Universally Designed Beacon-Assisted Indoor Navigation for Emergency Evacuations

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Abstract.

The United Nations (UN) Convention on the Rights of Persons with Disabilities (CRPD) obligates national governments to ensure the protection and safety of persons with disabilities in emergency situations. This article examines the application and accessibility of state-of-the-art ICT solutions in emergency situations. Research has indeed shown that the design and implementation of evacuation procedures in emergency situations play a critical role in ensuring personal safety and protection. While research has examined the experiences of persons including persons with disabilities in emergency situations, research has yet to examine fully the role that cutting-edge indoor navigation solutions including, for example, Internet of Things (IoT), mobile device and big data analytics hardware and software, in simultaneously ensuring the safety and protection of persons with disabilities and everyone from a universal design perspective. Emerging research on IoT indoor navigation solutions has shown that networks of low-energy Bluetooth (BLE) beacons paired with a mobile application provide a usable wayfinding solution for persons with disabilities in laboratory and controlled experimental settings. This article fills this gap by asking "To what extent can BLE networks ensure the safety and protection of persons with disabilities and everyone in simulated emergency situations? Data from a multimethod study of user experience in emergency evacuations shows that BLE beacon networks could provide a more accessible user experience for persons with disabilities and everyone to evacuate indoor environments during emergency situations.

Introduction

The United Nations (UN) Convention on the Rights of Persons with Disabilities (CRPD) obligates national governments to ensure the protection and safety of persons with disabilities in emergency situations. The CRPD contains an additional obligation for countries to ensure access to information and communication technology (ICT) for

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persons with disabilities, and the UN has argued that this obligation includes designing ICT that is usable for persons with disabilities. Considering these obligations, this article examines the application and accessibility of state-of-the-art ICT solutions in emergency situations. Research has indeed shown that the design and implementation of evacuation procedures in emergency situations play a critical role in ensuring personal safety and protection [1]. However, supporting ICT tools will improve this critical stage and has gradually been adopted to help crisis response processes such as for alert, communication, information sharing and navigation. Research also suggests that persons involved in emergency evacuation procedures may experience “situational disabilities” due, for example, to physical injury, impaired vision from smoke, impaired hearing from alarms, or impaired cognition from acute stress [2]. Universal design - i.e., the design of ICT to be usable by everyone - provides a useful framework for examining emergency situations by focusing on the barriers that people experience using ICT. While research has examined the experiences of persons including persons with disabilities in emergency situations, research has yet to examine fully the role that cutting-edge indoor navigation solutions including, for example, Internet of Things (IoT), mobile device and big data analytics hardware and software, in simultaneously ensuring the safety and protection of persons with disabilities and everyone from a universal design perspective [3]. Emerging research on IoT indoor navigation solutions has shown that networks of low-energy Bluetooth (BLE) beacons paired with a mobile application provide a usable wayfinding solution for persons with disabilities in laboratory and controlled experimental settings [4]. This article fills this gap by asking “To what extent can BLE networks ensure the safety and protection of persons with disabilities and everyone in simulated emergency situations?

This article will present the design for an indoor navigation and evacuation app that builds on the principles of inclusive universal design to ensure that the app will benefit a broad range of users such as people with diverse disabilities, including situational disabilities. The design will build on experiences with the general-purpose navigation assistance app from the IN-SIDE project as well as fire prediction, indoor victim localization and evacuation assistance app from the Smart Rescue project. This will be combined with requirements and design ideas gathered from first responders and a diverse group of potential users and tested through experiments in simulated risk scenarios.

This article explores the use of mobile applications in combination with BLE beacon networks to support diverse evacuation scenarios including fire, explosions, bomb threats, earthquake, gunfire/active shooters, flooding, and hazmat/gas leaks. It may include the ability to analyze and share (via conventional or ad-hoc networks) information gathered from mobile as well as fixed point sensors (e.g. location, gunshots or smoke detected) with peers as well as first responders, and to mark yourself safe/trapped at a specific location.

Literature Review

Indoor navigation has been studied by researchers using various technologies such as smartphones, wireless beacon, sensor networks, magnetometer, magnetic tracking, optical character recognition 3D graphics, surveillance camera [5-21]. These works are presented as theoretical works such as development of algorithms and simulations, or as practical-oriented works manifested as technology prototypes. The literature was obtained from IEEE Digital Xplore using keywords search “indoor navigation” AND emergency* in the Title and Abstract (2008-2018) which returned 12 articles. Adding keyword “beacon” to the original keyword search returned only 4 articles, with 2 duplications. We also include papers that exploit multiple smartphone sensors for indoor navigation [19-21].

The use of a smartphone is apparently a popular technology for supporting navigation. For example, Chen and Liu [5] develop a prototype Go FAST, i.e. a group-based emergency guiding system equipped with spatiotemporal mobility and indoor path planning using a combination of android app and iBeacon. The prototype can determine the shortest evacuation time for each group and takes into account the corridor capacities and lengths, exit capacities, simultaneous movement, distribution of people indoor, and dedicated escape path. By exploiting this estimated evacuation time information, the evacuation load can be evenly distributed among exits to minimize the total evacuation time while avoiding the congestion of all corridors and exits.

Inoue et. al [6] suggest the use of wireless beacon signals that incorporate the threat element, individual positioning and route selections through the autonomous navigation prototype. The mobile device receives wireless beacon signals from the surrounding environment and can thereby detect a user’s position. Not only can the system detect all residents' positions, but it also informs the individual user the safe evacuation routes. Kitamura, et. al. [7] develop ERESS or emergency rescue evacuation support system to detect the position of disasters and provides evacuation support in real time. The system can detect disaster and identify the disaster position using area information.

Wang et. al. [8] combine the use of mobile phone and wireless sensor network (WSN) for emergency navigation and develop SEND. The SEND solution considers the hazard levels of emergencies and the evacuation capabilities of exits and provides the mobile users with the safest navigation paths accordingly. The authors model the situation-aware emergency navigation problem and establish a hazard potential field in the network. By guiding users following the descending gradient of the hazard potential field, SEND can achieve a successful navigation and provide optimal safety. Despite offering a new solution, this work basically provides an algorithm that is tested through the simulation and scenarios analysis.

Orlosky et al. [9] conduct an experiment with on-body multi-input indoor localization by applying fusion of magnetic tracking and optical character recognition (OCR). In addition, the mixed-reality display and the eye gaze-based method are used to recognize door plates and position related text to provide more robust localization. This fused system can be used in low-lighting, smoke, and areas without power or wireless connectivity. Eye gaze tracking is also used to improve time to localization and accuracy of the OCR algorithm.

Chen, et. al [10] propose a VIPS prototype (video-based indoor positioning system). VIPS makes use of the surveillance cameras and claimed to have “centimeter-grade localization accuracy for the IoT". It supports individual-based path planning, group-based emergency evacuation and geofencing-based micro-location.

VIPS can supposedly estimate the precise position of an individual and detect the facing direction for each individual.

Ahmed et al. [11] introduce SmartEvacTrak for counting people during the evacuation in large buildings. SmartEvacTrak can count people entering and exiting with over 98% accuracy and can also localize people at a coarse level with around 97% accuracy, from results obtained from an evacuation experiment performed on a set of 350+ people randomly exiting a building.

Gozick et al. [12] explore magnetic maps for indoor navigation using mobile phones' built-in magnetometer and create the landmark identification that will then be used as guideposts information in assisting individuals during emergency evacuations. Magnetic signatures are used for identifying locations and rooms and are independent of the person, the phone, and the sensitivity of the sensor being used. The magnetic maps are particularly useful during limited visual feedback in poor lighting conditions.

Eaglin ad Payton [13] suggest a crowdsourced 3D modeling using the mobile app to improve the knowledge about 3D geometry of large buildings and urban structures for navigation and emergency evacuations. The system works based on a client-server architecture, where users of a mobile application create, submit, and vote on 3D models of building components; the server collects and uses votes pertaining to accuracy and completion of a model for the approval.

Chandel et al. [14] introduce InLoc, an end-to-end, smartphone-based indoor tracking, localization, and route finding by employing Bluetooth low energy (BLE) beacons. The system exploits raster-based building floor maps which are converted into a vector model. The indoor navigation is basically a combination between the vector map and the fusion of location information from phone IMU sensors and BLE beacons. For estimating the distance from BLE beacons, the authors use the measurement from received signal strength indication (RSII).

He and Dong [15] provides a complete prototype based on asynchronous time difference of arrival (A-TDOA) technique is implemented in hardware for localization. The authors develop and update from scratch all A-TDOA components such as transmitter, receiver, antenna, and baseband processing unit for improved reliability. The prototype is intended to support broader applications such as cargo tracking, tourist guiding, or emergency evacuation.

Mazlan, et. al., [16] use wireless sensor network (WSN) for personnel's indoor positioning and personnel tracking in prone-to hazard oil and gas platform scenario. Personnel position application using WSN is determined based on RSSI values of multiple XBee multipoint RF modules consist of personnel node, fixed nodes and server node. In addition to applying a positioning algorithm for spotting personnel's location, a sectioning method using XBee IEEE 802.15.4.

Muthukrishnan et. al. [17] provides ad-hoc, inertial sensing-based solutions for positioning and tracking of emergency response teams. The authors address the problem of how to locate the deployed static beacons, and on how to track the responders by using a combination of ultrasound and inertial measurements. The authors suggest an algorithm for ultrasound beacon localization (using multidimensional scaling) and formulate a Kalman filtering based algorithm for tracking the responder using a combination of ultrasound range and inertial measurements. The algorithms are evaluated using data collected from real deployments and are compared against an ultra-wideband (UWB) precision location system.

Zhang et. al., [18] propose a super low-frequency quasi-static field localization scheme, which with penetration localization prospects. The authors conduct a set of experiments, where the results show that in the range supported by the magnetic beacon transmit power, this scheme has the feasibility of positioning, and the average error is within the acceptable range relative to its application scenario.

Lazreg et. al., [19, 20] and Radianti et. al. [21] use smartphone sensors such as humidity, pressure, temperature, GPS sensors, Wi-Fi signals to locate fire hazards, predict its spread and locate the victims' position indoor in the case of fire. The Bayesian network is applied and infers the probability of each state of the fire based on the sensor data collected from smartphones in the fire area and the state of the fire in the previous time step. The Wi-Fi signals are used to locate victims trapped in the fire building.

To sum-up, the previous studies have tried to develop algorithms, and smartphone-apps that make use of sensor networks and beacons for indoor navigation. However, in these articles, none has taken into account the universal design of these proposed indoor navigation technologies. The summary of reviewed articles is listed in the Table 1.

Table 1. Summary of Literature on Indoor Navigation

Authors	Solution	Prototype / Experiment / Theoretical works	Technology	Scenario and Users
Chen &Liu [1]	Go FAST	Prototype	Mobile phone, BLE iBeacon	all
Inoue et. al [2]	Indoor Navigation System	Prototype	Cell phone, beacon, sensor networks	general indoor disasters/ all
Kitamura, et. al. [3]	ERESS	Prototype	Smartphone sensors, wearable sensors, BLE iBeacon	general indoor disasters/ all
Wang et. al. [4]	SEND	Theoretical and experiment	Sensor networks	general disasters/all
Orlosky, at. al. [5]	Magnetic Tracking and OCR	Theoretical and experiment	Magnetic tracking, optical character recognition, mixed reality, head mounted display	general disasters/all
Chen, et. al. [6]	VIPS	Prototype	Surveillance camera	Indoor public buildings/all
Ahmed, et. al. [7]	SmartEvacTrak	Prototype	Mobile phones, magnetometer, inertial sensors	disasters in large buildings/ all
Gozick et. al., [8]	MMIN	Theoretical	Magnetometer, smartphones, sensors	general indoor disasters/ all
Eaglin ad Payton [9]	3D Model App	Prototype	Smartphone, 3D geometric	general indoor disasters/ all
Chandel et. al., [10]	InLock	Theoretical, experiments and prototype	Smartphones and BLE beacon	Indoor office disasters/ all

He and Dong [11]	A-TDOA	Theoretical, experiments and prototype	Hardware: transmitter, receiver, antenna	General tracking including emergency evacuation/all
Mazlan, et. al., [12]	WSN-based indoor positioning	Theoretical	Wireless Sensor Network	Oil and gas platform/all
Muthukrishnan et. al. [13]	Positioning System	Theoretical and experiment	Ultrasound sensors, inertial measurement unit, static Beacon	Indoor fire/ emergency responders
Zhang et. al., [14]	Localization System	Theoretical and experiment	Beacon, super low frequency; quasistatic field	Indoor fire/ emergency responders
Radianti et. al. [15]	SmartRescue	Theoretical, experiments and prototype	Smartphone sensors: GPS, humidity, barometer, temperature, Wi-Fi signals	Fire, public and responders

Methods

This article aims to address the barriers that persons with disabilities experience when evacuating complex indoor environments during emergency situations. Data from multiple methods was used to investigate the experiences of persons with disabilities and situational disabilities in indoor navigation with a special focus on evacuations in fire emergency situations. Data collection focused on both persons with and without disabilities and included a questionnaire, qualitative semi-structured interviews, field research, and desk research.

A 17-item questionnaire was completed by 15 participants. While most of the participants did not have a disability, two had a physical disability. The questionnaire focused on emergency situations and the use of technology to improve the autonomy of the people evacuating indoor environments. In addition, two semi-structured interviews were conducted, one with a person with a visual disability and one with an electrical automation engineer. The results of the semi-structured interviews were used to validate and further explore the results from the questionnaire.

In addition, observational data was collected during one fire drill at Oslo Metropolitan University (OsloMet) and through documentary data collected from policies and archive material from a recent installation of a low-energy Bluetooth (BLE) beacon network at OsloMet. Bluetooth beacons are tiny radio transmitters that emit signals within a radius of 10-30 meters. BLE beacons are low-cost, easy to install, highly accurate, and interoperable BLE beacons are also energy efficient and can last approximately five years without replacing the battery. Beacons can be used for both client-based and server-based applications. BLE beacons in combination with a smartphone application can display location data based on the BLE beacon signals and uses the signal strength measurement for positioning. Usually one beacon is asked to detect the presence of smartphone in one room, and minimum three beacons to identify a more precise positioning [22].

Experiments and Results

The questionnaire results showed that the most prevalent reactions to an emergency evacuation alarm included panic, curiosity or surprise, and seeking help. These themes were supported by the qualitative interviews and was further supported by one participant, who stated, “I was a bit surprised, because I knew my route, as a seeing person, but during the evacuation it was difficult to find marks to find the right way out”. In emergency situations, people can react in different ways.

The results also suggest that during an evacuation, people do not react immediately after hearing the alarm signal, because an evacuation test is more common. This is further supported by the results of the questionnaire, which showed that during an evacuation, the participants are curious about what is going on and will follow others. Therefore, people will start to evacuate as more information is provided. The fire drill observation showed that the fire alarms are not equally audible on each floor and in each room, and there are persons that are responsible for guiding people to safety. This suggests that people would like to have something that shows them where to go and what is going on.

The results of the questionnaire also showed that crowded areas and unorganized evacuations are common challenges. The theme of crowded areas was further supported by an interview with a person with a visual disability. According to the participant, it was difficult to find the evacuation meeting place with too many people at one place. The results suggest that crowded areas and unorganized evacuations provide crucial focus areas for improving the universal design of emergency evacuations.

The results of the questionnaire also showed that several key features could promote the accessibility of emergency evacuation procedures. One of the key features included providing relevant information for emergency evacuation. Clear and precise instructions can enable persons with disabilities and everyone to autonomously and efficiently evacuate a building. Participants suggested that these instructions would also have the effect of improving self-reliance and enabling evacuees to stay calm. The interview with the person with a visual disability also revealed that instructions for evacuation should be provided multimodally including through voice assistant and through haptic communications such as vibrations.

A state-of-the-art BLE beacon network paired with a smartphone app could provide much of the functionality that the participants described. In particular, the questionnaire results revealed that providing instructions should include both where to evacuate as well as areas to avoid, for example, due to overcrowdedness or safety hazards. According to the interview with the participant with a visual disability, knowing where hazards including environmental features such as staircases are located, would be particularly helpful for evacuating efficiently. In addition, providing information for first responders about the identity and location of evacuees during an emergency can help persons with disabilities and everyone evacuate safely and securely.

Conclusions and Future Work

In this article, the application and accessibility of state-of-the-art ICT solutions for evacuation assistance in emergency situations has been examined. Design and implementation of evacuation procedures play a critical role in ensuring personal safety and protection for everybody, including people with disabilities as well as people affected by situational disabilities caused by the emergency situation.

The results from this study indicate that people experiencing a fire alarm often are confused and would like to have something that shows them where to go and what is going on. It is also clear from the results that crowded areas and unorganized evacuations provide crucial focus areas for improving the universal design of emergency evacuations.

Experiments with an existing network of Bluetooth Low Energy (BLE) beacons and a universally designed indoor navigation app point to this approach as being a feasible way to go for navigation assistance during emergencies.

Future work in this research include initiating a user-centered design process for development of a prototype app, and to further try it out in practice in dedicated experiments as well as in regular fire drills. The app should consider issues such as enabling the users to mark themselves trapped or safe, to find a less congested evacuation route, and to be updated with dynamic information about safe and dangerous areas.

Furthermore, the system could also be enhanced by integrating the BLE beacons in an IoT network with various sensors such as temperature, smoke and movement, providing a fuller image of the situation for enhanced situational awareness among first responders and emergency personnel, allowing them to see where people are located, what areas are congested by evacuating crowds, and what areas are successfully evacuated.

References

1. Rowland, J. L., White, G. W., Fox, M. H., & Rooney, C. (2007). Emergency response training practices for people with disabilities: Analysis of some current practices and recommendations for future training programs. Journal of Disability Policy Studies, 17(4), 216-222.
2. S. L. Henry, S. Abou-Zahra, and J. Brewer, "The role of accessibility in a universal web," Proceedings of the 11th Web for All Conference, ACM, 2014, p. 17.
3. Christensen, K., & Sasaki, Y. (2008). Agent-based emergency evacuation simulation with individuals with disabilities in the population. Journal of Artificial Societies and Social Simulation, 11(3), 9.
4. Giannoumis, G. A., Ferati, M., Pandya, U., Krivonos, D., & Pey, T. (2018, April). Usability of indoor network navigation solutions for persons with visual impairments. In Cambridge Workshop on Universal Access and Assistive Technology (pp. 135-145). Springer, Cham.
5. Chen, L., J. Chung, and J. Liu. *GoFAST: A Group-Based Emergency Guiding System with Dedicated Path Planning for Mobile Users Using Smartphones*. in *2015 IEEE 12th International Conference on Mobile Ad Hoc and Sensor Systems*. 2015.
6. Inoue, Y., et al. *Indoor Emergency Evacuation Service on Autonomous Navigation System using Mobile Phone*. in *2008 Second International Symposium on Universal Communication*. 2008.
7. Kitamura, T., et al. *Detection and position identification of disaster by using area information for emergency rescue evacuation support system*. in *2015 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*. 2015.
8. Wang, C., et al., *SEND: A Situation-Aware Emergency Navigation Algorithm with Sensor Networks.* IEEE Transactions on Mobile Computing, 2017. **16**(4): p. 1149-1162.
9. Orlosky, J., et al. *On-body multi-input indoor localization for dynamic emergency scenarios: fusion of magnetic tracking and optical character recognition with mixed-reality display*. in *2014 IEEE International Conference on Pervasive Computing and Communication Workshops (PERCOM WORKSHOPS)*. 2014.
10. Chen, L., C. Chi-Ren, and C. Da-En. *VIPS: A video-based indoor positioning system with centimeter-grade accuracy for the IoT*. in *2017 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*. 2017.
11. Ahmed, N., et al. *SmartEvacTrak: A people counting and coarse-level localization solution for efficient evacuation of large buildings*. in *2015 IEEE International Conference on Pervasive Computing and Communication Workshops (PerCom Workshops)*. 2015.
12. Gozick, B., et al., *Magnetic Maps for Indoor Navigation.* IEEE Transactions on Instrumentation and Measurement, 2011. **60**(12): p. 3883-3891.
13. Eaglin, T., K. Subramanian, and J. Payton. *3D modeling by the masses: A mobile app for modeling buildings*. in *2013 IEEE International Conference on Pervasive Computing and Communications Workshops (PERCOM Workshops)*. 2013.
14. Chandel, V., et al. *InLoc: An end-to-end robust indoor localization and routing solution using mobile phones and BLE beacons*. in *2016 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*. 2016.
15. He, S. and X. Dong, *High-Accuracy Localization Platform Using Asynchronous Time Difference of Arrival Technology.* IEEE Transactions on Instrumentation and Measurement, 2017. **66**(7): p. 1728-1742.
16. Mazlan, M.A.A.A., M.H.M. Khir, and M.N.M. Saad. *Implementation of wireless sensor network in oil and gas specifically for personnel positioning application*. in *2015 International Conference on Computer, Communications, and Control Technology (I4CT)*. 2015.

17. Muthukrishnan, K., S. Dulman, and K. Langendoen. *Towards a rapidly deployable positioning system for emergency responders*. in *2010 Ubiquitous Positioning Indoor Navigation and Location Based Service*. 2010.
18. Zhang, N., et al. *Indoor Localization Scheme for Fire Rescue Based on Super Low Frequency Quasi-Static Field*. in *2018 2nd IEEE Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC)*. 2018.
19. Lazreg, M.B., J. Radianti, and O.-C. Granmo. *A Bayesian network model for fire assessment and prediction*. in *International Workshop on Machine Learning, Optimization and Big Data*. 2015. Springer.
20. Lazreg, M.B., et al. *SmartRescue: Architecture for Fire Crisis Assessment and Prediction*. in *ISCRAM*. 2015.
21. Radianti, J., M.B. Lazreg, and O.-C. Granmo, *Fire simulation-based adaptation of SmartRescue App for serious game: Design, setup and user experience.* Engineering Applications of Artificial Intelligence, 2015. **46**: p. 312-325.
22. Insoft. (2018). Indoor Positioning, tracking and indoor navigation with beacons. Retrieved from Infsoft: https://www.infsoft.com/technology/sensors/bluetooth-low-energy-beacons