The New Frontiers of “Wireless Motion Capture and Fine-Scale Localization”

(Guest Editorial of the First Special Issue Promoted by the IEEE CRFID TC on Motion Capture and Localization)

THIS special issue in the IEEE JOURNAL OF RADIO FREQUENCY IDENTIFICATION (JRFID) was born as an initiative of the IEEE Council Of Radio Frequency Identification (CRFID) Technical Committee on “Motion Capture and Localization” (TC-MoCap) (http://mocap.ieee-rfid.org/). The latter (Fig. 1) was established in Spring 2021 to promote activities and research in the field of RFID-based localization, ultra-precise Radio-Frequency (RF) positioning, and related fields. This initiative began with a highly successful workshop at IEEE RFID 2020 Conference (https://2020.ieee-rfid.org/workshop-on-wireless-mocap/). Since then, other workshop editions have followed each other at the IEEE RFID 2021 Conference (https://2021.ieee-rfid.org/workshop-on-wireless-motion-capture-and-fine-scale-localization/), IEEE RFID-TA 2021 Conference (https://2021.ieee-rfid-ta.org/social-event/), IEEE WiSEE 2021 Conference (https://attend.ieee.org/wisee-2021/program/workshops/) and are currently scheduled for the 2022 editions of the IEEE CRFID flagship conferences.

The general scope of the Location and Motion Capture at the first 2020 workshop was originally cutting-edge localization and positioning technology that:

1) has cm-scale wireless positioning accuracy;
2) approaches or exceeds the 100:1 range-to-accuracy RF localization limit;
3) identifies or classifies *motion* using wireless techniques;
4) images scenes with radio waves.

Although not limited to RFID-based technology, RFID has emerged as a key contributing technology for achieving all of these attributes.

Motivation: Location and motion awareness open new frontiers in society and industry. New applications are emerging in smart industry, logistics, smart city, smart healthcare, safety and security, smart agri-food, aerospace, and so on. The adopted technologies range from transponder-based solutions, e.g., RFID systems, wireless beacons, and so on; to passive markers, e.g., chipless RFID and retroreflectors; to marker-less, e.g., radar. All these technologies can be adopted alone or combined to pursue positioning, tracking, or navigation through *sensor fusion*. Over the years, solutions based on signal amplitude and time-of-flight have been joined by phase-based techniques. Some of the best known of them include radar-based techniques, synthetic aperture radar methods, Doppler-based techniques, mm-wave imaging and so on. More recently, wireless motion capture and fine-scale localization also benefit from machine learning and artificial intelligence to develop new methodologies particularly suitable in dynamic environments. However, many open problems and challenges have to be faced for these localization and wireless identification systems to achieve the reliability and accuracy required, especially in real-time applications. This special issue collects works from diverse academic researchers to discover the actual trends in this emerging field.

Fig. 1. Logo of the IEEE CRFID TC-MoCap established in Spring 2021.

Summary of Recent Work: We can distinguish among localization schemes based on fixed readers, typically with more antennas [A1]–[A4], or moving readers both carried out by a human, e.g., handheld readers [A5] or robot-mounted readers [A6]–[A7]. Besides, new methods for robot self-localization are proposed in [A7]–[A8].

In [A1], Mo *et al.* developed a localization method based on a neural network, i.e., Back Propagation-Support Vector Regression (BP-SVR), adopting amplitude and phase difference of the tag backscattering signal as input features. The system consists of two pairs of reader antennas which are 60-cm apart each other. Within each pair, the two antennas are very close to measure phase samples within the same period, by avoiding the 2π-periodicity issue. RSSI values gathered by all antennas are the input features together with phase sample differences collected by each pair of antennas. All these data are also gathered from the reference tags during an offline calibration procedure with a grid step of 10 cm. The method shown an average 2D positioning error of around 10 cm in an indoor area of 6 m $\times$ 8 m for 10 tags. The error never exceeded 14 cm and the algorithm outperforms the stand-alone BP method and the SVR one.

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Skyvalakis *et al.* proposed a novel Direction-of-Arrival (DoA) estimation and tag localization technique based on the formation of ellipses in a bistatic RFID setup, hence the name Elliptical DoA (EllDoA) [A2]. One transmitting and two, three or four receiving antennas were employed to determine the DoA, the 2D tag position, or the 3D tag position, respectively. The experimental setup has been realized with a Software Defined Radio (SDR) emulating the reader. The EllDoA performed similarly to the classical MUSIC algorithm in measuring the DoA, with a mean absolute error of around 4°-5° in 20 experiments. Centimeter-level localization error was reached for both 2D and 3D localization.

Megalou *et al.* proposed a novel real-time tracking method [A3] to track the interests of RFID-tagged visitors inside a museum. Two pairs of fixed reader antennas are deployed in the scenario and phase differences are measured for each antenna pair detecting the target tag. Then, the tag position is obtained from the intersection of two hyperbolas. The cross section of the hyperbolas is derived by a trained neural network. Any knowledge of the tag initial position, nor the trace followed is required. Experiments were conducted inside a multipath-rich 6 m $\times$ 8m laboratory by considering both a tag moving through a robot and a human. A mean error under 0.5 m for the tag tracking has been reached for several trajectories. The method computational complexity allows for real-time applicability.

Yang *et al.* presented a 3D human-pose tracking system, i.e., Meta-Pose [A4]. It is based on the meta-learning framework for greatly enhanced environmental adaptability. The system is completely designed with off-the-shelf RFID hardware and exploits Kinect-captured video data both for supervised training and as ground truth. RFID data are collected, pre-processed and then employed in a deep neural network. Two different meta-learning algorithms were employed. In the experimental campaign, three fixed antennas are deployed at different positions in front of the user carrying on 12 tags. The mean estimation error for different users and eight area domains, where the subject performs several activities, is of few centimeters.

In [A5], Chatzistefanou *et al.* presented a mobile hand-held device composed by an UHF-RFID reader and an Inertial Measurement Unit (IMU) to guide the user towards a specific tag. The system has been developed within the "CultureID" Project in the context of the Archaeological Museum of Thessaloniki, Greece, to guide visitors in a kind of treasure hunt, but it can be applied also for locating misplaced items in retail. Any a priori knowledge of the environment is required and a local processing is adopted for tag localization. The proposed method leverages data measured by an RFID reader, i.e., phase samples, and a 9 Degrees-of-Freedom IMU. The latter is able to measure the device rotation-angle on a plane parallel to the ground. The user is instructed to perform three types of "commands" which allow to improve distance and direction estimation of the target tag through a Particle Filter (PF). In the experimental analysis, a mean error of 6° was obtained for angle estimation, while the distance error was less than 0.5 m after few PF iterations. The computational time is small enough to enable real-time tracking.

In [A6], Tzitzis *et al.* proposed a prototype method, i.e., "PD-Loc", for fast and accurate 3D localization of RFID tagged items via a mobile robot. The latter performs a Simultaneous Localization and Mapping (SLAM) of the surrounding scenario by employing odometry data and LIDAR (Laser Imaging Detection and Ranging) or RGBD-CAMERA measurements. The robot self-localization allows the creation of a synthetic aperture for each tag, thus enabling SAR-based localization. Phase data collected from each antenna are separately processed to determine the locus around its trajectory where the tag may be located. Then, a least square problem is formulated to determine the nearest location from all loci, by solving an overdetermined system of linear equations. Method performance has been demonstrated through an experimental campaign in a laboratory scenario, with a mobile robot carrying on four antennas for each side, deployed at different heights. The mean localization error was 11 cm and 17 cm for 2D and 3D localization, respectively, for robot straight-trajectories. It gets a little worse for non-straight paths, with a mean localization error of 15 cm and 23 cm in 2D and 3D space, respectively. Moreover, for straight paths, the PD-Loc method outperforms state-of-the-art methods such as Phase ReLock, SARFID, PSO-SAR method, while similar performance can be observed with Phase ReLock for non-straight trajectories.

Motroni *et al.* presented a UHF-RFID robotic system for tagged-item inventory and localization [A7], constituted by a multiple-antennas robot with wheeled rotary encoders. Firstly, the robot reconstructs its trajectory through a sensor-fusion among odometry data and RFID phase data from an infrastructure of passive reference tags, then a multi-antenna synthetic-aperture-radar (SAR) method is applied to localize target tags. A Particle Swarm Optimization (PSO) is applied to speed-up the tag-position estimation. An experimental campaign conducted in an office environment is presented to verify the system features and feasibility. The multi-antenna sensor-fusion can reconstruct the robot trajectory with errors comparable to those of a Laser Range Finder by preventing the occurrence of detrimental drifts, typical of systems based only on odometry. The use of multiple antennas was also advantageous with respect to the single-antenna sensor-fusion method. The 3D tag localization performance, by employing the reader antenna trajectory measured through the multi-antenna sensor-fusion method, exhibited an average error of 26 cm, in good agreement with performance of SAR-based localization where the antenna trajectory is measured with an LRF system.

Kammel *et al.* [A8] proposed a mobile-robot self-localization system with centimeter precision by fusing RFID localization results based on cost-effective, standard passive UHF RFID technology with the robot odometry data. A mobile robot is equipped with a multistatic UHF RFID system, and several RFID tags serve as landmarks being arbitrarily placed within the environment. Phase data are collected and to overcome the 2π-phase ambiguity issue, a novel iterative multi-hypothesis Kalman filter is designed. A real-world simulation setup is developed with a mobile robot platform composed by a commercial off-the-shelf (COTS) monostatic reader and an eight-channel UHF RFID listener, both of which are connected to a switch matrix. The sensor-fusion self-localization method allowed to get a Root Mean Square Error of 2.7 cm in open-plan office.

Generally speaking, tag localization implies tag identification. Widespread detectability issues occur in all application scenarios where numerous tags are deployed close to one another. In [A9], the authors presented an interesting analysis on the effect of retail store environment for tag identification and localization in smart IoT stores. An extensive empirical study is performed to characterize the tag responsiveness depending on the electromagnetic properties of the products, their amount and relative position on the basket. The *maximum throughput* mode guaranteed a reliable and stable reading process for the considered scenarios with static and moving items in the basket.

In closing, we hope this special issue is the first of many in the explosive wireless motion capture and localization field. The growing, multidisciplinary community housed by IEEE Council on RFID continues to solicit new work in this increasingly consequential area.

Finally, we would like to express our appreciation to all the authors who contributed to this first IEEE JRFID Special Issue on Motion Capture and Localization.

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APPENDIX: RELATED ARTICLES

[A1] L. Mo, Y. Zhu, and D. Zhang, "UHF RFID indoor localization algorithm based on BP-SVR," *IEEE J. Radio Freq. Identif.*, vol. 6, no. 1, pp. 385–393, 2022.
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