Trajectory Following with a MAV Under Rotor Fault Conditions

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Abstract

Lately, a novel multirotor aerial vehicle capable of handling single rotor failures was presented. When a rotor fails, physically reconfiguring one of the remaining rotors of an hexarotor allows to compensate for maneuverability limitations. In this work, experimental results show the performance of the vehicle in a trajectory-following task in both nominal and fault conditions.

1 Introduction

Multirotor aerial vehicles have become very popular in recent years, due to the fact that the electronic systems needed to fly them have increased their availability and usefulness, decreasing their cost and weight. Simplicity and cost-effectiveness have turned out to be very appealing and, as a consequence, an increasing number of applications have risen in many fields, such as agriculture, surveillance, and photography, among others. Fault tolerance has been addressed in the literature as a matter of high importance, in particular for multirotor vehicles, see for instance [1, 2, 3, 4, 5, 6] and references therein.

In particular, in [7] is studied the capability of compensating for a rotor failure without losing the ability to exert torques in all directions, and therefore keeping full attitude control in case of failure. For this, at least six rotors are needed, and have to be tilted with respect to the vertical axis of the vehicle. The proposed solution in [7], was tilting the rotor (or arms) of the hexarotor inwards. Experimental results for the proposed solution can be found in [8], where the vehicle takes off, performs different maneuvers and lands successfully with one motor in total failure, maintaining full attitude and altitude control. While the system proved to work correctly, there was a direction that, when exerted torque in, performed noticeably worse with respect to the rest.

To overcome this limitation, in [9] a slight modification was proposed for the vehicle, where, besides tilting the rotors inwards, servomotors were added in two of them to reconfigure their position in case of a failure. Simple experiments were performed with the vehicles in cases with and without failure, in a hovering state and with simple maneuvers, and it was concluded that the new fault tolerant design performed much better than the one proposed and evaluated in [7, 8].

This work presents a more extensive performance evaluation to compare the maneuverability of the vehicle proposed in [9] in cases with and without failure, by means of a trajectory following experiment in an indoor environment.

The manuscript is organized as follows. First, a short description of the proposed vehicle is presented. Then, the characteristics of the vehicle used as a platform for the experiments are described, as well as the setup of the indoor environment where the flights were carried out. Finally, the results obtained are shown and compared for the flights of the vehicle with and without a total failure in one rotor.

2 Proposed Fault-tolerant Hexarotor

When dealing with total rotor failures in hexarotors, it has been proved that a standard hexarotor configuration (one with the rotors spaced evenly in a plane, pointing upwards, with alternated spinning direction, as in Fig. 1) is not fault tolerant in the event of a failure of this type, in the sense of maintaining control over its four degrees of freedom (rotation around its three axis, and vertical speed). One degree of freedom will be lost, being generally the yaw axis the one chosen to be lost control of, as it allows the possibility to land the vehicle safely. From this point on, fault tolerance will be meant in the sense that the system maintains complete altitude and attitude control.

Suppose a standard hexarotor configuration with $\gamma = 90^o$ (see Fig. 2), which, with the vehicle in hovering mode, suffers a total loss of rotor number 3 (M3), a counter-clockwise (CCW) rotating motor. Then, this rotor no longer generates thrust to produce torque on the x-axis, and neither does it generate torque on the z-axis due to the spinning propeller. Then, turning off the opposite rotor (M6), which generates exactly the opposite torque, is an adequate solution. In this case, the system is not fault tolerant, as there will exist a torque $\mathbf{q}_w = (M_x, M_y, M_z)$ (worst case direction torque) that will require a negative speed from M6 (see [7]), which cannot be achieved. The solution using the inward-tilted rotors with $\gamma > 90^o$, allows M6 to hold the hovering state with a

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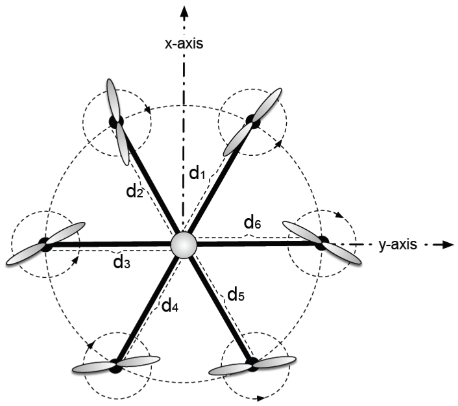

Figure 1: Top view of the proposed vehicle.

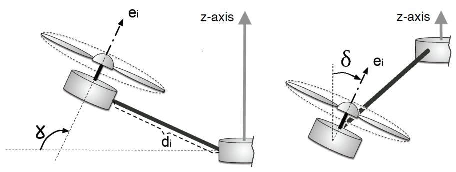

Figure 2: Side view of the proposed vehicle. γ denotes the inward/outward tilt and δ the side tilt.

small positive speed, which in turn allows the vehicle to exert torque in the direction $\mathbf{q}_w$. However, the maximum achievable magnitude of this torque is small, as the maneuver is limited by the saturation of M6. Rotation in the yaw axis is the most stressful maneuver, as they require higher speed variations from the motors with respect to similar maneuvers in pitch or roll.

The work done in [9] proposed to add servomotors in two of the vehicle's arms, in order to tilt the rotors at an angle $\delta \neq 0$ (see Fig. 2), in case of a failure of one of the rotors. By doing this, part of the vertical thrust produced by the rotor is used to generate torque in yaw, allowing to compensate the low maneuverability in that axis. Which rotor will be tilted, and the magnitude and direction of the tilt angle will depend in which of the six rotors is under failure.

3 EXPERIMENTAL SETUP

To provide a comparison of flight performance between the hexa-rotor in a nominal and a failure state, two identical experiments were carried out. An identical fixed trajectory to follow is given both for the case of the vehicle without failure, and for a case where rotor 3 is under total failure.

The vehicle used for the experiments is based on a commercial model. The frame is the DJI-F550, with a distance between rotors of 550mm. The actuators installed on this frame are T-Motor 2212-920KV motors, with 9545 plastic self-tightening propellers, driven by 20A electronic speed controllers (ESC). The battery used is a 4S 5000mAh 20C LiPo that allows approximately 15 minutes of hovering flight (without failures). The flight computer used is a custom-designed board [10] developed by the GPSIC Lab [11] to support experiments that are usually carried out on this kind of vehicles. It is based on the LPC-1769 microcontroller, an ARM Cortex M3 that runs at 120MHz, and several sensors such as the MPU-6000 IMU, the HMC5883L digital compass and the BMP180 barometer, sending flight information to MATLAB (for data analysis) through a 57600bps XBee wireless connection. The control loop runs at 200Hz, where the pitch, roll, and yaw angles are estimated and a PID control algorithm calculates the torque for vehicle stabilization. Then, the allocation algorithm gives the force of each motor in order to achieve the desired torque, and a simple function converts this value into the PWM signals commanded to the ESC. Two additional PID control loops are used for position control in the XY plane, where the input is the error in position, and the output actuates over the pitch and roll commands. One last PID control loop is used for height control, actuating directly on the vertical thrust command.

To switch between the different configuration of the rotors for the nominal and failure case, a servomotor is added in rotor 1, that tilts it over the arm's axis at $\delta_1 = 0^o$ for the vehicle without failures, and at $\delta_1 = 10^o$ in the case of a failure in rotor 3, as shown in Figure 3.

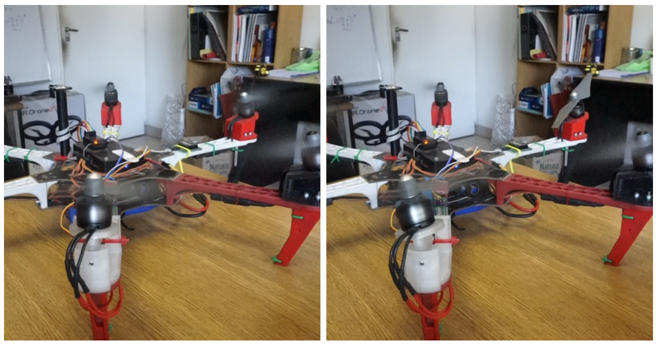

Figure 3: Servomotor in rotor 1 in the case without failure (left) and in the case of a failure in rotor 3 (right).

In order to provide position information, an ultrasonic-based indoor navigation system from Marvelmind was used. This system consists of a network of stationary ultrasonic beacons interconnected via radio interface, one mobile beacon installed on the vehicle to be tracked, and one central modem that calculates the position of the mobile beacon. For the experiments, four stationary beacons were placed in a square with a side length of 8m, 40cm above the floor, as shown in Fig. 4.

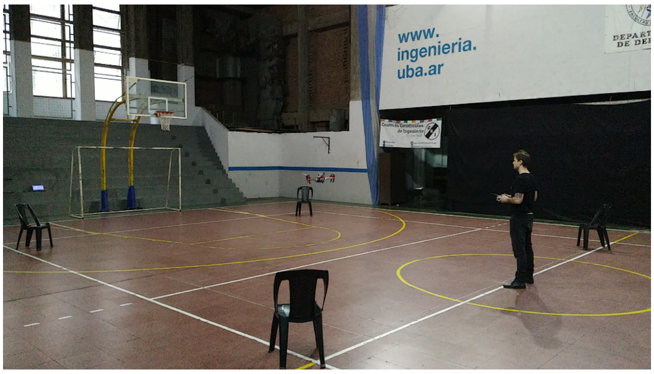

Figure 4: Environment setup for the experiments. The stationary beacons are placed on chairs at a height of 40cm, in a square of 8x8m.

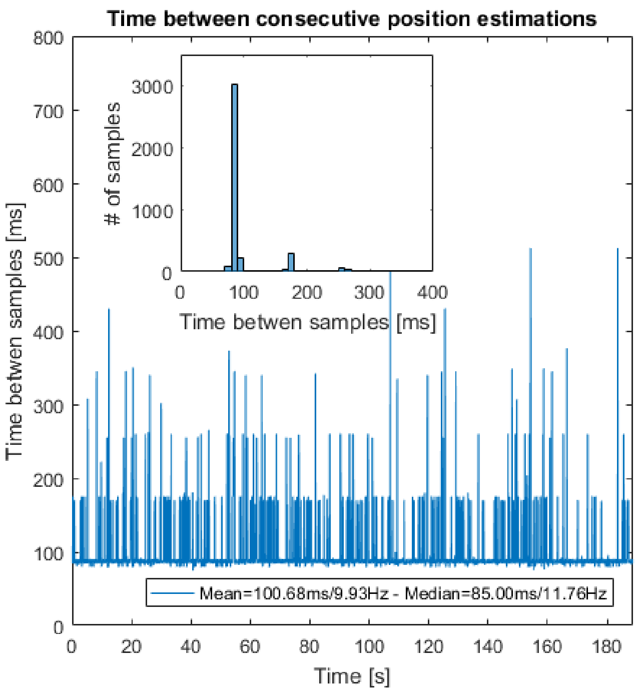

Figure 5: Time between consecutive position estimations from the indoor positioning system, during one of the flights. (Inset) Histogram of the time plot, using 10ms intervals.

The system was configured to provide position estimation at a 12Hz rate, but may not provide data (or provide data with low accuracy) in cases where the line of sight between the mobile beacon and the stationary beacons is obstructed. In Figure 5, the time between consecutive samples of position information (accurate or not) is shown, during one of the flights of the experiments. The data rate of the positioning system is mostly stable at 85ms (around 12Hz), but it can be observed that there are several occasions where this time is doubled, corresponding to a failure to obtain position information. An inset of axis shows the histogram of the same experiment, where around 90% of the samples correspond to a time interval of 85ms±10ms.

The chosen path for the experiments was the Gerono trajectory (or ”infinity” trajectory) in the *XY* plane. The yaw direction was fixed at zero during the entirety of the experiments, so that a maneuver in pitch moves the vehicle along the *X* axis, and a maneuver in roll moves it in the *Y* axis. The vertical thrust remained manually controlled by the pilot for safety reasons. The vehicle takes off from the ground, is positioned around the center of the flight area, and the position control is activated. In the moment of activation, the current position is taken as the center of the Gerono trajectory.

4 RESULTS

The flight trajectory for the vehicle without failures is shown in Figure 6. The vehicle takes off at $t = 0s$, and the position control is activated at $t = 33s$, where the current position is taken as reference. The vehicle performs three and a half full Gerono trajectories, before the position control is deactivated at $t = 190s$, where it lands safely. It can be observed that there are several outliers in the measured position at $t = 72s$, $t = 109s$, $t = 126s$ and $t = 184s$, that correspond to errors in the position calculation of the Marvelmind tracking system, to which the vehicle reacts accordingly, but recovers quickly and remains on path.

In Figure 7, the PWM values commanded to the six rotors are shown. As expected for a nominal case of a hexarotor in a near-hovering situation, all the PWM values are almost equal, driving the rotors at around 50% of their maximum speed, which provides a wide margin for performing maneuvers without saturating any rotor.

The flight trajectory for the vehicle with a failure in rotor 3 is shown in Figure 8. The failure is activated before take-off, and is present during the full flight. The vehicle takes off at $t = 0s$, and the position control is activated at $t = 18s$, where the current position is, again, taken as reference. The vehicle again performs three and a half full Gerono trajectories, before the position control is deactivated at $t = 176s$, and is returned to the take-off point to land. In this test, there were no occurrences of glitches in the position estimation.

It can be noticed that in the *Y*-axis sinusoidal trajectory, there is some overshoot in the positive direction, while there is no significant overshoot in the negative direction. This is because the rotor in failure state is positioned over the *Y* axis of the vehicle, and the roll maneuver in one direction seems to be less responsive than in the other.

In Figure 9, the PWM values commanded to the six rotors are presented for the case with failure. While the PWM value for rotor 3 is zero during the flight, the commands to the rest of the rotors do not significantly differ for the previous case.

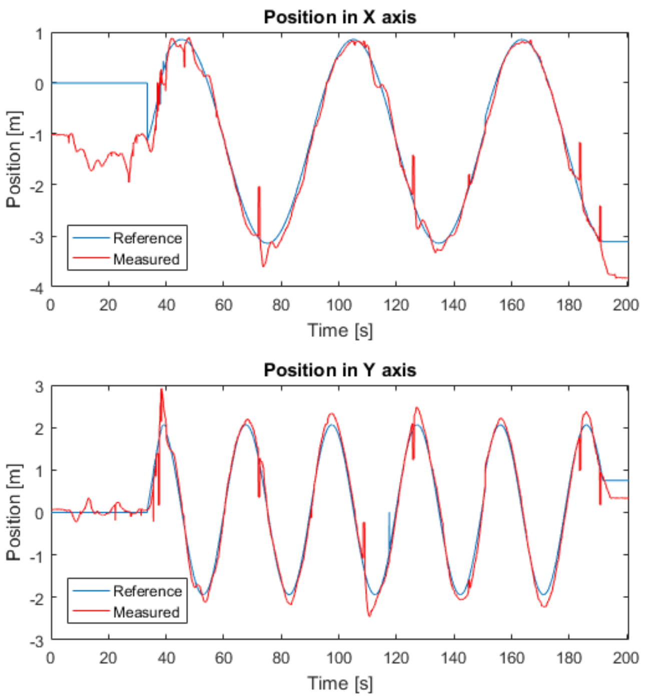

Figure 6: Gerono trajectory for an hexarotor without failure.

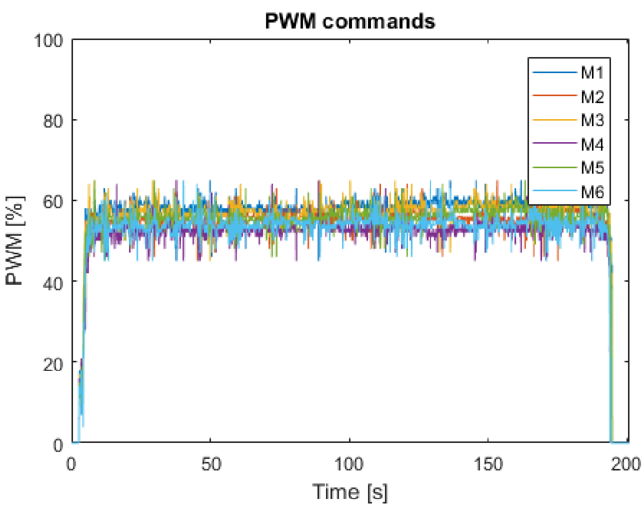

Figure 7: PWM values during the flight without failure

Rotors 2 and 4 increase its speed (and thus its thrust), to compensate for the lack of thrust of the motor located between them. All the maneuvers performed during the trajectory do not require a great variation of speed (the PWM values for all the rotors only vary around $\pm 5\%$). This suggests that the vehicle with failure also is able to perform aggressive maneuvers without saturating the rotors.

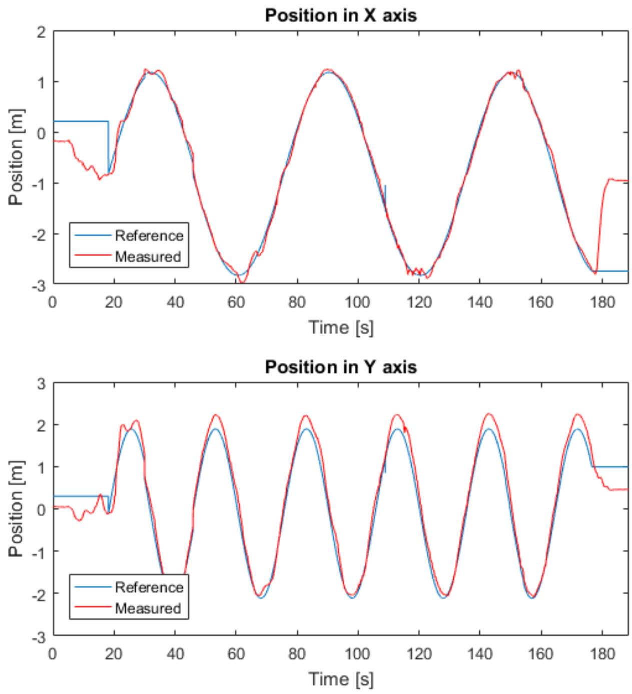

Figure 8: Gerono trajectory for an hexarotor with a failure in rotor 3.

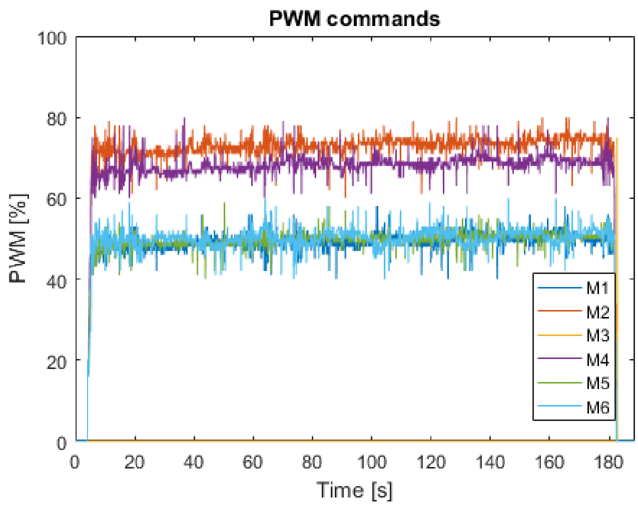

Figure 9: PWM values during the flight with a failure in rotor 3.

Both cases performed satisfactorily, as the trajectory was correctly followed. Moreover, during manual take off, landing, and the diverse maneuvers made to position the vehicle for the experiments, it was not noticeable any difference in maneuverability between both cases, even while performing very aggressive movements to test the system. A video of the preliminar test of the fault tolerant vehicle can be sen in [12], and another of one of the experiments is attached to this work.

5 CONCLUSION

The proposed hexarotor vehicle was able to follow with good performance a given trajectory, both in a nominal case, and with a total failure in one rotor. Moreover, there is no appreciable difference in the behaviour between both cases, as all the rotors operate at a speed pretty far away from their saturation limits, giving plenty of margin for different maneuvers.

Still, the failure case shows slight asymmetries in the trajectory, indicating that there are some maneuvers that are performed better than others. This may be caused either by the rotors working at different average speeds, or by the maneuver requiring different speed variations from each rotor.

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