

An Overall First Responder Tracking and Coordination Framework

Susanna Kaiser  and Stephan Sand , German Aerospace Center, Wessling, 82234, Germany

Magdalena Linkiewicz , Henry Meißner , Dirk Baumbach , and Ralf Berger , German Aerospace Center, Berlin, 12489, Germany

For professional use cases like police or fire brigade operations, a reliable self-localization is advantageous for the coordination of first responders (FRs). Self-localization is especially difficult in indoor scenarios where neither global navigation satellite systems' signals may be received nor additional signals of opportunity exist for enabling reliable positioning. In this article, we propose an overall system that combines self-localization, communication of the FRs' locations, 3-D building reconstruction or floor plans (if available), and visualization. The indoor navigation technique is based solely on inertial sensors and builds on a simultaneous localization and mapping technique. It is capable of using any information about the building layout as prior information for enhancing indoor positioning, georeferencing the positions, and finally, visualizing the results in a suitable visualization tool.

For professional use cases like firefighter rescuing and policemen supervision, it is desirable for the head of first responders (FRs) to know the positions of the emergency personnel. Self-localization works well in outdoor areas but is still very difficult in indoor scenarios where global navigation satellite systems (GNSS) signals may not be received and no additional signals of opportunity exist for enabling reliable positioning. Highly accurate positioning is mandatory for the professional use cases that we mainly address in this article, without excluding other applications. For instance, in the case of a building on fire, knowledge about FRs' locations supports the commander to be able to decide on assisting an FR or injured person inside the building. In addition, not only is the outer hull of the building of interest to the FRs but also the geographical location and inner structure of the building. Prior information about the building in georeferenced form improves the planning of actions and also the indoor localization of people during the operation.

In this article, we propose an overall system based on self-localization, communication of the positions

to a central unit, optionally using floor plans or 3-D reconstruction, and finally, visualization of the FRs' positions at the central unit. Self-localization systems for pedestrians usually apply a sensor fusion approach to obtain a reliable position. A lot of different sensor fusion solutions can be found in the literature and also on the market for indoor navigation: from using radio-frequency (RF) signals like Wi-Fi, Bluetooth Low Energy beacons, RFID, Zigbee, and ultrawideband (UWB) transmitters; to the use of different sensor types like visual, sound, and optical sensors (light and infrared); and finally, inertial and magnetic sensors. A survey of different indoor navigation solutions can be found in Brena et al.¹ and Simoes et al.,² and, for smartphones, in Retcher.³ An overview of visual self-localization techniques can be found in Morar et al.⁴ Furthermore, the following techniques, which are especially designed for FRs, can be found in the literature: Boguslawski et al.⁵ summarize FR applications, which are about 3-D building models and indoor navigation. They provide an overview of different indoor localization techniques, including artificial intelligence-based methods; different 3-D representations of a building, including the Industry Foundation Classes, a standard for data exchange of building information modeling (BIM) models; and 3-D visualization techniques.

In Boyle and Torrentino,⁶ several transceivers and ranging systems are investigated for FRs, where the

© 2023 The Authors. This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see <https://creativecommons.org/licenses/by/4.0/>. Digital Object Identifier 10.1109/MITP.2023.3339449 Date of current version 12 January 2024.

best transceivers are UWB transceivers with a symmetric two-way ranging protocol. According to the authors, these systems still need improvements and they depend on the composition of indoor spaces. In these systems, usually, a network of transmitters or passive elements is needed, which has to be installed inside the building. In Rantakokko et al.,⁷ a cooperative UWB ranging for FR localization is proposed, where FRs themselves wear UWB-ranging equipment beside inertial sensors. The performance will depend on the range of the UWB system and may degrade if a FR is too far away from another UWB unit. A more comprehensive description of the state of the art can be found in Kaiser et al.⁸

Overall, most of the systems for real-time 3-D reconstruction and self-localization are either computationally complex with high demands on battery power, or require infrastructure, which might not be available during an emergency; for instance, in a tunnel, in mines, or even in a building on fire. Note that it is usually impractical to send large amounts of data (as with visual sensors) in real time to the control center, and that privacy issues must be considered when using body cameras. Therefore, we propose a real-time infrastructureless system that minimizes the amount of data to be transmitted using a reliable communication system with high building penetration and ad hoc configurability in the case of an emergency. This system is capable of using prior information from 3-D reconstructions or other kinds of building information (if available) and properly visualizing FRs' positions using available building information.

OVERVIEW OF THE SYSTEM

For self-localization, we use a system especially designed for FRs. A requirement for FRs is that the tools to be worn by each FR are robust and lightweight, offer precise localization, and that the system should not rely on preinstalled infrastructure. These requirements are considered in our overall system design. We prefer to use a navigation system based only on a single small, lightweight, and low-cost inertial sensor. This system is designed to operate in real time, can be integrated in a shoe or at other locations of the body (e.g., in a pocket), and can also be standalone. Moreover, all movements of the FRs can be captured, including jogging and running. This pedestrian dead reckoning (PDR) system based on inertial measurements with a sensor attached to the foot is called *NavShoe*.⁹ It is combined with a simultaneous localization and mapping (SLAM) algorithm, where the map of the environment is estimated during walking. This system is capable

of providing very accurate positions and is called *FootSLAM*.¹⁰

NavShoe and *FootSLAM* are cascaded and can be performed separately, which is advantageous as the PDR can be integrated in the *NavShoe*, and the more complex *FootSLAM* algorithm can be computed on a more powerful laptop, tablet PC, or PC at the central unit. The only data transmitted to the central station are the time and position estimated by the *NavShoe*, including some necessary flags.

For communication of FRs' positions, we propose using the long-range (LoRa)¹¹ communication protocol at the physical layer. The advantages of LoRa communication is its high communication range (roughly 2 km in urban areas and 15 km in free space), low battery consumption, secure data transmission, and configurability. With LoRa, we can use low frequencies for transmission, which achieve better building penetration. The main disadvantage of LoRa is its small transmission data rate (below 27 kbit/s), but this is not a limiting factor as we only send a position update every second. Alternatively to LoRa, LTE-narrow-band-Internet of Things (LTE-NB-IoT) and Bluetooth Long Range could be used. But LTE-NB-IoT depends on availability of base stations, and Bluetooth Long Range offers only a smaller range, therefore, we decided to use LoRa.

Although the *FootSLAM* algorithm learns the environment during walking and can be used standalone, prior information about the building's layout is helpful in two ways: 1) it can assist the planning and coordination of FRs by suitable visualization and 2) it can help indoor localization be more accurate and contribute to georeferencing. To obtain such prior information without knowledge of the building's layout in advance, a 3-D building reconstruction obtained using different kinds of sensors is advantageous. The outer building hull can be obtained from visual sensors mounted on a flying vehicle, e.g., a drone, helicopter, or airplane. For this, we use the Modular Aerial Camera System (MACS),¹² a fully automated system that generates scaled maps on demand and on site within minutes. For instance, this system can be installed on a vertical takeoff and landing drone. To obtain an indoor scan of the building, a camera system or laser scanner can also be applied. For this purpose, we propose using the Integrated Positioning System (IPS),¹³ a multisensor approach that includes a low-cost inertial measurement unit combined with a stereo camera system. The combined map of the MACS and the IPS can then be used for indoor navigation. These maps can be pre-computed and stored in a database or the cloud for emergency services and finally used for indoor navigation and visualization. This database can be created

specifically for the protection of public buildings. In cooperation with FRs, we could identify that a good visualization is advantageous, and it shall be easy to handle and to understand. If not stored on a local database, retrieving prior information from the cloud can be done using satellite communication (e.g., inReach) or mobile communication (5G/6G).

The overall system is depicted in Figure 1 and further explained in the following. Each FR will be equipped with a small and lightweight NavShoe mounted on the foot and a small and lightweight LoRa transmitter unit mounted on the back or breast pocket. The first estimate of positions is transmitted via LoRa communication to an LoRa receiver located at the central station, which can, for instance, be an emergency vehicle. LoRa receivers can also be realized with a single LoRa gateway. Further transmission of the FRs' locations beyond the LoRa range can, for instance, be established by LoRa gateways using alternative communication, such as satellite or mobile communication. At the central station, FootSLAM is performed for each FR, giving a final, drift-reduced estimate for the FRs' positions.

Ahead of the emergency case, the results from the MACS (outer hull) and the IPS (inner building layout) are combined to provide a 3-D reconstruction of the whole building. The prior map to be used within the localization system is generated from it and can be enhanced using prior information from the FootSLAM system itself by additionally walking through the building and scanning walkable areas with the NavShoe. If a 3-D reconstruction is not available, an existing floor plan like the one from Google Indoor Maps can be used. Alternatively, an escape plan can be photographed or scanned and a floor plan extracted from it. As an indoor scan of the building is more time consuming, these alternatives enable faster access of floor plans.

In its current version, FootSLAM uses floor plans in an XML format, but it can also be adapted to other formats in the future. The floor plan should be georeferenced. The outer-situation picture can nevertheless be obtained within minutes from the MACS system. Beside the MACS and the IPS, other 3-D reconstruction systems can also be considered if they provide a semantic 2.5-D floor plan. If no prior information is

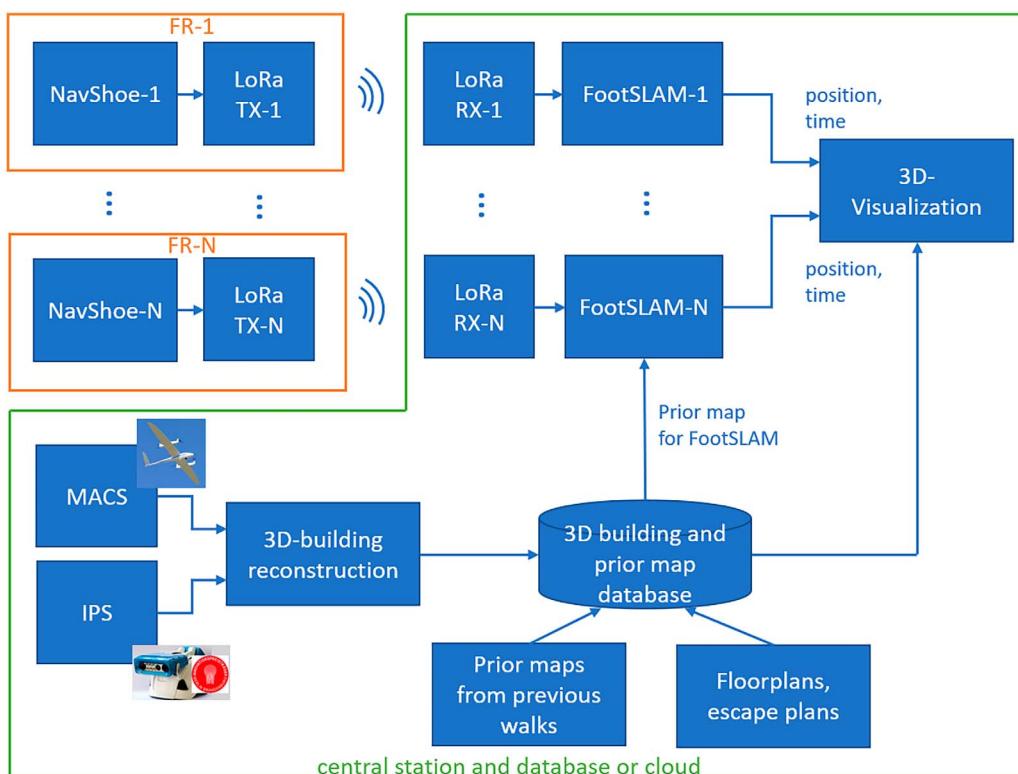


FIGURE 1. Overview of the whole system. As shown in the orange boxes, N FRs are equipped with NavShoe and LoRa transmitters, where N is total the number of FRs. The green box depicts the system of the central station, receiving and further processing the positions.

available, FootSLAM will nevertheless learn the environment and localize FRs. The resulting position will be more uncertain, especially at the beginning, without loop closures or revisited areas. The FootSLAM map might be slightly rotated because it is not georeferenced. A comprehensive performance analysis of the system, including a comparison to other techniques, is given in Kaiser et al.⁸ The accuracy of FootSLAM lies between 1–2 m without prior information and below 1 m with previous information, assuming map convergence. Finally, the FRs' positions are visualized with 3-D visualization (see Figure 1).

DEVELOPED SYSTEMS AND PROTOTYPES

FR Localization: NavShoe and FootSLAM

For FR localization, we apply the NavShoe mounted on the foot of the emergency force. For testing the system in real emergency scenarios, a robust prototype was assembled, comprising a mini-CPU and an inertial Xsens MTi 600 sensor, which is connected to the CPU. The position is calculated from the inertial measurements via a 15-state unscented Kalman filter,⁹ which is performed on the mini-CPU. The output of the NavShoe is a drifted position and heading of the FR. Figure 2(a) shows the NavShoe prototype with a size of $7 \times 4 \times 3$ cm and a weight of 137 g (including battery). The prototype is fastened on the foot with Velcro tape. It is powered by a check-card-sliced power bank of 2300 mAh, sufficient for approximately 3–4 h of

operation. In the future, we foresee the NavShoe prototype miniaturized to fit into the sole of a shoe.

To reduce the remaining drift, FootSLAM is applied on the positions resulting from the NavShoe at the central station using the prior map if available. FootSLAM can be extended by several sensors like an altimeter or GNSS receiver, can use known locations or learn places, and can be used in a collaborative way (FeetSLAM), either applied on the whole walk or successively.¹⁴

Communication: LoRa Transmitters and Receivers

The LoRa transmitter is implemented with a Pycom LoPy4 ESP32 microcontroller.¹⁵ The position data of the NavShoe are communicated via Wi-Fi to the ESP32, which is connected to an external LoRa antenna. The ESP32 is equipped with software for transmitting the NavShoe data using the LoRa protocol via the LoRa antenna. For better building penetration, LoRa transmits at low frequencies. Hence, we used a relatively large dipole antenna. Integrating the whole transmitter together with the NavShoe on the foot is not preferable due to signal reflections of the body and the ground. The LoRa transmitter receives the NavShoe data via Wi-Fi. Figure 2(b) shows a small device the size of $4 \times 3 \times 2$ cm, which can be mounted in a breast pocket and weighs 165 g, including the battery. The antenna is 10 cm in length. The LoRa receiver, including its antenna located on top of the emergency car, is depicted in Figure 2(c).

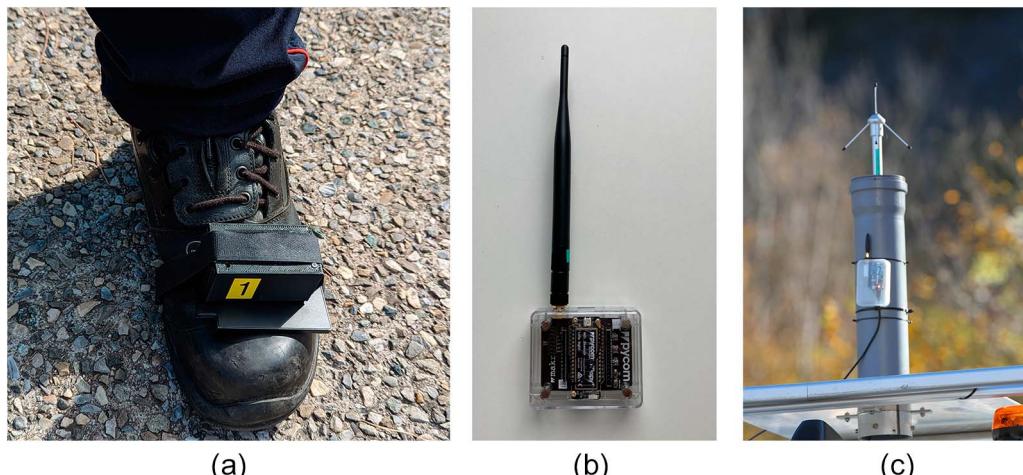


FIGURE 2. (a) NavShoe prototype to be worn on the foot or ankle. It was tested from a firefighter of École nationale supérieure des officiers de sapeurs-pompiers (ENOSPS) in a field trial of the RESCUER project. (b) The LoRa prototype built on an ESP32. This device can be worn on the front or back of the person. (c) The LoRa receiver and antenna on top of the emergency car.

3-D Reconstruction: MACS and IPS

The MACS system scans the building with an unmanned aerial vehicle carrying a camera system (see Figure 1). The large aperture angle of the camera lens and a flight pattern in cross configuration provides sufficient information about building facades and makes a 3-D reconstruction possible. This system also provides geospatial information about the position of the building. During flight, the images are georeferenced via GNSS, and the orientation information is added using photogrammetric software. Finally, a digital surface model is calculated using the semiglobal matching (SGM) approach.¹⁶

The inner layout of the building is reconstructed using the IPS. For this, we scan the building using the multisensor fusion approach, including stereo camera systems of the IPS. The IPS can be a handheld device or mounted on a helmet (see Figure 1). A 3-D indoor vector building model is calculated by preprocessing the oriented IPS images, i.e., converting them into a 3-D point cloud using the SGM algorithm.¹⁶ The 3-D cloud will then be projected onto the xy-plane subdivided by a rectangular grid. The facade pieces are identified by the density, spatial distribution, and characteristic height histogram of each grid cell.¹⁷

Visualization

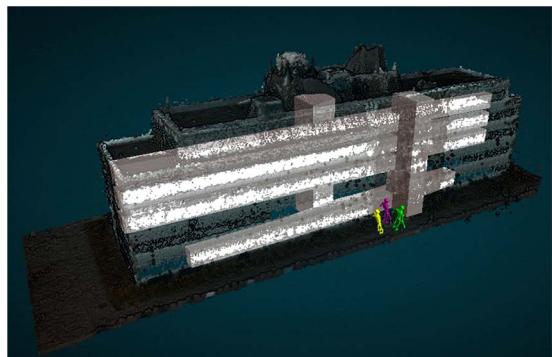
A customized version of the Potree Viewer¹⁸ is used to display all the data products given in JavaScript Object Notation format in a common framework. It encapsulates the outer hull represented by several millions of reconstructed points and over 100 planes for the interior representation extracted from the IPS [see Figure 3(a)]. The custom-built Viewer version is also prepared to visualize real-time data (e.g., personnel moving through the scene). The visualization will further be adapted to the requirements of end users.

Figure 3(b) shows the central station, where FR positions were visualized in real time during a demonstration. Our car served as the emergency car. The positions of the FRs walking through a building could be visualized on the monitor in the middle of Figure 3(b).

CONCLUSION

We presented an overall FR-localization system, including communication, 3-D reconstruction, and suitable visualization. This system is capable of providing a situation assessment during an emergency operation. By visualizing FRs' locations inside buildings, the actions can be better planned to minimize risks during an operation.

In future work, the influence of missing packets due to communication losses will be further analyzed.



(a)



(b)

FIGURE 3. (a) A 3-D point cloud from aerial images, reconstructed interior from the IPS, and initial position of FRs. (b) Visualization at the central station during demonstration of the whole system.

In addition, it is intended to automate especially the prior map generation and the setup process to minimize the time to operation during an emergency operation. The self-localization system will be extended with a GNSS receiver to also precisely provide outdoor positions. This will be done by including the findings of the GNSS localization tool developed within the European project first RESpounder-Centered support toolkit for operating in adverse and infrastrUcture-less EnviRonments (RESCUEr).¹⁹ Finally, in the future, we will investigate how to collaboratively use FootSLAM-estimated maps in real time during the operation, especially if the prior map is available.

ACKNOWLEDGMENTS

Both German Aerospace Center (DLR) institutes, Institute of Communications and Navigation and Institute

of Optical Sensor Systems, contributed equally to the work. The work was mainly supported by DLR internal project Computergestützte innerobjektive Aufklärung. Additional tests of the NavShoe with end users were also supported by the RESCUER project, which has received funding from the European Union's Horizon 2020 program under Grant 101021836. Susanna Kaiser is the corresponding author.

REFERENCES

- R. F. Brena, J. P. García-Vázquez, C. E. Galván-Tejada, D. Muñoz-Rodríguez, C. Vargas-Rosales, and J. Fangmeyer, "Evolution of indoor positioning technologies: A survey," *J. Sensors*, vol. 2017, Mar. 2017, Art. no. 2630413, doi: [10.1155/2017/2630413](https://doi.org/10.1155/2017/2630413).
- W. C. S. S. Simoes, G. S. Machado, A. M. A. Sales, M. M. d Lucena, N. Jazdi, and V. F. d J. Lucena, "A review of technologies and techniques for indoor navigation systems for the visually impaired," *Sensors*, vol. 20, no. 14, 2020, Art. no. 3935, doi: [10.3390/s20143935](https://doi.org/10.3390/s20143935).
- G. Retscher, "Indoor navigation—User requirements, state-of-the-art and developments for smartphone localization," *Geomatics*, vol. 3, no. 1, pp. 1–46, 2023, doi: [10.3390/geomatics3010001](https://doi.org/10.3390/geomatics3010001).
- A. Morar et al., "A comprehensive survey of indoor localization methods based on computer vision," *Sensors*, vol. 20, no. 9, 2018, Art. no. 2641, doi: [10.3390/s20092641](https://doi.org/10.3390/s20092641).
- P. Boguslawski, S. Zlatanova, D. Gotlib, M. Wyszomirski, M. Gnat, and P. Grzempowski, "3d building interior modelling for navigation in emergency response applications," *Int. J. Appl. Earth Observ. Geoinf.*, vol. 114, Nov. 2022, Art. no. 103066, 2022, doi: [10.1016/j.jag.2022.103066](https://doi.org/10.1016/j.jag.2022.103066).
- A. Boyle and M. E. Tolentino, "Localization within hostile indoor environments for emergency responders," *Sensors*, vol. 22, no. 14, 2022, Art. no. 5134, doi: [10.3390/s22145134](https://doi.org/10.3390/s22145134).
- J. J. Rantakokko et al., "Accurate and reliable soldier and first responder indoor positioning: Multisensor systems and cooperative localization," *IEEE Wireless Commun.*, vol. 18, no. 2, pp. 10–18, Apr. 2011, doi: [10.1109/MWC.2011.5751291](https://doi.org/10.1109/MWC.2011.5751291).
- S. Kaiser, M. Linkiewicz, H. Meißner, and D. Baumbach, "3D visual reconstruction as prior information for first responder localization and visualization," *Sensors*, vol. 23, no. 18, 2023, Art. no. 7785, doi: [10.3390/s23187785](https://doi.org/10.3390/s23187785).
- F. Zampella, M. Khider, P. Robertson, and A. Jimenez, "Unscented Kalman filter and magnetic angular rate update (MARU) for an improved pedestrian dead-reckoning," in *Proc. IEEE/ION Position Location Navig. Symp. (PLANS)*, Myrtle Beach, SC, USA, Apr. 2012, pp. 129–139, doi: [10.1109/PLANS.2012.6236874](https://doi.org/10.1109/PLANS.2012.6236874).
- M. Angermann, and P. Robertson, "FootSLAM: Pedestrian simultaneous localization and mapping without exteroceptive sensors—hitchhiking on human perception and cognition," *Proc. IEEE*, vol. 100, no. Special Centennial Issue, pp. 1840–1848, May 2012, doi: [10.1109/JPROC.2012.2189785](https://doi.org/10.1109/JPROC.2012.2189785).
- "What is LoRa®." SEMTECH. Accessed: May 31, 2023. [Online]. Available: <https://www.semtech.com/lora/what-is-lora>
- F. Lehmann, R. Berger, J. Brauchle, D. Hein, H. Meißner, and S. Pless, "MACS - Modular airborne camera system for generating photogrammetric high-resolution products," *Zeitschrift Der Deutschen Gesellschaft Für Geowissenschaften*, vol. 2011, no. 6, pp. 435–446, Dec. 2011, doi: [10.1127/1432-8364/2011/0096](https://doi.org/10.1127/1432-8364/2011/0096).
- A. Schischmanow, D. Dahlke, D. Baumbach, I. Ernst, and M. Linkiewicz, "Seamless navigation, 3D reconstruction, thermographic and semantic mapping for building inspection," *Sensors*, vol. 22, no. 13, 2022, Art. no. 4745, doi: [10.3390/s22134745](https://doi.org/10.3390/s22134745).
- S. Kaiser, "Successive collaborative SLAM: Towards reliable inertial pedestrian navigation," *Information*, vol. 11, no. 10, 2020, Art. no. 464, doi: [10.3390/info1100464](https://doi.org/10.3390/info1100464).
- "Lopy4." Pycom. Accessed: Oct. 31, 2023. <https://docs.pycom.io/datasheets/development/lopy4/>
- H. Hirschmüller, "Accurate and efficient stereo processing by semi-global matching and mutual information," in *Proc. IEEE Comput. Soc. Conf. Comput. Vision Pattern Recognit. (CVPR)*, 2005, vol. 2, pp. 807–814, doi: [10.1109/CVPR.2005.56](https://doi.org/10.1109/CVPR.2005.56).
- D. Dahlke, M. Linkiewicz, and H. Meißner, "True 3D building reconstruction – Façade, roof and overhang modeling from oblique and vertical aerial imagery," *Int. J. Image Data Fusion*, vol. 6, no. 4, pp. 314–329, 2015, doi: [10.1080/19479832.2015.1071287](https://doi.org/10.1080/19479832.2015.1071287).
- M. Schütz, "Potree: Rendering large point clouds in web browsers," Technische Universität Wien, Wiederín, Austria, 2016. [Online]. Available: https://publik.tuwien.ac.at/files/publik_252607.pdf
- D. Dahlke, S. Kaiser, and S. Bayer, "Self-localization: A proposal to equip first responders with a robust and accurate GNSS device," in *Proc. 20th ISCRAM Conf.*, Omaha, NE, USA, May 2023, pp. 242–251.

SUSANNA KAISER is a researcher with the Multi-Modal Navigation Group in the Department of Communication Systems at the Institute of Communications and Navigation, German Aerospace Center, Wessling, 82234, Germany. Her research interests include indoor localization of persons and first responders, movement models, Bayesian estimation, and collaborative

simultaneous localization and mapping. Kaiser received her Ph.D. degree in electrical and information engineering from the Technical University of Munich. Contact her at susanna.kaiser@dlr.de.

STEPHAN SAND leads the Vehicular Applications Group in the Department of Communication Systems at the Institute of Communications and Navigation, German Aerospace Center, Wessling, 82234, Germany. His research interests include wireless communications and multisensor navigation for protecting vulnerable road users, and increasing traffic efficiency and safety in railways. Sand received his Dr. Sc. degree in communication from the Swiss Federal Institute of Technology. He is a Senior Member of IEEE. Contact him at stephan.sand@dlr.de.

MAGDALENA LINKIEWICZ is a researcher in the Department of Real-Time Data Processing at the Institute of Optical Sensor Systems, German Aerospace Center, Berlin, 12489, Germany. Her research interests include broadly data processing, with a particular focus on semantic segmentation and vectorizing of 3D point clouds from oblique images. Linkiewicz received her master's degrees in agricultural economics and engineering from the Warsaw University of Life Sciences and her master of science degree in geoinformation from the Berlin University of Applied Sciences and Technology. Contact her at magdalena.linkiewicz@dlr.de.

HENRY MEIßNER is a researcher in the Security Research and Applications department at the Institute of Optical Sensor Systems, German Aerospace Center, Berlin, 12489, Germany. His research interests include 3-D reconstruction, semantic image understanding, and geovisualization. Meißner received his Ph.D. degree in computer science from Humboldt University of Berlin. Contact him at henry.meissner@dlr.de.

DIRK BAUMBACH is a scientific associate in the Department of Real-Time Data Processing at the Institute of Optical Sensor Systems, German Aerospace Center, Berlin, 12489, Germany. His research interests involve inertial navigation, sensor fusion, and calibration. Baumbach received his Dipl.-Ing. degree in computer engineering from the Technical University Ilmenau. Contact him at dirk.baumbach@dlr.de.

RALF BERGER is head of the Security Research and Applications department at the Institute of Optical Sensor Systems, German Aerospace Center, Berlin, 12489, Germany. His research interests include the development of innovative airborne optical sensor systems as well as image and geodata processing for applications in the fields of security, civil protection, and disaster relief. Berger received his Dipl.-Inf. degree in computer science from the Humboldt University of Berlin. Contact him at ralf.berger@dlr.de.



CALL FOR ARTICLES

IT Professional seeks original submissions on technology solutions for the enterprise. Topics include

- emerging technologies,
- cloud computing,
- Web 2.0 and services,
- cybersecurity,
- mobile computing,
- green IT,
- RFID,
- social software,
- data management and mining,
- systems integration,
- communication networks,
- datacenter operations,
- IT asset management, and
- health information technology.

We welcome articles accompanied by web-based demos.
For more information, see our author guidelines at
www.computer.org/itpro/author.htm.

WWW.COMPUTER.ORG/ITPRO