Institute of Standards and Technology, who aimed to advance technologies for first responders [31]. The researchers decided to initially take a combination of IMUs, UWB and long-range wide-area network radios in their positioning system. They envision a live system that involves firefighters wearing IMUs and radio frequency tags that communicate information to beacons planted around the building. Though not specified, their system will most likely exploit the fact that firefighters operate in pairs and perform peer-to-peer localisation as UWB has relatively short range, like the TOR system. Their study is currently being undertaken.

2.4.4. Robots

Due to the many advantages and applications of robots, many positioning systems have been developed for them, even for fire-smoke environments. In [11], a lidar-based system performing SLAM was developed. A multi-echo lidar was used on a robot, however it was not successful in filtering out all levels of smoke. The study concluded that it was not possible to rely solely on the intensity of the returned signal. It was suggested that additional sensors are required to evaluate the uncertainty of the data received by the lidar. In [32], a combination of radar and IMU technologies are proposed, while [33] uses a TIC, radar and lidar. Though these systems are on robots, the SLAM principles used can be used in the same way if sensors were placed on firefighters.

2.4.5. Chameleon on Fire

In 2014, the Swedish Defence Research Agency adapted the Chameleon system [29] for soldiers and firefighters. This system uses stereo TICs and IMUs to perform both localisation of firefighters and mapping of the environment [34]. As this system uses TICs it can be a challenge to detect landmarks because of the lower resolution of heatmaps, in contrast to an optical camera that can produce sharper images and hence features. The Chameleon system is one of the few systems that do not use foot-mounted IMUs. The IMU data is fused with landmark observations using an Extended Kalman filter to estimate 3D position, velocity and orientation. IMU data is also used to predict the movement of the landmarks for the short periods of time when the TIC alone is unreliable. The system was designed to be mounted on the firefighter's helmet, however the device was handheld as the prototype was too bulky and enclosed in a large protective case. Tests were conducted at a training facility with thick smoke from a fire that resulted in mostly sub-meter level accuracy. In most cases there was high thermal contrast, allowing the system to perform well, however, areas with low contrast such as narrow corridors displayed errors of up to 4 meters.

2.4.6. IMU and Lidar Systems

In [30], a wearable IMU and lidar on a helmet was developed. Like the Chameleon, this system does not use foot-mounted IMUs and step detection. Instead, the output of the SLAM is used to reduce positioning drift. The approach claims to not need a model of human motion, however, it has yet to be tested against scenarios where a user switches gait. A similar system is HeadSLAM [35] which uses step-length estimation to detect whether the user is walking, however such an approach would not work well for irregular firefighter motions. The performance of these systems, especially mapping, is sufficient for a firefighting environment as the basic layout of a room can be created. The issue is none of these systems have been tested in smoke-filled environments.

3. Research Intent

From the literature review, it is shown that positioning systems for firefighters have strict requirements, in particular they must be reliable, non-intrusive, infrastructure-less, have metre-level accuracy, and work for firefighter movements. Existing systems have combined technologies such as IMU, UWB, TIC, radar, sonar and lidar, with varying results. As shown in Table II, existing systems do not meet all requirements, and hence have yet to be commercialised. As this is a safety-critical system, every requirement is crucial for commercialisation. For example, many systems use IMU and ZUPT which have achieved meter-level accuracy do not work well with firefighter motions. Meanwhile, TIC systems are less dependent on fire fighter motions but are too bulky for firefighters to carry. It is evident that no single sensor technology alone can meet the requirements of a firefighting positioning system. A sensor fusion approach is a must.

The purpose of this study is to contribute to this complex issue by developing an initial prototype consisting of IMU, ultrasonic, and lidar sensors. The inertial measurement unit has been chosen as it is a core technology across existing systems. Though it is prone to drift, the idea is for the lidar and ultrasonic sensors to make up for it. As DVFB is also interested in mapping, lidar has been chosen to perform SLAM and potentially improve the position estimate from the IMU. Lastly, as ultrasonic sensors have been chosen as they are cheap and may have better performance with smoke. It is envisioned that the system will also include thermal imaging cameras, however, due to cost and time constraints it will not be considered in the first iteration.

3.1. Project Scope

Meeting all requirements and complexities of the final system within the timeframe of this study is unlikely. For this reason, the initial prototype will be constrained to 2D localisation and offline processing. The emphasis of this study will be in developing the fundamental blocks of the positioning system and designing innovative data fusion solutions such that additional sensors and features can be added in the future. Off-the-shelf technologies will be purchased to reduce development time.

4. Conclusion

The review of literature on IPS technologies, techniques and systems for firefighter positioning shows it is still an unsolved problem. The system is required to be infrastructure-less, have metre-level accuracy, night-proof, smoke-proof and be able to perform both localisation and mapping. In addition, the system needs to be robust in a fire-smoke environment for all firefighter motions and non-intrusive such that a firefighter can still perform their manoeuvres. All these requirements are safety critical and must all be satisfied in order for a firefighting positioning system to be commercialised.

Several studies have shown systems consisting of various sensor combinations and techniques attempting to solve the problem. However, many have yet to be tested in firefighting scenarios. In many cases, researchers do not continue with the future improvements they suggest. To the student's knowledge, there is yet to exist a system that fully meets the aforementioned requirements.

This study will develop an initial prototype consisting of IMUs, ultrasonic sensors and a lidar. Techniques for each technology will be briefly investigated and chosen. The key focus of the study will be on investigating various data fusion techniques for the technologies. Upon completion, it is envisioned an initial prototype will have been developed. The system will be tested in the laboratory as well as with DVFB at their training facility. The system will be modular such that refinements and additional features can be made.

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References

[1] National Coordination Office for Space-Based Positioning, Navigation, , and Timing, "GPS Accuracy," 2017. [Online]. Available: https://www.gps.gov/systems/gps/performance/accuracy/ [Accessed 2018-04-21].

[2] F. van Diggelen, "Indoor GPS theory & implementation," *2002 IEEE Position Location and Navigation Symposium (IEEE Cat. No.02CH37284)*, pp. 240–247, 2002.

[3] M. Harris, "The way through the flames," *IEEE Spectrum*, vol. 50, no. 9, pp. 30–35, 2013.

[4] W. Sakpere, M. Adeyeye-Oshin, and N. Mlitwa, "A State-of-the-Art Survey of Indoor Positioning and Navigation Systems and Technologies," *South African Computer Journal*, vol. 29, no. 3, pp. 145–197, 2017.

[5] F. Zafari, A. Gkelias, and K. Leung, "A Survey of Indoor Localization Systems and Technologies," pp. 1–26, 2017.

[6] R. Mautz, "Indoor Positioning Technologies," Ph.D. dissertation, ETH Zurich, 2012.

[7] R. F. Brena, J. P. García-Vázquez, C. E. Galván-Tejada, D. Muñoz-Rodriguez, C. Vargas-Rosales, and J. Fangmeyer, "Evolution of Indoor Positioning Technologies: A Survey," *Journal of Sensors*, vol. 2017, no. 2630413, pp. 1–21, 2017.

[8] J. Rantakokko, J. Rydell, P. Strömbäck, P. Händel, J. Callmer, D. Törnqvist, F. Gustafsson, M. Jobs, and M. Grudén, "Accurate and reliable soldier and first responder indoor positioning: Multisensor systems and cooperative localization," *IEEE Wireless Communications*, vol. 18, no. 2, pp. 10–18, 2011.

[9] J. Rantakokko, P. Händel, M. Fredholm, and F. Marsten-Eklöf, "User requirements for localization and tracking technology: A survey of mission-specific needs and constraints," *2010 International Conference on Indoor Positioning and Indoor Navigation, IPIN 2010 - Conference Proceedings*, no. October, 2010.

[10] A. Szajewska, "Development of the Thermal Imaging Camera (TIC) Technology," *Procedia Engineering*, vol. 172, pp. 1067–1072, 2017.

[11] M. Zakardissnehf, "Localisation and mapping in smoke filled environments," Ph.D. dissertation, 2017.

[12] J. W. Starr and B. Y. Lattimer, "Evaluation of Navigation Sensors in Fire Smoke Environments," *Fire Technology*, vol. 50, no. 6, pp. 1459–1481, 2014.

[13] M. Kok, J. D. Hol, and T. B. Schön, "Using Inertial Sensors for Position and Orientation Estimation," 2017.

[14] A. Filippeschi, N. Schmitz, M. Miezal, G. Bleser, E. Ruffaldi, and D. Stricker, "Survey of Motion Tracking Methods Based on Inertial Sensors: A Focus on Upper Limb Human Motion," *Sensors*, vol. 17, no. 6, p. 1257, 2017.

[15] C. L. Fischer, "Localisation, Tracking, and Navigation Support for Pedestrians in Uninstrumented and Unknown Environments," Ph.D. dissertation, 2012.

[16] R. Harle, "A survey of indoor inertial positioning systems for pedestrians," *IEEE Communications Surveys and Tutorials*, vol. 15, no. 3, pp. 1281–1293, 2013.

[17] T. J. Chong, X. J. Tang, C. H. Leng, M. Yogeswaran, O. E. Ng, and Y. Z. Chong, "Sensor Technologies and Simultaneous Localization and Mapping (SLAM)," *Procedia Computer Science*, vol. 76, no. Iris, pp. 174–179, 2015.

[18] C. Cadena, L. Carlone, H. Carrillo, Y. Latif, D. Scaramuzza, I. Reid, and J. J. Leonard, "Past , Present , and Future of Simultaneous Localization and Mapping : Toward the Robust-Perception Age," vol. 32, no. 6, pp. 1309–1332, 2016.

[19] S. Riisgaard and M. R. Blas, "SLAM for Dummies," pp. 1–127, 2004. [Online]. Available: http://ocw.num.edu.mn/NR/rdonlyres/Aeronautics-and-Astronautics/16-412JSpring-2005/9D8DB59F-24EC-4B75-BA7A-F0916BAB2440/0/1aslam{_}blas{_}repo.pdf

[20] D. Lymberopoulos and J. Liu, "The Microsoft Indoor Localization Competition: Experiences and Lessons Learned," *IEEE Signal Processing Magazine*, vol. 34, no. 5, pp. 125–140, 2017.

[21] C. Fischer and H. Gellersen, "Location and navigation support for emergency responders: A survey," *IEEE Pervasive Computing*, vol. 9, no. 1, pp. 38–47, 2010.

[22] J. W. Starr and B. Y. Lattimer, "Evidential Sensor Fusion of Long-Wavelength Infrared Stereo Vision and 3D-LIDAR for Rangefinding in Fire Environments," *Fire Technology*, vol. 53, no. 6, pp. 1961–1983, 2017.

[23] J. O. Nilsson, A. K. Gupta, and P. Handel, "Foot-mounted inertial navigation made easy," *IPIN 2014 - 2014 International Conference on Indoor Positioning and Indoor Navigation*, no. October, pp. 24–29, 2014.

[24] J.-o. Nilsson, I. Skog, H. Peter, and K. V. S. Hari, "Foot-mounted INS for Everybody – An Open-source Embedded Implementation," pp. 140–145, 2012.

[25] D.-p. Yuan, Z.-h. Li, and M. Li, "Research on Indoor Firefighter Positioning Based on Inertial Navigation," pp. 473–483, 2017.

[26] J. Borenstein and L. Ojeda, "Personal dead-reckoning system for GPS-denied environments," *SSRR2007 - IEEE International Workshop on Safety, Security and Rescue Robotics Proceedings*, 2007.

[27] J. Borenstein and L. Ojeda, "Personal Dead-Reckoning System," 2010.

[28] Carnegie Mellon University, "Tracking firefighters through heat and smoke," 2017. [Online]. Available: https://engineering.cmu.edu/news-events/magazine/fall-2017/tracking-firefighters-heat-smoke.html [Accessed 2018-04-25].

[29] J. Rydell and E. Emilsson, "CHAMELEON: Visual-inertial indoor navigation," *Record - IEEE PLANS, Position Location and Navigation Symposium*, pp. 541–546, 2012.

[30] M. Baglietto, A. Sgorbissa, D. Verda, and R. Zaccaria, "Human navigation and mapping with a 6DOF IMU and a laser scanner," *Robotics and Autonomous Systems*, vol. 59, no. 12, pp. 1060–1069, 2011.

[31] National Institute of Standards and Technology, "NIST Awards $38.5 Million to Accelerate Public Safety Communications Technologies," 2017. [Online]. Available: https://www.nist.gov/news-events/news/2017/06/nist-awards-385-million-accelerate-public-safety-communications [Accessed 2018-04-25].

[32] J.-H. Kim and G. I. Kim, "Extended Kalman Filter Based Mobile Robot Localization in Indoor Fire Environments," *International Journal of Mechanical Engineering and Robotics Research*, vol. 5, no. 1, pp. 62–66, 2016.

[33] P. Pritsche, B. Zeise, P. Hemme, and B. Wagner, "Fusion of radar, LiDAR and thermal information for hazard detection in low visibility environments," *SSRR 2017 - 15th IEEE International Symposium on Safety, Security and Rescue Robotics, Conference*, pp. 96–101, 2017.

[34] E. Emilsson and J. Rydell, "Chameleon on fire - Thermal infrared indoor positioning," *Record - IEEE PLANS, Position Location and Navigation Symposium*, pp. 637–644, 2014.

[35] J. A. Hesch, F. M. Mirzaei, G. L. Mariottini, and S. I. Roumeliotis, "A Laser-Aided Inertial Navigation System (L-INS) for human localization in unknown indoor environments," *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 5376–5382, 2010.