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Ad-Hoc UWB 360° Localization with In-Mask AR Visualization for Emergency Operations

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***Abstract*—Reliable localization of emergency responders under zero-visibility conditions remains a major challenge, particularly when no pre-installed infrastructure is available. This demo presents an ad-hoc body-mounted UWB-based omnidirectional localization system targeting real-world rescue operations with respiratory protection. The wearable system performs fully decentralized cooperative multilateration based on mutual UWB distance and phase-difference-of-arrival measurements. Robust omnidirectional positioning is achieved through an iterative software-in-the-loop optimization process, using high-precision motion capture as ground truth to refine algorithmic performance under realistic conditions. The localization hardware is miniaturized, using an energy efficient custom operating system, and specifically designed for integration into protective gear. It streams on-device rendered real-time position information to an in-mask augmented reality display. This work showcases the current fully-operational system prototype and a hands-on demonstration highlighting the system's practicality and robustness.**

***Demo Video*—Video demonstration can be accessed at: http://tiny.cc/UwbLoc**

I. Introduction

RELIABLE localization of emergency responders is a key enabler for safe rescue operations, particularly in scenarios with zero visibility such as smoke-filled or collapsed buildings. In such environments, visual orientation is severely limited. Consequently, infrastructure-free localization approaches that can be rapidly deployed and operate under harsh propagation conditions are of growing interest.

Ultra-Wideband (UWB) radio technology has emerged as a promising candidate for accurate localization due to its high time resolution and multipathing robustness [1]. While previous work has demonstrated the feasibility of UWB-based localization for first responders as part of a building emergency infrastructure [2] or in training scenarios [3], transferring such systems to practical rescue operations remains challenging. In particular, ad-hoc operation without pre-installed infrastructure, integration into personal protective equipment, and reliable omnidirectional localization under dynamic conditions must be addressed (Fig. 1).

This demo paper presents a scalable ad-hoc UWB-based 360° localization system, performing localization using mutual distance measurements between nodes. The iterative optimization process leverages high-precision motion capture as ground truth to improve localization accuracy. The demo setup includes a handheld demonstrator for visitors, allowing to experience live 360° localization with real-time AR visualization.

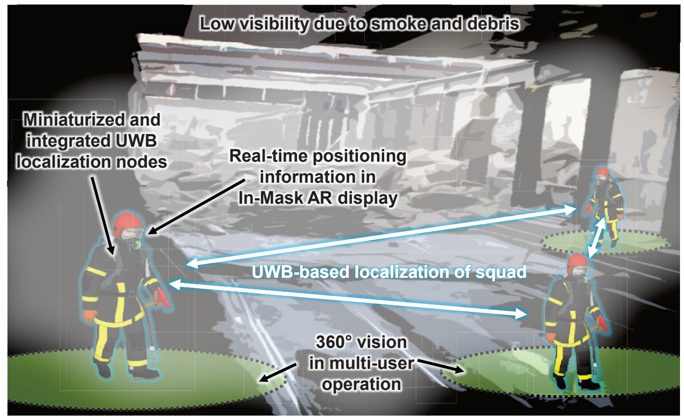

Fig. 1: 360° UWB-based AR localization ensures safety to rescue squad members even in low-visibility scenarios.

II. UWB Localization of Emergency Responders

The localization system consists of two major components, a group of UWB nodes attached to the compressed air breathing apparatus (BA) of each first responder, and an in-mask Augmented Reality (AR)-display, which receives a video stream with localization information generated by one of the attached nodes (Fig. 2). While the preceding hardware platform [4] was sufficient to explore one-to-one ad-hoc localization, from a single base station to multiple mobile nodes, this iteration has the goal of integrating into real firefighting equipment with multi-user localization. To this end we choose to design and build custom node hardware, including a low-power microcontroller, an UWB chipset capable of measuring PDoA using a single transceiver and integrating an Inertial Measurement Unit (IMU) and compass with sensor-fused data output.

Localization is performed using a custom distributed 2D multilateration algorithm, where the distances between all nodes attached to one BA with respect to one or more of the localized nodes, attached to another BA, are used to calculate the relative distance and heading. The system also produces angle measurements on reception, which are fused into the location estimate. Time-synchronization, round-robin scheduling and randomized request-rate throttling are implemented to distribute the airtime, and thus measurement rate, evenly among all nodes. System performance degrades gracefully with larger number of nodes, with the channel access opportunities being divided evenly across all nodes.

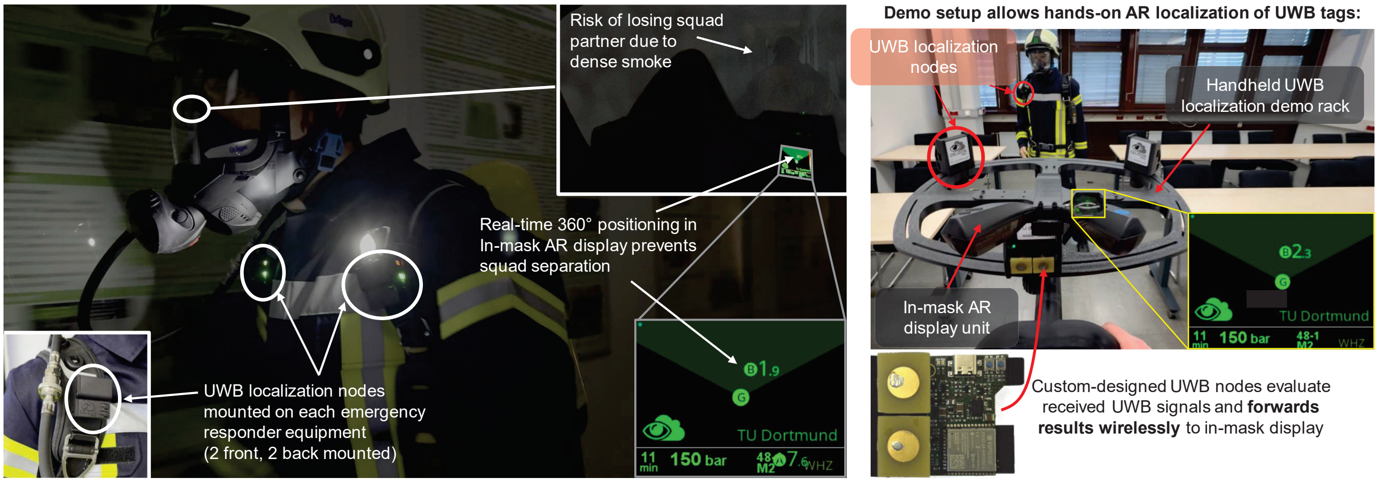

Fig. 2: Custom-designed UWB-based real-time localization system designed for integration into personal protective equipment, providing robust position tracking of emergency responders and AR-based visualization under operational conditions.

III. System Performance Optimization

The localization systems performance is evaluated using room-scale motion-capture for ground truth. Simultaneously, the raw sensor data (UWB distance and Angle of Arrival (AoA), Heading, RSSI) are shared amongst all UWB nodes over a connectionless WiFi link and captured by a gateway for further processing. Recording the complete raw data stream of our distributed system enables an offline software-in-the-loop replay with optimized localization algorithms, which is then checked against the motion capture trajectory automatically.

An initial evaluation of the system performance towards the 360° tracking accuracy was performed by positioning the test subject, wearing the system, at a fixed distance from a statically mounted node, then rotating the body in 45 degree increments. The position reported by the UWB system is then checked against our ground truth reference.

For the distance estimation, a Mean Absolute Error (MAE) of 21.75 cm (14.3%) was achieved, with a median error of 11 cm, and one outlier at 81 cm. The direction estimation showed an MAE of 6.75° (3.75% of half circle), with one outlier of 18°, corresponding to the same sample as the distance outlier. While for the rescue scenario this precision is sufficient, we will further optimize the algorithms in the future by integrating IMU related information.

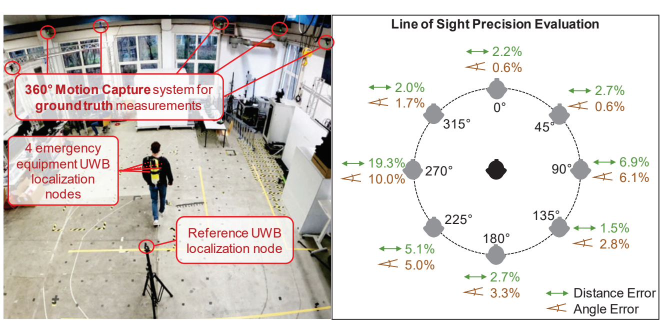

Fig. 3: Left: 360° Motion Capture system provides ground truth for software-in-the-loop optimization of localization algorithms. Right: Optimization enables good precision in front and back area, with more optimization required on the sides.

IV. Conclusion

This demo paper presents an ad-hoc UWB-based 360° localization system for emergency responders operating under low-visibility conditions. The proposed wearable system enables cooperative, infrastructure-free localization using mutual UWB measurements and provides intuitive real-time feedback via an in-mask augmented reality display. Experimental evaluation with motion-capture-based ground truth demonstrates promising accuracy in both distance and direction estimation, validating the feasibility of robust omnidirectional positioning. The presented architecture is specifically designed for integration into protective equipment and realistic rescue scenarios.

Acknowledgment

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