A Modular Long-Range UWB Testbed with SubGHz Backbone for Multi-Drone Localization Algorithms

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Abstract

Reliable multi-UAV localization in complex environments demands a flexible and scalable test infrastructure capable of supporting real-time positioning and flexible distributed communication. This work presents a modular hardware testbed designed for evaluating indoor and outdoor localization algorithms in aerial robotic networks. The platform combines a long-range Ultra-Wideband (UWB) module for precise ranging, an Inertial Measurement Unit (IMU) for motion tracking, a long-range SubGHz transceiver as a communication backbone between mobile nodes, and an ESP32 micro-controller for local computation. This platform enables the development and validation of cooperative localization strategies in realistic, multi-agent scenarios. The proposed system serves as a practical tool for bridging the transition from simulation to real-world deployment in location-aware UAV applications.

Keywords

Ultra-Wideband (UWB), UAV localization, Mesh network, Anchor-based ranging

1. Introduction

Accurate and robust localization is a fundamental requirement for the deployment of autonomous UAVs, particularly in cooperative or swarm configurations. These systems are increasingly used in complex applications such as distributed sensing, automated inspection, and real-time mapping, where precise and timely position estimates are essential [1, 2]. While GPS is widely adopted, its accuracy—typically on the order of meters—is insufficient for tasks requiring decimeter-level precision, especially in partially covered or cluttered environments where signal quality is degraded [3, 4].

Ultra-Wideband (UWB) technology has emerged as a viable alternative for high-accuracy ranging and localization. Thanks to its high temporal resolution and resistance to multipath effects, UWB enables centimeter-level distance measurements and has been extensively adopted in indoor scenarios [5]. However, its application in outdoor localization systems for UAVs remains limited, partly due to the perceived adequacy of GPS and partly due to the complexity of managing distributed and scalable UWB networks in large open areas [6].

Recent research has highlighted several protocol-level challenges in UWB-based localization systems, especially in multi-agent or swarm UAV scenarios. Unlike passive positioning methods, UWB localization requires active ranging sessions—typically using the Double-Sided Two-Way Ranging (DS-TWR) protocol—where each UAV must initiate and complete a transaction with individual anchors. This procedure is inherently stateful, as anchors must process, respond, and temporarily allocate resources for each polling request [7]. Moreover in dense multi-UAV networks, the management of UWB localization protocols introduces several critical challenges that impact both scalability and reliability. One of the

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most important aspects is the selection of anchors to poll. Since each UAV can only range with a limited number of anchors at a time, choosing the most informative subset—based on geometry, distance, or visibility—is essential to maintain localization accuracy and reduce unnecessary communication overhead [8]. Furthermore, as the number of mobile nodes increases, anchors become shared resources and may be simultaneously targeted by multiple UAVs. This leads to contention, increasing response delays and degrading overall system responsiveness. Another major concern is the risk of message collisions and coordination failures, particularly in systems without centralized scheduling or contention resolution mechanisms. In single-channel networks, concurrent ranging requests can interfere with each other, especially when multiple UAVs attempt to interact with the same anchor without any form of time-slot allocation or asynchronous protocol design [7].

To support the rapid development of localization algorithms, a variety of UWB development boards have become available. Notable open-source platforms such as Makerfabs' ESP32 UWB and ESP32 DW3000 UWB boards offer accessible entry points for UWB experimentation, especially when paired with low-cost microcontrollers like the ESP32 [9]. These platforms typically integrate Qorvo's DWM3000 module, a transceiver compliant with the IEEE 802.15.4z standard, which ensures high interoperability with modern UWB localization ecosystems and supports secure ranging features [10].

In this work, we present the design of a set of usage scenarios and the preliminary validation of a testbed aimed at supporting the development of multi-UAV localization networks. The proposed system builds upon and extends existing UWB development platforms [9], by introducing key enhancements that enable operation in wide-area, cooperative environments. Specifically, we developed a custom hardware platform that integrates a long-range UWB transceiver [11], a sub-GHz communication module for out-of-band data exchange, and a 6-axis Inertial Measurement Unit (IMU). This improved architecture allows UAVs to maintain precise ranging with ground anchors while simultaneously exchanging coordination data over a robust, multi-standard sub-GHz radio link capable of supporting mesh topologies. The use of an out-of-band channel enables advanced strategies such as asynchronous anchor discovery, reduction of UWB packet overhead, and energy-aware communication policies. Furthermore, the onboard IMU allows each UAV to perform short-term dead reckoning and dynamically adapt its ranging frequency based on its motion profile.

2. Architecture and Communication Scenarios

The proposed localization testbed is designed to support flexible experimentation with various coordination and communication strategies in multi-UAV environments.

2.1. Testbed Architecture

The testbed consists of two primary elements: a set of UAVs equipped with localization and communication hardware, and a number of static anchor nodes deployed on the ground. All devices—both mobile and static—are interconnected through a long-range sub-GHz radio network, which provides reliable multi-hop communication over large areas and supports mesh topologies. Each UAV is equipped with a modular hardware platform that integrates a UWB transceiver for precise ranging, an ESP32 microcontroller for local processing, a sub-GHz radio module for network communication, and an IMU for inertial sensing. The anchor nodes are similarly equipped, although in some configurations they may be optimized for low-power operation.

The goal of the system is to localize all UAVs simultaneously in real-time, leveraging both UWB ranging and the auxiliary communication channel to support algorithmic flexibility. The overall system architecture includes two key components:

- **UAV (mobile tag):** equipped with a UWB module for ranging, an ESP32 microcontroller for local data processing and decision-making, a sub-GHz radio module for long-range, low-power communication with the infrastructure, and a 6-axis Inertial Measurement Unit (IMU) for motion estimation. The onboard software is responsible not only for handling communication and ranging, but also for executing localization algorithms, anchor selection logic, and adaptive ranging strategies based on the UAV's motion profile.

- **Ground anchors:** fixed nodes deployed across the operating area, each with a UWB transceiver and a sub-GHz radio module. Anchors periodically transmit their known positions via the out-of-band channel and respond to ranging requests from UAVs. In contrast to the UAVs, anchors do not include IMUs and run simplified firmware focused on communication handling, status broadcasting, and ranging reply.

This hybrid architecture allows UAVs to dynamically select which anchors to query based on their spatial geometry and expected contribution to localization accuracy. This flexibility reduces communication overhead and enhances the scalability of the system.

2.2. Out-of-Band Communication

A key feature of the proposed system is the integration of a sub-GHz out-of-band communication channel, which operates independently from the UWB ranging process. This channel is used to exchange metadata, such as anchor positions, status information, and coordination messages, allowing the system to implement advanced strategies for efficient localization and network scalability.

The sub-GHz out-of-band channel plays a dual role in the system. First, it enables anchor position dissemination: all ground anchors, pre-surveyed via GPS-RTK or manual measurement, periodically broadcast their coordinates to nearby UAVs. This allows each UAV to maintain a local map of visible anchors without triggering unnecessary ranging requests, significantly reducing overhead. Based on this information, UAVs implement dynamic anchor selection, choosing which anchors to poll according to criteria like distance, geometry, and line-of-sight. Only the most relevant anchors are selected at each cycle, reducing communication load, energy consumption, and interference—especially in large or dense networks.

Second, the out-of-band channel is used directly in the localization process. The anchor positions received asynchronously are used by the onboard multilateration algorithm to estimate the UAV's position. This decoupled design—using UWB solely for distance measurements and sub-GHz for geometric context—improves modularity and allows for adaptive ranging rates, informed for example by IMU data. It also lays the groundwork for more advanced localization techniques, such as anchor weighting or distributed estimation.

2.3. Testbed scenarios

To explore different levels of coordination among UAVs, we define three operating scenarios:

- **Scenario 1 – Independent UAVs with Anchor-Based Localization:** Each UAV independently computes its own position using UWB ranges obtained from static ground anchors. No information is shared between UAVs. This scenario represents the baseline configuration, focusing on anchor-to-UAV localization only.
- **Scenario 2 – Collaborative UAVs with Peer-to-Peer Localization:** In addition to interacting with anchors, UAVs can exchange range or position data among themselves. This allows for peer-to-peer relative localization, improving robustness in areas with fewer anchors or degraded geometry. However, each UAV still computes its position independently.
- **Scenario 3 – Swarm Localization with Mutual Constraints:** UAVs operate as part of a coordinated swarm, where both absolute and relative positions are relevant. In this case, the system estimates not only each UAV's global position but also enforces consistency in the inter-UAV distances. This scenario enables the study of swarm-aware localization algorithms, such as those based on graph optimization or consensus-based estimation.

In all configurations, the sub-GHz network plays a central role in enabling efficient information exchange. By offloading metadata and control messages to the out-of-band channel, UWB traffic can be reserved for essential ranging operations, reducing congestion and enabling energy-saving policies—especially on battery-powered anchor nodes.

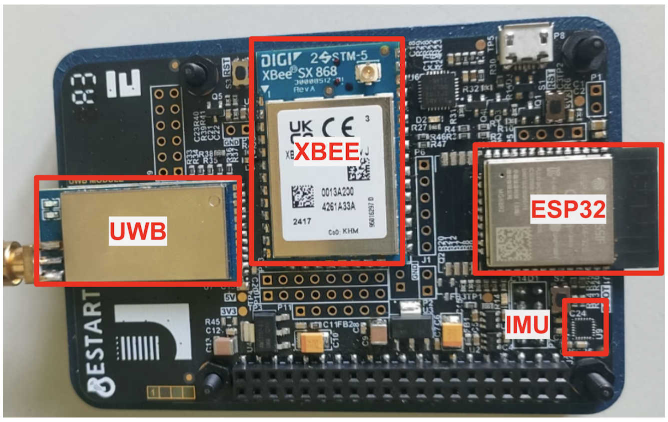

Figure 1: Top view of the custom localization board.

3. Hardware Platform

For the implementation and experimental validation of the proposed system, a compact and integrated hardware platform was developed, specifically designed to operate on small UAVs in outdoor scenarios and under realistic operating conditions. The board, visible in Figure 1, integrates the essential components for UWB-based localization, inertial sensing, and long-range communication into a single, lightweight circuit suitable for aerial deployment.

3.1. Main Components

UWB Module

The UWB module, located at the top of the board, is based on the NiceRF UWB-DW3000 series [11], which integrates the Qorvo DWM3000 chip into a compact, long-range transceiver module. It supports the IEEE 802.15.4a/z standards and is capable of performing distance estimation using the Double-Sided Two-Way Ranging (DS-TWR) protocol. This protocol enables accurate ranging by compensating for clock offsets and asymmetric delays, making it suitable for distributed outdoor localization. The NiceRF module offers extended communication range compared to standard UWB development kits, making it particularly well-suited for UAV-based localization in large, open areas. Under ideal conditions, it provides sub-decimeter accuracy, with typical ranging errors below 10 cm. In addition to its robust performance, the module's compatibility with the Qorvo UWB ecosystem ensures integration with both tag-based and anchor-based positioning systems, and future support for multilateration methods such as Time Difference of Arrival.

IMU (Inertial Measurement Unit)

An onboard 6-axis IMU (accelerometer + gyroscope) provides motion sensing capabilities. While not strictly required for UWB localization, the IMU supports several enhancements. First, it can be used to improve UAV stabilization. More importantly, it enables dead reckoning, which can reduce the frequency of UWB measurements by propagating motion estimates during intervals between ranging updates. This is especially useful for reducing power consumption and bandwidth usage in both the mobile node and the anchor infrastructure.

ESP32 Microcontroller

At the core of the system is an ESP32-WROOM microcontroller, which orchestrates the operation of all onboard components. This module handles UWB ranging sessions, processes distance measurements, manages the communication stack over the sub-GHz radio, and—when required—performs local position estimation. The ESP32-WROOM was chosen for its excellent balance between computational capabilities, low power consumption, and integrated wireless interfaces (Wi-Fi and Bluetooth), making it ideal for embedded applications on resource-constrained UAV platforms. Its dual-core architecture allows for real-time execution of lightweight localization algorithms, including filtering and fusion strategies. In addition, the ESP32-WROOM supports the implementation of advanced features such as dynamic anchor selection, out-of-band coordination, and time-slot scheduling for communication and ranging, offering flexibility and scalability for various UAV swarm scenarios.

XBee SX868 (Sub-GHz Communication)

The board features an XBee SX868 module operating in the 868 MHz sub-GHz band, which serves as the out-of-band communication channel. Unlike UWB, which is used for high-precision ranging, the XBee network supports long-range transmission (up to 14 km in line-of-sight) and mesh topologies. This link is used to exchange control information, broadcast anchor positions, and support coordination among UAVs in cooperative localization scenarios. It provides a reliable and scalable backbone for swarm-level operations without congesting the UWB communication layer.

3.2. Modes of Use

The board is designed to offer maximum flexibility in integration and deployment. It supports two main operating modes:

- **Autonomous Mode:** The board operates as a self-contained localization unit controlled entirely by the ESP32. This mode is particularly suitable for lightweight UAVs or mobile robots with constrained payload and processing capabilities. Localization and communication are performed locally without the need for an external computer.
- **Raspberry Pi Shield Mode:** The presence of a dual GPIO header on the right edge of the board allows it to be used as a shield for single-board computers such as the Raspberry Pi. In this configuration, the ESP32 and other onboard components act as peripherals, while the main processing is delegated to the host SBC. This setup enables advanced localization algorithms, integration with ROS or high-level control software, and access to greater computing power.

3.3. Power Supply

The platform supports two power supply modes to accommodate both development and deployment use cases. For laboratory and development activities, the board can be powered via the micro-USB port located on its right side. This option also enables programming, debugging, and configuration, making it the preferred method for software development and parameter tuning. For operational use in the field—particularly onboard UAVs or other mobile systems—the board can be powered through a dedicated connector compatible with standard LiPo batteries. Internal voltage regulators ensure safe and stable operation of all components during autonomous missions. This battery-powered mode is ideal for scenarios where cable-free and lightweight power solutions are required.

4. Experimental Evaluation

4.1. Long-Range Ranging Tests

The first experiment aimed to evaluate the maximum effective distance of the ranging system based on the proposed hardware platform, focusing specifically on the performance of the out-of-band communication channel using the XBee SX868 module. Tests were carried out in the open fields surrounding the University of Rome Tor Vergata, using the rooftop of the Department of Information Engineering as the reference point for transmission.

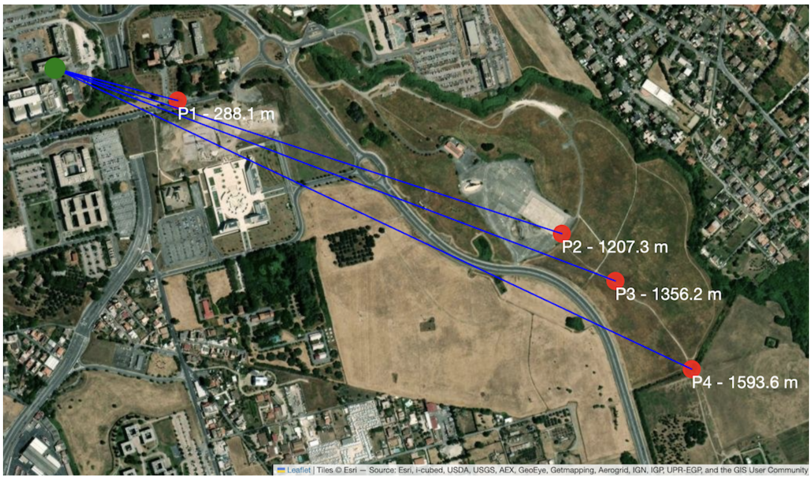

Figure 2: Map of the long-range ranging test. Measurements were taken from the rooftop of the Department of Information Engineering at the University of Rome Tor Vergata.

Figure 2 shows the test configuration: four test points (P1–P4) were selected at increasing distances from the transmitter, ranging from approximately 288 meters up to nearly 1.6 kilometers. The positions were manually surveyed on satellite imagery and chosen to represent realistic open-field deployment scenarios.

The points were as follows:

- **P1: 288.1 m** — located near the engineering campus
- **P2: 1207.3 m** — near the beginning of the open field
- **P3: 1356.2 m** — slightly beyond the hilltop
- **P4: 1593.6 m** — at the maximum line-of-sight distance within the test area

These tests confirmed that the XBee SX868 module, operating in sub-GHz band with proper antenna tuning, can sustain robust bidirectional communication up to nearly 1.6 km in outdoor conditions with minimal interference. Ranging messages were exchanged and confirmed via acknowledgment protocols, validating the feasibility of employing the XBee backbone for coordination and data relay in wide-area UAV localization scenarios.

This setup demonstrates that the system is well-suited for experiments involving UAVs operating over large areas, and can serve as the basis for future tests involving dynamic mobile nodes and cooperative localization strategies.

Figure 3: Test UAV equipped with the custom UWB/XBee board.

4.2. Airborne Ranging Experiment with UAV

The goal of the second experiment was to evaluate the reliability and stability of UWB ranging measurements in real flight conditions, and to verify the feasibility of integrating the proposed localization system onboard a small UAV. In particular, the test aimed to assess whether accurate and continuous distance measurements could be maintained during UAV motion, at altitude, and with real-time constraints.

The experiment was conducted in the open area in front of the CNR ARTOV (Area della Ricerca di Tor Vergata), a UAV-authorized test zone with a maximum flight ceiling of 45 meters. The UAV flew at a steady altitude of approximately 40 meters, following a predefined trajectory with intermediate hovering points for static data acquisition. The custom localization board developed in this work was mounted on a DJI Air 2S quadcopter, selected for its high stability, sufficient payload capacity, and autonomous flight capabilities. As shown in Figure 3, the board included the UWB transceiver, the ESP32 microcontroller (ESP32-WROOM), and the sub-GHz communication module (SX868), all housed within a compact 3D-printed protective enclosure. The antenna was positioned vertically to ensure optimal propagation and consistent line-of-sight (LOS) with the fixed ground node throughout the entire flight.

Figure 4: Flight path and measurement points for the airborne ranging experiment near CNR ARTOV.

Throughout the experiment, line-of-sight (LOS) was consistently maintained between the airborne node and the ground station. The UWB ranging module successfully measured distances at each waypoint, and the XBee communication link ensured reliable transmission of control and ranging data across the entire route. The results demonstrate the system's ability to operate in mobile, real-world conditions and confirm its suitability for deployment in UAV-based localization scenarios.

5. Conclusions

In this work, we presented a modular and lightweight hardware platform designed to support the development and evaluation of UWB-based localization algorithms in multi-UAV systems. By combining precise ranging capabilities with a long-range, multi-standard communication backbone, the proposed system enables the deployment of flexible and scalable localization networks suited for both cooperative and swarm-based scenarios.

We described the architecture and components of the board, which integrates a UWB transceiver, a sub-GHz XBee module, an ESP32 microcontroller, and an onboard IMU for motion sensing and energy-aware operation. Two experimental campaigns were conducted to validate the system: one focused on long-range static ranging up to 1.6 km in open field, and the other on real-world UAV flight tests in a controlled airspace. The results confirmed the platform's ability to maintain robust communication and accurate ranging under both static and dynamic conditions.

Future work will focus on expanding the system to support full 3D localization, exploring onboard sensor fusion with the IMU, and validating multi-agent cooperative localization strategies involving multiple UAVs operating simultaneously in shared airspace.

Declaration on Generative AI

During the preparation of this work, the author(s) used GPT-4 in order to: Grammar and spelling check. After using these tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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