Preliminary Design of a Remotely Piloted Aircraft System for Crop-Spraying on Vineyards



(Article begins on next page)

# Preliminary Design of a Remotely Piloted Aircraft System for Crop-Spraying on Vineyards

Nicoletta Bloise
*Politecnico di Torino*
*Department of Mechanical and Aerospace Engineering*
Torino, Italy
nicoletta.bloise@polito.it

Manuel Carreño Ruiz
*Politecnico di Torino*
*Department of Mechanical and Aerospace Engineering*
Torino, Italy
manuel.carreno@polito.it

Domenic D'Ambrosio
*Politecnico di Torino*
*Department of Mechanical and Aerospace Engineering*
Torino, Italy
domenic.dambrosio@polito.it

Giorgio Guglieri
*Politecnico di Torino*
*Department of Mechanical and Aerospace Engineering*
Torino, Italy
giorgio.guglieri@polito.it

***Abstract*—This paper describes the preliminary design of an innovative concept rotary-wing Unmanned Aircraft System (UAS) for precision agriculture and aerial spraying applications. Aerial spraying of plant protection products and pesticides shows open challenges in terms of performance and regulatory requirements. In particular, the focus here is on highlighting the advantages of the proposed solution in performing precise and expeditious interventions, coping with the spray drift problem (i.e. minimization of drift). Flight performances and agronomists' requirements are combined to define the mission and the aerial vehicle and spray system design.**

***Keywords*—*Precision agriculture, Unmanned aircraft systems, Spray systems, Rotor aerodynamics, CFD, AI.***

## I. Introduction

Demographic increase, natural resources scarcity, climate changes and food waste are the main factors that apply pressure on agriculture to meet the needs of the future, following the modern concept of Agriculture 4.0. This evolution is possible thanks to the maturity of Precision Agriculture techniques in combination with Internet Of Things (IOT) and Big Data science. More and more sophisticated devices and robotic systems enable safer farming as they become increasingly efficient, profitable, and sustainable. In particular, the use of Unmanned Aircraft System (UAS) technology is growing in this sector, partially replacing conventional technologies for accurate mapping, fast operations and high levels of precision, regardless of the rough nature of terrain and/or obstacles.

The most common UAS applications (also known as RPAS - Remotely Piloted Aircraft Systems, improperly called drones) are generally discussed in Ref. [1], which focuses on methods and technologies, summarizing their advantages and disadvantages. In consequence of technological and regulatory issues, crop spraying appears less frequently than the other two most common applications that can be carried out with UASs, that is survey and monitoring. Considering the several open challenges posed by aerial spraying of Plant Protection Products (PPP), we decided to analyse this kind of operation. The great advantages of crop management and control using RPAS are the lower operator exposure and the improvement in terms of precision, timeliness and cost. The reference scenario for the present study is the vineyard, since this cultivation is ideal to evaluate the efficiency of precision agriculture and it is characterized by sloped terrain (hostile environment), usually muddy soils and narrow rows (complex and variable operating environments).

Most studies on spray applications focus on rice cultivation and paddy fields [2,3] where droplet distribution control is not so strictly fundamental for an efficient crop handling. Conversely, the main goal of our research is proposing an innovative UAS design able to perform precision operations, minimizing the spray drift problem. Thanks to a collaborative study between various scientific areas, a dedicated spray system can be designed, and possible mission modes are envisaged. In Refs. [4,5,6,7,8,9,10], crop spraying missions are considered and developed with emphasis on the spray system. In addition, droplet deposition on the targeted surface is also analysed using laboratory and/or field testing.

In accordance with the project's concept, spray applications should be as autonomous as possible in terms of control and precision crop management. To this purpose, many studies using deep learning approaches in agriculture have been carried out in recent years, as shown in [11,12,13,14]. In particular, the use of Artificial Intelligence will significantly improve the quality of production, by reducing the response time and the environment impact, and will also help to generate optimal UASs trajectories. A robust guidance and control algorithm combined with Wireless Sensor Networks will guarantee to visit all plants that need PPP or any other operations.

In order to precisely assess the UAS spray system, several CFD simulations have been performed. In these simulations different fluid flow characteristics have been analysed to decide on the positioning of the spray nozzles. As shown in [32], one of the typical design drivers is to avoid the spray drift caused by the formation of a horseshoe vortex in the quadcopter wake. However, in our application the horseshoe vortex might be in fact beneficial to ensure a homogeneous spray over the whole plant and not just on the top. A preliminary analysis was carried out to check the validity of our hypotheses and to propose a test matrix specifying conditions and parameters for an experimental campaign.

The paper is organized as follows. In Section II, we propose a preliminary UAS design for agricultural applications. Then, spray application modes and related mission planning tools are described in Section III. Section IV contains an aerodynamic analysis and key results. Finally, in

Section V, our conclusions and future work developments are discussed.

## II. PRELIMINARY UAS DESIGN

Experimental testing is extremely important in the conceptual design of UASs, especially when unconventional weather conditions are considered. Here we report on the vehicle preliminary design based on mission requirements and we propose a possible solution for an optimal crop-spraying system.

### *A. Experimental testing on UAS propulsion system*

Wind tunnel tests for isolated rotor and full vehicle UAS were performed by Russell et al. [15] at NASA Ames research centre. This work provides important experimental data to assess UAS performance considering standard atmosphere (ambient temperature and sea level altitude) and wind conditions. Unfortunately, limited data on UAS performance are available concerning unconventional atmosphere conditions, including high altitude and temperature effects on overall system performance. Moreover, standard test protocols for propulsion system testing of UAS are still missing and manufacturers usually perform on-site tests to assess the vehicle overall performance. To fill the gap and provide high quality set of data, our research group has been involved in experimental testing of propulsion systems for UAS vehicles in a climate-controlled environmental simulator. Temperature and pressure effects on propeller and quadrotor thrust capabilities were investigated inside terraXcube [16], an innovative climatic-hypobaric chamber where desired atmospheres are simulated for industrial testing. Preliminary experimental data focused on the isolated rotor performance were reported in [17], while additional measurements on propeller and full vehicle thrust, torque and power coefficients were published in [18]. High altitudes (low density and temperature) are responsible for low Reynolds numbers conditions, which worsen aerodynamic performances due to the presence of laminar separation bubbles on propellers blades [19]. The overall effect is a reduction of the thrust coefficient so that high motor speed and electrical power are required for a desired thrust value (i.e. hover thrust). Moreover, air temperature also affects the electrical characteristics of UAS vehicles. As an example, the no-load current of brushless motor increases when the surrounding air temperature is reduced. At the same time, the electric motor and electronic speed controller resistances are also affected by temperature, showing high values and thus deteriorating the motor efficiency, as temperature increases.

The experimental testing of the propulsion system for UAS applications is a relevant step in vehicle design and sizing, as simple predictive methods estimating propeller thrust and power (i.e. Blade Element Momentum Theory) are usually not applicable due to their limitations in describing the 3D effects that characterize propellers at low Reynolds number conditions. At the same time, experimental data allow the validation of Computational Fluid Dynamic (CFD) methods when complex aerodynamic fields are considered. In this way, an optimal UAS design capable of leveraging propeller downwash with a dedicated spraying system for agriculture applications is possible.

### *B. UAS conceptual design*

The definition of technical requirements and components for the design of a UAS with a Maximum Take - Off Weight (MTOW) smaller than 25 kg is proposed starting from an agricultural UAS market analysis, which is essential to define general design characteristics and performances. First of all, we carried out a trade-off analysis comparing quadrotors and hexarotors. The solution with four rotors is here considered as the best choice for simplicity and reliability (robustness against failures), good manoeuvrability and reduced aerodynamic interaction between rotors in advanced flight. The carbon frame selected for the aerial vehicle is produced by Gryphon Dynamics. Thanks to detailed information concerning propellers available in Ref. [20], we selected a P30X15 T-Motor propeller combined with a P80 motor. Furthermore, the Li-Po battery must have sufficient capacity to provide an acceptable flight time considering its relevant weight fraction (about 20% of Maximum Take-Off Weight). For the present project, a battery with a capacity of 22000 mAh is adopted, with 12 cells in series, giving a maximum output voltage of 44.4 V. The estimated endurance for an aerial vehicle with a structural mass of less than 15 kg plus 10 kg of payload mass (the spray system mass that decreases with spraying the PPP) is on average 23 minutes, with a maximum speed of 14 m/s and an efficacy of 6.2 g/W. Thus, the size and main performances of the UAS have been obtained and, considering the meters of row per hectare that characterize a vineyard, it was possible to define the maximum area that can be overflown with a single battery charge and the spray mode applications.

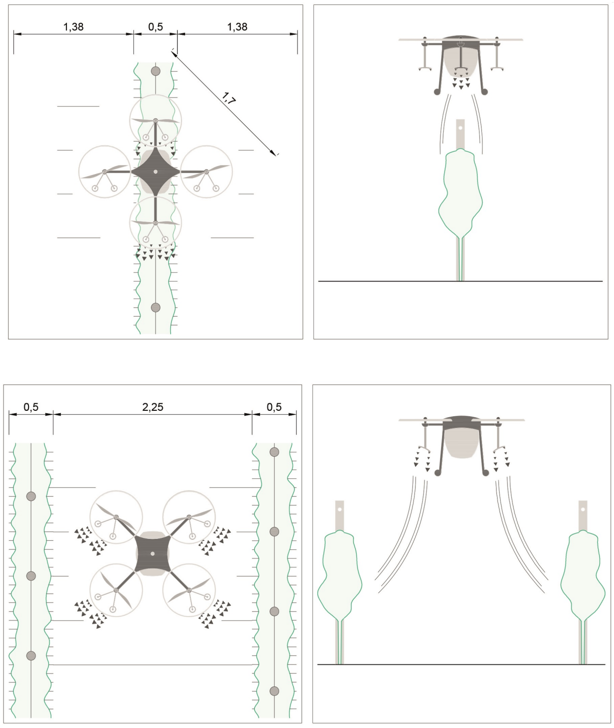
The spray system is constituted by a pump, electronic valves, tube connectors, nozzles and a dedicated controller. The nozzles position and other parameters, such as the charge pressure and duty cycle of the pump, the nozzles diameters in combination with flight velocity and altitude, air speed, air temperature and humidity, are fundamental to minimize the spray drift problem. In addition to the UAS requirements, a list of mission requirements is necessary to identify mission limits, such as wind speed constraints. In addition to a robust guidance, navigation and digital control system for the UAS, the spray system is equipped with a specific controller to switch on and off individual nozzles.

## III. SPRAY APPLICATION MODES

A graphical representation is used to explain our concept of spray application modes. Fig.1 represents two possible configurations of UAS architecture, which we define as cross configuration and X configuration. These two designs can be adapted to spray applications taking into account realistic dimensions of the vehicle and of the vineyard. The first scenario involves the overflight of the vineyard row using only four nozzles, in order to exploit at best the downwash of rotors #1 and #3. Anyway, the spray controller shall be able to open nozzles under rotors #2 and #4 in case of changing wind heading and sideslip with respect to the forward speed vector. In the second mode, the UAS flies over the centre line section of two neighbouring rows of the vineyard, spraying two rows at the same time. The purpose is to exploit vortices that are generated under the rotors at certain advance ratios and height above plants and soils. Optimizing this solution is slightly complicated, but large lateral vortices can help to spray the entire plants surface in the lower part also, where bunches of grapes usually reside.

These hypotheses shall be confirmed by CFD analyses and laboratory tests varying all concerned data, such as vertical and radial nozzles position, altitude and forward speed, type of nozzles and spray system pump pressure.

a)




b)

Fig. 1 Two spray application modes in vineyards with different UAS architecture a) cross configuration, b) X configuration

### *A. Pattern recognition to target a guidance algorithm*

The proposed solution for these spray application modes exploits an innovative conceptual design based on guidance algorithm combined with Artificial Intelligence (AI) methods. In an initial mapping phase, the UAS will collect a set of images that will be processed for reconstructing the area of interest and for creating prescription maps with the help of an agronomist. From these maps, a path planning and crop spraying management can be developed using AI algorithms.

In particular, we propose a method based on Convolutional Neural Network (CNN), a class of deep neural networks, which shows a great success in various applications in the field of pattern recognition. LetNet-5, the pioneering 7-level convolutional network, was designed by Le-Cun in 1998 and it remains one of the most popular [21]. Since then, the computing power and size of datasets has significantly increased, ImageNet [22] being probably the best example. In 2012, during the ImageNet competition, the vanishing gradient problem was solved by Alex Krizhevsky using the function ReLu in his proposed networks, named Alexnet [23], which originated from the LeNet network. In our project, the structure of AlexNet will be used once the images of the vineyards have been collected. The main objective is training a neural network capable of autonomously classifying which plants need a timely intervention. Nowadays, one of the biggest threats in vineyards is a type of grapevine trunk disease, named Esca. Esca symptoms are chlorotic and necrotic interval spots of the leaves, edged with yellow or red, as described in [24]. To this purpose, the differentiation between diseased and healthy plants may be sufficient and it can be simply obtained using a visible camera, but combining multi spectral channels also, the research could potentially be extended to other specific vegetation indices that aim to highlight the plant features.

Maps resulting from the AI technique provide important inputs for the development of UAS path planning. In fact, the plants requiring PPP according to the data contained into the map are viewed such as waypoint positions that must be crossed by the UAS trajectory. To this aim, we plan to introduce the Travelling Salesman Problem (TSP) in order to determine an optimal sequence of visits to the target plants, [25]. This optimization aims at obtaining the shortest trajectory while ensuring the visit of a set of waypoints. The objective function of this optimization could also be related to the UAS energy consumption, following the work in [26].

Finally, real and simulated scenarios will be certainly limited by obstacles or environmental constraints that requires a dedicate guidance algorithm. A path planning in a tri-dimensional environment based on graph-search algorithms, like A* and Theta*, are the most important solutions in this field [27]. These algorithms suggest several trajectories, each one with a different weight in terms of distance or consumption. Minimizing the operating power supply is the only way to optimize the UAS endurance, which, as mentioned above, is particularly low.

### *B. UAS and spray control system*

The result of the guidance algorithm, together with on-board sensors for the navigation system, contains essential data for the UAS control system. The control system, even more so in precision agricultural applications, must be able to guarantee excellent performance and stability, and robustness against external disturbances and bounded noises. In particular, the application to vineyards that are characterized by narrow rows with different orientations and mutual distances requires a scrupulous spray application.

Despite the non-linear dynamics of quadrotors, the use of linear control techniques such as Proportional-Integral-Derivative (PID) controllers is common. Several works study other complex control architecture for this application, as in [28], where a robust Model Predictive Control (MPC) is proposed and in [29], where a comparison between LQR and PID is done.

In addition, spraying products along the entire height and depth of a row requires both the UAS and the spray control. The on-board Global Positioning System (GPS) allows to follow pre-planned trajectories by guidance system and to read the spraying parameter from prescription maps. To this purpose, separate spraying control signals to the spray system are necessary for an a precise feedback control. Thus, to enrich work opportunities, the introduction of variable-rate spraying is a further needed upgrade. A Pulse Width Modulation (PWM) variable sprayer can be designed with a PID control, as described in [30], to control the flow rate varying the valve duty cycle at a given frequency.

A fundamental aspect to robustly design both controllers is keeping in to account the wind gust speed as an external disturbance. In fact, the choice of the nozzle is not the only variable that is used to minimize the particle drift problem. Other aspects, such as wind speed and direction, air temperature and physical barriers also come into play. To accomplish mission objectives, different ground sensors embedded in a wireless sensor network are required, allowing the monitoring of the vineyard environmental conditions in real time. A weather station, consisting of an anemometer, a barometer and a pluviometer, is also needed to optimize irrigation and treatments.

## IV. Aerodynamics: Modelling and Results

CFD analysis is essential to fulfil one of the most important goals of our study, that is the reduction of spray drift. The idea is to exploit the downwash of the multi-rotor UAS, positioning nozzles where the airflow is most energetic and thus maximizing the spraying over the plants, as studied in [20,31,32].

To assess PPP concentration and particles path in the wake of the rotor, several passive scalar sources have been introduced at different radial and vertical positions to study the effect of nozzle positioning. Each transport equation corresponding to different passive scalars have been studied without including a diffusion term to analyse particles convection only. Fig.2 shows that the tracer tends to be more focused when the nozzles are positioned near the blade root. On the other hand, the outer location produces a high value of the passive scalar concentration at large radial locations due to the increasing local speed of the blade with the radial position. These preliminary results suggest that positioning the nozzle near the blades root would favour the cross-configuration spray mode, whereas an outer location would favour the X configuration spray mode.

Apart from nozzle positioning relative to the rotor, according to [32] the two most critical parameters affecting the spray drift are the advance flight speed and the altitude. Preliminary simulations show that forward speed plays a determinant role in the formation of horseshoe vortices that are directly responsible for particle drifting. Fig.3 shows the break-down of the helical vortex and vortex sheet into the previously mentioned horseshoe vortex for an advance speed of 5 m/s, whereas no such effect is noticed at 1 m/s. Further analyses are currently under way including different combinations of advance velocities and flight altitudes.

The interaction between different rotor wakes, whose effect will be noticeable as the rotors spacing decreases, has been initially addressed to by simulating a full quadcopter in X configuration in advance flight at 5 m/s. Apart from strong periodic oscillations in thrust and torque of the rear rotors, the flowfield behind the quadcopter is qualitatively consistent with the observations done in the single rotor analysis. Figure 4 shows the formation of a horseshoe vortex behind each rotor. This fact shows that, yet more complex, the wake of the quadrotor is also characterized by the formation of horseshoe vortices that will definitely cause the drifting of particles in a helical motion. In addition, these vortices persist for several rotor diameters behind the quadcopter, as shown in figure 5a, which represents the vorticity magnitude in a plane 2 m behind the rear rotors. It is clear that the horseshoe vortices are still a dominant structure in the flow field. Figure 5b represents a detailed view of the vorticity magnitude superimposed to projected velocity vectors and it also shows that the helical motion is preserved.

The aim of these analyses is understanding which ranges of the considered parameters favour the formation of horseshoe vortices that, depending on the configuration, should be avoided or might be used to improve the spray dispersion. After the validation of CFD simulations in the experimental campaign, specific solutions will be proposed to optimize particle spraying. Among these solutions, the ideal one would be to exploit just the wake of the quadrotor to ensure a homogenous and efficient spray. However, if this would not possible, the inclusion of devices designed to deflect the particles laterally may also be considered.

a)

b)

c)

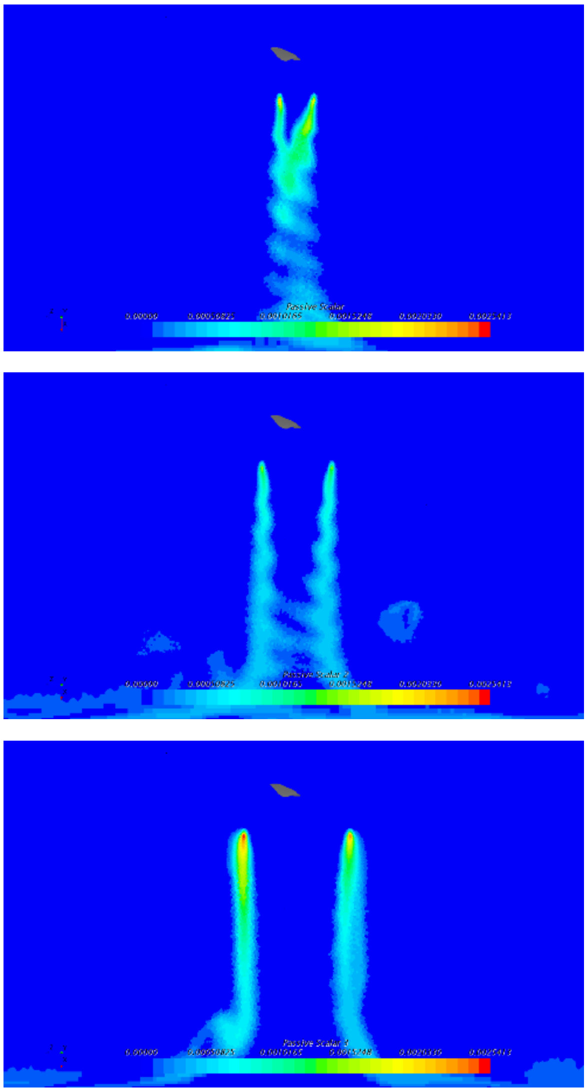
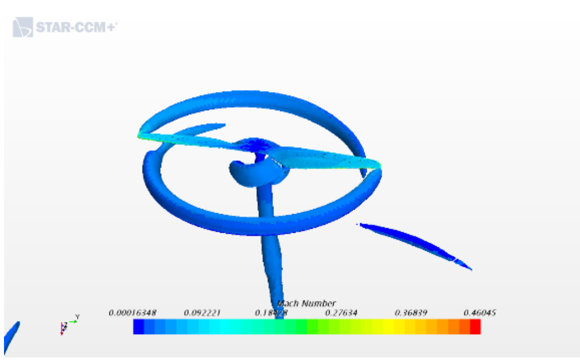
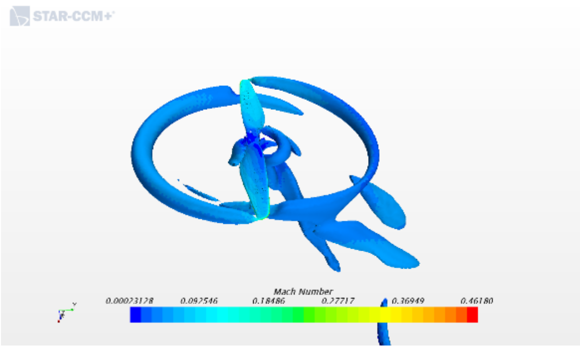


Fig. 2 Passive scalar distribution with source at a)25% of the Radius b) 50% of the Radius and c)75% of the Radius.

a)






b)

Fig. 3 Q-Criterion iso-surface colored with Mach Number a) Advance speed 1m/s, b) Advance speed 5m/s.

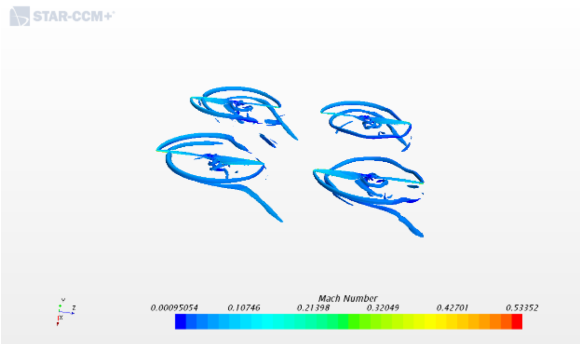
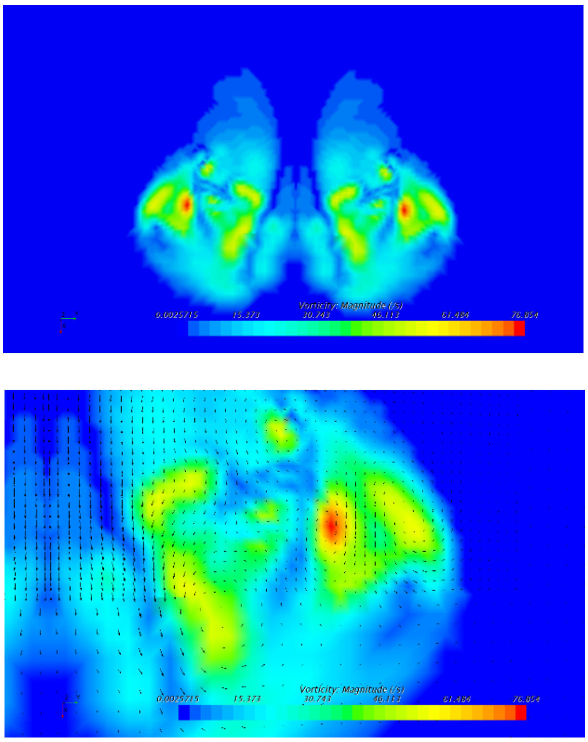



Fig. 4 Full multicopter.Q-Criterion iso-surface colored with Mach Number advance speed 5m/s.



a)

b)

Fig. 5 Vorticity magnitude in plane z=3.5m.a) Full wake, b) Detailed view with velocity vectors projections in the plane.

## V. Conclusions and Future Work

We presented a preliminary design solution for a UAS capable of performing accurate and efficient spray dispersion on vineyards.

Several parameters and aspects are considered to improve the operations in terms of spray drift and grape quality. In particular, as discussed in the previous section, the key point is the combination between comprehensive aerodynamic analysis and UAS design, giving specific attention to the spray system, the nozzle position and the flight parameters, such as flight speed and altitude. It is therefore essential to continue this analysis, performing the design of a robust guidance and control algorithm that may fulfil the mission requirements.

The next step is organizing experimental (indoor laboratory) demonstrations and field tests to validate the numerical simulations, as performed in [31, 32]. Once the reliability of CFD simulations in this framework is assessed, numerical predictions could be used to define a test matrix where relevant parameters, such as flight speed and altitude, different nozzle types, vertical and radial position of nozzles, vary within significant ranges for studying droplet deposition. Experimental tests and detailed CFD simulations can be selected within the range limits of the test matrix used to optimize the UAS design.

## Acknowledgment

This research was funded by the project “New technical and operative solutions for the use of drones in Agriculture 4.0” (Italian Ministry of University and Research - Progetti di Ricerca di Rilevante Interesse Nazionale – PRIN 2017, Prot. 2017S559BB). In addition, we thank Matteo Scanavino for his support for experimental testing on UAS propulsion systems.

## References

[1] D.C. Tsouros, S. Bibi and P.G. Sarigiannidis, “A Review on UAV-based Applications for Precision Agriculture”, Information, Vol. 10, No. 11, pp. 1-26, 2019

[2] M.N.A. Kharim, “Droplet deposition density of organic liquid fertilizer at low altitude UAV aerial spraying in rice cultivation”, Computers and Electronics in Agriculture, Vol. 167, 2019

[3] S. Chen, “Effect of Droplet Size Parameters on Droplet Deposition and Drift of Aerial Spraying by Using Plant Protection UAV”, Agronomy, Vol. 10, No. 2, 2020

[4] W-C Qin, “Droplet deposition and control effect of insecticides sprayed with an unmanned aerial vehicle against plant hoppers”, Crop Protection, Vol. 85, pp. 79-88, 2016

[5] S. Wen, “Design and experiment of a variable spray system for unmanned aerial vehicles based on PID and PWM control”, Applied Sciences, Vol. 8, No. 12, 2018

[6] Y. Zhang, “Near ground platform development to simulate UAV aerial spraying and its spraying test under different conditions”, Computers and Electronics in Agriculture, Vol. 148, pp. 8-18, 2018

[7] J. Martinez-Guanter, “Spray and economics assessment of a UAV-based ultra-low-volume application in olive and citrus orchards”, Precision Agriculture, Vol. 21, pp. 226-243, 2020

[8] X. Xue, “Develop an unmanned aerial vehicle based automatic aerial spraying system”, Computers and electronics in agriculture, Vol. 128, pp. 58-66, 2016

[9] F. Ahmad, “Effect of operational parameters of UAV sprayer on spray deposition pattern in target and off-target zones during outer field weed control application”, Computers and Electronics in Agriculture, Vol. 172, 2020

[10] G. Wang, “Field evaluation of an unmanned aerial vehicle (UAV) sprayer: effect of spray volume on deposition and the control of pests and disease in wheat”, Pest Management Science, 2019

[11] WAGHMARE, Harshal, “Detection and classification of diseases of grape plant using opposite colour local binary pattern feature and machine learning for automated decision support system.”, 3rd international conference on signal processing and integrated networks, pp. 513-518, 2016

[12] KUSSUL, Nataliia, “Deep learning classification of land cover and crop types using remote sensing data”. IEEE Geoscience and Remote Sensing Letters, pp.778-782, 2017

[13] KAMILARIS, Andreas, “Deep learning in agriculture: A survey. Computers and electronics in agriculture”, 147: 70-90, 2018

[14] BAH, M. Dian, “Deep learning based classification system for identifying weeds using high-resolution UAV imagery.”, Science and Information Conference. Springer, pp. 176-187,2018

[15] C. Russell, “ Wind tunnel and hover performance test results for multicopter UAS vehicles”, AHS 72nd Annual Forum, West Palm Beach, USA, 2016

[16] EURAC Research, “terraxcube – home page”, 12 Aug. 2020: https://terraxcube.eurac.edu/

[17] Scanavino, M., Vilardi, A. and Guglieri, G., “An Experimental Analysis on Propeller Performance in a Climate-controlled Facility”, Journal of Intelligent & Robotic Systems, 2020, pp.1-13.

[18] Scanavino, M., Avi, A., Vilardi, A. and Guglieri, G., “UAS testing in low pressure and temperature conditions”, International Conference on Unmanned Aircraft Systems (ICUAS), Athens, Greece, 2020.

[19] Lorefice, L., Pralio, B., Quagliotti, F.,“Fluorescent Oil Visualization Technique Applied to 2D Airfoils at Very Low Reynolds Numbers”, 11th International Symposium On Flow Visualization, University of Notre Dame, Notre Dame, Indiana, USA, 2004.

[20] Y. Lei, and H. Wang, “Aerodynamic Optimization of a Micro Quadrotor Aircraft with Different Rotor Spacings in Hover”, Applied Sciences, Vol. 10, No. 4, 2020

[21] LECUN, Yann, “Gradient-based learning applied to document recognition. Proceedings of the IEEE, 1998, 86.11: 2278-2324.

[22] DENG, Jia, “Imagenet: A large-scale hierarchical image database”, IEEE conference on computer vision and pattern recognition, pp. 248-255, 2009

[23] KRIZHEVSKY, Alex, “Imagenet classification with deep convolutional neural networks.”, Advances in neural information processing systems, p. 1097-1105, 2012

[24] LECOMTE, Pascal,.” New insights into esca of grapevine: the development of foliar symptoms and their association with xylem discoloration.” Plant Disease, 96.7: 924-934, 2012

[25] APPLEGATE, David L.,“The traveling salesman problem: a computational study”,Princeton university press, 2006

[26] MORBIDI, Fabio, “Minimum-energy path generation for a quadrotor UAV”, IEEE International Conference on Robotics and Automation, pp. 1492-1498, 2016

[27] DE FILIPPIS, Luca, “Path planning strategies for UAVS in 3D environments”, Journal of Intelligent & Robotic System, pp.247-264, 2012

MAMMARELLA, Martina,“Waypoint Tracking via Tube-based Robust Model Predictive Control for Crop Monitoring with Fixed-Wing UAVs”, IEEE International Workshop on Metrology for Agriculture and Forestry, pp. 19-24, 2019

[28] BOUABDALLAH, Samir, “PID vs LQ control techniques applied to an indoor micro quadrotor”, IEEE/RSJ International Conference on Intelligent Robots and System, pp. 2451-2456, 2004

[29] WEN, Sheng, “Design and experiment of a variable spray system for unmanned aerial vehicles based on PID and PWM control”, Applied Sciences, 8.12: 2482, 2018

[30] Q. Tang, R. Zhang, L. Chen, W. Deng, M. Xu, G. Xu, L. Li, and A. Hewitt, “Numerical simulation of the downwash flow field and droplet movement from an unmanned helicopter for crop spraying”, Computers and Electronics in Agriculture, Vol. 174, 2020

[31] S. Wen, J. Han, Z. Ning, Y. Lan, X. Yin, J. Zhang, and Y. Ge, “Numerical analysis and validation of spray distributions disturbed by quad-rotor drone wake at different flight speeds”, Computers and Electronics in Agriculture, Vol. 166, 201