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A novel distributed architecture for UAV indoor navigation

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Abstract

In the last decade, different indoor flight navigation systems for small Unmanned Aerial Vehicles (UAVs) have been investigated, with a special focus on different configurations and on sensor technologies. The main idea of this paper is to propose a distributed Guidance Navigation and Control (GNC) system architecture, based on Robotic Operation System (ROS) for light weight UAV autonomous indoor flight. The proposed framework is shown to be more robust and flexible than common configurations. A flight controller and companion computer running ROS for control and navigation are also included in the section. Both hardware and software diagrams are given to show the complete architecture. Further works will be based on the experimental validation of the proposed configuration by indoor flight tests.

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Keywords: Quadcopter, Indoor navigation, ROS

1. Introduction

Thanks to technological advancements and cost reduction, Unmanned Aerial Vehicles (UAVs) have gained significant attentions in last decade. Various UAV platforms have been developed for different applications (Valavanis et al. (2015)), such as precision farming, geo-referencing land survey and photogrammetry. According to

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Gupte et al (2012), UAVs can be divided into fixed-wing and rotary wing by the flying principle and propulsion mode. Compared to rotary wing, the fixed wing UAV has much simpler structure, which provides advantages in payload capabilities, cruising speed and flight durations. However, all fixed wing solutions need more space for taking off and maneuver, this is a critical problem for indoor flight due to restricted environment. Thanks to capabilities of vertical takeoff and landing (VTOL), hover and agile maneuvering, rotary wing UAVs are well suitable for indoor flight. Comparatively, their endurance and effective load is limited as all thrusts are generated by the UAVs themselves.

Table 1. Summary of UAV indoor navigation architecture

Team	Institution	Navigation Architecture	Year
Sungsik Huh	KAIST	IMU/Camera/Laser scanner	2013
Nils Gageik	University of Würzburg	IMU/Infrared/Optical flow(ADNS3080)	2013
Korbinian Schmid	DLR	IMU (Analog Devices ADIS16407) /Stereo Camera (PointGrey Firefly FMVU-03MTM)	2014
Jin Q. Cui	National University of Singapore	IMU/Lidar (UTM-30LX&URG-04LX) /Camera	2015
Dong Ki Kim	Cornell University	IMU/Ultrasonic altimeter/Optical flow/Camera (Parrot Bebop)	2015
Shaima Al Habsi	UAE University	IMU/Ultrasonic altimeter/Vicon Mo-cap	2015
Chong Shen	North University of China	IMU (MPU6050) /Optical flow + Ultrasonic (PX4Flow)/Magnetometer (HMC3883L)	2016
Yu Zhang	NUAA, China	IMU/Optical flow + Ultrasonic (PX4Flow) /Camera (UI-1221LE)	2016
Kang Li	Chinese Academy of Sciences	IMU/UBW (DW1000) /laser scanner	2016
Aiden Morrison	Norwegian Defence	IMU (MPU9250/Mti-100) /Optical flow + Ultrasonic (PX4Flow) /Vision (Sony IMX250)	2017
Kimberly McGuire	TU Delft	IMU/Optical flow /Stereo camera	2017
Elena López	Alcalá University	IMU/Scanner/Monocular camera	2017
Zhou Qiang	Shanghai Jiao Tong University	IMU/Ultrasound/Stereo camera/Motion Tracking	2018
Mattew A Copper	Air Force Institute of Technology	IMU/Scanner/motion tracking	2018

For applications performed outdoor, autonomous navigation is heavily based on GPS signal availability. However, for indoor applications like silos inspection, warehouse management and disaster relief, etc., many new challenges emerge due to GPS-denied environments where traditional outdoor navigation system cannot be used. As reported by Mautz et al (2009) and by Mainetti et al. (2014), the main challenge in UAV indoor applications, especially when performing indoor autonomous flight, is the attenuation of Global Navigation Satellite System (GNSS) signal induced by severe multi-path effects and signal reflections due to walls and furniture (20-30 dB compared to outdoor). Moreover, the obstacle density is much higher due to mass of static objects like pillars and

good shelves. What is worse, human activities are more frequent indoor, which have serious impact on UAVs. For example, opening a window will could affect the environment, by changing obstacle locations, illumination intensity and pressure distribution.

Light and small onboard sensors with high precision and accuracy performance (centimeter level) and low latency are mandatory for UAV indoor applications. Some navigation architectures are proposed over academia and industry, to overcome the challenges above in indoor applications. A summary of UAV indoor navigation architecture over the past five years is listed in Table 1. The core element of all the navigation architectures is the inertial sensor, also known as Inertial Measurement Unit (IMU), coupled with other sensor solutions to overcome its limitations and allow the UAV to be aware of obstacles.

The architecture proposed by Sungik et al. (2013) is based on an IMU, a laser scanner and a camera: the output data from the sensors is fused by an online Extend Kalman Filter to perform simultaneous localization and mapping (SLAM). In another similar work published by Elena López et al, a 2D laser scanner integrated with IMU is used to obtain a local 2D map and a footprint estimation, while a monocular visual SLAM algorithm enlarges the pose estimation through an Extended Kalman Filter (EKF).

The work proposed by Gageik et al. (2013) consists of optical flow camera, for position estimation, in addition to IMU and infrared sensors, for attitude and height estimation respectively. Test results show high accuracy but a custom PID controller for the UAV control is mandatory. A similar approach is proposed Shen et al. (2016), in which an EKF combines IMU and optical flow data for velocity and position estimation. At the same time, a two-stage Kalman filter computes the attitude estimation using gyro, accelerometer and magnetometer information in static or uniform moving state, during accelerating and decelerating phases, only the gyro is used to estimate the UAV attitude.

Vision-based navigation system is an emerging solution that allows tackling indoor environment challenges. The architecture proposed by Dong Ki Kim et al. (2015) relies on a single camera to allow autonomous navigation and identification of specific target by a MAV: a deep learning model has been implemented in a custom-made controller to mimic the control strategy of an expert pilot. The main drawback of this solution is that the deep learning algorithm requires a suitable dataset of indoor scenarios so that the architecture is not flexible enough if the multi-copter has to fly diverse indoor environments (room, warehouse, stairways, corridors and so on).

As many computer vision approaches are computationally too heavy, McGuire et al. (2016) present a 4 grams' stereo-camera application for optical flow detection using edge-feature histograms. An extension of this work is reported by McGuire et al. (2017), in which a facing forward stereo camera is also used for navigation purposes. The main contribution of McGuire is the discussion of a method able to provide both velocity and distance estimates, while being computationally efficient enough to run on a limited embedded processor.

Absolute position estimation can be also achieved by exploiting Time-of-Flight (ToF) measurements. Li et al. (2016) describe an autonomous navigation system for 3D position estimation based on Ultra-Wide Band (UWB) anchor and tag sensors. A 3D Laser Scanner, for obstacle detection, and an IMU are needed by the data fusion strategy implemented, which integrates the positioning data provided by these sensors and generates a consistent, accurate and useful position estimation. Zhou et al. (2018) describes a complex architecture in which ultrasonic sensor, IMU, stereo camera and optical motion tracking system are combined to perform autonomous indoor navigation. In this case, the absolute positioning is provided by optical motion tracking system called *Vicon*; two stereo cameras and the ultrasonic sensor are needed for obstacle avoidance purposes. Thanks to the ultrasonic sensor, the system can detect obstacle that are transparent or texture-less.

Previous investigation indicates that vision-based systems, both stereo cameras and optical flow sensors, take more and more important role in autonomous indoor flight as embedded computers become increasingly powerful. However, additional sensors are needed to compensate the drawbacks such as sensitivity of illumination, dependence of reflective surface and high latency due to heavy computational load. On addition, SLAM algorithms become much more popular in indoor applications, since their capability of reconstructing surrounding scenario is vital in a changing indoor environment.

The architecture proposed in this work implements control and navigation algorithms on FCU and companion computer, respectively. Compared to modifying the original firmware, this configuration makes it easier to replace specific modules, especially for the development of new algorithms. Another advantage of this framework is its

lower payload requirement and higher flexibility for data synchronization and fusion. Both of them make it particularly suitable for small UAVs performing autonomous missions in complex and risk indoor environment.

This paper is structured as follows. Section II makes a comparison of different sensor technologies in performance, limitation and cost, etc. Section III explains the complete architecture of proposed GNC system both in hardware and software. Section IV details current and scheduled experimental activities. Brief conclusions are summarized in Section V.

2. Sensor comparison

This section provides an overview of the sensors for indoor navigation applications. Fig 1 shows a sensor classification, based on the main characteristics of these sensors.

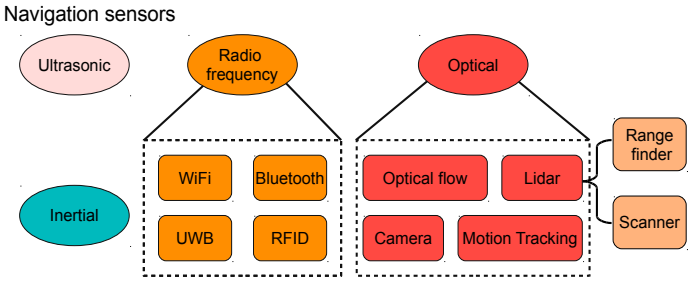


Fig 1. Navigation sensor categories

2.1. Ultrasonic sensors

Ultrasonic sensors are used for obstacle detection to evaluate a straight-line distance from the closest object in vehicles' path. Their light weight (10 g), small size dimension (few centimeters) and low power consumption (50 mW typical) make ultrasonic sensors extremely interesting for UAV applications with constrained payload capabilities. Furthermore, this sensor family is quite cheap, limited to tens of euros. Even though sonars have high accuracy level, usually in the range of millimeters, the main drawbacks of these sensors are their limited range performance, close to few meters. Furthermore, ultrasonic sensor performances are close related to humidity and temperature characteristics.

Ultrasonic sensors can also be used as an absolute positioning system by configuring mobile beacons with several stationary anchors. The sensor generates ultrasound pulses to stationary detectors: based on Time of Flight (ToF) and triangulation algorithms, a central router evaluates the position of the mobile beacon in an absolute reference system. A typical solution is Marvelmind (Run R. S. et al (2018)), which will be used in our framework. Eurac Research is performing tests on Marvelmind environmental performance in a climate-controlled chamber to evaluate its possibility as a suitable solution for DronEx Project inside terraXcube facility (Dronex 2018).

2.2. Lidar sensors

When considering Lidar (Light Detection and Ranging) sensors, two categories are included: rangefinder and scanner. The former is characterized by a single laser beam, provided by the sensor emitter and reflected by obstacles: ToF is used to measure a single point distance. Rangefinder costs vary depending on the considered performance, but they remain inside the range 100 € to 1000 €. On the contrary, scanners allow to acquire point cloud information thanks to a controlled steering systems or mirror systems. The point cloud data includes distance of obstacles, based on ToF, orientation angles, surface reflection level, and GPS coordinates (for geo-referenced sensors only). Normally, to create a complete environment model a single scan is not sufficient; furthermore, the point cloud management requires suitable computational capabilities. Finally, scanners are expensive than rangefinder: cost range from 1,000 € up to 30,000 €.

Infrared laser or LED are the main technologies used by Lidar sensors. While lasers allow single point long measure range, up to 100 m, they suffer from atmospheric loss, need threshold drive current and extra cooler so that dimensions and weight make laser Lidar sensor not suitable for light-weight UAV applications. Infrared LED, instead, are usually lighter, smaller and cheaper than laser; they experience less power consumption, however their performances are also limited. The infrared LED diffuse beam reduces sensor range, often around 10 m, with a field of view of 3°.

2.3. Radio frequency sensors

Radio frequency sensors are used to detect the absolute position of a mobile emitter by Received Signal Strength Indication (RSSI) evaluation, or ToF triangulation. Bluetooth and Ultra-Wide Band (UWB) are the main technologies considered, showing different range and accuracy performance. While UWB allows centimeter level accuracy, thanks to the short time pulses duration (1 ns typical) and range up to 300 m, Bluetooth solutions show lower accuracy level and range performance (100 m max), according to the Bluetooth Class considered. A complete set of stationary and mobile beacon cost is usually within 1,000 €.

The main drawbacks of this sensor family are multi-path reflection and interference with other indoor devices: as they provide fake GPS signal to the autopilot board, multi-path and interference could cause GPS glitches, resulting in dangerous unexpected commanded position during autonomous flights.

2.4. Optical flow sensor

Optical flow cameras are used for velocity, azimuth and position increment sensing by comparing sets of consecutive images. Accuracy level performances are related to both sensor and algorithm considered. Optical flow cameras are characterized by small size and lightweight with limited computational capabilities requirements and acceptable cost (usually within 100 €).

Stereo or IR depth perception cameras are emerging technologies in robotics because they allow a 3D reconstruction and understanding of the environment. The high position and orientation accuracy, 1 mm and 0.1° respectively, make these sensors suitable to perform visual odometry algorithms. However, high computational cost must be taken into account so that a dedicated Graphics Processing Unit (GPU) is required. For infrared depth perception camera, as reported by Zhou et al. (2018), additional sensors are required due to IR light cannot detect window and glass objects.

2.5. Camera motion tracking systems

Motion tracking systems use reflected markers, usually installed onboard, to detect position, speed and orientation data. Different UAVs can flight at the same time using markers with different shapes. Each camera has its own coverage area, depending on the field of view, and infrared light is often used to compensate weak light conditions. A ground station receives and processes camera data, allowing motion-tracking reconstruction. An onboard companion computer is needed to provide the fake GPS signal from the ground station to the autopilot board. Even though their high performances, camera motion systems need a custom-made infrastructure and monthly calibration: high cost should be considered (up to 30,000 €) so that camera motion tracking systems are suitable only for control law tuning and development in indoor environment.

Table 2. Summary of different sensors for indoor navigation

	Inertial sensors	Rangefinder sensors	Laser scanner sensors	Ultrasonic sensors	Radio frequency sensors	Optical and camera-based sensors
Advantages	High accuracy, stability, comprehensive	Light weight, low price sensors	2D or 3D point cloud data	Good accuracy, light weight and small size, low	Small size, low power consumption	High accuracy, 2D and 3D point cloud data

	information			price sensors		
Limitations	Error propagation over time	Single point measurements	High computational cost	Influenced by temperature and humidity	Multi-path and RF interference	Potentially computational heavy and high cost

Table 2 summarizes and compares the main advantages and limitations of this sensor family. Inertial sensors perform the key role in all navigation system, even if many additional sensors are needed to compensate long-term accumulated errors induced by sensor drift. Among these sensors, laser scanner and camera perform higher accuracy, even though they consume more onboard resources and require additional payload capabilities. Other sensors are light and small, but in some conditions, they are not reliable, thus a filtering algorithm is required to fuse all sensor data.

3. GNC architecture

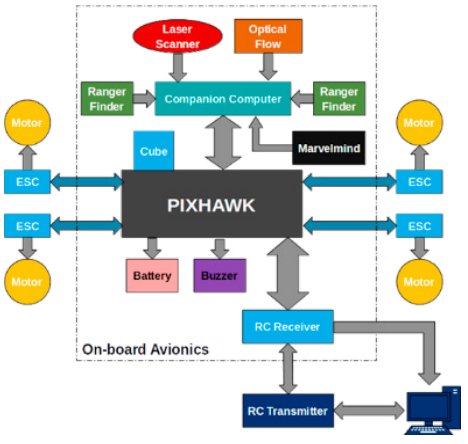
3.1. Hardware architecture

Based on the previous investigations and observations, an architecture of indoor Guidance Navigation and Control (GNC) system for quadcopter has been designed. The complete diagram is shown in Fig 2.a, while Fig. 2.b shows the multi-copter configuration.

Table 3. Overview of external sensors

Sensor Module	Sensor Type	Measurement	Frame	Update Frequency
TF-mini TeraRanger Evo	LED ranger finder	Distance	Optical axis	100 Hz
Scanse Sweep	Laser Scanner	Point clouds	Scanner frame	1 ~ 10 Hz
PX4Flow	Flow camera	Optical flow	Camera frame	400 Hz
Marvelmind	Ultrasonic	Position	Local frame/WGS-84	0.5 ~ 16 Hz

a)



b)

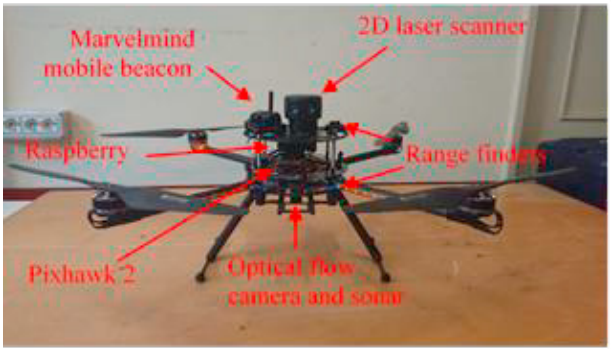


Fig 2. a) hardware architecture, b) drone platform and sensors

The whole system has been divided into four parts: ground station, onboard avionics, onboard actuators and accessories. The details are listed below:

- *Ground station*: a ground monitor communicates with on board avionics to obtain real-time status and send control commands through radio or Bluetooth telemetry. In our case, we used Bluetooth instead of radio signals in order to avoid frequency jamming with Marvelmind, since both devices work at the same frequency (433MHz).
- *Onboard avionics*: the whole on-board avionic system consists of three parts:
  1. Different sensors, which provide all required navigation information like current position, velocity and attitude, etc. In our application, three redundant IMUs are already mounted in PIXHAWK 2.0 Cube, other external sensors and their details are reported in Table 3.
  2. Companion computer: since most data processing and fusing algorithms are quite time-consuming and cannot be handled by normal flight control unit (FCU) board, the most suitable solution is to use a companion computer to read all sensor data and process all navigation and guidance algorithms. The control part is on the FCU.
  3. Fight controller, which is used to deal with all management and control actions works like arming/disarming, responding to RC transmitter, motor speed adjustment and so on. The most popular open source FCU is PIXHAWK and, as mentioned above, the module we used is PIXHAWK 2.0 Cube.
- *Onboard actuators*: our quadcopter consists of four brushless motors with the respectively Electronic Speed Controllers (ESC) arranged in a cross-configuration frame.
- *Accessories*: battery regulator, buzzer, external LED, etc.

3.2. Software architecture

In order to obtain a more flexible and robust performance, a distributed structure based on Robotic Operation System (ROS) is implemented on companion computer, Raspberry 3 Model B. The whole system is divided into three parts: ROS core, ROS topic and ROS service. The full diagram is shown in Fig 3 and their details are described below.

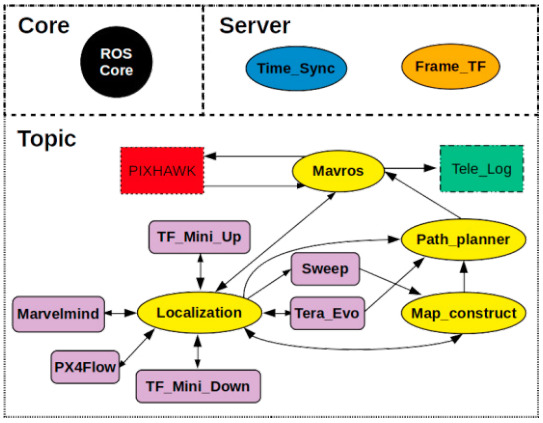


Fig 3. ROS diagram on Raspberry Pi 3B+

- ROS core: it is the unique Master node in a ROS system, each ROS system should have a single ROS core and all other ROS components (e.g., service, topic, action and so on) are all registered to ROS core.
- ROS service: they are one of ROS communication mechanism. In this mechanism, client node requests service from server node, which responses to this request by calling per-defined functions. So, we implemented two functionalities which would be inquired in all ROS nodes as service, that is *time synchronization* (*Time_Sync*) and *frame transformation* (*Frame_TF*).
- ROS topic: ROS topic is another power communication mechanism in ROS. The publisher node keeps publishing messages to topic and subscriber node can obtain message by subscribing to this unique topic. Thus, the topic mechanism is quite suitable for nodes keep publishing data like sensor reading, localization and path planning, etc. In Fig 4, different nodes are distinguished by colors, purple one are node that manages data from hardware while yellow one process data and run guidance and navigation algorithms. Blocks with dash board means they

are nodes of this ROS system but running on other terminals, for example, *Tele_log* is node running on ground station which only recording flight logs.

3.3. Comparison with traditional GNC architecture

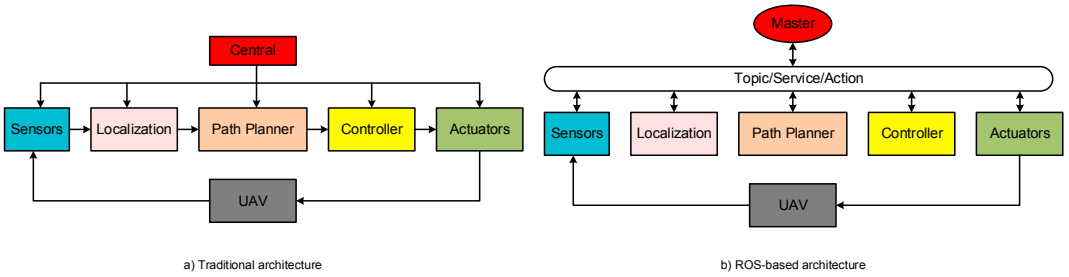


Fig 4 Comparison of architectures

With respect to traditional ones, this new GNC architecture presents several innovative features, which make it suitable for developing small UAVs performing autonomous missions in complex and risk indoor environment.

- *Decentralized*: In traditional GNC architectures, there is a central control unit, which is in charge of workflows of the whole system. Meanwhile, each node keeps waiting until tasks of its former node are finished. This central control unit is non-mandatory for ROS based architecture, which means all units may work parallel. As shown in Fig. 4, instead of exchanging and processing data following commands from the central control unit, in this distributed architecture, each node exchanges data only based on their own input/output (IO) interface and data time stamps. Master node is nothing but a database that contains information of all nodes in the system as no control commands are sent to other nodes. All data processing are conducted locally and periodically. This feature clearly makes the system more robust as failure in one node will not affect other nodes in this system.
- *Plug and play*: When adding an extra sensor unit, or removing a faulty unit, the only operation needed is registering/deleting its information to the master node. All other nodes are kept unchanged and the whole system keeps working without rearrange the architecture. This feature renders the proposed solution quite flexible, especially for developing small UAVs for indoor flight as different on board sensors may be unusable in different scenarios.

4. Sensor experiments performed

A characterization of all the sensors has been conducted to evaluate all sensor performance in accordance to the datasheet provided, such as update frequency, static bias, dynamic noise.

a) b)

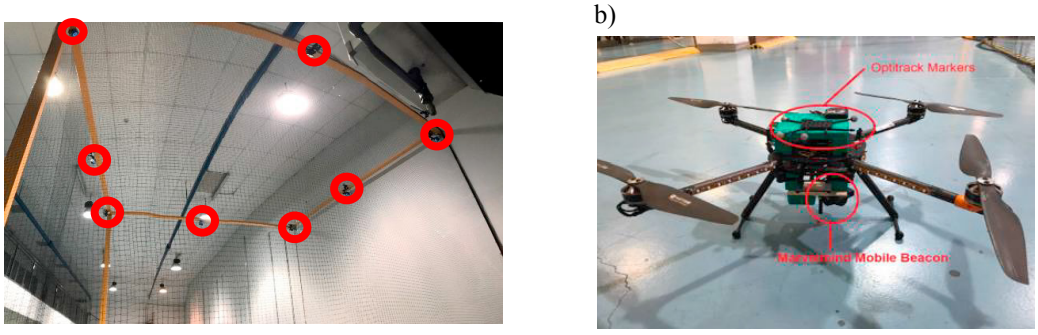


Fig 5 a) lab environment, b) drone platform

In order to define a suitable indoor absolute positioning system, several indoor flights have been performed in collaboration with the Department of Aerospace Science and Technology of Politecnico di Milano. The flight area is

a 5x5x5 m cage (Fig.4.a) with eight OptiTrack cameras installed on the top. A reflective marker has been installed on the top of the quadcopter, to track its position by the cameras, while the Marvelmind mobile beacon has been placed on the bottom as in Fig.4.b, with all the ultrasonic anchors on the floor. As Marvelmind and OptiTrack use different reference frame, a transformation has been applied to OptiTrack output data for a comparison. The ultrasonic mobile beacon has been connected to the autopilot board for control purposes through the GPS port, when the optical system has been used only for trajectory tracking.

The tests have been performed in Loiter Mode: the copter is controlled using the position data from the fake-GPS to maintain its current location when the control sticks are released. As reported in Fig.5.a, the pilot commands are limited to channel 3, which is throttle. The altitude is shown in Fig.5.b, where the offset between OptiTrack and Marvelmind is induced by the vertical distance of the positions of the two onboard sensors. The reversion of the offset when the copter is landing is caused by the law accuracy of the system when the mobile beacon is close to the plane of the anchors, according to the manufacturer. In Fig.5.c and Fig.5.d, the relative position between the two systems in North and East show that Marvelmind position has lower accuracy than the declared static accuracy of 2 cm, for example an error of 33 cm in the relative North position is found at 50.91s; a similar behavior is found at the relative East position at 18.55s with an error of 23.9 cm. This could be related to its sensitivities of attitude and noise disturbance.

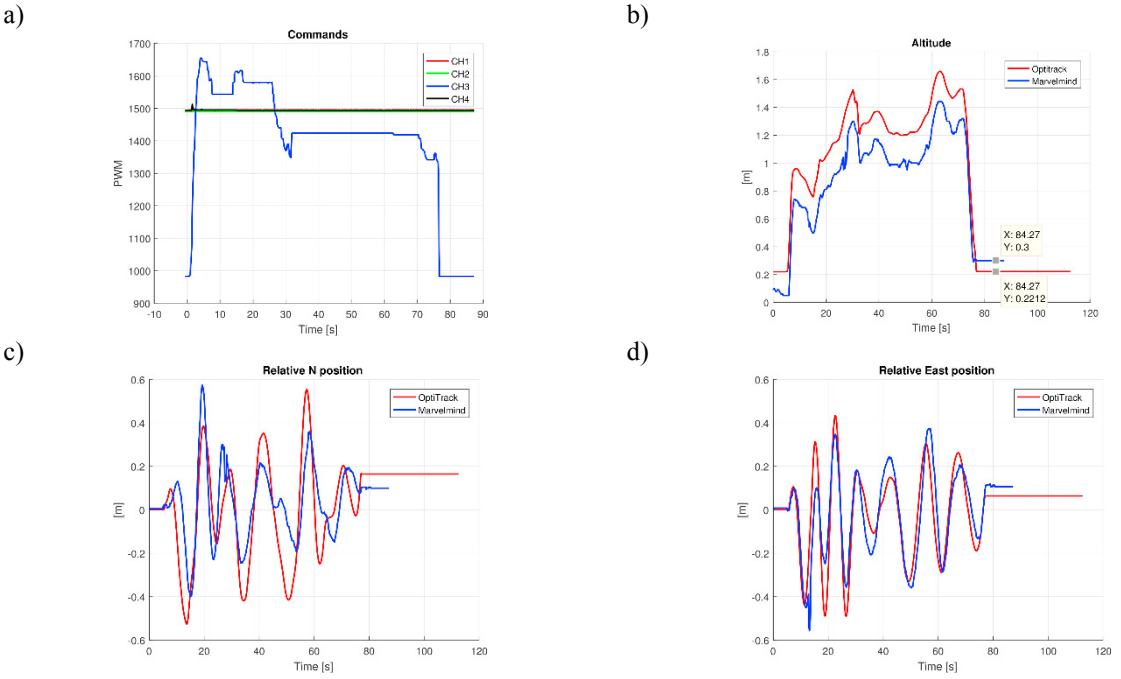


Fig 6. Indoor flight test results

5. Conclusion

A detailed review of navigation configurations and sensor technologies for lightweight UAV autonomous indoor flight has been made, especially focused on their advantages, limitations and cost. After a comparison of different sensor technologies, a new GNC architecture based on ROS has been proposed. A companion computer and FCU have been proposed for navigation and control respectively. This distributed design makes the system more robust and flexible compared to traditional GNC architectures, which is particularly suitable for developing small UAVs performing autonomous missions in complex and risk indoor environment. Several tests of onboard sensors have been conducted to evaluate different sensor performances and more experiments are scheduled to validate other flight performance.

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