Multirotor UAS for bridge inspection by contact using the ceiling effect

P. J. Sanchez-Cuevas, G. Heredia and A. Ollero.

***Abstract*— The inspection of bridges and other infrastructure with UAVs when the sensors need to be in contact with the surface (i.e. ultrasound for crack inspection or reflector prism for beam deflection) is a great challenge due to the coupling which occurs between the aerial and the inspection problems. This paper presents a new design of a multirotor UAV that can be used in some of these applications to eliminate the coupling and to be able to carry out the inspection by contact in a more effective way. The proposed solution uses the so-called ceiling effect to maintain in contact a specially designed aerial platform to the ceiling. So, the coupling disappears because the multirotor is still in contact with the ceiling in a fixed position while performing inspection. Moreover, the presented results show that making use of the ceiling effect also improved the maximum flight time of the platform. The solution is presented with experimental results in a test stand and flight tests representing a bridge inspection application (Fig. 1). A video of the experiments is also included.**

I. Introduction

In the last years, there has been a growing interest in Unmanned Aerial Vehicles (UAVs) [1]. UAVs of different sizes have been used in applications such as exploration, detection, precise localization, monitoring and measuring the evolution of natural disasters. However, in most of these applications the aerial robots are mainly considered as platforms for environment sensing. Then, these aerial robots do not modify the state of the environment and there are no physical interactions between the UAV and the environment.

Recently the development of autonomous aerial robots capable of physical interaction is catching much interest in robotic research [2],[3]. For example, aerial robots with integrated robotic manipulators (usually known as aerial manipulators) [4],[5],[6], offer strong potentialities for applications as the inspection and maintenance of industrial plants and infrastructures, aerial power lines, moving objects and taking samples of material from areas that are difficult to access.

In the area of infrastructure inspection, UAVs with cameras have been used for an initial visual inspection of difficult to access areas of bridges [7]. When cracks or other damages are detected in the images, an in-depth inspection has to follow with experienced human inspectors in need of hands-on-access to bridge elements, and assess the crack depth using ultrasound testing sensors which need to be in contact with the bridge to take measurements. Another task that inspectors have to do is measuring bridge beam deflection placing manually a reflector prism in several points under the beam and measuring precisely their vertical position with a total station [8]. The AEROBI European Project [9] is developing a UAV system capable of performing these tasks for bridge inspection by contact.

The authors are with the Robotics, Vision and Control group, Universidad de Sevilla, Camino de los Descubrimientos s.n., 41092 Sevilla, Spain. (e-mail: {psanchez16, guiller, aollero}@us.es).

Fig. 1. Multirotor operating in contact with the ceiling.

Aerial manipulators with the arm attached on top of the multirotor body above the rotors have been proposed for conducting the inspection by contact of bridge elements without human intervention, since the arm can be used to hold the ultrasound sensor that must be in contact with the bridge while the multirotor is hovering [10],[11]. However, due to the additional weight of the manipulator arm, the UAV platform has to be large and heavy, and the controllers are more complex. This paper proposes a multirotor design that is able to fly very close to the bridge and touch it for doing these contact inspections.

When a rotary wing UAV has to fly close to a surface, as for example the bridge deck or piers, the airflow entering the rotor and coming out of it may interfere with these surfaces, changing the thrust and torque characteristics of the rotors. The best known is the *ground effect*, which happens when the UAV is flying very close above the ground [12],[13], causing an increment in the thrust generated by the rotor for the same power. Less known is the *ceiling effect*, which emerges when the UAV is approaching from below to a horizontal surface, as is the case when inspecting bridge beams or deck. This ceiling effect induces an additional thrust that brings the UAV towards the ceiling, which is dangerous for standard multirotors because the rotors may hit the ceiling and break, causing them to crash.

In this paper, a special design of a multirotor is proposed. The rotors with a protective armature that allows it to touch the bridge deck and beams from below, placing the rotors safely very close to the beams and contact with them taking advantage of the ceiling effect.

The organization of the rest of the paper is as follows: section 2 presents the analysis of the ceiling effect for a single rotor and for a typical quadrotor using experimental results in a test stand and introduces different problems which can be partially solved using the ceiling effect. Section 3 shows the changes necessaries to guarantee that the multirotor will be able to maintain the contact with the ceiling successfully. Section 4 is focused in the validation of the previous studies and it is illustrated with flight test results obtained during a flight with contact operation, ending with the conclusions and future works for this research.

II. Ceiling Effect

The behavior of the wake of a rotorcraft can be greatly influenced by the proximity of the rotor to obstacles that disturb the development of the rotor wake or constrain the flow into the rotor. The most significant of these obstructions is the ground surface. This phenomenon, usually known as ground effect, mostly affects rotorcraft operating in hover and low speed, and has been studied extensively in the literature for helicopters [12],[14],[15] and more recently also for multirotors [13],[16],[17]. However, there are few researches related with the aerodynamic effect flying close to the ceiling [17],[18]. The interest in the changes produced in the thrust of small rotors flying very close below a horizontal surface, known as the ceiling effect. This effect appears when the propeller is very close to a ceiling surface. So, the propeller cause a suction upwash generating a greater pressure difference on the propeller disk. Moreover, this decreases the drag and increases the thrust because the rotors can rotate faster. The ceiling effect appears because this effect can help to solve typical problems that arise in some applications of aerial vehicles that need to physically interact with the environment, as is the case in inspection by contact of bridges and other infrastructure. This paper is focused in the analysis, application and validation of these benefits produced by the ceiling effect, and their quantification through experimental results. A test stand is first used to perform the first static experiments. Then, a platform specifically designed to take advantage of this effect has been designed, developed and validated in the flight tests.

A. Test Stand

In order to study the ceiling effect in different conditions, a series of tests have been performed in a specially designed testbench, which has been built for experimental motor/rotor aerodynamic characterization close to surfaces. This testbench, shown in Fig. 2, is able to measure rotor thrust, rotor speed and motor pwm input, controlled from a computer with a data acquisition card and a graphic user interface. The testbench has a mechanical structure for attaching the motors, and moving parts that allow making tests with different distance/inclination angle of the rotor plane with respect to the ceiling surface.

The procedure in the different tests was to measure the thrust produced by the rotor when it is working close to a surface (ceiling). The pwm input signal will be the same in all tests and the rotor will be kept in steady-state for a given time with this constant input. Then the measurements registered by the load cell will be filtered to get the mean value. The results of the test are this last mean value of the thrust and the distance to the surface at which the test was done. Each distance is tested several times to get realistic results and obtain a standard deviation estimate.

Fig. 2. Test stand used in the static experiments.

B. Ceiling Effect - Single Rotor Experiments

First step is to analyze the ceiling effect in a single rotor, Fig. 3 shows the configuration of the test stand. The results obtained in these experiments are shown in Figs. 4 to 6, where T is the thrust generated by the rotor, z is the distance to the surface, R the radius of the rotor (in this case 9.4 inches with DJI 2312 rotor), ICE means "In Ceiling Effect" and OCE "Out of Ceiling Effect".

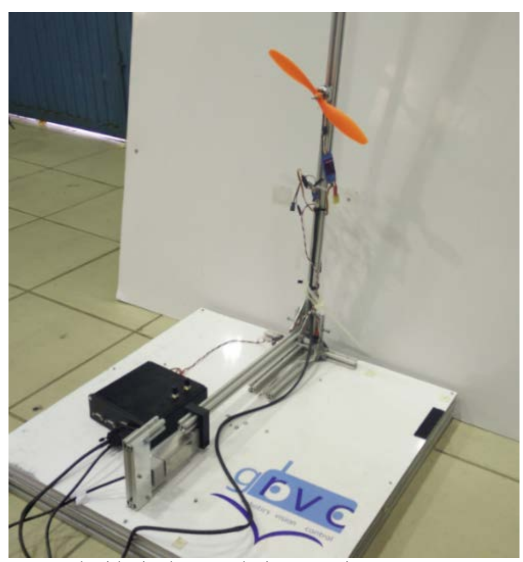

Fig. 3. Test stand with single rotor during experiments

Fig. 4 shows the mean value and the standard deviation of the thrust for each normalized distance z/R. It can be clearly seen that the thrust increases significantly when the rotor approaches the ceiling. This result is very important for controller development because when the multirotor is flying close to the ceiling the thrust of the rotors will also increase and it will push the multirotor even closer to the ceiling, so that it can collide with the ceiling surface.

Fig. 5 shows how the rotor rotational speed (in rpm) changes when the rotor approaches to the ceiling. It can be observed the increase of the rpm is consistent with the large increase in thrust of Fig. 4. And finally, in Fig. 6 it is shown the pwm input signal commanded to the rotor in all the experiments.

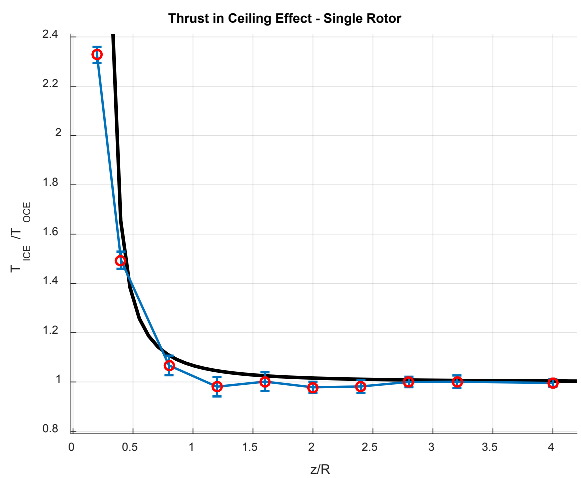

Fig. 4. Ceiling effect in a single rotor. Errorbar is the blue curve, mean values are the red circles and numerical approximation is the black curve.

As conclusion, flying close to the ceiling increases the rotor thrust for the same power, producing a vacuum effect and decreasing the propeller drag, so then the rotor can rotate faster generating this thrust increase. As discussed in the blade element theory, the thrust generated by a rotor increases proportionally to the square of the rotational speed, so this justifies the abrupt increase in the thrust developed by the rotor close to the ceiling.

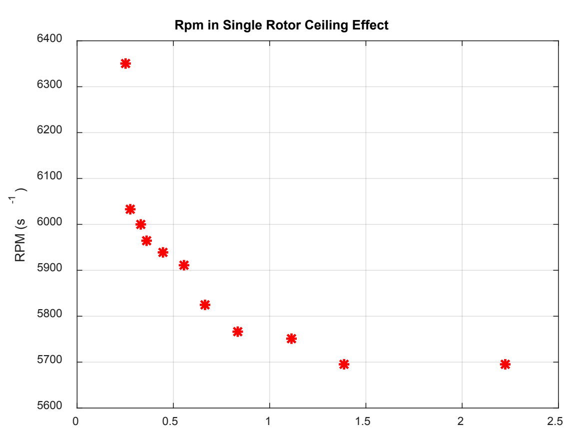

Fig.5. Rotor rotational speed (rpm) as a function of the normalized distance to the ceiling.

The increment in thrust due to the ceiling effect as a function of the normalized distance to the ceiling surface of Fig. 4 can be approximated by an analytical function with a similar form to the typical ground effect approximation [14]:

$$\frac{T_{ICE}}{T_{OCE}} = \frac{1}{1 - \frac{1}{K_1}\left(\frac{R}{z + K_2}\right)^2} \quad (1)$$

The coefficients can be obtained by least squares minimizing the error with the experimental results, and were obtained as $K_1 = 6.924$ and $K_2 = 3.782$.

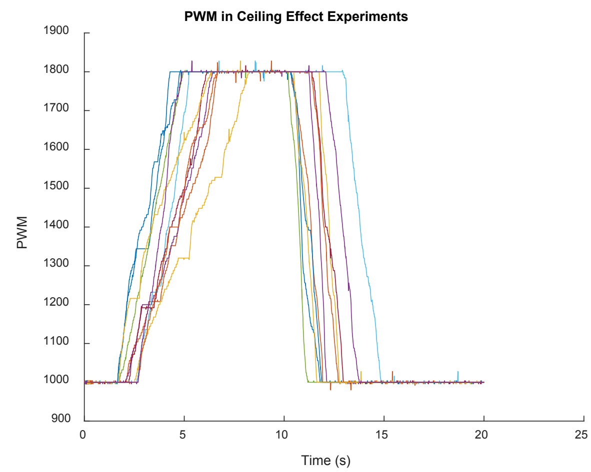

Fig. 6. PWM motor input commanded in the different tests.

C. Ceiling Effect – Full Multirotor Experiments

When a multirotor is flying subject to the ceiling effect, the flow field generated around each rotor depends on the other rotors and the multirotor frame. Thus, the results in the previous section cannot be applied to a full multirotor due to the above mentioned interaction. Fig. 7 shows a scheme of the flow field generated by a multirotor operating close to the ceiling. In this figure, it can be observed the main interaction zone, which is in the area between each pair of rotors above the rotors' plane. To analyze the ceiling effect when all the rotors of a multirotor are very close to the ceiling surface, several experiments where performed with the complete quadrotor at the test stand, as shown in Fig. 8. The experiments were done following the same procedure explained for a single rotor.

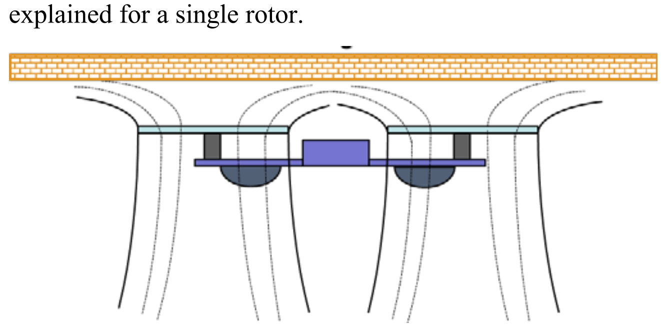

Fig.7. Flow field scheme for a multirotor in ceiling effect

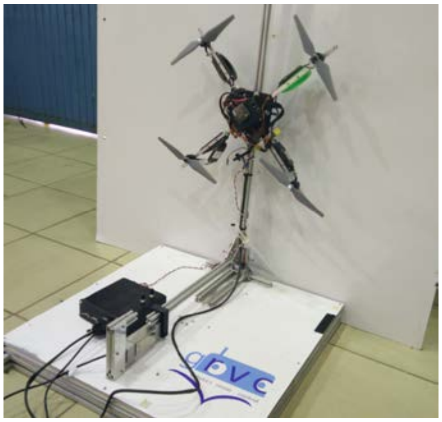

Fig.8. Test stand with quadrotor during experiments.

The experimental results for the complete quadrotor are presented in Fig. 9, showing also the results for a single rotor for comparison. As can be seen in Fig. 9, the increment in thrust due to the ceiling effect is larger for the complete multirotor, and it becomes more significant at a larger distance to the surface than for a single rotor. The evolution is also smoother.

These results can be interpreted from different points of view. On the one hand, it is possible to develop more thrust for the same power if the multirotor is subjected to the aerodynamic ceiling effect. On the other hand, the multirotor can increase its maximum flight time because the rotor decreases its energy consumption. It is a great benefit which can be used in different UAV applications. Section 2-D discusses this and other benefits for different applications.

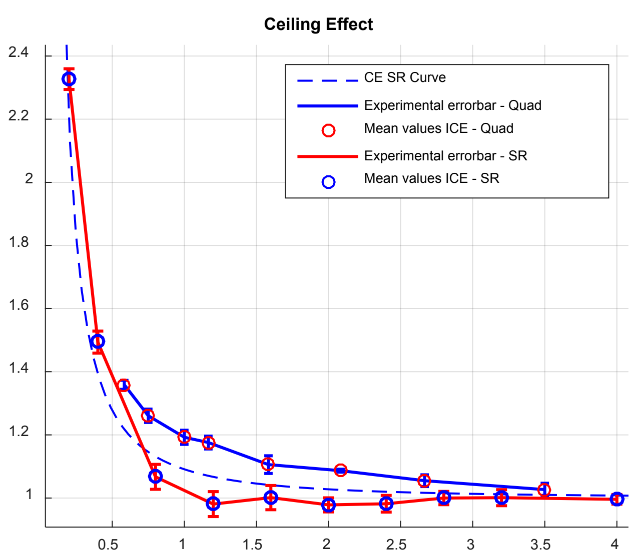

Fig.9. Comparison between the ceiling effect in a quadrotor and a single rotor.

D. *Applications of Ceiling Effect in Multirotors*

Two typical problems appear in the applications of multirotors. These are the maximum flight time and the stability during operation. Last problem arises especially in high precision applications, such as aerial manipulation close to a surface which generates aerodynamic effects or inspection by contact applications. In these applications, high precision and controlled flight are required. The ceiling effect can help to minimize these problems. This paper proposes using a platform which can maintain in contact with the ceiling. Thus, the proposed design helps to solve these problems in the following way.

The solution of the first problem is deduced from the previous sections. If the platform is in contact with the ceiling the rotors can work at a lower rate and the consumption decreases, increasing the maximum flight time.

The second problem was solved designing a platform which can maintain safely the contact with the ceiling. Thus, the platform can operate with better precision. Maintaining the contact with the ceiling allows to uncouple the flight and the application problem. This research is focused in bridge inspection by contact application.

Next sections are about the design of a platform which can work maintaining the contact with the ceiling. The test to validate the results will be under a bridge in the same conditions that an inspection by contact application.

III. Design of Contact-to-ceiling Multirotor

A. *Platform design*

Standard multirotor configurations are not well suited for flying very close to the ceiling because in general rotors are not protected from impacts at the upper part, and in many cases sensors and antennas are placed at the central part of the body above the rotors' plane. This section presents the design of the aerial vehicle that has been done for this purpose.

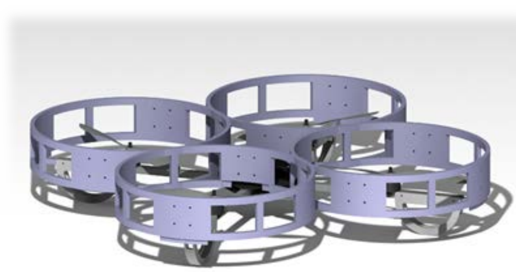

Fig.10. CAD Design of the platform

The design is based on a quadrotor in cross configuration, with all the elements (autopilot, batteries, sensors…) placed at or below the plane of the rotors, and special fairings that surrounds each rotor as can be seen in Fig. 10. The design of the multirotor allows it to maintain the contact firmly to the lower part of the bridge at a fixed distance of 0.36R, placing the fairings in contact with the bridge beam surface with the rotors spinning at few centimeters of the surface without colliding with it.

The multirotor platform used in the research is a quadrotor with cross configuration, the DJI E305 motorization and a 4s LiPo as power supply. The weight of the platform is approximately 1.5 kg with a maximum flight time of 14 min. The distance between rotors axis is 480 mm.

The fairings are located surrounding the rotors with circular form to easily guarantee the safety of the propellers and the multirotor. The diameter of this fairing is 280 mm and the height is 74 mm. The top of the fairing must be covered with a rubber material to avoid wearing it and facilitate contact with the surface. The fairing must have air intakes to ensure the generation of thrust by the rotors when the multirotor will be in contact with the ceiling.

Fig. 11 shows the final prototype of the quadrotor with the fairings surrounding the rotors. The fairings have been made with PLA with 3D printing technology. In Fig. 11 we can see in orange the front rotors and in black the rear rotors.

Fig.11. Final prototype of the platform

B. *Autopilot*

Flying under structures like bridges and very close to them imposes some restrictions in the autopilot used to control the UAV. The main limitations come from the sensors used for position and attitude estimation. The GPS signals are partially or completely blocked under a bridge, so it cannot be used for position estimation. Furthermore, when flying close to reinforced concrete bridges, the armatures may distort severely the magnetic field, so magnetometers cannot be used reliably for attitude estimation.

For the flight experiments with the multirotor presented in this paper, the PX4 autopilot has been used. Several modifications have to be done in the autopilot, mainly in the state estimation module due to the abovementioned constraints. Since GPS is not available, optical flow and visual odometry can be used for relative position estimation. Also, the attitude estimator has been modified to not use the magnetometer, which affects mainly the accuracy of the estimation of the yaw orientation angle. Then in the autopilot only the yaw controller has been modified to avoid the problems that arise with the error accumulation and controller saturation when the multirotor is in contact with the ceiling and cannot correct this error. To guarantee the contact in safe position the only controller used in the yaw dynamic is the yaw rate controller. We assume that the ceiling surface is horizontal so then pitch and roll controller as setting by default.

C. *Changes in Ceiling Effect*

The aerodynamic behavior of the designed multirotor is different now due to the fairings around the rotors. The flow field is similar in both cases, the single rotor and the complete quadrotor. However, the fairing that surrounds each rotor allows to isolate the aerodynamic effects, and it is expected that there will be no much difference between the single rotor and the complete quadrotor cases.

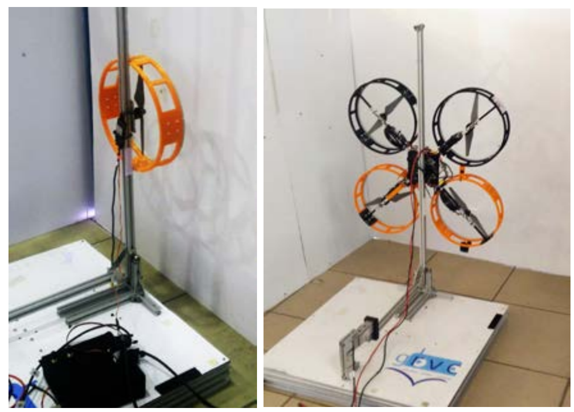

Fig.12. Single rotor and Quadrotor with the fairing prepared to the experiments in the test stand.

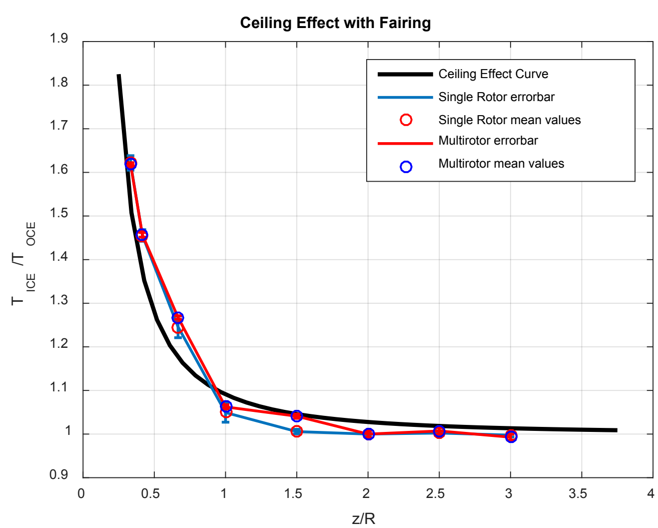

Fig.13 Comparison between the ceiling effect in a quadrotor and a single rotor, both with fairing.

Then it is necessary to assess the ceiling effect with the fairing before the experiment validation. This implies the realization of the new experiments in the test stand with the fairing designed. Fig 12 shows both experimental configuration in the test stand, the single rotor and the complete quadrotor. The experiments were done with the pwm of hovering (52%).

Fig. 13 shows the results for these experiments. The ceiling effect in both cases is very similar. As above mentioned this is an expected result. The fairing surrounding each rotor allows to isolate the aerodynamic effects when the rotors are close to the ceiling. Then the interference between the airflow entering each rotor is reduced.

IV. Experimental Validation

The goals of the experiments is to check that the multirotor can maintain the contact with the ceiling in safety conditions. The experiments have been done flying the multirotor under a bridge, and taking it to contact with the bottom part of the bridge deck. The multirotor has mounted a reflector prism, so that its position can be precisely determined using a total station (see Fig. 14). Different points of the bridge surface can be measured maintaining the multirotor in contact with the bridge while the prism touches it. These points can be used to approximate the bridge deflection which is an important result for bridge inspection.

Fig.14. Leica total station and reflector prism to be mounted on the UAV

Moreover, the experiments allow to validate the design and can confirm the benefits of using the ceiling effect in application discussed in section 2-D. Fig. 15 shows a sequence of one of the experiments (see video in [19]) in which the multirotor starts flying towards the ceiling, holds in contact with it and returns to normal operation.

Fig.15. Quadrotor in contact with the ceiling while the prism is in contact.

The reflector prism is placed on a special device which has been designed to guarantee the contact when the multirotor is in contact with the ceiling (see Fig. 16). This device consists of two printed planes and four silent blocks, which stands the prism out to the fairing in normal conditions and can be compressed when the prism and the multirotor are touching the ceiling.

Fig.16. Quadrotor in contact with the ceiling while the prism is in contact.

Telemetry data allows to assess the benefits of using the ceiling effect presented in the previous section. These data were sent to a ground control station and recording in a memory onboard during the flight and the results are presented in the Figs. 17, 18 and 19. In these figures when the multirotor is in contact with the ceiling is represented with a cyan background, and normal free flight conditions with white background.

Fig. 17 shows the height of the multirotor and the value of the thrust commanded in the ordinate axis. The abscissa axis of the figure is the flight time in seconds. It can be seen how the value of this height is almost constant on 3 meters in the contact condition (cyan background). Moreover, the figure shows that although the percentage of throttle commanded is decreasing below the hover value (52 %) the multirotor holds the altitude. This is because the ceiling effect increases the thrust and the hover value in this condition is lower than the normal value. The transition appears with a throttle value of 42%. This produces a decrement in the power consumption and increase the maximum flight time.

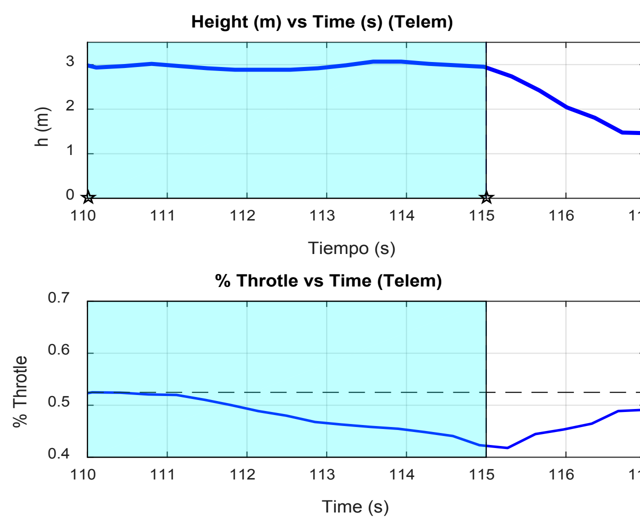

Fig.17. Height and throttle vs time in flight test.

The benefits related with the uncoupling between the flight and the application problem are shown in Fig. 18. This figure illustrates that the fact of maintain the contact with the ceiling limits the roll and pitch angles. This is because the multirotor holds in contact with a surface which restricts the platforms movements. It can be observed in this figure that while the quadrotor is in the contact condition (cyan background) the pitch and roll values registered in telemetry are almost constant. In fact, the angles are constant because the multirotor is in contact with the ceiling but the data registered include estimation errors. This figure includes the throttle values to have another reference of the flight condition.

These results are relevant for the aerial robots which need a high precision in their positioning and stability to carry out their application. For applications which need contact with the surface this new way to operate allows to uncouple the flight to the manipulation problem.

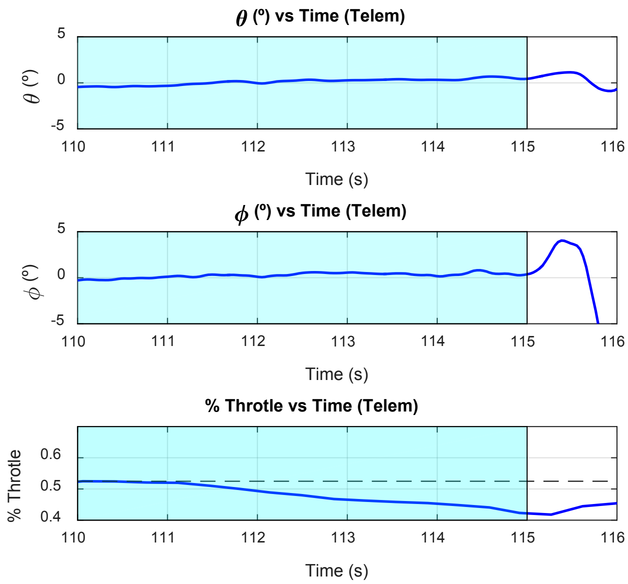

Fig18. Pitch and roll angles vs time in flight test.

As last results, z-accelerometer filtered value versus time is presented in Fig. 19. This measure can be used to detect the transition and differentiate the operation condition. The figure shows that the contact is easily detectable with this sensor. The transition points can be detected with peaks in the accelerometer value. It can be observed in the figure how at the transitions the value reaches its maximum and minimum values. In the contact condition (cyan background), the measure is much less noisy and equal to gravity. The platform in this condition is quiet and contact with the ceiling. Thus, we can use this sensor to detect when the platform is in contact and start to carry out the manipulation or inspection application using the feedback of this sensor as if it were a trigger.

A video of the experiments can be found at https://www.youtube.com/watch?v=jLYra8TrQLc.

V. Conclusion

In this paper, we propose a new way to carry out the inspection by contact applications with a UAV. The so-called ceiling effect has been studied to assess its benefits and problems which may appear in this type of applications. Once these benefits and problems are analyzed we design a platform which can exploit the benefits and avoid the problem to realize the application in safety conditions. Finally, flight tests have been performed and their flight data have been presented.

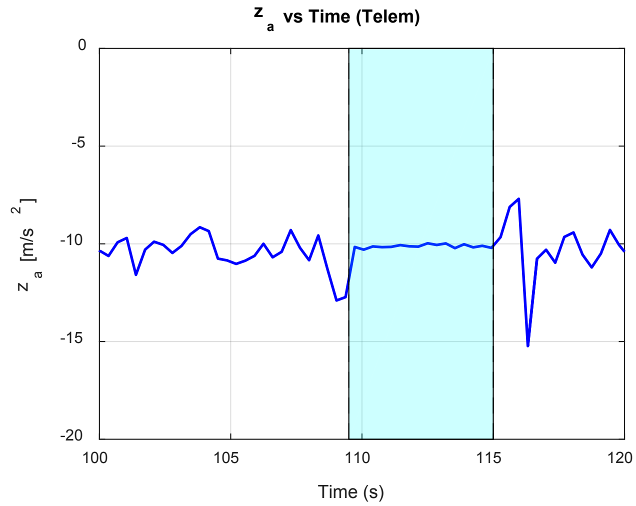

Fig.19. Z-accelerometer vs time in flight test.

The presented design improves the maximum flight time and stability of the platform during the application, since the rotors develop more thrust for the same power due to the ceiling effect. Thus, the ceiling effect allows that the platform remains attached to the ceiling with a throttle commanded less than the hoverfly level in a normal operation, so then the consumption decreases and the maximum flight time increases. On the other hand, when the multirotor is in contact with the ceiling the position of the aerial platform is fixed and the precision of the inspection operation is greater. These benefits has been demonstrated with experimental results in the section 4 of this paper.

It is important to highlight the need for a special design like the one presented in the section 3, i.e. the multirotor mechanisms which ensures the safety operation conditions. Moreover, several changes must be introduced in the estimator and the controller to consider the constraints imposes by flying under structures like the ceiling.

Future work related with this research will be the implementation of a dedicated control system using contact, distance and global position sensors to improve the transitions process and increase operational safety during applications like the bridge inspection or aerial manipulation.

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