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Precise sensors for localization in the drone swarm

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Abstract: Drones can be connected as a swarm to precisely monitor large agricultural areas and manage them more sustainable. They test sensor technology in real environments and solve complex tasks faster. Key aspects include accurate localization, reliable communication, and dynamic flight control. The localization accuracy of RTK-GNSS-enabled system, which includes GPS, GLONASS, GALILEO positioning systems is compared with Ultra-Wideband (UWB) one. The UPWARDS communication hub is presented as a processing and connection point across swarm agents. This controller also incorporates collision avoidance features and testing of evasion strategies.

Keywords: ROS, GNSS, UWB, communication hub, UAV swarm

Introduction

Drones can be cooperatively connected to form a swarming flock to precisely survey large agricultural areas, manage them more sustainably, and set up a test environment to check and characterize micro-sensor technology in critical real-world environments. In cooperation drones can solve complex tasks faster and be used in new or previously unsuitable scenarios. Reliable swarm flight requires accurate localization, reliable communication, and dynamic flight control. We compare the obtained localization accuracy by RTK-GNSS with the one based on distance measurements by Ultra-wideband (UWB). Commercial-grade available on the market DWM1000 UWB modules were picked out to be used for point-to-point and multi-point near distances localization. This approach enables resilient positioning in environments without GNSS reception and allows for a self-sufficient operation. As the second step, the developed UPWARDS communication hub is presented. This device features not only a UWB controller functionality, but also it enables the decentralized connection between different swarm agents. The third step allows collision avoidance capabilities to the standard open-source Pixhawk based architecture of drones via the connected flight controller. In addition, the drones can be used to test different obstacle avoidance scenarios. Both, within-swarm, and external obstacles on the planned flight path are covered. We present artificial potential functions strategy as an example to avoid obstacles near the swarm.

Related Work

When talking about recent developments in UAV swarm technology, Drone air and light entertainment shows have become a common occurrence. [1] is a good example, which originated from a collective research project at Eötvös University in Budapest. It became one of the first drone light show providers, it stands out for its high precision, modular structure, organized and readable code, and extensive documentation. CollMot Robotics, which is behind Skybrush, has released their multi-UAV mission and drone show management platform, as an open-source project to enable collective development and improvements. The localization of UAVs during such shows is often realized through RTK-GPS and point-to-multipoint telemetry radios.

The authors in [2] comprehensively analyzed and summarized relative positioning technologies for large robot swarms, evaluating existing measurement systems, positioning algorithms, and two localization systems. Their study focuses on UWB's potential for large-scale robotic swarm applications, considering aspects like measurement frequency, positioning mode, and energy consumption. The analysis covers both indoor and outdoor applications, addressing challenges with increasing swarm size. Additionally, the paper proposes a detailed fully distributed relative localization mechanism for large swarms in grouped networks, offering insights for future research directions.

When it comes to interior localization, UWB and cameras are the most commonly utilised technology, but in the outdoor scenarios other sensors play a more significant role. The authors in [3] introduce a localization system tailored for (UAVs) doing infrastructure inspections. It addresses such challenges as flying with limited or no GNSS signal and often Beyond Visual Line of Sight (BVLOS) operations. The proposed system combines multiple stereo cameras with a robotic total station to achieve defect traceability, accuracy, reliability, and fault tolerance. A robotic total station refers to a tool used in surveying and construction that integrates electronic theodolite with electronic distance measurements, as well as measurements of vertical and horizontal angles.

The authors in [4] review and discuss two main approaches: relative visual localization (RVL), encompassing methods like visual odometry (VO), simultaneous localization and mapping (SLAM), and absolute visual localization (AVL). While RVL faces challenges of error accumulation over time (drift), AVL offers immunity to drift by relying on previously collected georeferenced data. AVL utilizes reference data sources such as orthorectified satellite imagery or imagery from previous flights, providing known and constant error bounds. The reference data is matched against the current view to achieve UAV localization.

The authors of [5] introduced a novel approach for 3D position estimation of UAVs using 3D cameras such as the Structure Sensor, eliminating the reliance on GPS. Tailored for lightweight onboard processing during bridge inspections, the algorithm considers data nature but depends on a pre-captured 3D map. By matching 3D point cloud data from UAV sensors with a model of the structure (a bridge in their case), the authors successfully estimated the UAV's position without GPS coordinates. In the broader context of UAV localization, the collision avoidance system (CAS) plays a crucial role, with strategies constantly evolving, as outlined in [6]. CAS techniques, particularly those based on the geometrical approach and tested with a Wi-Fi localization system in [7], are relevant. For their specific purpose, rapid implementation and real-time capabilities are essential, qualities met by the artificial potential function presented in [8], which, when integrated with a well-designed localization system, enhances collision avoidance in UAV swarm systems effectively.

UWB-based localization to support GNSS

We compared the localization accuracy of the Real-time kinematic global navigation satellite system (RTK-GNSS) based on sole and fused GNSS systems. The combination of the GALILEO and GPS positioning systems with GNSS offers a precision of 3 metres. By adding ground-based RTK correction data, deviations of 0.13 metres can be achieved in the AI-supported comparison of the metadata from 464 images generated with the Mavic 3T industrial drone. This is the gold standard of surveying technology as used in total stations. Without mobile communications and in densely built-up industrial environments, its use is impossible. Our approach as GNSS extension with distance measurements by Ultra-wideband (UWB).

We tested the performance of UWB localization modules in real flight condition. To do so, one UWB responder was secured to a drone, which holds an altitude of 35 m above the ground and its position. The second drone with the UWB initiator performed an orbital movement around the static drone. The altitude of the moving drone and the radius of its circular trajectory varied in a step-wise manner. Thus, an estimate of the distance between two drones was obtained in a semisphere with a radius of 35 m with truncation at the bottom.

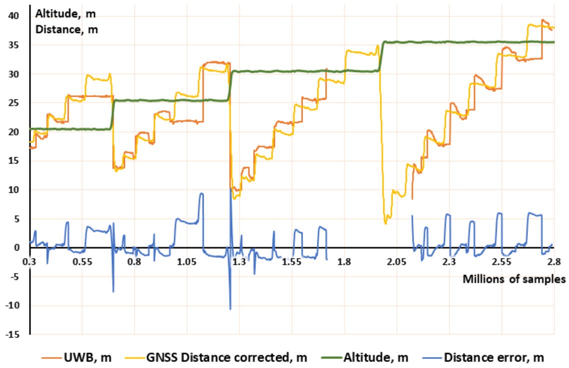

Fig. 1: Accuracy estimation of UWB-based localization technique: the blue curve denotes difference between GNSS- and UWB-based distances to the static drone. The gap in the datarow corresponds to the removed invalid distance data.

UWB initiator and responder are represented by a pair of boards of our own design, introduced in [9]: one with a UWB DWM1000 module and a WiFi board with an ESP32 MCU. On the initiator side, the ESP32 was connected via UART to the PixHawk drone flight controller. The ESP32 firmware performed the distance calculation and transmitted the result to the flight controller using the sonar data format. This approach allows UWB distance data to be logged directly on the flight controller and eliminates the need to synchronize it with the GNSS coordinates of the moving drone. However, during analysis of the flight log, we discovered a constant 3.4 s delay of UWB data relatively to the GNSS data.

In order to assess accuracy of UWB localization system, we calculated RTK-GNSS-based distances between the static and moving drones using Haversine formula and Pythagorean theorem. The resulted distances versus drone height are shown in Figure 1 as a yellow line. UWB-based distance to the static drone is shown as a red line, difference between GNSS and UWB distance is shown as a blue line, which is UWB distance error.

Standard deviation of UWB distance error σ is 2.44 m for the described circular flying pattern. According to the figure, the highest UWB distance error appeared during altitude change by the moving drone. Such behavior may derive from temporary connection loss between UWB initiator and responder. The flight controller itself is unable to invalidate data related to this situation and it keeps the latest measured distance. However, UWB data pre-processing, validation, and fusion with RTK-GNSS data can be done using a dedicated hardware, which is described in the next section.

Integrated communication hub

Reliable collision avoidance and formation flight requires communication with low latency and high update rate between nearby UAVs. For this, BLE and Wi-Fi technologies provide sufficient throughput and we choose ESP32-S3 based Wi-Fi radios as prototype. In contrast, the swarm management requires long-range communication to the pilot's ground control station but less throughput for control commands. The subGHz radios and cellular technologies such as NB-IoT and LTE-M are better suited and we choose a XBee SX868 and a SIM7080G GSM modem for the prototype. Finally, one or more UWB radios for localization as well as application-specific sensors need to be integrated.

Overall, this exceeds the number of available communication ports on PixHawk flight controllers and companion computers. Commercial solutions hide this partially by combining multiple radio technologies into one module. However, their closed design inhibits research and their support for swarm communication is very limited. In order to solve this, we introduce the communication hub as mediator. Our reference implementation is shown in Figure 2. It provides several UART and SPI ports for custom radio and sensor modules. A dedicated UART port connects to the flight controller and the 40-pin connector allows to connect any Raspberry Pi compatible companion computer. Integrated voltage converters provide power from the UAVs battery to the companion computer and the attached modules. Integrated high-side switches and current sensors allow to control the power distribution.

The data exchange between the ports is implemented on an embedded STM32H7 microcontroller. Communication with the flight controller is based on the MAVLink protocol. Other attached radios and sensors can also use this protocol directly but custom drivers can be implemented. For example, the DWM1000 UWB radio is operated via the SPI bus connector. The microcontroller implements the logic for forwarding of MAVLink messages between the ports, which can be extended by custom filtering rules. For example, such that the long-range radios transmit UAV telemetry at a lower update rate than the swarm's collision avoidance radio.

The companion computer can also be integrated via MAVlink. However, this complicates its interaction with custom components on the communication hub. The Robot Operating System (ROS) is a communication infrastructure widely used on companion computers and micro-ROS provides the same programming model for micro-controllers, see e.g., [10]. Our implementation exchanges MAVLink messages with the MAVROS component on the companion computer via ROS topics.

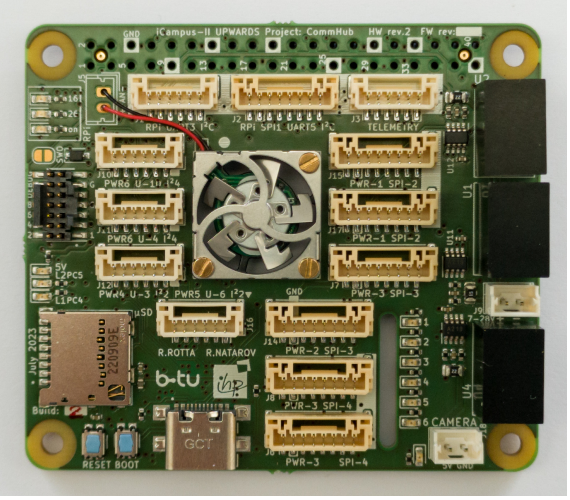

Fig. 2: The communication hub combines different wireless links into a virtual radio for the UAV's flight controller and companion computer.

Collision Avoidance

Considering the system localisation, we extended the implementation to collision avoidance for UAV system applications. The system used Pixhawk, a standard open-source platform, as a flight controller. This hardware, in combination with firmware Ardupilot, enables the control of the UAV as the CAS determines. For stationary obstacle detection, a Lidar sensor is used. This technology gives a range obstacle vision of 360° around one plane of the UAV.

Among the requirements desired of CAS are fast response and easy implementation. Artificial potential function is a strategy that generates artificial forces around the principal points of interest, e.g., target or obstacle positions. We associate this method with the earth's gravity phenomenon. Instead of attracting the objects, the method generates a repulsion around obstacles.

Formally, we define the target position as η and the obstacle position as ζ. The artificial forces, respectively, are $F_\eta = k_\eta(\eta - \xi)$ and $F_\eta = -k_\zeta(\zeta - \xi)$, where ξ is the current position of the UAV and k_η, k_ζ are positive constants. In this case, there is an attraction force to the desired target and a repulsion force for the obstacle. The last one is applied when the Lidar detects the obstacle around. The area close to the obstacle is called repulsion area. Considering the last formulation, we extend the method to multiple UAVs and obstacles in scenarios. Figure 3 shows an experimental test with two stationary obstacles at one goal position. The experiment compares the position of giving for the localization system (POS) and a simulation. The differences between experiment and simulation are due to environmental disturbance and discrepancies between real UAV and the UAV simulation model.

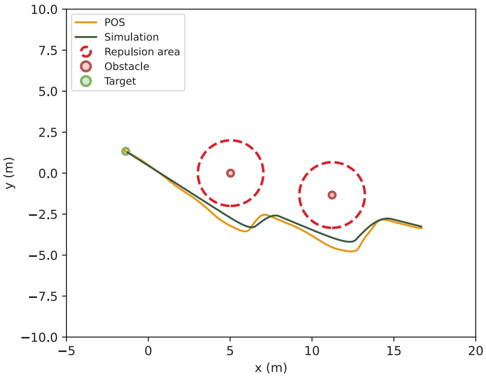

Fig. 3: Experimental test of collision avoidance with two obstacles and one target position. Yellow Line correspond to the drone localization and green to simulation position.

Conclusion

We assessed accuracy of UWB-based drone localization withing actual flying condition. The resulted standard deviation of UWB distance error is 2.44 m. This localization uncertainty are influenced by various factors: temporal desynchronisation between UWB and GNSS systems, ambiguity of location and altitude of the static drone-responder during the experiment, and lack of automatic invalidation of the faulted data. These issues can be solved by tight integration of the Communication Hub into our UAV system.

A collision avoidance system for UAV systems is tested as an application of the localization problem. The results show that by applying the artificial potential function, we can avoid obstacles by maneuvering and maintaining the UAV outside of the repulsion area. Besides, open-source technology integrates the avoidance strategy into the UAV system.

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