Sensors for Indoor Mapping and Navigation

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With the growth of cities and increased urban population there is a growing demand for spatial information of large indoor environments. This includes location information of pedestrians, goods and robots in indoor spaces as well as detailed indoor maps and models, which can be used for route planning, navigation guidance and several other applications.

Obtaining spatial information in indoor environments is a challenge. In the absence of GNSS signals, a range of technologies have been used for positioning and mapping indoors. However, limitations in accuracy and coverage, dependence on infrastructure and calibration issues limit the existing solutions to only a few application scenarios.

Articles in this special issue provide an overview of the most recent developments in sensor technology and methodology for indoor positioning, mapping and new applications enabled by indoor location information. The majority of these works focus on the positioning problem. Inertial sensors, accelerometers and gyroscopes, which are available on most smartphones, are used for positioning in [1–6]. The position estimation in these works is mainly based on the Pedestrian Dead Reckoning (PDR) approach, which involves step length estimation using accelerometer data. In [7–12] inertial sensors are combined with map information or landmarks to strengthen the positioning solution. In [13] inertial sensors are integrated with a 2D laser scanner to obtain the position of a mobile robot. The simultaneous map generation and positioning methods in [14,15] combine inertial sensors with camera images. In [16] accelerometer data and ambient radio sensed by a smartphone are used to detect place visits of the user. The pressure sensor built in smartphones (usually referred to as barometer) is used to estimate the vertical position or to recognize vertical movements in [7,10,13,17,18].

The magnetic sensor built in smartphones (usually referred to as magnetometer or digital compass) is used for attitude estimation as part of a positioning system in [1,4,7–10,12,19,20]. In [21] a complete magnetic positioning system is described, in which the positioning is based on a magnetic sensor measuring the strength of the magnetic field generated by a number of coils installed in the environment.

Indoor positioning using WiFi signals is investigated in [22–27]. The common approach to position estimation in these works is based on the received signal strength (RSS) and the fingerprinting method. In [1,7,12] the authors integrate the WiFi positioning with the PDR approach using smartphone sensors. In [20] the received signal strength is combined with orientation information obtained by smartphone magnetometer. A positioning method using wireless motes with varying transmission power is described in [28]. In [29] the authors investigate the use of directional antennas for positioning based on RSS and the fingerprinting method. Efficient methods for the generation and updating of fingerprint databases are presented in [30–32].

Other sensors used for positioning in indoor environments include Ultrasonic [33], Pseudolites [34–36], RFID (including near field communication—NFC) [37–39], Ultra Wide Band (UWB) [40–42], microphone and light sensor [19]. In [43] an afocal optical flow sensor is introduced for reducing the odometry error in a mobile robot. Camera images [14,15,44] and range data captured

by a 2D laser scanner [13] are also used for positioning indoors. In [45] infrared images are used to localize and track moving targets in large indoor environments.

3D mapping and modeling of indoor environments is the focus of several articles in the special issue. In [46] a simultaneous localization and mapping (SLAM) approach based on data captured by a 2D laser scanner and a monocular camera is introduced. In [14,15] visual SLAM using camera images is used for positioning and mapping in indoor environments. The SLAM approach in [47] relies on data acquired by an RGB-D sensor. RGB-D data of indoor scenes are used for detecting small tabletop objects in [48]. In [49–51] 3D laser scanning is used for mapping indoor environments. In [50,51] the authors also propose methods for the generation of a building information model (BIM) from the point cloud data.

Applications of indoor location information are discussed in [37,40,52]. In [37] indoor location information is used for tracking health processes and analyzing medical protocols in a hospital. In [40] the authors describe an indoor navigation system for the visually impaired people. In [52] the authors introduce a fading memory model for decision making in indoor emergency situations such as evacuations.

In summary, the special issue presented substantial efforts in the research and development of indoor positioning, tracking and mapping. Many papers address positioning, e.g., by WiFi fingerprinting, but the progress in autonomous approaches for indoor mapping and positioning is also significant. In the presented papers the use of 3D indoor models is relatively limited, but 2D maps are largely applied to support positioning and improve the accuracy. 3D approaches are, however, largely envisaged for simultaneous localization and mapping.

This special issue is the result of the collective efforts of many individuals. We wish to thank the authors for contributing high quality research articles to the special issue. We are also grateful to the anonymous reviewers who thoroughly reviewed the submissions and provided constructive feedback to the authors. We hope the special issue will provide new insights and stimulate further research in indoor mapping, positioning and navigation.

References

1. Chen, G.; Meng, X.; Wang, Y.; Zhang, Y.; Tian, P.; Yang, H. Integrated WiFi/PDR/Smartphone using an unscented kalman filter algorithm for 3D indoor localization. *Sensors* **2015**, *15*, 24595–24614. [CrossRef] [PubMed]
2. Deng, Z.-A.; Wang, G.; Hu, Y.; Wu, D. Heading estimation for indoor pedestrian navigation using a smartphone in the pocket. *Sensors* **2015**, *15*, 21518–21536. [CrossRef] [PubMed]
3. Diaz, E. Inertial pocket navigation system: Unaided 3D positioning. *Sensors* **2015**, *15*, 9156–9178. [CrossRef] [PubMed]
4. Renaudin, V.; Combettes, C. Magnetic, acceleration fields and gyroscope quaternion (MAGYQ)-based attitude estimation with smartphone sensors for indoor pedestrian navigation. *Sensors* **2014**, *14*, 22864–22890. [CrossRef] [PubMed]
5. Xu, Z.; Wei, J.; Zhang, B.; Yang, W. A robust method to detect zero velocity for improved 3D personal navigation using inertial sensors. *Sensors* **2015**, *15*, 7708–7727. [CrossRef] [PubMed]
6. Yuan, X.; Yu, S.; Zhang, S.; Wang, G.; Liu, S. Quaternion-based unscented kalman filter for accurate indoor heading estimation using wearable multi-sensor system. *Sensors* **2015**, *15*, 10872–10890. [CrossRef] [PubMed]
7. Chen, Z.; Zou, H.; Jiang, H.; Zhu, Q.; Soh, Y.; Xie, L. Fusion of WiFi, smartphone sensors and landmarks using the kalman filter for indoor localization. *Sensors* **2015**, *15*, 715–732. [CrossRef] [PubMed]
8. Chiang, K.-W.; Liao, J.-K.; Tsai, G.-J.; Chang, H.-W. The performance analysis of the map-aided fuzzy decision tree based on the pedestrian dead reckoning algorithm in an indoor environment. *Sensors* **2016**, *16*, 34. [CrossRef] [PubMed]
9. Qian, J.; Pei, L.; Ma, J.; Ying, R.; Liu, P. Vector graph assisted pedestrian dead reckoning using an unconstrained smartphone. *Sensors* **2015**, *15*, 5032–5057. [CrossRef] [PubMed]

10. Shang, J.; Gu, F.; Hu, X.; Kealy, A. Apfiloc: An infrastructure-free indoor localization method fusing smartphone inertial sensors, landmarks and map information. *Sensors* **2015**, *15*, 27251–27272. [CrossRef] [PubMed]

11. Tian, Q.; Salcic, Z.; Wang, K.I.-K.; Pan, Y. A hybrid indoor localization and navigation system with map matching for pedestrians using smartphones. *Sensors* **2015**, *15*, 30759–30783. [CrossRef] [PubMed]

12. Wang, J.; Hu, A.; Liu, C.; Li, X. A floor-map-aided WiFi/pseudo-odometry integration algorithm for an indoor positioning system. *Sensors* **2015**, *15*, 7096–7124. [CrossRef] [PubMed]

13. Gao, Y.; Liu, S.; Atia, M.; Noureldin, A. INS/GPS/LiDAR integrated navigation system for urban and indoor environments using hybrid scan matching algorithm. *Sensors* **2015**, *15*, 23286–23302. [CrossRef] [PubMed]

14. Guerra, E.; Munguia, R.; Bolea, Y.; Grau, A. Human collaborative localization and mapping in indoor environments with non-continuous stereo. *Sensors* **2016**, *16*, 275. [CrossRef] [PubMed]

15. Gerstweiler, G.; Vonach, E.; Kaufmann, H. Hymotrack: A mobile AR navigation system for complex indoor environments. *Sensors* **2016**, *16*, 17. [CrossRef] [PubMed]

16. Kim, B.; Kang, S.; Ha, J.-Y.; Song, J. Visitsense: Sensing place visit patterns from ambient radio on smartphones for targeted mobile ads in shopping malls. *Sensors* **2015**, *15*, 17274–17299. [CrossRef] [PubMed]

17. Gu, F.; Kealy, A.; Khoshelham, K.; Shang, J. User-independent motion state recognition using smartphone sensors. *Sensors* **2015**, *15*, 30636–30652. [CrossRef] [PubMed]

18. Xia, H.; Wang, X.; Qiao, Y.; Jian, J.; Chang, Y. Using multiple barometers to detect the floor location of smart phones with built-in barometric sensors for indoor positioning. *Sensors* **2015**, *15*, 7857–7877. [CrossRef] [PubMed]

19. Galván-Tejada, C.; García-Vázquez, J.; Galván-Tejada, J.; Delgado-Contreras, J.; Brena, R. Infrastructure-less indoor localization using the microphone, magnetometer and light sensor of a smartphone. *Sensors* **2015**, *15*, 20355–20372. [CrossRef] [PubMed]

20. Sánchez-Rodríguez, D.; Hernández-Morera, P.; Quinteiro, J.; Alonso-González, I. A low complexity system based on multiple weighted decision trees for indoor localization. *Sensors* **2015**, *15*, 14809–14829. [CrossRef] [PubMed]

21. Kasmi, Z.; Norrdine, A.; Blankenbach, J. Towards a decentralized magnetic indoor positioning system. *Sensors* **2015**, *15*, 30319–30339. [CrossRef] [PubMed]

22. Caso, G.; de Nardis, L.; di Benedetto, M.-G. A mixed approach to similarity metric selection in affinity propagation-based WiFi fingerprinting indoor positioning. *Sensors* **2015**, *15*, 27692–27720. [CrossRef] [PubMed]

23. Castañón–Puga, M.; Salazar, A.; Aguilar, L.; Gaxiola-Pacheco, C.; Licea, G. A novel hybrid intelligent indoor location method for mobile devices by zones using Wi-Fi signals. *Sensors* **2015**, *15*, 30142–30164. [CrossRef] [PubMed]

24. Ma, L.; Xu, Y. Received signal strength recovery in green WLAN indoor positioning system using singular value thresholding. *Sensors* **2015**, *15*, 1292–1311. [CrossRef] [PubMed]

25. Ma, R.; Guo, Q.; Hu, C.; Xue, J. An improved WiFi indoor positioning algorithm by weighted fusion. *Sensors* **2015**, *15*, 21824–21843. [CrossRef] [PubMed]

26. Zhou, M.; Zhang, Q.; Xu, K.; Tian, Z.; Wang, Y.; He, W. Primal: Page rank-based indoor mapping and localization using gene-sequenced unlabeled WLAN received signal strength. *Sensors* **2015**, *15*, 24791–24817. [CrossRef] [PubMed]

27. Zou, H.; Lu, X.; Jiang, H.; Xie, L. A fast and precise indoor localization algorithm based on an online sequential extreme learning machine. *Sensors* **2015**, *15*, 1804–1824. [CrossRef] [PubMed]

28. Canedo-Rodriguez, A.; Rodriguez, J.; Alvarez-Santos, V.; Iglesias, R.; Regueiro, C. Mobile robot positioning with 433-MHz wireless motes with varying transmission powers and a particle filter. *Sensors* **2015**, *15*, 10194–10220. [CrossRef] [PubMed]

29. Guzmán-Quirós, R.; Martínez-Sala, A.; Gómez-Tornero, J.; García-Haro, J. Integration of directional antennas in an RSS fingerprinting-based indoor localization system. *Sensors* **2016**, *16*, 4. [CrossRef] [PubMed]

30. Du, Y.; Yang, D.; Xiu, C. A novel method for constructing a WiFi positioning system with efficient manpower. *Sensors* **2015**, *15*, 8358–8381. [CrossRef] [PubMed]

31. Jan, S.-S.; Yeh, S.-J.; Liu, Y.-W. Received signal strength database interpolation by kriging for a Wi-Fi indoor positioning system. *Sensors* **2015**, *15*, 21377–21393. [CrossRef] [PubMed]

32. Tang, J.; Chen, Y.; Chen, L.; Liu, J.; Hyyppä, J.; Kukko, A.; Kaartinen, H.; Hyyppä, H.; Chen, R. Fast fingerprint database maintenance for indoor positioning based on UGV SLAM. *Sensors* **2015**, *15*, 5311–5330. [CrossRef] [PubMed]

33. Gualda, D.; Ureña, J.; García, J.; Lindo, A. Locally-referenced ultrasonic – LPS for localization and navigation. *Sensors* **2014**, *14*, 21750–21769. [CrossRef] [PubMed]

34. Fujii, K.; Sakamoto, Y.; Wang, W.; Arie, H.; Schmitz, A.; Sugano, S. Hyperbolic positioning with antenna arrays and multi-channel pseudolite for indoor localization. *Sensors* **2015**, *15*, 25157–25175. [CrossRef] [PubMed]

35. Gioia, C.; Borio, D. Stand-alone and hybrid positioning using asynchronous pseudolites. *Sensors* **2015**, *15*, 166–193. [CrossRef] [PubMed]

36. Xu, R.; Chen, W.; Xu, Y.; Ji, S. A new indoor positioning system architecture using GPS signals. *Sensors* **2015**, *15*, 10074–10087. [CrossRef] [PubMed]

37. Fernandez-Llatas, C.; Lizondo, A.; Monton, E.; Benedi, J.-M.; Traver, V. Process mining methodology for health process tracking using real-time indoor location systems. *Sensors* **2015**, *15*, 29821–29840. [CrossRef] [PubMed]

38. Ozdenizci, B.; Coskun, V.; Ok, K. NFC internal: An indoor navigation system. *Sensors* **2015**, *15*, 7571–7595. [CrossRef] [PubMed]

39. Shen, B.; Zheng, Q.; Li, X.; Xu, L. A framework for mining actionable navigation patterns from in-store RFID datasets via indoor mapping. *Sensors* **2015**, *15*, 5344–5375. [CrossRef] [PubMed]

40. Martinez-Sala, A.; Losilla, F.; Sánchez-Aarnoutse, J.; García-Haro, J. Design, implementation and evaluation of an indoor navigation system for visually impaired people. *Sensors* **2015**, *15*, 32168–32187. [CrossRef] [PubMed]

41. Nguyen, V.-H.; Pyun, J.-Y. Location detection and tracking of moving targets by a 2D IR-UWB radar system. *Sensors* **2015**, *15*, 6740–6762. [CrossRef] [PubMed]

42. Yin, Z.; Cui, K.; Wu, Z.; Yin, L. Entropy-based TOA estimation and SVM-based ranging error mitigation in UWB ranging systems. *Sensors* **2015**, *15*, 11701–11724. [CrossRef] [PubMed]

43. Yi, D.-H.; Lee, T.-J.; Cho, D.-I. Afocal optical flow sensor for reducing vertical height sensitivity in indoor robot localization and navigation. *Sensors* **2015**, *15*, 11208–11221. [CrossRef] [PubMed]

44. Kim, H.; Lee, D.; Oh, T.; Choi, H.-T.; Myung, H. A probabilistic feature map-based localization system using a monocular camera. *Sensors* **2015**, *15*, 21636–21659. [CrossRef] [PubMed]

45. Mossel, A. Robust 3D position estimation in wide and unconstrained indoor environments. *Sensors* **2015**, *15*, 31482–31524. [CrossRef] [PubMed]

46. Oh, T.; Lee, D.; Kim, H.; Myung, H. Graph structure-based simultaneous localization and mapping using a hybrid method of 2D laser scan and monocular camera image in environments with laser scan ambiguity. *Sensors* **2015**, *15*, 15830–15852. [CrossRef] [PubMed]

47. Zhang, H.; Liu, Y.; Tan, J. Loop closing detection in RGB-D SLAM combining appearance and geometric constraints. *Sensors* **2015**, *15*, 14639–14660. [CrossRef] [PubMed]

48. Bao, J.; Jia, Y.; Cheng, Y.; Xi, N. Saliency-guided detection of unknown objects in RGB-D indoor scenes. *Sensors* **2015**, *15*, 21054–21074. [CrossRef] [PubMed]

49. Adán, A.; Quintana, B.; Vázquez, A.; Olivares, A.; Parra, E.; Prieto, S. Towards the automatic scanning of indoors with robots. *Sensors* **2015**, *15*, 11551–11574. [CrossRef] [PubMed]

50. Díaz-Vilariño, L.; Khoshelham, K.; Martínez-Sánchez, J.; Arias, P. 3D modeling of building indoor spaces and closed doors from imagery and point clouds. *Sensors* **2015**, *15*, 3491–3512. [CrossRef] [PubMed]

51. Kim, S.; Kim, J.; Jung, J.; Heo, J. Development of a 3D underground cadastral system with indoor mapping for as-built BIM: The case study of gangnam subway station in korea. *Sensors* **2015**, *15*, 30870–30893. [CrossRef] [PubMed]

52. Zhao, H.; Winter, S. A time-aware routing map for indoor evacuation. *Sensors* **2016**, *16*, 112. [CrossRef] [PubMed]