Experimental approach to the aerodynamic effects produced in multirotors flying close to obstacles.

P.J. Sanchez-Cuevas[1], G. Heredia[1] and A. Ollero[1]

[1] University of Seville,
{psanzhez16, guiller, aollero}@us.es

Abstract. Ground effect on rotary aircraft has been studied for many decades. Although a large body of research results is now available for conventional helicopters, this topic is just beginning to receive attention in the unmanned aerial vehicles community, particularly for small size UAVs. The objective of this papers is to assess the applicability on small rotary wing UAV of a widely-used ground effect model, developed in the middle of the last century by Cheeseman and Bennett, for predicting the ground effect on helicopters. Furthermore, other aerodynamics effects associated with flying close to surfaces or obstacles. Test stand has been designed to experiment with different configuration as walls, ceiling or combinations of them have been studied. A test stand has been designed for testing the aerodynamic effects with different configurations, and experiments with ground, ceiling and wall surfaces have been done. Also, experiments to assess the combined effect of ground+wall and the ground effect for a tandem rotor have been carried out. The experimental procedures and the implications on the obtained results is also included in the paper.

Keywords: Aerodynamic effects, UAS, Experimental study.

1 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, the aerial robots do not modify the state of the environment and there are no physical interactions between the UAV and the environment. Furthermore, the interactions between the UAVs themselves are essentially information exchanges, without physical couplings between them.

Recently, autonomous aerial robots are being increasingly used with integrated robotic manipulators [2][3]. These aerial manipulators [4], [5], [6] are used for multiple applications such as inspection and maintenance of industrial plants and infrastructures [7], aerial power lines, moving objects [8] and taking samples of material from inaccessible areas.

These applications usually require that the multirotor flies close to different objects, structures, and other obstacles. For example, this situation appears if the application is the grasping of one object placed on the ground or the inspection by contact using sensors onboard in the aircraft [9]. In all of these applications, the multirotor have to operate very close to different obstacles or surfaces. This paper studies the effect produces in the performance of the multirotor when it is flying under the influence of close surfaces. Thus, for example in the AEROARMS European project [10] the aerial manipulator is used for inspection and maintenance in industrial settings flying close to horizontal surfaces, in the ARCAS European project [11], aerial robotic manipulation for assembly over a surface is considered and in the AEROBI European project [12] the UAVs carry out task of bridge inspection by contact very close to ceiling surfaces.

When the multirotor is flying close to obstacle the wake cannot be developed freely. This produces changes in the forces generated by the rotors. This aerodynamic effect has been widely studied in helicopters flying close to a ground surface, for example with the classical analytical model for ground effect provided in [13] or empirical expressions for the rotor thrust increment in ground effect for large [14] and small UAV helicopters [15]. However, the ground effect in complete multirotors and the effect produced by other surfaces have received much less attention. The only experimental results that have been reported making experiments with a small quadrotor flying hover over the ground at different heights [14], and using a testbench [15] suggest that the ground effect in multirotors may be larger than the predicted by [13].

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. This effect was studied in [9] for bridge inspection by contact application with UAS. Other aerodynamic effects like wall effect or the effect produced combining different surfaces for the typical rotors of multirotors have not being studied before.

In this paper, the authors experimentally study the different effects which appear in small rotors when they operate close to different surfaces and explains the design of the test stand used to carry out these experiments.

The organization of this paper is as follows. In section 2 we present the test stand and the experimental procedure. In Section 3 we studied the effect in the thrust of the small rotors when they are working close to different obstacles and the effect in the total thrust of a tandem rotor disturbed by the ground effect. Lastly, section 4 introduces the conclusions of the paper.

2 Test Stand

This research is focused on approaching the aerodynamic effects when multirotors fly close to different obstacles. A test stand has been designed and manufactured to evaluate these aerodynamic effects experimentally.

First, the test stand must be designed for the typical rotors which are used in multirotors. These rotors are called small rotors in the rest of the paper and are those whose size is between 6 and 20 inches. Second, the test stand must be able to measure the

PWM signal transmitted to the rotors, the response in rpm and the total thrust generated. Lastly, it is necessary to export the data to a PC for online visualization and postprocessing.

In order to meet the requirements, the test stand uses a load cell to measure the thrust connected to an Arduino board. This allows controlling the PWM signal manually or automatically. The Arduino is used to send the data to MATLAB through the serial port too. Additionally, the test stand includes an rpm sensor working with the board and has implemented an algorithm to calculate the PWM based on interruptions. Fig. 1 shows the test stand used for experiments and the data which can be obtained in the experiments.

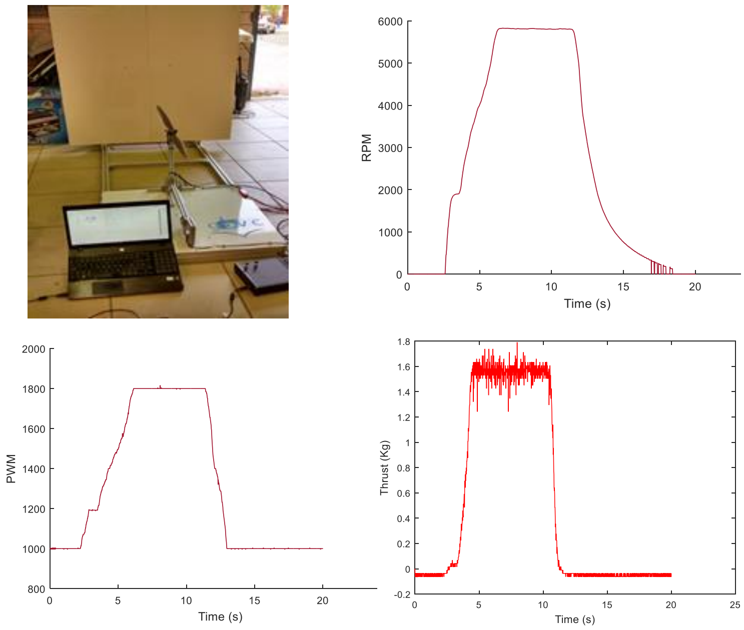

Fig. 1. Test stand & typical measure of PWM, rpm and load respectively.

The main goal of the experimental procedure is to measure the thrust produced by the rotor placed at different distances to an obstacle. The PWM signal must be the same in all tests to have comparable results. Thus, the differences in the thrust are only produced by the aerodynamic effect. The test will be repeated five times for each distance to obtain the standard deviation and the mean value of each experiment. Then, if the thrust "in effect" is called as TIE and the thrust "out effect" is known as TOE, the graph of TIE/TOE versus z/R (z is the surface distance and R is the radius of the propeller) can be plotted.

Fig. 2 shows that is necessary to transform the measure of the load cell (R_y) to obtain the value of the thrust (T) because the designed test stand has a "L" structure. Through balance equations can be obtained the expression (1) which allows to convert R_y into the thrust using the torque distance (L_b and L_h).

$$T = R_y\left(\frac{L_b}{L_h}\right) = T(R) \quad (1)$$

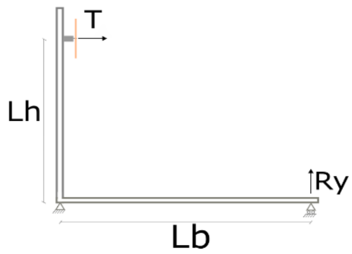

Fig. 2. Test stand isostatic structure scheme.

3 Experimental Results

Once the test stand has been described, the next section will be focused in the experimental results. First, it is important to assess if the widely-used ground effect model for helicopters can be applied on the typical rotors used in multirotors. The next step is to approach the changes in the thrust when the rotor is close to other obstacles, like ceiling and wall. Lastly, experiments will be carry out to assess combined effect and even a tandem rotor.

3.1 Ground Effect Results

The authors of [13] presented (2) as the simplest possible form to consider the ground effect. This result is obtained due to the assumptions of the potential aerodynamic and is widely-used to approach the ground effect in helicopters. However, this result is not very tested for small rotors.

$$\frac{T_{IGE}}{T_{OGE}} = \frac{1}{1-\left(\frac{R}{4Z}\right)^2} \quad (2)$$

Fig. 3. shows the results obtained in the ground effect experiments using small rotors. This result shows how the expression (1) is a good approximation for smaller rotors too.

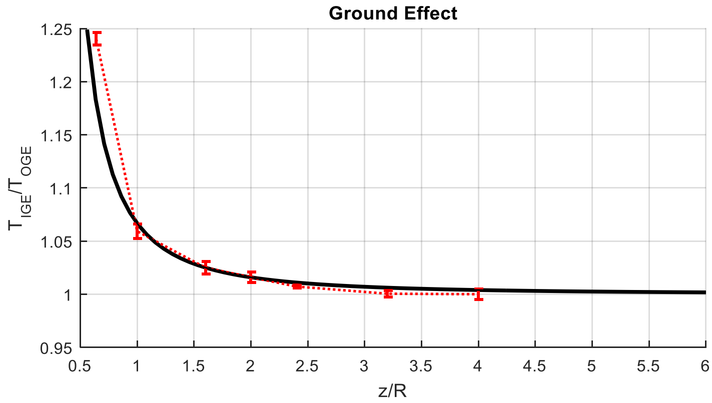

Fig. 3 Ground Effect Results. Black line represents the results of the classical model of ground effect and red errorbar is the experimental result in the test stand.

The experiments conclude that the thrust increase when the rotor operates closer to the ground. The effect starts to be significant when ground distance is approximately $z \sim 2R$. In the experiment, a value of $T_{IGE} \sim 1.2\, T_{OGE}$ for $z/R \sim 0.5$ has been obtained, this value will be used to compare the result with other experiments.

In conclusion, the ground effect "push up" the rotor when it operates very close to the ground surface. So, the rotors develop more thrust for the same transmitted power due to the presence of the ground effect. This aerodynamic effect produces that the wake of the propeller cannot freely expand. Since the air flow is subsonic, the pressure field completely changes and the thrust generated by the rotor is different. In this case, the changes in the pressure and the velocity fields produce an increase in the thrust. Furthermore, the experimental results allow us to verify the validity the test stand and the experimental procedures used in this study.

3.2 Ceiling Effect Results

The ceiling effect appears when the multirotor flies close to a ceiling effect surface. There are very few studies about this phenomenon; however, the ceiling effect can appear in multiple UAV applications. For example, this effect appears flying under a bridge in an inspection by contact application [9] or flying along a tunnel.

The test stand designed can be used to assess the ceiling effect and the results obtained are shown in the Fig. 4 and 5.

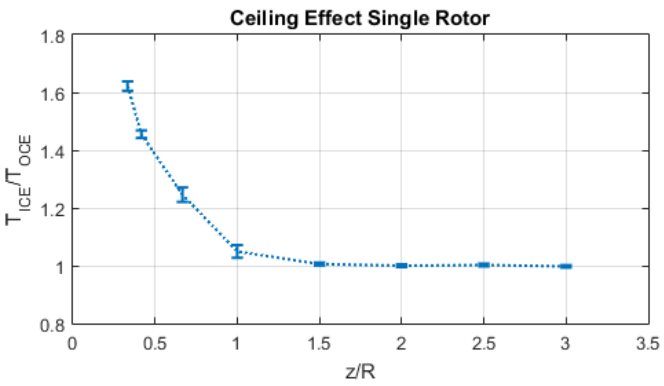

Fig. 4 Ceiling Effect Results.

Fig. 4 presents the experimental results obtained for a rotor with a radius of 12 cm. The trend of the ceiling effect results is similar to the trend in the ground effect results, i.e., when the rotor is closer to the ceiling surface it is able to generate more thrust. However, although the trend is similar the results are different. The ground effect appears for a greater distance to the obstacle but increase the thrust slower than the ceiling effect.

Fig 5 shows the PWM and the rpm of the rotors for the experiments at different distances to the ceiling respectively. In these figures, a new effect related with the velocity of the rotors appears in the ceiling effect experiments. It can be observed that although the input signal received by the rotors is the same, the response in the rotational speed is different in each experiment. The rotor rotates faster as the rotor gets closes to the ceiling. This is because the propeller drag decreases when the rotor flies closer to the ceiling. This effect in the rpm increases the thrust even more, because the rotational speed appears squared in the thrust expression. This justifies the abrupt increase in the thrust developed by the rotor close to the ceiling.

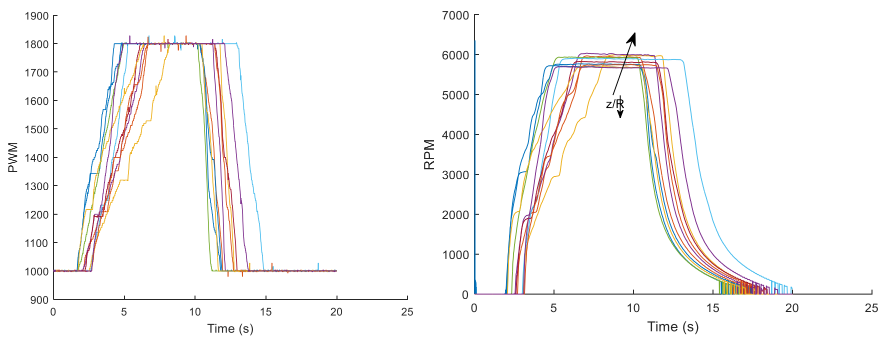

Fig. 5 Rpm and PWM in ceiling effect experiment.

In this case, it has been considered a function with the same form that expression (2) but two empirical coefficients, $K_1$and K_2, has been added to fit an expression for the ceiling effect. The coefficients can be obtained by least squares minimizing the error with the experimental results, and were obtained as $K_1 = 6.9246$ and $K_2 = 3.7820$.

$$\frac{T_{ICE}}{T_{OCE}} = \frac{1}{1-\frac{1}{K_1}\left(\frac{R}{z+K_2}\right)^2} \tag{3}$$

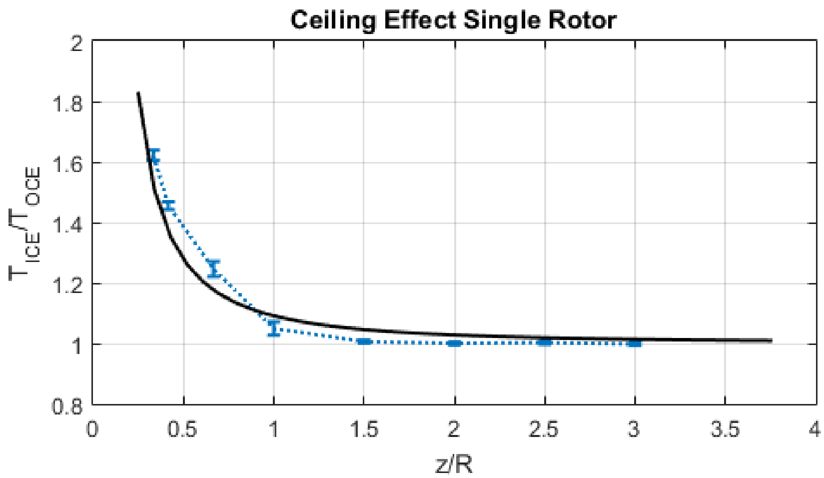

Fig. 6 Ceiling Effect Results Black line represents the approximation in (3) and blue errorbar is the experimental result for the ceiling effect in the test stand.

Fig. 6 compares the experimental results with results from (3).

From the multirotor controller point of view, the ceiling effect is more dangerous than the ground effect. In the ground effect, flying close to the ground increases the thrust of the rotors, and the multirotor is "pushed" away from the surface. However, when the multirotor is flying close to the ceiling the thrust of the rotors will also increase and it will "pull" the multirotor to the ceiling, so that it will collide with the ceiling surface.

On the other hand, according to our experiments the ceiling effect begins to be relevant later that the ground effect, i. e., when the rotor is closer to the surface (approximately at one radio distance) and then the thrust grows abruptly. However, the ground effect starts in at distances of around two radii and manifests more smoothly.

3.3 Wall Effect Results

One of the classical assumptions in helicopter theory assumes that the airflow is almost perpendicular to the rotor plane. According to this hypothesis, the expected results in the wall effect experiment is that the wall has no influence on rotor thrust. Several experiments have been done to test if this can be applied also to small rotors. The results of the experiments are shown in Fig. 7. It can clearly see that the wall effect is negligible because there is not a clear effect in rotor thrust when the rotor operates close to the wall. The changes obtained in Fig 7. are very light compared with the ground effect which increases the thrust almost 25% and the ceiling effect which increase approximately 50-100% the rotor thrust.

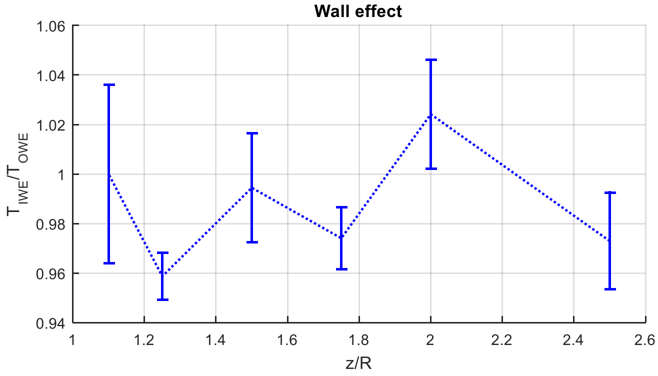

Fig. 7 Wall Effect Results

3.4 Ground + Wall Effect Results

Next question consists of evaluating the combine effect of ground and vertical wall effect. It is expected that the result can approximate the ground effect in tandem rotor because the wall acts as a symmetry conditions except for the tangential velocity which in zero in the wall and not necessarily in a symmetry plane. The experimental results are shown in figure 8.

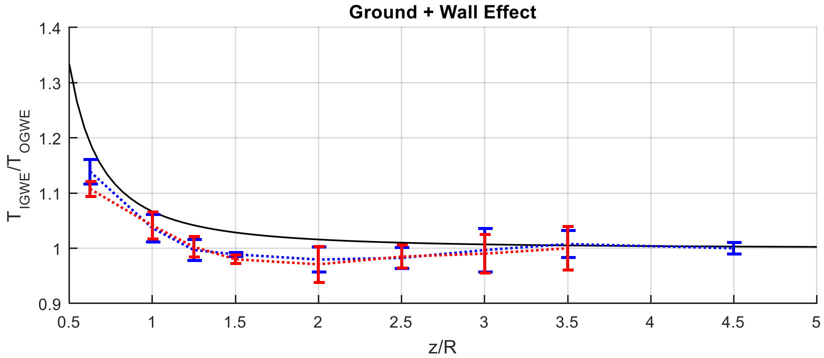

Fig. 8 Ground + Wall Effect Results Black line represents the results of the classical model of ground effect, the errorbars are the experimental result for ground + wall effect in the test stand, red errorbar is whit a distance between propeller tips of 2 cm and in blue errorbar the distance is 15 cm.

The result shows how the thrust have a different trend in this case, for values of $z/R \sim 2$ the thrust decrease respect the thrust out of effect, and the trend is reversed in values of $z/R \sim 1.2$ where the thrust is greater than the thrust out of effect. This result can be explained with the fountain effect presented in [16]. In this distance, the fountain effect is greater than the ground effect. The fountain effect produces significant changes. The flow in the wall has the reverse direction relative to the main rotor. This flow disturbs the normal rotor operation. Then, the rotor efficiency decreases and produces a lower thrust. Reverse flow can be observed in the figure 9. This CFD simulation intends to show the flow flied. The impacts of the rotational flow and the flow disturbance in the rotor for reversed flow have not been considered. The approximation of the classical ground effect model is not valid in this case, we suggest studying this situation in detail by other methods such as CFD.

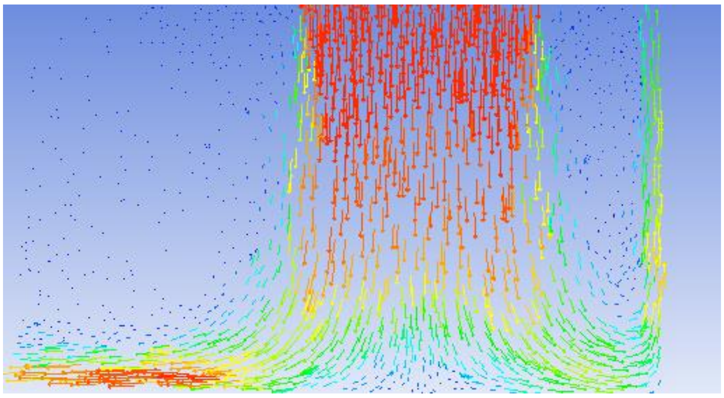

Fig. 9 Ground + Vertical Wall Effect – Approach to velocity field.

3.5 Ground Effect Tandem Rotor

These experiments have been done to assess the ground effect in a tandem rotor aircraft. It is expected that the results obtained are like those obtained for "Ground + Wall Effect" effect for the reasons discussed in section above. The experimental results show in figure 10. The trend and behavior of the results are qualitatively the same as in "Ground + Wall Effect".

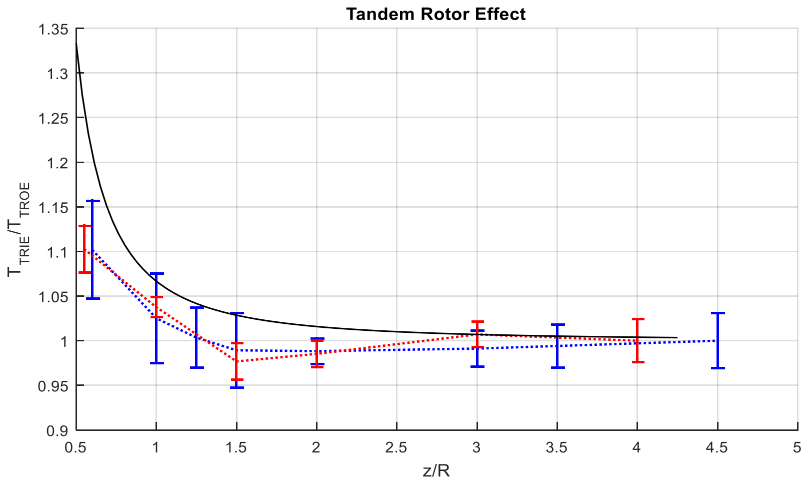

Fig. 10 Ground + Vertical Wall Effect – Approach to velocity field. Black line represents the results of the classical model of ground effect, the errorbars are the experimental result for tandem rotor ground effect in the test stand, red errorbar is whit a distance between propeller tips of 2 cm and in blue errorbar the distance is 15 cm.

The experiments were done with a different distance between blade tips. Firstly, the thrust decreases reaching a minimum value in $z/R \sim 1.5$, then increases gradually overcoming the value out of effect.

The fountain effect is more significant in this case respect of the "Ground + Wall Effect", and is important in a wider range of z/R. This can be explained because the fountain effect is a harder constraint for two reasons. First, in the middle of the tandem rotor two flows are mixing and second, there is not a wall, so the tangential velocity in the symmetry plane is not zero. Then, the influence in the efficiency is higher. Again the approximation of the classical ground effect model is not valid in this case and we suggest studying this situation in detail by other methods such as CFD.

4 Conclusion

In this paper, we presented an initial approximation to different aerodynamic effects which can appear in the multiple rotary wing UAV applications. The effects presented are the ground effect, ceiling effect, wall effect, combined effects and a tandem rotor in ground effect. The results from this paper can be used to develop new control strategies for rotorcraft flying close to surfaces which consider these aerodynamic effects. Future work includes the analysis of the rotor airflow interference in multirotors.

Acknowledgments

This work has been supported by the AEROARMS (H2020-2014-644271) and AEROBI (H2020-ICT-2015-687384) projects, funded by the European Commission under the H2020 Programme, the AEROMAIN (DPI2014-59383-C2-1-R) and AEROCROS (DPI2015-71524-R) projects, funded by the Spanish Ministerio de Economia y Competitividad and the FPU Program, funded by the Spanish Ministerio de Educación, Cultura y Deporte.

References

1. K. Valavanis and G. Vachtsevanos (Eds.), Handbook of Unmanned Aerial Vehicles, Springer, 2015.
2. M. Orsag, C. Korpela and P. Oh, Modeling and control of MM-UAV: mobile manipulating unmanned aerial vehicle. Journal of Intelligent & Robotic Systems, vol. 69(1-4) 227-240, 2013.
3. M. Fumagalli, R. Naldi, A. Macchelli, F. Forte, A. Keemink, S. Stramigioli, R. Carloni and L. Marconi, "Developing an aerial manipulator prototype: physical interaction with the environment," in IEEE Robotics & Automation Magazine, vol. 21, no. 3, pp. 41-50, 2014.
4. K. Kondak, A. Ollero, I. Maza, K. Krieger, A. Albu-Schaeffer, M. Schwarzbach, M. Laiacker, “Unmanned aerial systems physically interacting with the environment. Load transportation, deployment and aerial manipulation”, in Springer Handbook of Unmanned Aerial Vehicles, 2015.
5. S. Kim, H. Seo and H. J. Kim, “Operating an unknown drawer using an aerial manipulator”, in IEEE International Conference on Robotics and Automation (ICRA), May 2015, pp. 5503–5508.
6. G. Heredia , A. Jimenez-Cano, I. Sanchez, D. Llorente, V. Vega, J. Braga, J.A. Acosta and A. Ollero. "Control of a multirotor outdoor aerial manipulator," IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2014), Chicago, 2014, pp. 3417-3422.
7. A. E. Jimenez-Cano, J. Braga, G. Heredia and A. Ollero, "Aerial manipulator for structure inspection by contact from the underside," IEEE/RSJ International Conference on Intelligent.
8. H. Tsukagoshi, M. Watanabe, T. Hamada, D. Ashlih and R. Iizuka, Aerial manipulator with perching and door-opening capability, in IEEE International Conference on Robotics and Automation (ICRA), Seattle, USA, 2015, pp. 4663-4668.
9. P. J. Sánchez-Cuevas, G. Heredia & A. Ollero. “Multirotor UAS for bridge inspection by contact using the ceiling effect”, in International Conference on Unmanned Aircraft Systems (ICUAS), Miami, FL, USA. 2017.
10. AEROARMS Project website, http://www.arcas-project.eu
11. ARCAS Project website, http://www.aeroarms-project.eu
12. AEROBI European Project, http://aerobi.eu/.
13. I. Cheeseman and W. Bennett, "The effect of the ground on a helicopter rotor in forward flight", ARC R&M 3021, 1955.
14. J. Hayden, "The effect of the ground on helicopter hovering power required", AHS 32nd Forum, 1976.

15. K. Nonaka and H. Sugizaki, Integral Sliding Mode Altitude Control for a Small Model Helicopter with Ground Effect Compensation, American Control Conference, San Francisco, USA, June 29 - July 01, 2011.
16. D. Griffiths and J. G. Leishman, A study of dual-rotor interference and ground effect using a free-vortex wake model. In Proc. of the 58th Annual Forum of the American Helicopter Society, Montreal, Canada, 2002.