Accepted for presentation in: 2023 IEEE 97th Vehicular Technology Conference (VTC-Spring)

# Bring Your Own Positioning System: An Infrastructure-free and Omnidirectional UWB-based Localization Approach

**Florian Schmickmann, Marcus Haferkamp, Janis Tiemann and Christian Wietfeld**
Communication Networks Institute, TU Dortmund University, 44227 Dortmund, Germany
e-mail: {florian.schmickmann, marcus.haferkamp, janis.tiemann, christian.wietfeld}@tu-dortmund.de

*Abstract*—**Wireless ad-hoc localization can play an enabling role for many safety-critical applications and help to save life. For instance, in challenging applications such as firefighting, first responders are often faced with the decision to enter a structure with limited to no visibility and lacking detailed information on the existing conditions. Relative position uncertainty or loss of contact may lower the operation's prospect of success or, in the worst case, result in human harm. This work aims to provide a novel ad-hoc localization system that allows for omnidirectional awareness of co-responders' locations, even under zero-visibility and non-line-of-sight conditions. To this end, we propose a novel ultra-wideband-based localization method combining multiple phase-difference of arrival capable nodes for accurate direction and distance estimation. A tightly integrated hardware setup enables time difference of arrival direction finding, augmenting the limitations of pure phase-based direction estimation. Additionally, single-sided two-way ranging is utilized for ad-hoc distance estimation. We have evaluated the localization performance for different realistic indoor scenarios under line-of-sight and non-line-of-sight conditions. Experimental results show an average 95th percentile 2D accuracy of 40 cm at a distance of up to 6 m in an unobstructed environment. In more challenging conditions which incorporate obstruction an accuracy of 1.2 m at up to 12 m distance could be achieved.**

*Index Terms* — **Ultra-Wideband (UWB), Angle of Arrival (AoA), Phase Difference of Arrival (PDoA), Time Difference of Arrival (TDoA), Infrastructure-Free, Wireless Positioning, Ad-Hoc Localization.**

## I. INTRODUCTION

Emergency responders often operate under high pressure in previously unknown environments. Smoke, debris, and obstacles in the environment create complex situations where coordination between and within teams of responders is encumbered. The risk of dangerous situations emerging is reduced by proceeding carefully, with practiced tactics and manual coordination. Localization may help first responders to remove part of the coordination overhead by providing an overview of the positioning of each responder in the emergency scenario. The ad-hoc localization system presented in this work enables omnidirectional and infrastructure-free localization as a means for intra-team coordination in low-visibility environments. Although there is a broad range of established localization systems and techniques, each intends to provide different services and, thus, sets additional requirements. Satellite-based Global Positioning System (GPS) allows agents to independently determine their position using precisely timed radio signals emitted by geostationary satellites with a sub-10-meter accuracy on average, provided that they sufficiently receive the emitted signals [1]. Unfortunately, such systems require the reception of multiple, undisturbed faint signals, disqualifying them for indoor localization, as buildings tend to attenuate the employed frequencies significantly. Moreover, indoor ad-hoc localization poses a significant challenge for radio-based systems as signal propagation is not just attenuated but also distorted by internal structures of buildings, such as walls and ceilings [2]. These drawbacks motivate using alternative systems dealing with indoor-specific side effects to enable accurate localization in enclosed spaces. Until now, most localization systems commonly provided depend on infrastructure-centric deployments allowing up to meter or even sub-meter accuracies and coverage levels required by various applications like warehouse asset tracking or autonomous robots. Yet, these systems commonly need custom-fit infrastructures, resulting in varying complexity and installation efforts, which make them unsuitable for temporary and unplanned operations, as is the case for, among others, emergency missions. For example, first responders cannot rely on an localization system being installed at the site, nor for it to be in working order during an incident.

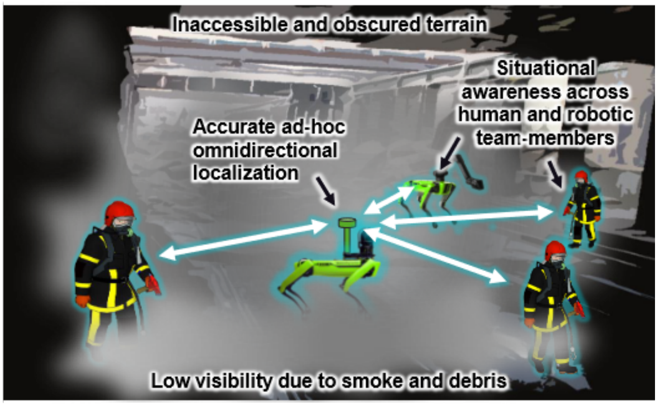

Fig. 1. Low-visibility scenario in which a legged robot carries the proposed ad-hoc localization system for position tracking of rescue squad members improving situational awareness and, thus, safety.

Taking up the previously mentioned rescue scenario, first responders would significantly benefit from ad-hoc, i.e., temporary, localization systems for locating other squad members (cf. Fig. 1). As each rescue squad member—regardless of whether human or robotic—carries either a UWB tag or a node, a dedicated system deployment phase is obsolete. The center node installed at the back of a legged robot acquires each member's relative position and broadcasts this information to the remaining members, ultimately enabling the team to navigate hazardous and fuzzy environments more efficiently, substantially lowering the risk of squad separation.

In recent years, multiple wireless communication technologies have been leveraged for localization. Although the IEEE 802.15.1 Bluetooth standard was initially not designed for accurate localization, its widespread usage has motivated the evaluation of its potential for this purpose. Common approaches utilize the Received Signal Strength Indicator (RSSI) for distance estimation or location fingerprinting. Furthermore, the Bluetooth Core Specification 5.1 introduced the Constant Tone Extension (CTE), which enables AoA and Angle of Departure (AoD) direction finding capabilities, highlighting the importance of localization. The IEEE 802.15.4a UWB standard provides rich ranging and timing capabilities, enabling large bandwidths to perform sub-nanosecond accurate reception and transmission times measurements [3], [4]. Using infrastructure-based approaches, UWB achieves localization accuracies in the single-digit to lower double-digit centimeter region. Furthermore, one can accumulate PDoA information of single or multiple transceivers to generate fine-grained direction estimates for accurate ad-hoc localization [5], [6], [7]. However, UWB-based Real Time Localization System (RTLS) need to be synchronized in the time domain to perform the more advanced and efficient ranging techniques, such as TDoA and PDoA, which is a tradeoff between system accuracy, complexity, and capacity.

This work proposes an ad-hoc localization system employing multiple UWB transceivers with directional antennas to perform two-dimensional and omnidirectional real-time localization. Single-Sided Two-Way Ranging (SS-TWR) is used to gather robust distance estimates. A central clock distribution allows TDoA estimates to be calculated from SS-TWR receive timestamps to form a rough AoA estimate. This TDoA-based direction estimate weighs the individual PDoA measurements of the three UWB transceiver pairs. Specifically designed filters and window functions enable smooth transitions between the three 120-degree offset tracking zones of the PDoA transceiver pairs. The post-processing hardens the system against the inherent sample noise and multipathing interference while still being able to track dynamic movement.

The remainder of this work is as follows: after presenting different approaches used for ad-hoc localization in Sec. II, we introduce the proposed system's architecture, and hardware and software components in Sec. III. Then, the chosen measurement scenarios will be presented in Sec. IV and evaluated in Sec. V.

## II. RELATED WORK

This section discusses the strengths and limitations of multiple proposed ad-hoc wireless localization systems. In particular, we compare approaches based on the standards IEEE 802.15.1 and IEEE 802.15.4a concerning their localization accuracy, operational constraints, and resilience to environmental influences.

Ledergerber et al. [8] propose a UWB localization system utilizing the unique mapping of Channel Impulse Response (CIR) to AoA, determined by the antenna transfer function of a given antenna setup, to enable single-antenna, single-receiver direction finding. The system was evaluated under Line-of-Sight (LOS) conditions in a testbed sized 2.5 x 3.5 $m^2$ using a motion capture system as ground truth. Five randomly transmitting UWB nodes with known positions were placed around the testbed at varying distances, as anchors for the self-localization of the mobile receiver. The measured AoA samples are processed by a particle filter assuming unknown object motion dynamics. The root-mean-squared accuracy achieved is 0.37 m for 2D positioning, and 3.6 ° for orientation estimation.

Botler et al. [9] analyzed and compared the direction-finding performance of two wireless localization development kits, one based on Bluetooth Low Energy (BLE) 5.1, and the other based on IEEE 802.15.4a [10] standard-compliant UWB technology. The Bluetooth system uses a single transceiver with a switched three-element linear antenna array. In contrast, the UWB system uses two separate transceivers, which are synchronized to a single clock source and each connected to one of the two antenna elements. While both systems are capable of PDoA-based direction finding, only the UWB system is natively capable of Time of Flight (ToF)-based ranging. Compared to Bluetooth-based systems, UWB radios communicate via narrow, cleanly defined radio pulses with significantly larger bandwidths, i. e., up to more than 500 MHz and above or 20 percent of the center frequency of 2.5 GHz. The bandwidth is the portion of the signal's spectral power density and is limited to $-41.3$ dBm/MHz [11]. This limitation results in an overall signal power of just $-14.3$ dBm for a 500 MHz UWB signal, thus limiting applications to short transmission ranges of less than 100 m. For data modulation, UWB either uses Binary Phase-Shift Keying (BPSK) or Burst Position Modulation (BPM) in combination with time-hopping to reduce interference [4], [12]. The current set of regulations allows the license-free operation of UWB applications in most regions worldwide [11]. A series of experiments were performed in an office environment with an area of 8 x 6 $m^2$. Additionally, two experiments were performed in a 3 m wide and 10 m long hallway, to subject both systems to increased multipathing. The transmitter and receiver were placed 3 m apart for most experiments, optionally using absorber foam and the human body for Non-Line-of-Sight (NLOS) experiments in addition to LOS experiments, at different angles of arrival. The LOS measurements in the office environment showed an overall lower Root Mean Squared (RMS) AoA error of 36.8 degrees for UWB and 41.9 degrees for BLE over the whole measurement range of -90 to +90 degrees AoA. Both systems become disproportionally inaccurate near the points of maximum phase shift. NLOS measurements in the office and in the hallway environment, using the above-mentioned obstruction elements, showed UWB to be less

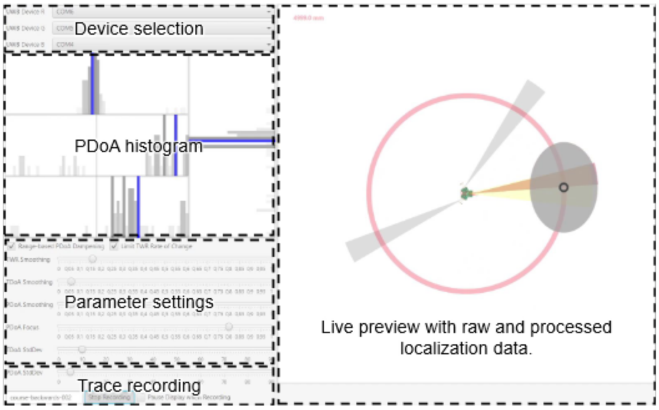

Fig. 2. The UWB Control and Analysis Suite (UCAS) enables a real-time live and trace-based evaluation of the proposed localization system. Mainly, it allows for dynamic device selection, parameter tuning, and displaying raw and processed sensor data. In addition, raw traces can be recorded for subsequent evaluations with different parameter sets or algorithms for simulation-in-the-loop analysis.

affected by NLOS conditions, especially when shadowed by the human body. The LOS experiments in the hallway scenario were conducted at an increased distance of 10 m, showing a constant bias in the UWB estimates, which decreased the UWB RMS accuracy below that of the BLE system. Correcting for this constant offset led to the UWB system being significantly more accurate than the BLE system, hinting at possible benefits of recalibration and bias elimination in changed environments. The UWB system exhibited a generally higher directional accuracy in LOS and NLOS conditions and was less affected by NLOS conditions than the BLE system.

Tiemann et al. [7] proposed an ad-hoc UWB localization system based on PDoA estimation for horizontal and vertical direction finding, combined with Double-Sided Two-Way Ranging (DS-TWR) for distance estimation, to enable 3D position estimation within the frontal hemisphere of the system. The PDoA of the signal emitted by the mobile unit is measured by a triangular antenna array using three synchronized UWB transceiver ICs. A series of three experiments were conducted to evaluate the effect of the tag's rotation and elevation on the positioning accuracy and to evaluate the general 3D LOS accuracy of the system at ranges of up to 4 m. The tag orientation affected the direction estimation accuracy for some specific orientations of the tag, likely due to the tag's antenna characteristics. The overall 3D positioning error is below 30 cm in 75 percent of cases, while the 95-percentile error is less than 50 cm.

## III. PROPOSED AD-HOC LOCALIZATION APPROACH

This section presents BYOPS (**B**ring **Y**our **O**wn **P**ositioning **S**ystem), a mobile, omnidirectional, and ad-hoc UWB localization system that enables accurate real-time localization of mobile agents in room-scale scenarios. The proposed localization scheme applies ToF ranging and simultaneous direction finding by exploiting a combination of TDoA and PDoA estimation. In the following, we summarize the most relevant information about the proposed positioning system:

- **Central node**: The primary hardware component consists of three clock-synchronous multi-transceiver units arranged with 120° circular offset. Each unit is outfitted with a patch antenna array capable of performing PDoA estimation in the horizontal plane. The clock synchronization between all units is enabled using a central Temperature Compensated Crystal Oscillator (TCXO)-generated 38.4 MHz reference clock signal, which is buffered and impedance-matched to the unit's external clock input. The central node listens for incoming Two-Way Ranging (TWR) requests from mobile nodes. Hereafter, it sends a ranging response via one of the node's transceiver units, the selection of which depends on the current direction estimate. The remaining passive multi-transceiver units listen and extract the CIRs and reception timestamps for subsequent PDoA and TDoA direction estimation. The UWB channel configuration used throughout measurements is shown in Tab. I.
- **Mobile nodes**: These nodes are the counterpart to the central node, trying to initiate SS-TWR rangings by sending ranging request messages with a rate of 100 Hz. Their hardware differs from the central node's in that only a single UWB transceiver module is fitted. A battery-powered and custom-designed setup is attached to a legged robot platform for the experiments.
- **UWB trace recording & visualization tool**: We have developed UCAS, a custom suite of tools with a Graphical User Interface (GUI) for recording and visualizing UWB traces on the host computer connected to the central node, shown in Fig. 2. Besides, UCAS allows tuning of the proposed localization algorithm's parameters following a simulation-in-the-loop approach.
- **Multi-scheme localization algorithm**: Since the raw UWB data is not suitable for a robust and precise indoor localization of mobile users, we implemented a localization algorithm fusing SS-TWR, TDoA, and PDoA data and applying different weighting techniques (cf. Fig. 3) to achieve a stable 2D location estimate, even for challenging environments.

The following section describes the weighting and filtering stages of the proposed multi-scheme localization algorithm. The process of deriving direction estimates from the CIR of multiple UWB transceivers is not elaborated on, as it has been extensively covered in previous works [7], [9], [5].

The input data of the fusion algorithm, shown in Fig. 3, are three node-offset corrected PDoA direction estimates, $\varphi_{p,1}$, $\varphi_{p,2}$, and $\varphi_{p,3}$, one TDoA-based direction estimate $\varphi_t$, and the raw SS-TWR distance estimate $d_{raw}$. The PDoA-based direction estimates exhibited unpredictable behavior in previous tests if the directional PDoA antenna array is facing away from the mobile unit by more than 90 degrees in either direction, leading to at least one of three PDoA units not producing reliable direction estimates, depending on the mobile node's location. Also, the accuracy of the PDoA-based direction estimation degrades as the tracked node is

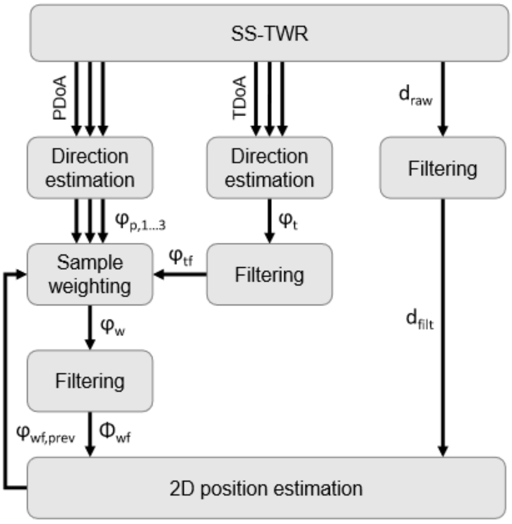

Fig. 3. Conceptional overview of the proposed multi-stage localization algorithm. Each SS-TWR measurement allows for extracting raw TDoA, PDoA, and distance information for direction finding. Contrary to PDoA, TDoA allows for rough direction estimates. The algorithm weights both direction estimate types and aggregates a filtered distance estimate to gather the final 2D position estimation.

TABLE I
UWB CHANNEL CONFIGURATION USED THROUGHOUT EXPERIMENTS

| $f_c$ [GHz] | $B$ [MHz] | $n_{prc}$ | $f_{pr}$ [MHz] | $R$ [Mbps] | $c_{pr}$ | $n_{pr}$ |
|---|---|---|---|---|---|---|
| 6.4896 | 499.2 | 127 | 62.4 | 6.8 | 9 | 256 |

moved close to perpendicular to the PDoA antenna array, which was also observed by others with similar antennae [9]. The TDoA-based direction estimate $\varphi_t$ does not suffer from the aforementioned effects but is limited in resolution compared to the PDoA-based direction estimation by the low antenna separation of less than 30 cm. The exponentially smoothed average of $\varphi_t$, $\varphi_{tf}$, is thus used in combination with the previous final direction estimate $\varphi_{wf,prev}$, to weight the three PDoA-based direction estimates by their codirectionality with $\varphi_{tf}$ and $\varphi_{wf,prev}$. The raw distance estimate $d_{raw}$ is exponentially smoothed and rate limited to form the stable distance estimate $d_{filt}$. Scaling the smoothed direction vector $\varphi_{wf}$ by the smoothed distance estimate $d_{filt}$ produces the final 2D position relative to the central node.

## IV. METHODOLOGY

This section describes the two experimental setups in which we evaluated the proposed Bring Your Own Positioning System (BYOPS). One scenario offers near-free space and LOS conditions, whereas the second one is more challenging, introducing various obstacles, user mobility, and varying distances between the central and mobile node. Tab. I lists all relevant UWB radio parameters we used within our measurements.

The first scenario incorporated an industrial hall environment with ideal radio link conditions, i.e., continuous LOS during the measurement process, facilitating a baseline system performance for an almost static scenario. Although this scenario lacks mobility, it allows analyzing different aspects, like the impact of varying positions between the central and mobile node. Fig. 4 illustrates the placement of the central node and the measurement markers' positions defining the scenario's track (lollipop track). The track comprises straight and circular sections with eight equidistantly spaced measurement points. We conducted the measurements by carrying the UWB tag at the same level as the center node (0.9-m height) along the track from reference point A toward G, with the mobile node facing the central node, always ensuring a LOS. Furthermore, we hold each position for around 20 s at each reference marker before moving on. Thus, we consider only location samples gathered for these reference positions for the accuracy analysis.

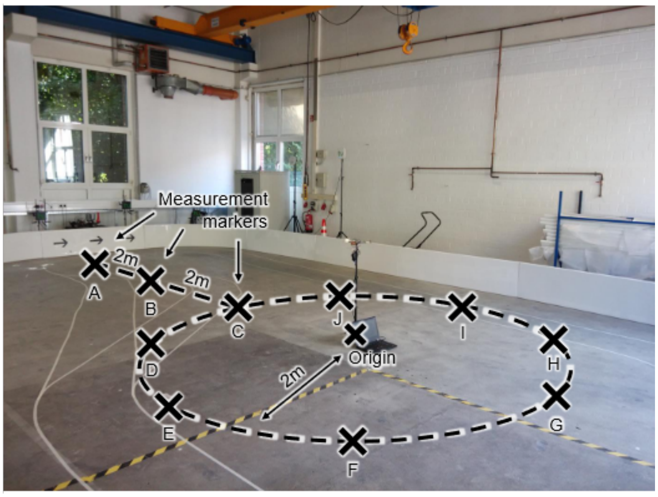

Fig. 4. **Scenario A**: With the central node at the center of the extended circle trajectory, we conducted quasi-static and LOS measurements at the highlighted position markers.

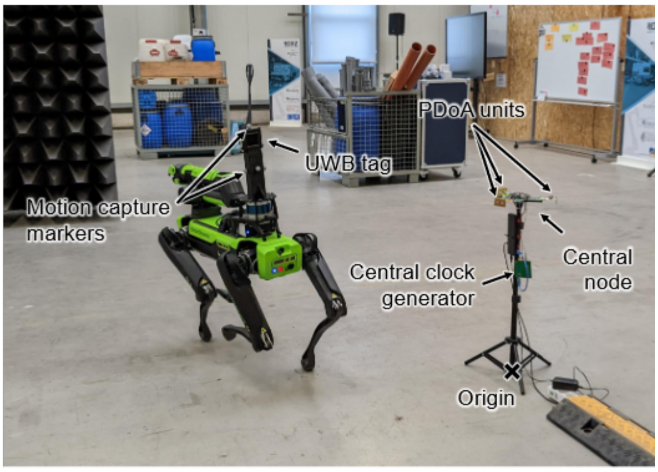

Fig. 5. Evaluation scenario showing the central node, its three PDoA units synchronized via the central clock generator, and the legged robot carrying the mobile node. We define the central node's position as the scenario's origin for localizing the mobile node.

The second scenario features a more challenging evaluation setup with different obstacles, mobility, and varying distances between the central and the mobile node. We conducted this scenario's measurements in the German Rescue Robotics Centre (DRZ e.V) laboratory hall, which provides various indoor and outdoor scenarios for developing and evaluating mobile robot systems for civil security. In contrast to the prior scenario, we mounted the UWB tag onto a legged robot with a comparable installation height as the center node, as shown in Fig. 5. In addition, we used a visual motion capture system installed in the laboratory hall as high-accuracy positioning ground truth to assess the proposed system's relative 2D position estimation error. The motion capture system continuously tracked the positions of both the central node and the mobile tag during the measurements.

Fig. 6 illustrates the scenario layout, depicting the position of the BYOPS node, marked as origin, as well as the different obstacles deployed within the scenario's playground and the trajectory traversed by the legged robot carrying the UWB tag. We started traveling the circuit track close to the central node, passing different obstacles with various Radio Frequency (RF) interferences on the course. During the measurement, there is an NLOS link between the central node and mobile tag due to shadowing by obstacles such as an absorber wall and loaded metallic mesh boxes. Apart from the obstacle-induced impact, the trajectory section close to the central node is also relevant as it allows us to assess the proposed system's robustness for multiple PDoA sector transitions, i.e., the overlapping area covered by two PDoA nodes. Contrarily, the trajectory's remaining parts mainly address the effect of the UWB tag's rotations on the resulting 2D position estimation error.

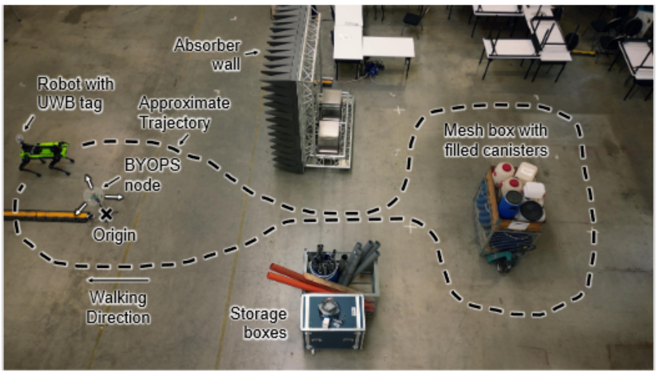

Fig. 6. **Scenario B**: Explorative trajectory at the DRZ facility, incorporating strong shadowing (absorber wall) and refraction and absorption (metallic boxes). Moreover, the overlays mark the center node's position and PDoA nodes' orientation.

## V. PERFORMANCE ANALYSIS

This section compares the proposed system's positioning accuracy for the two industrial indoor scenarios described in the previous section. First, we discuss the results for a static LOS scenario allowing us to assess the performance under mostly controlled environmental conditions. Hereafter, we explain the results for a significantly more challenging industrial scenario with a mixture of LOS and NLOS radio propagation conditions and increased tracking distance.

### A. Industrial LOS Scenario

The first scenario incorporated an industrial hall environment with ideal radio link conditions, i.e., continuous LOS during the measurement process, facilitating a baseline system performance for an almost static scenario. Although this scenario lacks mobility, it allows analyzing different aspects, like the impact of varying center node and tag orientations. The 2D scatter plot in Fig. 7 illustrates the center node's position, its sectors' orientations, the equidistantly spaced measurement markers (A-J) on the traversed trajectory, and the distributions of the raw and filtered position samples. In the following, we consider only samples gathered for these reference positions. For markers D, G, and J, we can observe a distinct distribution of the position samples since these markers are roughly located in the intersection of two PDoA units, i. e., in their respective angular measurement ranges, lowering the directional accuracy. More precisely, a mixture of non-linear geometric mapping between PDoA and AoA, and non-linear antenna characteristics affect the direction estimation. However, the AoA-based distance estimation seems more robust as raw and filtered position samples for each marker have similar distances. Fig. 8 displays each measurement marker's 2D position error distribution allowing for a more detailed analysis of the position estimation performance. For markers A, B, and C, we identify a distance-proportional characteristic of the positioning errors' outliers related to the sensitivity of the PDoA-aided direction estimation. Moreover, we can determine significant error outliers and, thus, a higher average 2D positioning error for markers D, G, and J, which are within the crossover zone of two PDoA nodes. In total, BYOPS achieves a mean 2D positioning error of 0.18m and a maximum error of around 0.8m which is sufficiently accurate for the rescue scenario considered in this paper.

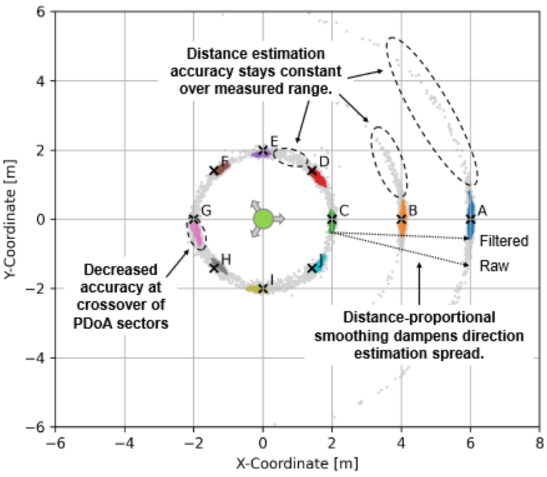

Fig. 7. **Scenario A**: Top-down 2D scatter plot of raw and processed (highlighted) sample distribution. Each reference marker (A-J) annotates a measurement location. The circle-shaped sample distribution implies high robustness of the distance estimation, whereas the error caused by direction estimation is distance proportional.

### B. Industrial NLOS Scenario

We conducted the second, more realistic evaluation in a scenario with different obstacles and user mobility in the German Rescue Robotics Centre laboratory hall using the

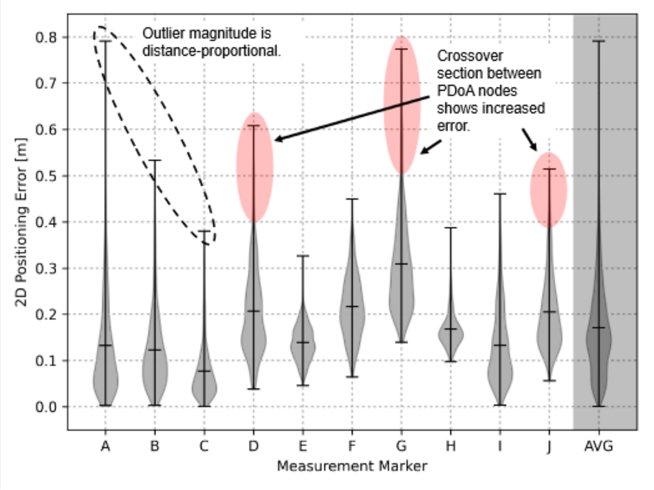

Fig. 8. **Scenario A**: Violin plot of the 2D positioning accuracy. There is a clear indication of a distance-proportional increase of outliers, going from point C (closest) to point A (furthest away). The direction estimation degrades at adjacent PDoA nodes' crossover sections.

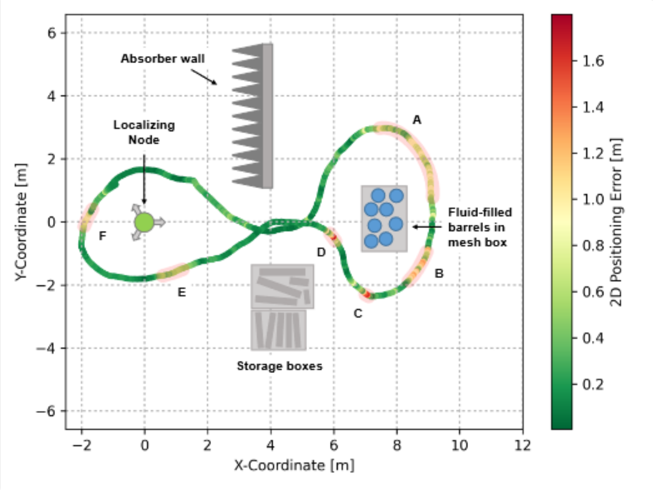

Fig. 9. **Scenario B**: Scatterplot of the ground truth trajectory of the mobile node, illustrating the placement of the absorber wall and the metallic boxes. The colorization indicates the 2D position estimation error for that specific sample at a given location.

provided high-resolution visual motion capture system as a ground truth reference. Analogously to the first scenario, we placed the center node 0.9m above the ground, whereas the mobile UWB tag was mounted onto a legged robot at a similar height using a 3D-printed plastic mounting bracket. Fig. 9 illustrates the scenario's setting, including the center node's position and orientation relative to the scenario's playground, the obstacles and their respective locations and dimensions, and the resulting positioning error for each sample on the ground truth trajectory. For a better overview, we marked relevant subsets of the trajectory with notable deviations regarding the position error estimation as A-F. Contrary to the first scenario, we determined the positioning error as the difference between the visual motion capture system (ground truth) and the proposed UWB system. We first discuss the different zones and their characteristics, resulting in lowered positioning accuracies, before we analyze possible effects in more detail:

- **Zone A**: The absorber wall partially blocks the LOS path between the center node and the mobile tag mounted onto the legged robot leading to a degraded positioning accuracy.
- **Zone B:** From the center node's view, zone B is partially located behind two metallic boxes, each filled with different items (e.g., fluid-filled barrels), influencing the signal link due to scattering.
- **Zone C & D:** Although both zones differ in terms of the presence of a LOS RF link, we can observe short-term variations of the positioning error during the legged robots' rotation. An angle-specific characteristic of the antenna used by the mobile UWB tag is a possible explanation, considering that similar observations with respect to the mobile node's orientation were made in [7].
- **Zone E & F**: Despite the distance between the center node and zones E and F being less than 2m, there is a short-term but significant distribution of the positioning error. Considering the center node's orientation, we identify the cross-zone, i.e., moving from one logical section to another, as a possible reason.

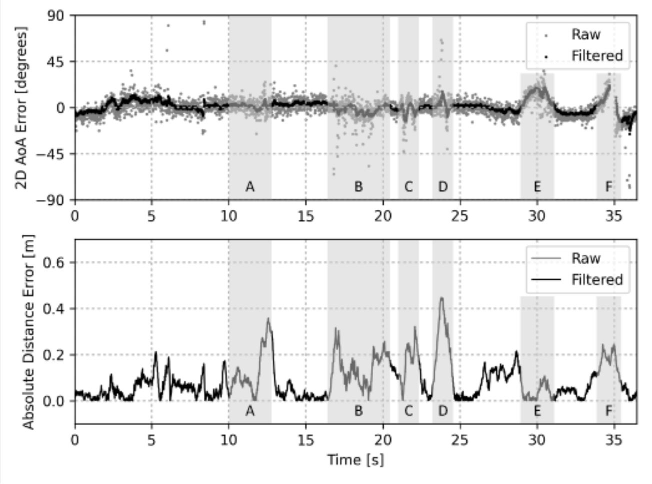

Fig. 10. **Scenario B**: Time series plot of the direction and distance estimation error. Shadowing in zones A and B mainly decreases the distance estimation accuracy. However, the UWB tag's rotation causes more severe directional estimation errors, leading to inflated distance estimates. Overall, adjacent PDoA crossover sections have the highest effect on the direction estimation accuracy but less on the distance estimation.

Fig. 10 plots signed direction and absolute distance estimation error over time as a scatterplot. Raw samples are indicated in grey, while the samples processed by the BYOPS smoothing algorithm are colored black. The extent of zones A to F, which are also marked in Fig. 9, are highlighted by grey rectangles. The first observation is that distance estimation is the minor contributor to the overall 2D localization error, considering that the absolute worst-case distance estimation error is below

50 cm. Zone A, where the LOS is shadowed by an absorber-wall, does not show significant AoA deviations, but a spike in distance error is noticeable. Excessive outliers in the angular estimates, as well as increased distance error, are observed in zone B, where the scattering between and behind the mesh boxes takes hold. Sharp AoA oscillations occur in zones C and D and may be caused by the antenna characteristics of the mobile node, considering that both spikes occur with the robot oriented in that specific direction. The highest angular deviations are observed in zones E and F, where the robot crosses PDoA sector boundaries of the central node at a short distance and thus with relatively high angular velocity from the perspective of the base station. The decision to switch between PDoA-sectors was delayed by errors and biases in the AoA estimation, causing the system to not quite reach the handover point until the influence of the TDoA-based direction estimate forced a sector transition. Fig. 11 illustrates the resulting cumulative distribution functions of the absolute 2D positioning error for both scenarios. The LOS scenario A obviously shows the lowest error distribution, which is in part caused by the median measurement distance of 2 m. The below 6 m distance and LOS parts of scenario B have an increased error that expresses itself mostly in the 95th percentile, where it is increased by 40 cm. The NLOS and above 6 m distance part of scenario B shows a stronger increase in median error and an increase of 45 cm in the 95th percentile. The proposed system performs better than comparable systems [7] which were also tested under LOS and short-distance conditions.

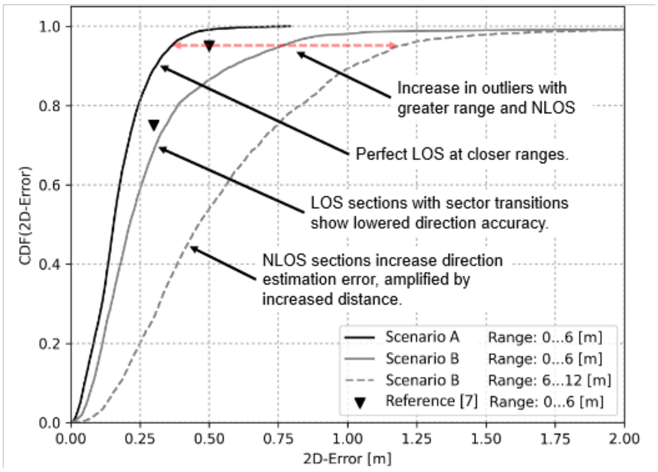

Fig. 11. Cumulative distribution of the filtered samples' 2D positioning error for each shown scenario. We compare these results with the 75- and 95-percentile 2D positioning accuracy of another ad-hoc UWB positioning system (CELIDON Cerberus) [7], which has been evaluated under short-range LOS indoor conditions. The plot shows an increased positioning error for higher distances and NLOS. BYOPS offers at least comparable positioning performances but also provides omnidirectional localization.

## VI. CONCLUSION AND FUTURE WORK

This paper presents a novel approach to enable robust omnidirectional, infrastructure-less, and ad-hoc localization using a combination of PDoA, TDoA, and SS-TWR realized through custom-built UWB hardware and software. The proposed system aims to support emergency responders by providing increased situational awareness in low-visibility scenarios through seamless omnidirectional localization. We performed multiple experiments to evaluate the system performance under LOS and NLOS conditions and at varying ranges, showing a 95-percentile 2D accuracy of below 40 cm under LOS conditions. The 2D accuracy at ranges of up to 12 m under mixed LOS and NLOS conditions is below 1.2 m in 95 percent of cases in our experiments. In future work, we will explore the potential for miniaturization, and the matters of energy efficiency, scalability, and robustness to other challenging environments are to be explored. Combining the proposed system with other wireless and inertial localization technologies may improve the operational range and robustness of the system in challenging environments.

## ACKNOWLEDGMENT

This work has been supported by the German Federal Ministry of Education and Research (BMBF) in the course of the 6GEM research hub under grant number 16KISK038. The authors would like to thank Nils Heidemann (DRZ e.V.) for supporting part of the field experiments.

## REFERENCES

[1] Satellite Navigation Branch, ANG-E66 NSTB/WAAS T&E Team, "GLOBAL POSITIONING SYSTEM STANDARD POSITIONING SERVICE PERFORMANCE ANALYSIS REPORT," FAA William J. Hughes Technical Center, Tech. Rep., Jan. 2021. [Online]. Available: https://www.nstb.tc.faa.gov/reports/2020_Q4_SPS_PAN_v2.0.pdf (Accessed 2023-03-20).

[2] P. Puricer and P. Kovar, "Technical limitations of GNSS receivers in indoor positioning," in *2007 17th International Conference Radioelektronika*. IEEE, apr 2007.

[3] "IEEE Standard for Low-Rate Wireless Networks," *IEEE Std*, vol. 802, pp. 1–800, 7 2020. [Online]. Available: https://ieeexplore.ieee.org/document/9144691

[4] B. G. N. Mohammadreza Yavari, "Ultra wideband wireless positioning systems," *Dept. Faculty Comput. Sci., Univ. New Brunswick, Fredericton, NB, Canada, Tech. Rep. TR14-230*, Mar. 2014. [Online]. Available: https://www.qorvo.com/innovation/ultra-wideband/resources/white-papers

[5] I. Dotlic, A. Connell, H. Ma, J. Clancy, and M. McLaughlin, "Angle of arrival estimation using decawave DW1000 integrated circuits," in *2017 14th Workshop on Positioning, Navigation and Communications (WPNC)*, 2017.

[6] M. Heydariaan, H. Dabirian, and O. Gnawali, "AnguLoc: Concurrent angle of arrival estimation for indoor localization with UWB radios." Marina del Rey, CA, USA: IEEE, 2020, pp. 112–119.

[7] J. Tiemann, O. Fuhr, and C. Wietfeld, "CELIDON: Supporting First Responders through 3D AOA-based UWB Ad-Hoc Localization." Thessaloniki, Greece: IEEE, 2020, pp. 20–25.

[8] A. Ledergerber, M. Hamer, and R. D'Andrea, "Angle of Arrival Estimation based on Channel Impulse Response Measurements," in *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, nov 2019.

[9] L. Botler, M. Spork, K. Diwold, and K. Romer, *Direction Finding with UWB and BLE: A Comparative Study*. IEEE, 12 2020, pp. 44–52.

[10] *Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs): Amendment 1: Add Alternate PHYs*, Std., 8 2007.

[11] Decawave. (2020) APR001 APPLICATION NOTE. [Online]. Available: https://www.qorvo.com/innovation/ultra-wideband/resources/application-notes (Accessed 2023-03-20).

[12] Qorvo. (2021, May) Getting Back to Basics with Ultra-Wideband (UWB). [Online]. Available: https://www.qorvo.com/resources/d/qorvo-getting-back-to-basics-with-ultra-wideband-uwb-white-paper (Accessed 2023-03-20).