POLITECNICO DI TORINO
Repository ISTITUZIONALE

Customized Design and Preliminary Testing of a Precision Spraying Drone for Vineyard Applications

Original
Customized Design and Preliminary Testing of a Precision Spraying Drone for Vineyard Applications / Primatesta, S., Enrico, R., Ruiz, M.C., Bloise, N., Guglieri, G.. - (2025), pp. 882-889. (2025 International Conference on Unmanned Aircraft Systems (ICUAS) Charlotte, NC (USA) 14-17 May 2025) [10.1109/icuas65942.2025.11007801].

Availability:
This version is available at: 11583/3018333 since: 2026-11-23T14:08:01Z

Publisher:
IEEE

Published
DOI:10.1109/icuas65942.2025.11007801

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright
IEEE postprint/Author's Accepted Manuscript

©2025 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collecting works, for resale or lists, or reuse of any copyrighted component of this work in other works.

(Article begins on next page)

28 November 2026

Customized Design and Preliminary Testing of a Precision Spraying Drone for Vineyard Applications

Stefano Primatesta[1], Riccardo Enrico[1], Manuel Carreño Ruiz[1], Nicoletta Bloise[1], Giorgio Guglieri[1]

***Abstract*— Unmanned Aircraft Systems (UAS) for spraying plant protection products are an emerging technology aimed at enhancing the efficiency and sustainability of agricultural production. This paper presents the design and development of an innovative UAS-based spraying system for targeted and precise spraying applications in vineyards.**

The proposed solution introduces several innovations compared to state-of-the-art technologies. Nozzle positioning is optimized through Computational Fluid Dynamics simulations and wind tunnel tests to improve the control of sprayed droplets. The system reduces the sloshing effect, i.e. the oscillation of the onboard liquid, through a tank with internal baffles and with the adoption of a sloshing-aware control strategy. Precision spraying is further enhanced by a methodology for vineyard row tracking and following.

Although the system is under development, this article outlines the architecture, the design methodology, and presents some preliminary results. A first prototype has been successfully developed and preliminarily tested, demonstrating the feasibility of the project and validating some of the key design concepts, while further developments are ongoing to implement all system functionalities.

I. Introduction

In the last decades, Unmanned Aircraft Systems (UAS) have become widespread thanks to their flexibility and adaptability in conducting several applications, in both military and civil fields [1]. In particular, one of the most promising areas is their application in agriculture, embracing the concept of Precision Agriculture and Agriculture 4.0 [2]. UAS have been used to provide monitoring and data collection, enabling precise crop management, pest and disease detection, soil health analysis, and environmental assessment. The proper use of UAS allows to improve productivity, optimize resource utilization, and reduce the environmental impact, ensuring healthy and effective agricultural production. Another favorable aspect of the agricultural use of UAS is its application in non-critical environments from a regulatory point of view: agricultural lands are generally sparsely populated areas, distant from urban areas and, consequently, with few operational constraints [3].

Recently, however, UAS have also been used to carry out plant protection product treatments in agriculture, offering a more precise and efficient alternative to traditional methods. The proper use of drones for spraying treatments can bring several benefits: reduction of product and water, lower environmental impact, adaptation to any type of terrain, and improvement of working conditions and health of farmers [4], [5].

Despite the clear advantages of UAS for spraying plant protection products, current European legislation restricts the aerial pesticide application [6]. These restrictions were originally intended for helicopters and other large aircraft, not for UAS. Nonetheless, exceptions are allowed if it can be demonstrated that aerial spraying results in limited drift and is comparable to traditional ground-based spraying techniques. However, these regulatory limitations are absent in many non-European countries, which has contributed to the widespread adoption of UAS-based solutions for pesticide spraying in Asia.

The obvious advantages introduced by UAS have led several manufacturing companies to propose solutions on the market. Among the main ones are DJI, XAG, and ABZ Innovation, to name a few. However, the solutions proposed on the market are suitable for extensive crops (e.g., corn, rice, soy, etc.) in which treatments require the complete coverage of the crop without particular needs for targeted and precise treatments for each individual plant. In fact, the solutions on the market are unsuitable for vineyards, orchards, and other crops where a targeted treatment is required that must be carried out precisely on the row or, in some cases, on the single plant.

In this regard, this paper introduces a Proof of Concept (PoC) of a UAS for spraying plant protection products with the aim of ensuring targeted and precise treatments. The PoC under development presents several unique and innovative features compared to state-of-the-art solutions.

The spraying system is optimized through Computational Fluid Dynamics Simulations (CFD) and tunnel tests: the choice of the nozzle and its positioning, in addition to the definition of optimal operating conditions, allows for greater control of the sprayed droplets.

The spraying system has been designed to reduce the sloshing effect, i.e. the swinging of the liquid on board, which can have unwanted effects on the dynamics of the drone and, consequently, on the precision of flight and spraying operations. In particular, the sloshing effect is limited both passively and actively: by design thanks to a tank with perforated baffles and by an automatic control system that provides optimal control considering forces and momentum induced by the sloshing.

Another contribution of the proposed UAS-based spraying system applied to vineyards is the implementation of an algorithm able to track and follow vineyard rows, ensuring a precise flight over plants.

[1]S. Primatesta, R. Enrico, M. Carreño Ruiz, N. Bloise, and G. Guglieri are with the Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy. Corresponding author: Stefano Primatesta (e-mail: stefano.primatesta@polito.it)

Specifically, this paper describes the overall architecture of the developed PoC, reporting the main contributions and preliminary results. As detailed in the rest of the manuscript, some innovative features are still under study and implementation. However, this paper represents an important contribution to the literature by collecting the challenges, requirements, and some preliminary results for the development of an innovative spraying system with the potential to offer performances superior to state-of-the-art technologies.

The research group has already conducted several works in this research domain, contributing with several publications regarding the design and optimization of the spraying system, and the analysis of the spraying operations to have adequate control of the sprayed droplets [7], [8], [9], [10], [11], [12], [13]. However, this paper goes beyond the previously presented works by presenting the architecture adopted in the PoC, the design and development of the prototype, and some preliminary results regarding the benefit of the anti-sloshing tank. Although the project is currently ongoing, the paper is of interest and innovative for the topic of UAS-based spraying in precision agriculture.

The rest of the paper is organized as follows. Section II describes the M6 drone, used as a reference aerial platform. Section III presents the spraying system, detailing the main architecture and the design process to optimize the operations. Section IV introduces navigation and control, presenting the sloshing-aware control architecture and reporting the preliminary simulation results of the vineyard row tracking methodology. Finally, Section V draws our conclusions with a broad discussion on future works.

II. M6 Drone: Platform Overview

The reference aerial platform selected for designing and developing the UAS-based spraying system is the M6 drone developed by MAVTech. This aerial platform has been selected for its payload capacity, flight range, and size suitable to carry a 10-liter tank. Furthermore, both the drone and the tank capacity were chosen to have a MTOM (Maximum Take Off Mass) of less than 25 kg, a requirement to easily carry out experimental activities in the Open category defined by EASA without too many regulatory constraints.

The M6 drone is equipped with a PX4 Autopilot executed on a Cube Orange installed on a Kore Carrier board. The aerial platform is modular, and easily integrated with additional sensors and hardware. Specifically, the M6 drone is integrated with: an RTK module with a dual-antenna, able to provide yaw information to the autopilot; an NVIDIA Jetson Orin NX as a companion computer, suitable to perform advanced navigation and control algorithm; an Intel Realsense D456 depth camera, to support the navigation.

The M6 drone is shown in Figure 1, while the main technical specifications are reported in Table I.

III. Spraying System Design

The spraying system has been designed and developed ad-hoc to offer essential features for an innovative spraying system, such as remote control of spraying activities and the presence of an anti-sloshing tank.



Figure 1. The MAVTech M6 drone used as a reference platform for the development of the UAS-based spraying system.

The CAD model of the spraying system and tank designed for the PoC prototype assembly are illustrated in Figure 2.

The general architecture of the spraying system is illustrated in Figure 3. The liquid to be sprayed is located in the tank with a capacity of 10 liter, which has a specific design to limit the sloshing effect. More details about the tank design are provided in Section III-B. The liquid is taken through a small brushless hydraulic pump. Before reaching the two nozzles that perform the spraying, a pressure pulsation dumper and a pressure sensor are inserted into the hydraulic circuit. The pressure pulsation damper is essential to dampen pressure variations in the hydraulic circuit and to more easily maintain a constant pressure.

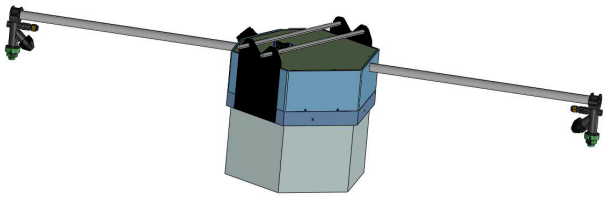
The spraying system is monitored and controlled through the use of a control board, i.e. an Arduino board. The main function of the controller board is the control and monitoring of the pressure of the hydraulic circuit. The pump is controllable through a PWM (Pulse-Width Modulation) command that is modulated to maintain a constant pressure, which is continuously measured with a pressure sensor. The closed-loop control is achieved through a simple PID (Proportional Integral Derivative) controller.

In addition, the level sensor allows the amount of liquid in the tank to be tracked. This is also useful to stop the spraying activity before the hydraulic circuit is completely empty, which could lead to damage to the hydraulic pump.

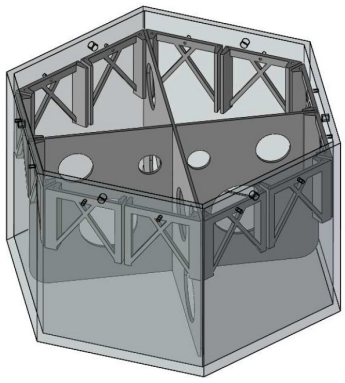
The control board has the role of managing the real-time interaction with the drone's autopilot. On the one hand,

TABLE I
MAVTech M6: technical specifications.

Diagonal Wheelbase	1400 mm
Aircraft Mass (inc. battery)	12.8 kg
MTOM	25 kg
Max Speed	12 m/s (limited)
GCS Transmission Range	Up to 12 km
Payload Mass	Up to 12 kg
Endurance (without payload)	Up to 30 min



(a)



(b)

Figure 2. In (a) is the CAD of the spraying system with 2 nozzles. This is the model used to construct the prototype. In (b) is the CAD of the tank equipped with two perforated baffles to limit the sloshing effect.

it sends to the drone the data on the tank level and the maintained pressure, which are also easily displayed on an LCD display. On the other hand, the autopilot is able to send a command to activate the spraying. This command is managed as an actuator by the autopilot, controllable both by the remote controller used by the UAS operator, and by the offboard module via a ROS2 topic.

The spraying system is powered by the drone battery. During the design phase, we considered the use of a dedicated battery, but to optimize space and resource management, we chose to use the drone battery. In this regard, a special plug was created both to supply power to the spraying system and for data exchange.

Figure 4 shows the layout of the components inside the spraying system. It should be noted that the compartment is watertight to preserve the devices. In addition, the control board and the LCD display are placed in an additional compartment to separate the hydraulic components from the electronic ones.

A. Spray Characterization and Optimization

The dimensioning and design of the final spraying system embedded in the prototype have been based on previous numerical simulations, wind tunnel experiments, and flight tests using the DJI Matrice 600. This commercial hexacopter, with a MTOM of approximately 14 kg—roughly half that of the final prototype—served as a reference platform for preliminary analysis. Initial flight condition assessments [14] revealed that forward speeds exceeding 3 m/s (for a system of this scale) promote the formation of coherent horseshoe vortical structures in the wake, leading to droplet entrainment and drift. Within this speed range, the rotor wake remains relatively vertical, imparting momentum to the droplets and directing them toward the vine row. In order to perform a targeted operation on vineyards, the UAS must fly in cross configuration placing nozzles only on leading and rear rotors to align the rotor wake with the vine row. Wind tunnel tests and simulations [13], [11] confirmed that positioning the nozzles below the rotors enhances deposition efficiency by leveraging the wake-induced airflow. Additionally, these studies demonstrated that wider spray angles, whether using fan or hollow-cone nozzles, exacerbate drift by allowing droplets to exit the wake region prematurely. Moreover, wider angles contribute to increased off-target deposition, as a significant fraction of droplets tends to accumulate in the inter-row region.

Two virtual testing environments were developed to evaluate different configurations and spraying conditions. A high-fidelity, computationally intensive model was implemented in the multiphysics software Simcenter STAR-CCM+ [7], while a reduced-order model was developed in MATLAB/Simulink [15]. The high-fidelity model incorporates aerodynamics, PID control, sloshing dynamics, and droplet modeling using a Lagrangian particle approach. An example of this tool showing a flight of a digital twin of the DJI Matrice 600 over a virtual vineyard at 2 m/s with 40° hollow cone nozzles located below front and rear rotors is presented in Figure 5.

The study revealed that a narrower spray angle (40°) improves on-target deposition by approximately 50% compared to a wider angle (80°). Additionally, nozzle orientation significantly influences performance; a wake-compliant orientation further enhances efficiency by an extra 10%. The on-target deposition comparing nozzles positioned below leading and rear rotors is similar. However, positioning nozzles below the rear rotors reduces the maximum drift compared to those mounted below the leading rotors. The reduced-order model, on the other hand, enables fast yet accurate spray predictions, making it well-suited for the development of advanced control algorithms.

The design of the M6 spraying system configuration follows the aforementioned considerations. Figure 3 shows how it consists of two nozzles, placed below the leading and rear rotors. The nozzle holder allows a rotation degree of freedom to adjust the orientation of the nozzle and a translation to position it below the rotor. Best practices to reduce drift and enhance deposition are to fly relatively low and slow, use reduced angle nozzles, and avoid excessively fine atomization. However, although the design of the spray system presented in this paper is based on the simulations and considerations presented in this section, the research group is planning to carry out CFD simulations and wind tunnel tests with the current design, in order to verify its effectiveness and, if necessary, provide micro-adjustments to optimize the spraying.

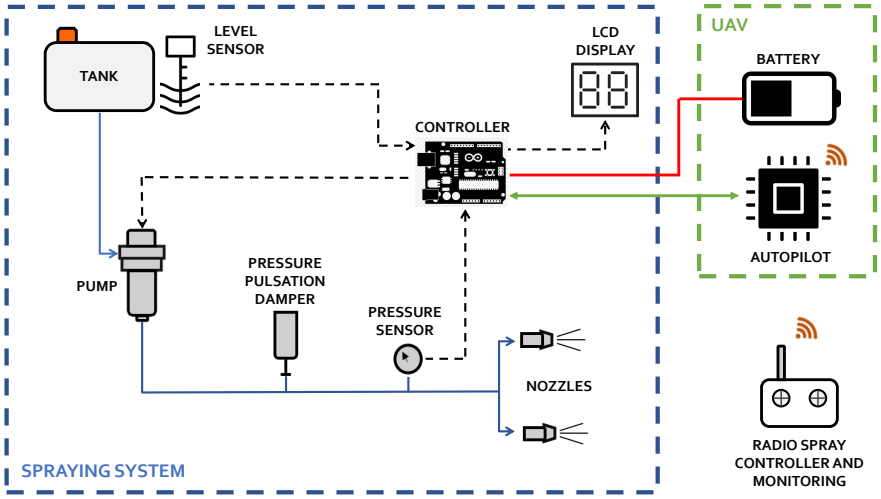


Figure 3. The main architecture of the spraying system.

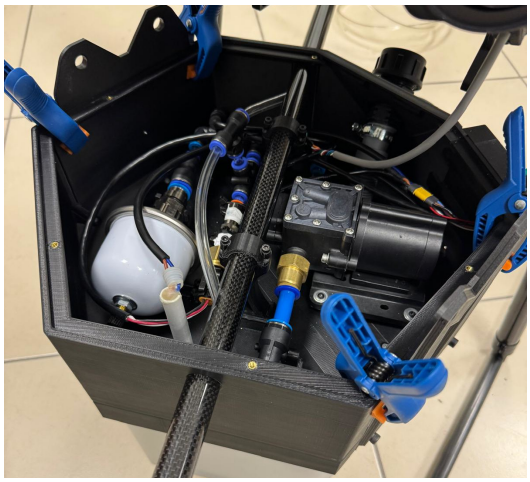


Figure 4. Internal view of the spraying system.

B. *Anti-sloshing Tank*

An essential feature of the proposed spraying system is the use of an anti-sloshing tank. The sloshing phenomenon is caused by the swinging of the liquid on board that generates forces and moments that affect the stability of the aircraft and, in the worst case, could also lead to instability.

In the application of aerial spraying, the sloshing effect causes oscillations during the flight operations that affect the precision of the spraying. Targeted and precise spraying is performed with an accurate positioning (both position and attitude) of the drone above the plant to be treated. Therefore, any disturbance affects the precision, leading to unwanted drift effects.

A simple but effective method is to insert baffles into the tank that dampen sloshing. In fact, the baffles create physical barriers that limit the freedom of motion of the liquid. The reduction of energy of the liquid causes a damping of the oscillations and the reduction of the peak values of the forces generated. Additionally, the inclusion of holes in the baffles helps to further reduce the sloshing effect: by allowing controlled fluid flow through the plates, dissipating energy, and minimizing wave reflections.

The layout and geometry of the baffles were established through a campaign of CFD simulations carried out with the open-source software OpenFOAM. The simulation methodology follows an approach based on the Navier-Stokes equations for incompressible fluids, including turbulence models (RAS - kEpsilon) and the treatment of fluid interfaces using the Volume of Fluid (VOF) method to handle the water and air phases.

Figure 6 shows the oscillations in response to an acceleration step of 2.6 m/s^2 both with and without baffles. This acceleration step is unrealistic in a real application, but it highlights the importance and effectiveness of the baffles in the tank. The force F_x corresponds to the resultant force applied to the centroid of the tank, which is rigidly attached to the drone but located away from its center of mass, thus introducing a significant disturbance.

To evaluate the actual sloshing effect, several CFD simulations have been conducted using an acceleration profile typical of a flight mission, starting from a hover condition and accelerating to a constant speed of 2 m/s. The simulations are performed at different filling levels, revealing that the worst case is at a level of about 70%, observing the highest peak value of the oscillations. Figure 7 illustrates the isolated dynamics of the sloshing effect, considering the known acceleration profile, oscillating mass, and inertial dynamics.

Even if the observed forces appear small, it should be noted that they act on an attached payload located away from the drone's center of mass, thus inducing significant disturbances that can affect flight stability. Moreover, the simulations assume a simple acceleration profile, without accounting for direction changes that may occur during real flights, which would further amplify sloshing effects along all axes, not just the x-axis.

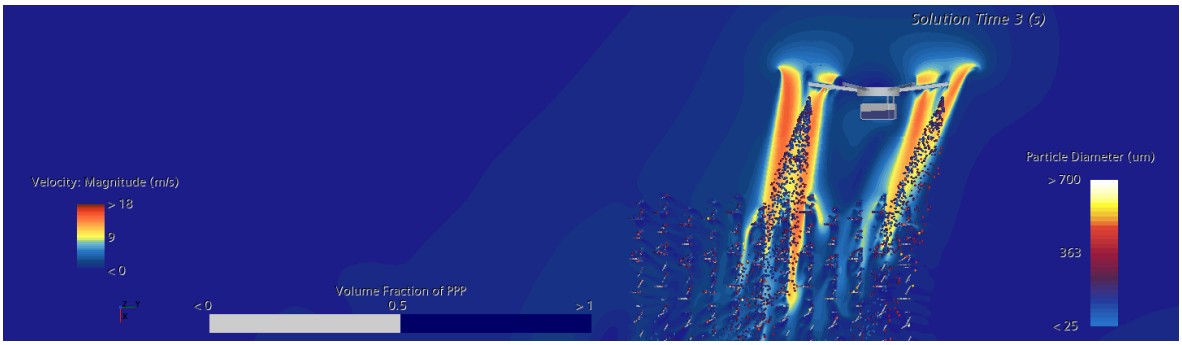
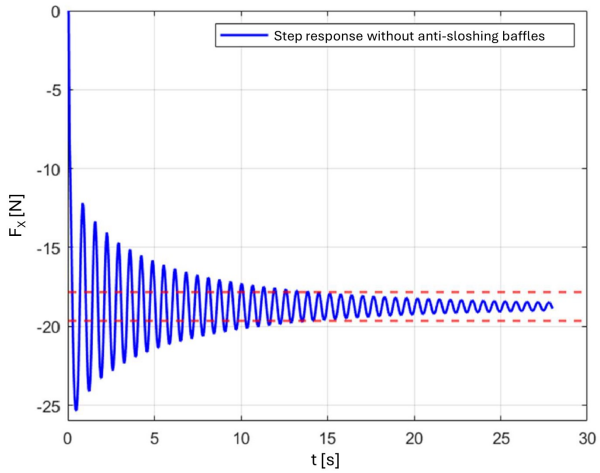
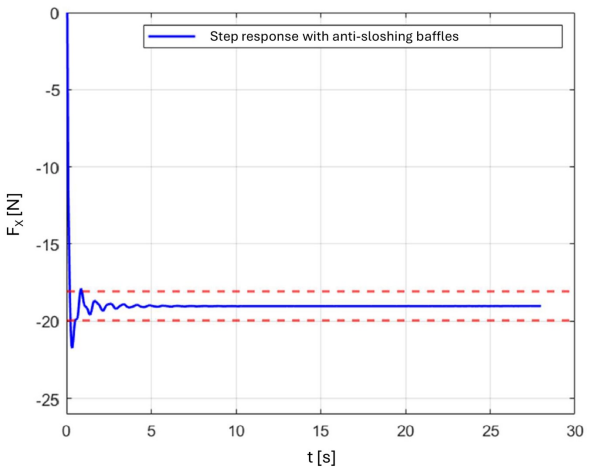


Figure 5. Virtual Spraying Operation.



(a)



(b)

Figure 6. Step response to an acceleration step of 2.6 m/s^2 without (in (a)) and with (in (b)) baffles.

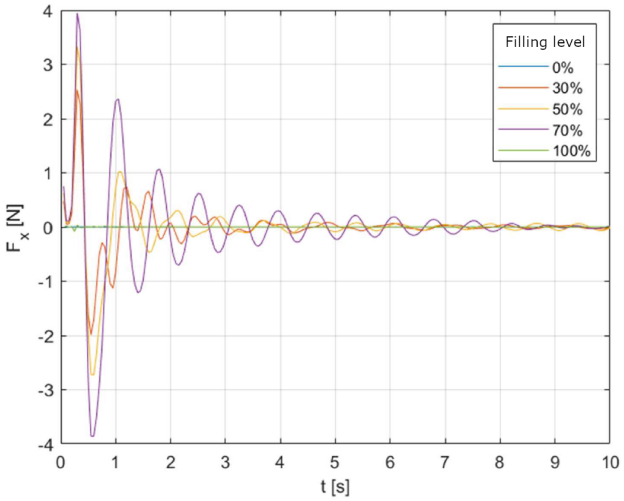


Figure 7. Results of CFD simulations with the dynamics of the sloshing effect with different filling levels. The reported sloshing dynamics is isolated, considering the known acceleration profile, oscillating mass, and inertial dynamics.

IV. Navigation and Control

To perform targeted spraying, the UAS-based spraying system should provide some advanced strategies to face the sloshing effect and guarantee a precise trajectory over the plants to be sprayed. In this section, we report some features that we consider essential for a UAS-based precision spraying system. However, as will be specified, both the sloshing-aware controller and the vineyard row tracking system are under development. For this reason, in the following paragraphs, we describe and propose the architecture of the methodology with some discussion and preliminary simulation results.

A. Sloshing-aware Controller

To address the effects of a sloshing payload, we propose a control architecture that integrates a Model Predictive Controller (MPC) with a payload dynamic disturbance estimator. As illustrated in Figure 8, the proposed architecture employs the MPC as the outer-loop controller to regulate the drone's position based on user-defined reference trajectories, while leveraging the built-in PX4 Autopilot software as the inner-loop controller.

The external estimator module operates independently from the MPC, receiving only the external disturbances as parameter variables. This modular approach, while not fully integrated with the MPC, provides flexibility in testing different types of estimation methods and allows us to focus on developing the disturbance estimation capabilities.

For real-time implementation of the MPC, we propose using `acados` [16], an open-source software package for fast embedded optimization. `acados` provides efficient code generation capabilities that allow the MPC to run at rates suitable for UAV control on companion computers such as the Raspberry Pi or NVIDIA Jetson series. The generated MPC controller communicates with the PX4 attitude controller through the uXRCE-DDS PX4-ROS2 Interface.

Many other works, such as [17], present adaptive MPC architectures that enhance robustness against external disturbances and unknown payloads. However, they do not explicitly account for the dynamics of a sloshing payload, even in a simplified form. Other works, such as [18], integrate an L1 adaptation algorithm directly into the MPC, allowing the controller to incorporate estimates of external disturbances. However, a drawback of [18] is that computation is performed offboard. In contrast, our proposed architecture implements MPC on an onboard companion computer.

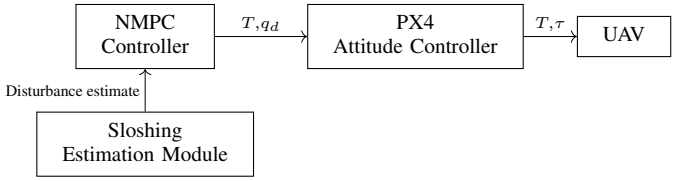


Figure 8. Block diagram of the control system with sloshing estimation.

B. Vineyard Row Tracking and Following

In a previous work [19], a vineyard-following algorithm was developed and tested in a simulation environment incorporating a point cloud derived from a real-world vineyard. The simulation was conducted in Gazebo, where the algorithm was integrated with the PX4 Autopilot using ROS 2 and evaluated in a Software-In-The-Loop (SITL) setup. The preliminary results demonstrated the ability of the approach to accurately track and follow a vineyard row under simulated conditions.

The detection and following framework is organized through ROS 2 nodes and generally comprises a detection node, a Kalman filtering node, and finally, a set of control nodes that directly interface with the PX4 Autopilot, which controls the UAV's low-level submodules (Figure 9).

The detection node employs the RANSAC algorithm to process the depth camera data. OpenCV is then used to identify the centroid position. This ensures that the detection algorithm remains computationally efficient for real-time operation and hardware implementation.

To express the position in the world frame, the output of the vineyard detection is processed by a transformation

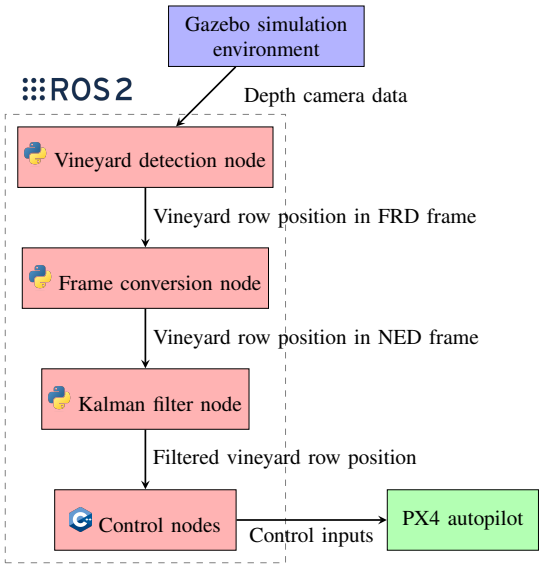


Figure 9. Flowchart showing the organization and data flow of the ROS 2 nodes.

and then a filtering node, which employs a Kalman filter algorithm. This correction data is then given to the control nodes, which are used as an interface with the PX4 Autopilot.

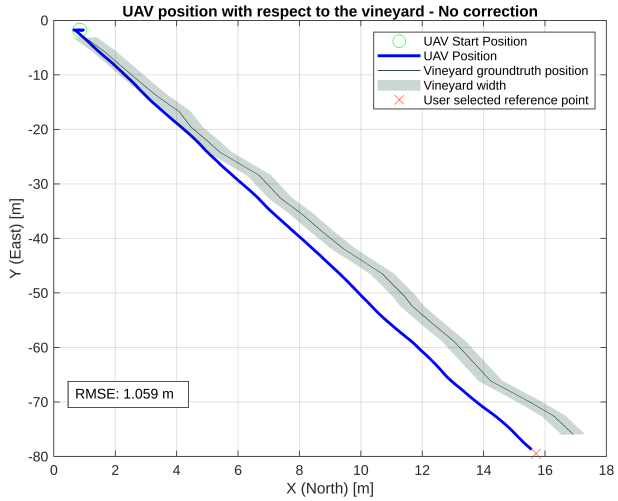
The simulation results demonstrated that the UAV navigation system, augmented with detection and correction algorithms, significantly improved the vineyard row following performance. The system's accuracy was evaluated by comparing its performance against a baseline GPS-only navigation approach, which relied exclusively on predefined vineyard endpoints without adaptive capabilities. As illustrated in Figure 10, the Root Mean Square Error (RMSE) of the UAV's lateral positioning relative to the vineyard row centerline decreased from 1.059 meters without correction (Figure 10(a)) to 0.265 meters with the correction algorithm enabled (Figure 10(b)). For more details about the vineyard row and tracking methodology, refer to [19].

The methodology proposed here is promising for vineyard row tracking and following. However, the main limitation is the evaluation of a simulated world with unrealistic graphical details. For this reason, the research group is working both to realize a more realistic simulation environment and to adapt the "Vineyard detection" node to process realistic data. An example of Gazebo simulation in an agricultural environment with more realistic features is presented in [20].

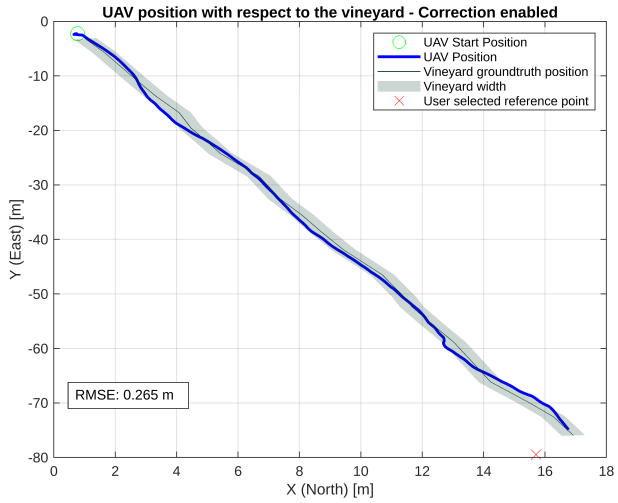
V. Conclusions and Future Works

In this paper, we have presented the design and preliminary development of a Proof of Concept of a UAS-based spraying system. In particular, the proposed system presents innovative and necessary features to conduct precise and targeted spraying activities in vineyards.

The proposed spraying system has been designed and optimized through CFD simulations and wind tunnel tests that allowed to analyze the effects of the rotor wake on the spraying activities, optimally sizing and positioning the



(a) UAV position with respect to the vineyard row true position. Case without position correction.



(b) UAV position with respect to the vineyard row true position. Case with position correction.

Figure 10. UAV Positioning error comparison in case in which the position correction is enabled (10(b)) and not (10(a)).

nozzles. Although the simulations reported in this paper refer to a first prototype equipped on a DJI Matrice 600, the same considerations can be reported on the developed PoC. However, further simulations and ad-hoc tests are needed for micro-adjustments to optimize the spraying system.

The proposed system aims to minimize the sloshing effect and its impact on the precise navigation of the UAS and, consequently, on the accuracy of spraying activities. The use of perforated baffles in the tank allows for passively limiting the sloshing effect, as demonstrated by the preliminary CFD simulations performed. In addition, we proposed to adopt a control algorithm that considers the sloshing dynamics in order to optimize the control of the drone and ensure a precise flight. The research group is currently working on this activity which will surely have an impact on the precision of the spraying activities.

Another important aspect is the tracking and following of the vineyard row. This feature is essential to adapt the navigation by positioning the UAS exactly above the plants to be sprayed. The proposed methodology has been preliminarily tested in simulation, but further developments are needed for the implementation on the real-world platform.

Although the presented project is under development, the preliminary results summarized in the paper are very promising. At present, the research group has implemented and assembled the UAS-based spraying system and performed the first test flight campaign. Some images of the PoC in flight while performing spraying operations are reported in Figure 11. However, further experimental activities are planned to comprehensively evaluate system performance and to implement all the functionalities described.

As already reported in the previous sections of the paper, there are several future developments already planned with the aim of implementing the various features described. Of considerable importance will be the planning of experimental activities to validate the effectiveness and precision of spraying activities. Due to regulatory limitations, the first activities will be carried out by spraying water, but, subsequently, we will start the authorization procedure for the spraying of pesticides, currently granted as an exemption for experimental activities.

ACKNOWLEDGMENT

This research activity has been supported by funds from the project ”Sistema di spruzzatura basato su drone con serbatoio anti-sloshing per applicazione in agricoltura di precisione”, funded by the Compagnia di San Paolo (PoC Instrument - Linea 1, PoC Launchpad, 2023. The authors would like to thank MAVTech s.r.l. for providing the M6 drone platform and for their technical support during the development and testing phases.

REFERENCES

[1] H. González-Jorge, J. Martínez-Sánchez, M. Bueno, and P. Arias, “Unmanned aerial systems for civil applications: A review,” *Drones*, vol. 1, no. 1, p. 2, 2017.

[2] P. Radoglou-Grammatikis, P. Sarigiannidis, T. Lagkas, and I. Moscholios, “A compilation of uav applications for precision agriculture,” *Computer Networks*, vol. 172, p. 107148, 2020.

[3] European Aviation Safety Agency, “Easy access rules for unmanned aircraft systems (regulations (EU) 2019/947 and 2019/945),” EASA, Tech. Rep., 2024.

[4] E. Ozkan, “Drones for spraying pesticides—opportunities and challenges,” *The Ohio State University: Columbus, OH, USA*, pp. 1–16, 2024.

[5] N. Delavarpour, C. Koparan, Y. Zhang, D. D. Steele, K. Betitame, S. G. Bajwa, and X. Sun, “A review of the current unmanned aerial vehicle sprayer applications in precision agriculture,” 2023.

[6] European Parlament and the Council of the European Union, “Directive 2009/128/EC of the european parliament and of the council of 21 october 2009 establishing a framework for community action to achieve the sustainable use of pesticides,” Official Journal of the European Union, Tech. Rep., 2009.

[7] M. Carreño Ruiz, N. Bloise, G. Guglieri, and D. D’Ambrosio, “Toward virtual testing of unmanned aerial spraying systems operating in vineyards,” *Drones*, vol. 8, no. 3, 2024. [Online]. Available: https://www.mdpi.com/2504-446X/8/3/98

[8] P. Surico, N. Bloise, S. Primatesta, and G. Guglieri, “Design and stability analysis of an agricultural sprayer uas integrated with an anti-sloshing tank,” in *2023 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor)*. IEEE, 2023, pp. 788–793.



(a)



(b)



(c)

Figure 11. Images of the first flight tests of the UAS-based spraying system. In (a) is the M6 drone equipped with the spraying system. In (b) is the drone in flight, in which the spray cone influenced and guided by the rotor wake can be observed. In (c) is the nozzle detail during the spraying activity.

[9] A. Biglia, L. Comba, L. E. Alcatrão, A. Sopegno, C. Messina, E. Mozzanini, N. Bloise, G. Guglieri, and M. Grella, "Comparison between 60° and 30° hollow cone nozzles for targeted uav-spray applications in vineyards," in *Precision agriculture'23*. Wageningen Academic Publishers, 2023, pp. 67–73.

[10] A. Biglia, M. Grella, N. Bloise, L. Comba, E. Mozzanini, A. Sopegno, M. Pittarello, E. Dicembrini, L. E. Alcatrão, G. Guglieri *et al.*, "Uav-spray application in vineyards: Flight modes and spray system adjustment effects on canopy deposit, coverage, and off-target losses," *Science of the total environment*, vol. 845, p. 157292, 2022.

[11] M. Carreño Ruiz, N. Bloise, G. Guglieri, and D. D'Ambrosio, "Numerical analysis and wind tunnel validation of droplet distribution in the wake of an unmanned aerial spraying system in forward flight," *Drones*, vol. 6, no. 11, 2022. [Online]. Available: https://www.mdpi.com/2504-446X/6/11/329

[12] N. Bloise, M. Carreño Ruiz, E. Mai, D. D'Ambrosio, and G. Guglieri, "Analysis and design of unmanned aerial systems for precision agriculture applications on vineyards," in *EUCASS 2022*, 2022.

[13] N. Bloise, M. Carreño Ruiz, D. D'Ambrosio, and G. Guglieri, "Wind tunnel testing of remotely piloted aircraft systems for precision crop-spraying applications," in *2021 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor)*. IEEE, 2021, pp. 378–383.

[14] ——, "Preliminary design of a remotely piloted aircraft system for crop-spraying on vineyards," in *2020 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor)*. IEEE, 2020, pp. 1–6.

[15] N. Bloise, "Design of an innovative spraying system for high precision aerial dispersion in vineyards," Ph.D. dissertation, Politecnico di Torino, 2023, available: https://hdl.handle.net/11583/2986291.

[16] R. Verschueren, G. Frison, D. Kouzoupis, J. Frey, N. van Duijkeren, A. Zanelli, B. Novoselnik, T. Albin, R. Quirynen, and M. Diehl, "acados – a modular open-source framework for fast embedded optimal control," *Mathematical Programming Computation*, 2021.

[17] D. Hanover, P. Foehn, S. Sun, E. Kaufmann, and D. Scaramuzza, "Performance, precision, and payloads: Adaptive nonlinear MPC for quadrotors," *IEEE Robotics and Automation Letters*, vol. 7, no. 2, pp. 690–697, Apr. 2022. [Online]. Available: http://dx.doi.org/10.1109/LRA.2021.3131690

[18] K. Y. Chee, T. C. Silva, M. A. Hsieh, and G. J. Pappas, "Enhancing sample efficiency and uncertainty compensation in learning-based model predictive control for aerial robots," in *2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, Oct. 2023, pp. 9435–9441. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/10341774/

[19] R. Enrico, P. Ricioppo, M. Mancini, and S. Primatesta, "Computer Vision-Based Autonomous Navigation for UAV Vineyard Row Following," in *2024 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor)*. IEEE, 2024. [Online]. Available: https://iris.polito.it/handle/11583/2995272

[20] M. Martini, M. Ambrosio, A. Navone, B. Tuberga, and M. Chiaberge, "Enhancing visual autonomous navigation in row-based crops with effective synthetic data generation," *Precision Agriculture*, pp. 1–22, 2024.