Abstract—Indoor localisation and mapping missions usually require several sensors to correctly calculate the position of the Unmanned Aerial Vehicle (UAV) within the space and detect and localize obstacles. This research paper presents the development of a mapping system for UAVs in unknown indoor environments resorting to ultrasonic sensors. The core of the system is the DJI Ryze Tello UAV, a small 80g Micro Air Vehicle (MAV) with very limited capabilities such as payload and available flight time. A distributed system was developed to ensure the successful execution of the mission without exceeding the capabilities of the MAV. A prototype was developed that consists of two hardware components, one integrated into the MAV and another in a tethered configuration. The operation of the system is independent of the environment and supports multiple simultaneous missions. An original autonomous flight and mapping algorithm was created, based on vertical motion patterns, to provide an efficient and effective mapping solution. Data processing procedures were also implemented to complement the initial framing of detected obstacles. The obtained system allows the digital reconstruction of the space. The mapped obstacle distances in the test environment have resulted in more than 90% of accuracy.

Index Terms—MAV, Indoor Environment, Ultrasonic Sensor, Database

I. INTRODUCTION

The use of Unmanned Aerial Vehicles (UAVs) has increased significantly over the past decade. Their high potential to be implemented in the most diverse scenarios has sparked the interest to further study the capabilities of UAVs and minimise their restrictions. Micro Aerial Vehicles (MAVs) follow in the UAV’s footsteps. Their small size allows mission development in smaller indoor environments, which impede most larger-scale UAV flights. They also present additional restrictions regarding payload capabilities and available flight time. On another hand, the exploration and mapping of indoor environments is a very interesting yet complex task [1] with several contributions resorting to UAVs. Visual SLAM ( [2], [3]) is a very popular approach, with both single [4] and multiple [5] robot approaches, predominantly in simulated environments. Implementations in real environments [6] are increasingly more common. UAV swarms have also been the focus of research for communication purposes, mostly in simulation ( [7], [8]). In the present work, the SLAM task was considered as the simultaneous estimation of indoor MAV positioning and the creation of a sparse map of the indoor space configuration and detected obstacles. To address MAV limitations, compatible solutions may include implementing low-cost lightweight sensors, such as ultrasonic sensors, remote computation and communication networks. Ultrasonic sensors can also be an interesting solution to develop these tasks in low-light environments.

This paper presents a MAV-based indoor mapping system prototype suitable for micro-sized aerial robots with very strict constraints. The main contributions of this work are the following: (1) A detailed analysis of the use of ultrasonic sensors (HC-SR04 sensor), in indoor mapping tasks, including the development of mechanisms to accurately interpret their results in flight instability. (2) The proposal and implementation of a vertical mapping approach to maximise coverage area and minimise the mission time. These contributions can be applied to other more complex types of quadrotor-related implementations, complementing other hardware components (especially limited or uni-directional sensors) to improve indoor mapping results. It is also compatible with the implementation of several simultaneous multi and single-UAV missions, conducted in a single set or divided into segments.

The rest of the paper is structured as follows. Section II describes the developed project and system architecture. Section III presents the developed data processing procedures. Section IV presents the system evaluation and analysis of static and in-flight test results. Section V concludes the paper.

II. SYSTEM ARCHITECTURE

Due to current MAV restrictions, focusing on the mapping algorithms, and thinking already about future implementations using more powerful MAVs, it was decided to divide the prototype into two components, in a tethered structure as presented in Figure 1-a). Component A (green numbered), which is responsible for sensor data collection and storage, can be placed on the MAV platform. However, the tested
MAV performed a more stable flight when one of the components was placed on the ground, tethered to the remaining components in the MAV. Component B (red numbered) is responsible for the User Interface, Mission Management, MAV Communication and Remote Data Processing. It can be placed on the ground and can be either static or mobile depending on the chosen power supply system. The component is constituted by a Raspberry Pi(1), responsible to perform all data processing; a NodeMCU(2), responsible to send, via Wi-Fi, flight commands from the Raspberry Pi mission development software to the MAV; and the battery. Component A consists of an ultrasonic sensor(3) to measure the obstacle distances and a NodeMCU(4) to enable sensor data storage in the database. The Online Database is a remote cloud component whose main purpose is centralising all the information gathered from the hardware components. This enables the final processing of the collected data as well as storing current and previous mission information. To provide the compatibility of data collected from different sources, all stored data is associated with a timestamp that saves the time of its measurement of ultrasonic sensor data, or MAV positioning data estimation. At the end of the mission, the scattered information is processed according to its timestamp. To integrate the data gathered through the mission into the final mapping, the system collects the registered MAV coordinates throughout the mission in the database, filters according to the timestamps and calculates the respective obstacle coordinates. The results are saved and a final mapping is produced for later visualization.

Autonomous flight is implemented through flight patterns. They consist of a sequence of commands. Four specific patterns were created. Two of them are used to generally explore the space, and the remaining to avoid any encountered obstacles. For each mission, a default exploration pattern is chosen, which will be repeated until a trigger activates the obstacle avoidance patterns. The latter can be either due to an obstacle found that prevents the implementation of the previous flight pattern or due to a user asynchronous command. Once overcome, the default flight pattern will be resumed. The developed simplified SLAM approach considers that all mission elements, namely the intervening MAVs and the detected obstacles, are associated with Cartesian coordinates. Three types of reference frames were defined to monitor the position of the elements for each mission. The first reference frame is static, representing a pre-defined target point in the space determined by the user before each mission. It is defined only once for each mission and is associated with the centre of the global reference frame (in Figure 1-b) it is centred at point 0). It will allow the framing of all detected obstacles. Each MAV also has two mobile local reference frames centred on it, which will monitor its movements. In Figure 1-b), O′ will monitor its translation movement, while O″ will monitor the combination of its translation and rotation movements in relation to the global referential. The detection of an obstacle undergoes a referential transformation, from the local rotated referential O“ to the global static referential O, to integrate the mission results.

Due to payload constraints, the estimation of the MAV movements per time unit (seconds) is calculated through a pre-mission Calibration Procedure. During a mission, the position and rotation of each MAV are periodically estimated according to its motion. This methodology supports multiple cooperative MAV contributions in the same mission. The individual MAV mapping results are stored in the database and the measurements are time-shifted. This procedure allows that data collected at the same time instants is not overwritten during the mapping data processing stage. Additionally, it is also compatible with the future resumption of previously completed missions.

III. POST-MISSION EXPERIMENTS AND DATA PROCESSING

Two data processes were developed to overcome error sources originated from a set of external factors, without requiring additional hardware. These factors will potentially lead to misidentifying obstacles, therefore promoting an unwanted lack of accuracy in the final coordinates. The first process, Removal Process (RP), identifies outlier points in the list of mapping data associated with each obstacle, referred to from now on as the mapping point. An outlier point may be the result of mapping under considerable flight instability. The second process, Removal and Reorganization Process (RRP), is accomplished in two steps. The first step is identical to the RP. The second step assesses if all mapping points are correctly framed. Due to small flight instabilities, influenced mainly by low battery status, the estimated and real angle may not match at the measurement time, producing an incorrect coordinate. During the testing phase, unexpected 45° rotations were observed in the clockwise and counter-clockwise directions. If any data is misplaced, the coordinate will be recalculated with the correct angle. In Figure 2, the red-coloured circle is an example of an outlier point (removed with RP), the orange-coloured circle of a point that should be reframed, and the green circle is an example of a correctly framed point.

IV. RESULTS ANALYSIS

Before the final mapping evaluation, a space and flight approach was chosen. Static and in-flight tests provided a further understanding of MAV and sensor behaviours. The
error was monitored throughout all system steps to assess its impact on the accuracy and reliability of the final mapping results. The sensor tests were used to improve the Calibration Process and were applied in the system to achieve more precise results. The full system was evaluated firstly with a deep comparison between real and obstacle-mapped distances, with RP and RRP, and then with the visualization of the mapping output and space 3D reconstruction. The performance is evaluated according to the relative error (RE) as a percentage and the standard error deviation (SED) in centimetres, of the sensor measurements with respect to the real obstacle distances in the testing environment.

A. Testing Environment and Mapping

The indoor space chosen to perform the mapping tests were an indoor corridor with an L-shape. It allows for the testing of several types of obstacles regarding size, position, texture and colour. Two approaches were evaluated to perform the mission flight. The first one is the most commonly applied: a sequence of horizontal flights, each fully exploring one mapping altitude level, from lower to maximum level. The second is a different approach. It chooses an initial starting point and vertically maps its surroundings. If the initial mapping points are strategically chosen, a full mapping mission can be completed faster and with the same level of precision. Only the vertical approach allowed a reliable mapping mission within the restrictions of the selected MAV and therefore was chosen for the final implementation. Additionally, the vertical mapping approach is set to allow the developed system, and the selected MAV, to perform the mapping of a maximum approximate cylindrical volume of 24 m$^3$ per minute. The following conditions were considered: a MAV velocity of approximately 0.6 ms, an interval of 5 seconds between the sending of two consecutive flight commands to the MAV, an altitude level of 0.2 m and a sensor range of 4 m.

B. HC-SR04 Sensor Performance

The results obtained were analysed regarding static and in-flight tests, as well as the impact of the developed Calibration procedure. The developed tests have shown a different behaviour of the sensor towards different types of obstacles: Parallel at Short Distances (P&S) – up to 100 cm –, Parallel at Long Distances (P&L) – 100 cm up to the range of the sensor used – and Non-Parallel (NP). An obstacle was considered parallel (P) if it is positioned parallel to the ultrasonic sensor structure, which connects the two transmitter and receiver cylinders — i.e., perpendicular to the central axis of the sensor’s emitting beam (Obst. A in Figure 2). Otherwise, the object is non-parallel (NP) (Obst. B and C in Figure 2).

The main identified sources of error are related to the opening angle of the HC-SR04 sensor [9] and, on a smaller scale, due to reflections of the signals sent by the HC-SR04 sensor on adjacent obstacles, returning a greater distance than the real one. The latter affects mainly the results obtained for NP obstacles. Additionally, P&S obstacles present an absolute error very close to the P&L obstacles. Therefore, their RE reflects the disproportionality of the absolute error concerning their real distances. The main source of error detected in flight tests was the vibration of the frame [10], which was transmitted to the sensor by contact, affecting its behaviour. The developed Calibration Process significantly improved the previously identified errors. Damping solutions were also tested to minimise vibration of the structure, with improvements in relative error, although reduced and not significant in the final mapping.

C. Mapping Results Analysis

The performance of the system focused on the two major obstacle categories: P and NP. The mapping results obtained are presented, for both mentioned processes and obstacle categories, in Figure 3.

RRP attains a smaller RE modulus and a smaller SED, for both obstacle categories. An in-depth analysis shows that the vast majority of the reorganised points were found to be points eliminated by the RP, which was able to reduce some of the errors made by the instability of the MAV. It is also possible to conclude that P obstacles present a higher relative error than NP obstacles, which is coherent with the conclusions drawn with the static sensor tests. P obstacles presented a smaller SED than the NP obstacles after RRP. In fact, after RRP, some obstacles were associated with a single mapping coordinate and a standard error deviation of 0, decreasing the average of the overall category. This phenomenon was also observed in NP obstacles albeit on a smaller scale. Additionally, considering the results of the static tests, the remaining NP SED averages were overall higher than those obtained for P obstacles, resulting in a higher final result.

Despite the setbacks introduced by the MAV flight, the chosen sensor revealed a good performance and characteristics for indoor missions, such as accuracy as well as independence
from the colour and roughness of the materials. The system is thus considered suitable for indoor mapping – especially if the initial MAV position is strategically chosen to avoid some of the errors previously identified in the application of its operation to the space.

D. Mapping Results Visualization

The mapping results were obtained through the combination of two main missions. The first was developed by a single MAV in a single initial mapping position. The second was developed by two MAVs simultaneously in a collaborative perspective. In both missions, the initial mapping points (IMPs) were chosen by the user. Three factors were taken into consideration: 1) The two collaborative MAVs cannot be in each other’s line of sight; 2) The IMPs must maintain a safe distance from the walls of the test space. This distance minimises the flight instability of the MAVs due to aerodynamic factors; 3) The combination of the three IMPs must allow a correct analysis of the space. At last, each mission integrates the combination of under 10 isolated mapping segments, and each segment had a mission time of approximately one minute. The visualization of the mapping results is presented in two formats: 2D (Figure 4-a) and two different 3D perspectives (Figures 4-b and 4-c). The visualization step is very straightforward since the system output mapping document contains all the mission coordinates. Although a sparse sensor was implemented, the digital reconstruction of the test space is possible and accurate.

V. Conclusion

A system capable of performing mapping of initially unknown spaces was developed, using the DJI Ryze Tello UAV, a small 80g MAV. The system implementation was designed to be compatible with the MAV platform, sensor and indoor environment constraints. The potential for the use of ultrasonic sensors was explored. The reduced payload capacity of the MAV leads to the need of dividing the prototype into distributed hardware components. The Online Database implementation allowed to aggregate and centralize all the information gathered by different MAVs and to combine them in the final mapping results. To minimise the negative effects of MAV flight instability, data processing techniques were developed to increase the accuracy of results. These techniques can correctly integrate out-of-context data caused by flight instability, enriching the final mapping results without requiring additional hardware implementation. In the end, the results presented an accuracy higher than 90% of the mapped distances and allowed the digital reconstruction of the test space and obstacles. As of today, MAVs with higher payload capacity are needed for the practical application of the system. Still, the obtained results are encouraging regarding the possibility of using light sensor payloads with acceptable results. Besides, a reduced MAV size will continue to be an important requirement to allow the exploration of spaces with narrow passages. In future work, a customized MAV platform with higher payload capacity will be developed, to increase flight autonomy and to provide the prototype with increased practical usability. The authors will also focus on improving system capabilities related to the optimization of swarm-based exploration of indoor environments.

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