Experiment Verification of a Novel Adaptive Robust Altitude Controller for UAVs Subject to Weight Disturbances*

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Abstract— **This study focuses on the challenges in controlling altitude changes in agricultural UAVs due to dynamic weight changes as a result of spraying. An innovative controller framework is developed to adapt quickly to weight changes, maintaining precise altitude control. The framework uses correction functions based on weight changes and height error, validated through experimental tests on quadcopters and hexacopters. The results demonstrate high performance in mitigating disturbances such as weight changes, wind, gusts, and thus enhance the reliability and effectiveness of UAVs in agriculture, promoting their broader adoption.**

I. INTRODUCTION

The use of unmanned aerial vehicles (UAVs) has an increased tendency nowadays. These vehicles have the advantage of overcoming obstacles and accessing areas that are beyond the reach of ground vehicles. Agricultural UAVs, in particular, can undertake significant tasks in agricultural fields, providing advantages in both speed and efficiency. Technological advancements have made autonomous vehicles more impactful, with UAVs standing out due to their ability to navigate challenging terrains. Agricultural UAVs efficiently scan fields, optimize spraying, and enhance traditional farming methods by automating processes and offering precise solutions to specific agricultural needs.

However, UAVs inherently face stability issues, especially when controlling motor speeds for desired orientation and altitude. The challenge of maintaining altitude control for agricultural UAVs subjected to dynamic loads is significant, requiring sensitively tailored robust control systems to ensure precise operation. Although various control systems exist for UAVs, the proportional integral derivative (PID) control is widely adopted for its simplicity and effectiveness. Different UAV models, however, require specific PID controller gains, making gain tuning a very complex task. This process is particularly time-consuming and challenging for new pilots who lack experience.

PX4 is one of the most widely used open-source autopilots for mobile robots. On the controller side, several researchers have proposed solutions to specific challenges within the cascade controller framework. P. Li introduced a cascade control framework called plug-and-play adaptation to mitigate the disturbing effects of weight variation on the flight dynamics of fixed-wing UAVs. Their study, conducted in a simulation environment, examined weight variations between 1 kg and 2.5 kg for a UAV with an initial weight of 2 kg. The proposed adaptive PID controller outperformed the standard PX4 autopilot controller in handling these variations [1]. Niit developed a model reference adaptive controller (MRAC) specifically for attitude control in quadcopters. The MRAC was integrated into the PX4 firmware as part of its cascade control structure. Autonomous flight tests demonstrated that the MRAC achieved smaller errors in mission angles (yaw, pitch, and roll) compared to the standard PX4 controller, indicating an improvement in attitude stability [2]. Marcellini proposed a fully actuated UAV system with tiltable rotors. Their system demonstrated successful trajectory tracking and hovering capabilities, delivering acceptable results even in random movement scenarios. Although their approach primarily involved a hardware modification, the control algorithm for the tiltable rotor system was incorporated into PX4's cascade control framework [3]. Ghignoni investigated a linear matrix inequality (LMI)-based anti-windup (AW) compensator to address directionality effects in quadrotor UAVs. The AW compensator was integrated into the PX4 controller and evaluated through simulations [4]. Later, Marzagalli validated Ghignoni's AW compensator through flight experiments, which confirmed the effectiveness of the proposed framework in real-world conditions [5]. Additionally, Asadi designed an adaptive sliding mode controller (SMC) for integration into PX4's cascade control system. This controller was developed as part of a proposed autonomous emergency landing architecture (AELA), aiming to enhance UAV safety during emergency situations [6].

This study is motivated to propose a novel control system framework tailored for UAVs subject to dynamic weights. Specifically, the control problems due to decreasing weight in agricultural spraying operations performed by UAVs will be addressed with an objective of ensuring precise altitude control for efficient spraying. The proposed approach aims to solve the altitude control problem caused by load changes that negatively affect mission success in UAV applications, via the design of a novel adaptive control framework which can enhance the stability of the UAV even with other perturbing factors, such as wind.

The performance of the proposed adaptive control framework is tested via both simulations and experiments. MATLAB Simulink environment is used for simulations and different from most relevant works in the literature, experiments are performed not only for a quadrotor UAV but also for a hexarotor UAV [7]. Both UAVs are supplied with

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sensors such as three barometers, RTK GPS, and LIDAR to measure altitude, and flow meters to measure the amount of sprayed liquid. The proposed approach is integrated with the PX4 autopilot software. The integration with PX4 aims to demonstrate improved performance over the existing fixed-gain PID controller embedded in the PX4.

II. Model and System Properties

In this research, we focus on autonomous mode control of UAVs by focusing directly on their z-axis motion. Based on the work of [8], the z-axis model of the UAV has the following structure

$$\ddot{z}(t) = -g + \frac{1}{m(t)} U_1 \cos\theta \cos\phi \tag{1}$$

where $z(t)$, $\dot{z}(t)$, and $\ddot{z}(t) \in \mathbb{R}$ represent, respectively, altitude, velocity, acceleration of z-axis, $m(t)$ denotes the dynamic mass of the UAV which decreases over time, g is the gravitational acceleration in the $-z$ direction, $\theta(t)$ and $\phi(t)$ describe yaw and pitch, respectively, and $U_1(t)$ is the force-torque component which serves as the control input on the z-axis. Via utilizing the small angle approximation approach, the simplified z-axis model can be obtained to have the following form

$$\ddot{z}(t) = -g + \frac{U_1}{m(t)}. \tag{2}$$

III. Control Problem and Proposed Solution

Precise altitude control is extremely critical for the use of agricultural UAVs in sensitive farming applications. The presence of varying weight further complicates the control design problem. In this work, we concentrate on controlling the altitude of a UAV that loses its weight during its mission.

There are various approaches that can be employed to overcome this issue. The first solution is based on increasing the number of motors or utilizing motors that could provide higher power. This solution can obviously mitigate the negative impacts of weight variations by enhancing the overall carrying capacity of the UAV via modifying its actuation capacity. While it could be considered as a possible solution for some tasks, it is to be emphasized that not only the costs related to the motors (and thus battery costs) are increased but a complete redesign may be essential as well. Another possible solution could be redesigning the controller of the UAV. Specifically, such solution aims to achieve altitude control without affecting the core functions of the current controller. However, the time cost of a redesign of the controller is high. Considering the weaknesses of the above-mentioned possible solution scenarios, a solution without requiring costly modifications or increasing the time costs of the mission seems to be essential.

An effective solution relies on modifying the system controller by adding a cascade controller to deal specifically with the weight losses. This solution can address the problem by being added to the existing controller structure so avoiding costly electro-mechanical modifications and saving on time. However, this approach involves integrating an additional controller into the existing structure so the transition should be smooth in the sense that the overall mission should not be altered during the transition of the addition of this controller. Therefore, in this study, integrating a cascade controller to the system controller that could be turned on when the spraying is initiated or when the consequences of weight changes start altering the motion of the UAV, is preferred. This solution will enable the cascade controller to be turned off when the spraying is over so a complete redesign of the overall controller could be avoided. This type of cascade controller is required to be integrated to not to risk the overall stability of the UAV, so the main requirement is the need of smooth transition. Secondly, the cascade controller must ensure compensation for the weight variations that cause the deviation of the altitude of the UAV in a robust manner. Additionally, in any real time application of aerial vehicles, there are additional disturbances, such as wind, that affect the overall mission performance negatively. So, the proposed controller should compensate for these disturbances as well. Additionally, the cascade controller should be designed to utilize the sensors in the system, specifically to avoid the need for new sensors to be integrated into the electro-mechanical system. Finally, the PX4 controller of [9] is among the most preferred controllers for UAVs so the designed controller should be capable of being integrated into the cascade structure of the PX4 controller, as shown in Figure 1.

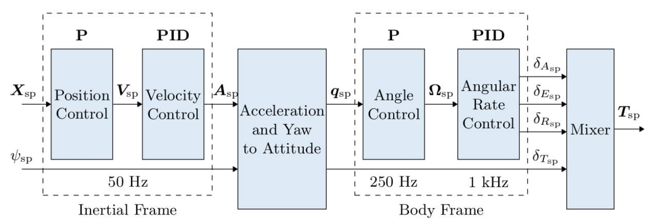

Fig. 1. PX4 cascade structure [9]

The experimental UAVs used in the tests are equipped with a flow meter to measure instantaneous weight of the liquid and can measure altitude using three barometers, real-time kinematic (RTK) GPS, and LIDAR. Considering the existing sensor infrastructure, it has been evaluated that weight and altitude measurements can be used in the controller design. So, in the subsequent subsections, two cascade control structures will be proposed where one will make use of weight measurements while the other one depends on height measurements.

A. Weight Based Control

Since the main problem is caused by the weight changes during the spraying operation, a trivial approach is to make use of the weight measurements, provided by the flow meter. So the yet to be developed cascade controller will be expected to make the motion of the UAV robust against weight variations.

In this study, when weight is fixed or its decrease rate level is so low that it could be considered as fixed, the UAV will operate with its *a priori* designed fixed-gain PID controller. However, as the weight change rate becomes significant, adjusting this controller based on the ratio of the current weight of the UAV to its initial weight is considered as a viable solution. Specifically, the initial weight of the UAV is shown with m_i, and after some amount of spraying, its weight changes to m_c. Therefore, the dynamical model of the z-axis motion as given in (2) is now rewritten as

$$\ddot{z} = -g + \frac{1}{m_i} U_1 \tag{3}$$

via the change of notation of the weight of the UAV (*i.e.*, $m \to m_i$). However, after some spraying, the UAV loses some weight to have a new weight of m_c. Thus, the equation of motion in z-axis becomes

$$\ddot{z} = -g + \frac{1}{m_c} U_1. \tag{4}$$

Since the fixed-gains of the PID controller are tuned for the model of (3), then they may not work properly for the model of (4). One way to remedy this is to modify the control input U_1 in the following manner

$$U_1 \to \frac{m_c}{m_i} U_1 \tag{5}$$

that is to multiply the control input with the ratio of the current weight to the initial weight, which serves as a correction term based on weight measurements. As can be seen from the cascade control structure design proposed in (5), when the UAV's weight does not change, *i.e.*, when $m_i = m_c$, the previously tuned PID controller will continue to fly the UAV. With the start of spraying, the control input to the system will be proportionally reduced by the ratio of the current weight to the initial weight. Since the flow meter is considered to provide online measurement of the weight of the UAV, then the transition from non-spraying to spraying phases is smooth. After substituting the controller of (5) into the dynamical model of (4), the dynamic behavior of the UAV in the z-axis can be rewritten as follows

$$\ddot{z} = -g + \frac{1}{m_c} \frac{m_c}{m_i} U_1 = -g + \frac{1}{m_i} U_1 \tag{6}$$

which is identical to (3). So the design of (5) makes the dynamics of (4) behave as the original system given in (3) (*i.e.*, when the weight of the UAV is fixed), thus achieving the control objective.

B. Height Based Control

Since the weight changes are the main source of the problem in the dynamics of the UAV, the development in the previous subsection has considered a weight based approach. While this is a reasonable approach, it is apparent that the deviations in the UAVs altitude are also caused by the other environmental disturbances, wind being the major one. In that aspect, height/altitude is the output state that is affected by all these changes. So, instead of weight based cascade controller, an altitude based correction parameter is proposed as an alternative. The proposed design considers the relationship between the target/desired altitude z_d and the current/actual altitude z_c and is mathematically structured as follows

$$U_1 \to \frac{z_d}{z_c} U_1. \tag{7}$$

A closer investigation of the correction function proposed in (7) reveals that is actually represents a multiplicative tracking error. Specifically, the altitude tracking error is expressed as $z_d - z_c$, and as this error approaches zero as z_c approaches z_d. When the multiplicative error $\frac{z_d}{z}$ approaches to 1 then the UAV will be operated with its already designed fixed-gain PID controller.

The primary motivation behind this novel design is that a PID controller depending on the tracking error may fail to compensate appropriately and on time for the adverse effects of weight changes on altitude. Thus, it relies on a multiplicative correction parameter. The controller using this correction parameter successfully achieves robust altitude control of the UAV along the z-axis. This solution uses altitude data which is obtained by fusing the altitude measurements received from the sensors and controls the thrust force in a multiplicative order, based on its relationship to the target altitude. A byproduct of this design, when compared with the weight based approach, is that it corrects all the errors that cause the actual altitude to deviate from its target.

Based on the developments proposed in the previous two subsections, the altitude deviation encountered along the z-axis of the UAV is resolved by multiplying it with a correction factor. This controller is named "Hover Thrust Adaptive Control (HTAC)" and the integrated cascade controller structure is shown in Figure 2.

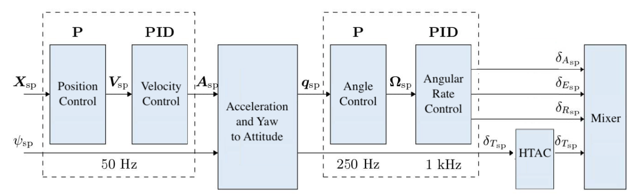

Fig. 2. HTAC integrated cascade controller structure

IV. Simulation Results

The HTAC algorithm developed in this study was implemented in the MATLAB Simulink environment [10]. The success of UAVs relies on precise control algorithms, which in turn require precise testing environments. The purpose of simulation tests is to prevent potential material losses in real-world tests. Open-source autopilot software, PX4, was used in this study. Simulations were performed for three different cases with the same weight changes scenario. Weight changes can be considered as tank level for real-world experiments, and we also call it the spray tank level in the paper(Figure 3).

A. Case 1: Without proposed systems

In this scenario, flight tests were simulated via original controller of the autopilot. Unfortunately, PX4 controller did

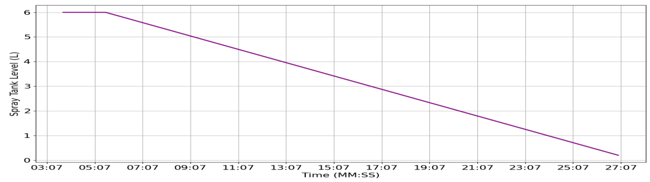

Fig. 3. Spray tank level in liter

not adapt well to the weight changes during the simulation tests. As a result of the simulation, the UAV ascended by 0.98 meters, with a root mean square error of 0.6 meters. Figure 4 displays the thrust force(top) and altitude(bottom) obtained from the simulation test. As can be observed from Figure 4, as the spraying starts the altitude of the UAV increases in a steady manner.

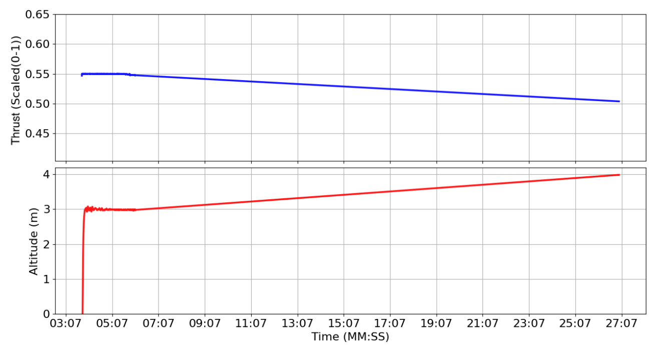

Fig. 4. [Simulation] Autonomous flight with the PX4 original controller

B. Case 2: Weight based control

In this case, numerical simulation tests were performed for autonomous flight with weight based control. During the simulation tests, it was observed that the weight based controller successfully adapted to weight changes, as shown in Figure 5 where, from top to bottom, thrust force and altitude are displayed. As a result of the simulation, the UAV's altitude error remained between -0.1 meters and 0.04 meters, with a root mean square error of 0.02 meters.

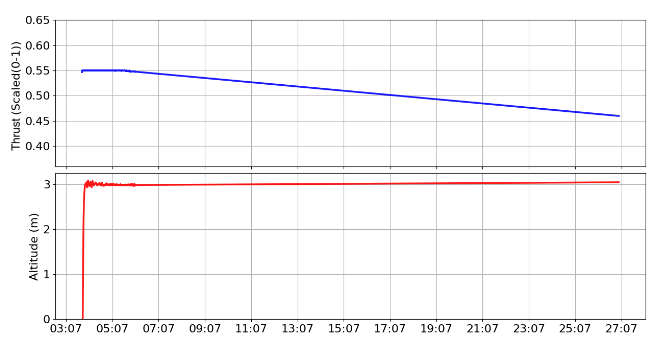

Fig. 5. [Simulation] Autonomous flight with weight based controller

C. Case 3: Height based control

Autonomous flight with height based control was simulated in this scenario. As shown in Figure 6, the height based controller successfully adapted to weight changes during the simulation test. As a result of the simulation, the UAV's altitude error remained between -0.02 meters and 0.02 meters, with a root mean square error of 0.02 meters.

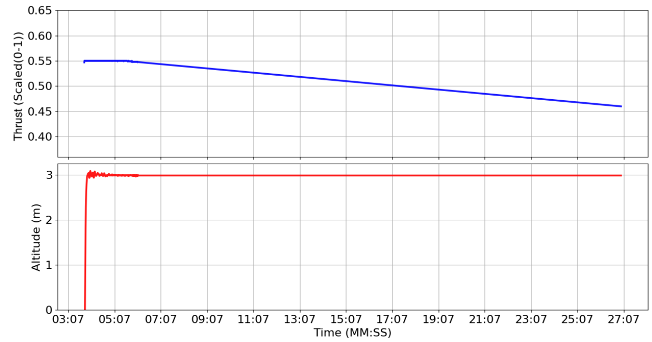

Fig. 6. [Simulation] Autonomous flight with height based controller

As seen in Figures 5 and 6, both weight based and height based controllers have yielded similar and acceptable performances in the simulation tests where both controllers exhibit robust behavior against weight changes. The error range, along with the root mean square error (RMSE), has been used as performance criteria, and the obtained results are presented in Table I.

TABLE I
COMPARISONS OF THE SIMULATION RESULTS

	Control Type		
Performance metric	**No HTAC**	**Weight based**	**Height based**
Negative error	0 m	-0.1 m	-0.02 m
Positive error	0.98 m	0.04 m	0.02 m
Root mean square error (RMSE)	0.6 m	0.02 m	0.02 m

V. EXPERIMENT RESULTS

The proposed HTAC algorithm was applied to two UAVs, namely UAV-A and UAV-B given in Figure 7. UAV-A is a quadrotor rotary-wing UAV, while UAV-B is a hexarotor rotary-wing UAV. Algorithm that was developed in MATLAB Simulink environment were directly uploaded to the autopilot of the UAVs. The developed controller in MATLAB Simulink is examined in three main blocks, each containing sub-controllers. These blocks are the position and altitude controller, the attitude controller, and the newly developed HTAC. Specifically, the developed HTAC uses thrust power calculated by the position and altitude controllers as input. It processes the data received from the sensors and updates the thrust parameter sent to the mixer by multiplying it with the calculated (weight based or height based) thrust correction factor. The updated parameter is then sent to the control block output. The developed controller was directly uploaded to the Pixhawk 6X autopilot board using MATLAB Simulink. Tests were carried on for three different cases.

Fig. 7. UAV-A (left), UAV-B (right)

A. Case 1: Without proposed systems

The test results where the HTAC was inactive is presented in Figure 8, where from top to bottom, thrust force and altitude are displayed. As depicted in the bottom figure, the altitude error of the UAV increased steadily after the spraying system was initiated, which consequently reduced the UAV's weight. Specifically, the altitude error escalated by 3.11 meters as the weight decreased by 6 kilograms.

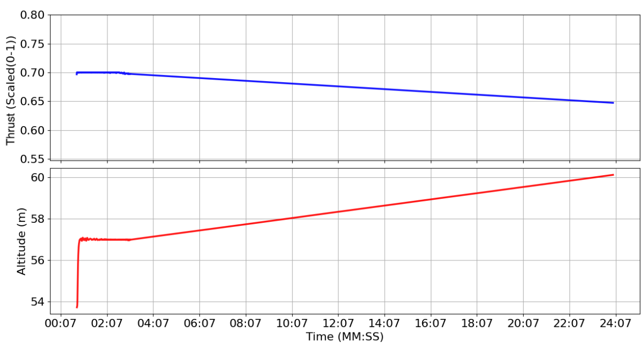

Fig. 8. [Experiment] Autonomous flight with UAV-B

B. Case 2: Weight based control

The test results of weight based HTAC for UAV-A are presented in Figure 9. As can be seen from the figures, the altitude error of the UAV still increases as the weight decreases. It is concluded that the weight based correction factor, being robust only against disturbances caused by weight changes, does not perform successfully against other types of disturbances. The altitude error of the UAV was incrementally measured to be 0.29 meters, with a root mean square error (RMSE) calculated at 0.17 meters. Due to the insufficient performance observed in tests conducted with the more powerful UAV-A, it was deemed unnecessary to repeat this test with the less capable UAV-B.

C. Case 3: Height based control

The tests of the height based HTAC for UAV-A were conducted at an altitude of 57 meters and are presented in Figure 10. As shown in the second figure, despite the UAV-A's weight decreased by almost 6 kilograms, the height based HTAC immediately adjusted the thrust correction gain, thus maintaining control of the system's output thrust throughout the flight. According to Figure 10, the thrust output decreased from 70% to 62%. The adaptive thrust output ensured that the altitude error remained within the range of -0.12 to 0.15

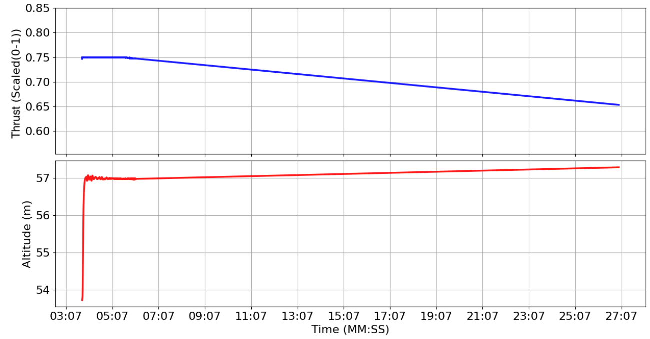

Fig. 9. [Experiment] Results of weight based HTAC with UAV-A

meters, which is an acceptable level for such agricultural spraying application.

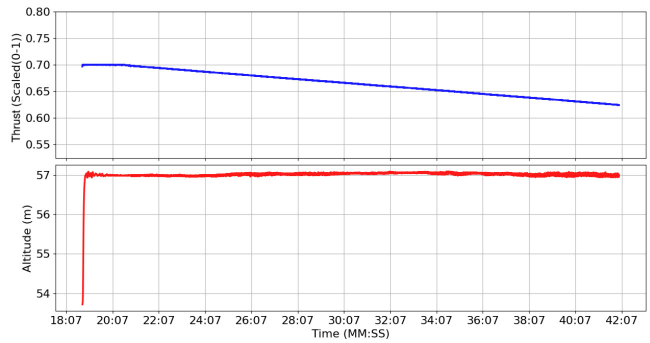

Fig. 10. [Experiment] Results of height based HTAC with UAV-A

The tests of the height based HTAC for UAV-B were operated at an altitude of 63 meters and are demonstrated in Figure 11. As can be seen from the thrust force graph, as the weight of UAV-B decreased approximately by 6 kilograms, the height based HTAC promptly reacted and adjusted the thrust correction factor to maintain accurate control of the altitude of the UAV throughout the flight. From Figure 11, the thrust output decreased from 80% to 65% and the adaptive thrust output ensured that the altitude error remained within the range of -0.11 to 0.11 meters.

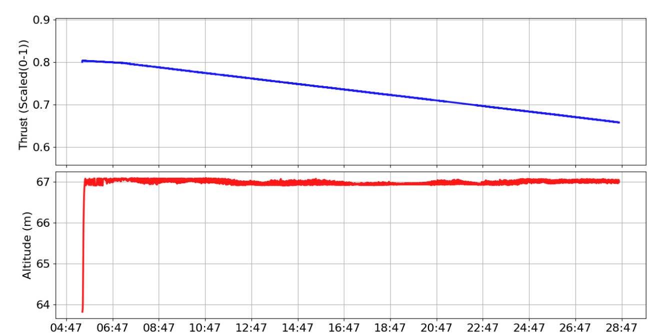

Fig. 11. [Experiment] Results of height based HTAC with UAV-B

Based on the experiment results for the height based HTAC, it can be stated that both UAV-A and UAV-B maintained their altitude throughout the flight and they performed much better than the weight based HTAC. Table 2 presents a comparative analysis of the performance results with the HTAC being active and inactive. The HTAC effectively addresses the altitude rise issue observed in agricultural UAVs when its weight decreases.

TABLE II

COMPARISONS OF THE EXPERIMENT RESULTS

	UAV-A			**UAV-B**	
	Controller Type			**Controller Type**	
Performance metric	**No HTAC**	**Weight based**	**Height based**	**No HTAC**	**Height based**
Negative error	-0.03 m	-0.02 m	-0.12 m	-0.05 m	-0.11 m
Positive error	2.07 m	0.29 m	0.15 m	3.11 m	0.11 m
Root mean square error (RMSE)	1.32 m	0.17 m	0.03 m	1.92 m	0.04 m

VI. CONCLUSION

In this study, a novel adaptive controller framework is proposed to address the altitude rise issue encountered during weight changes in agricultural UAV spraying applications. Two solutions are considered where the first one considered the UAV's weight measurements, while the second solution is based on altitude measurements. The proposed adaptive controllers were tested in simulation studies and applied experimentally on two different UAVs, a quadrotor and a hexarotor. Both of the UAVs are equipped with intelligent sensors such as flow meters to measure the amount of sprayed liquid, three barometers, RTK GPS, and LIDAR to measure altitude. The performance of the proposed controller framework was evaluated, and the experimental results obtained were deemed successful for agricultural spraying applications and have the potential to be considered as a autonomous system that could be integrated Agriculture 4.0.

There is much to be considered as possible future works. In our study, we tested the effects of continuous weight reduction. For future work, additional tests are required, including sudden weight changes, weight increases, and UAV stability during movement and maneuvers under varying weight conditions. These tests may necessitate further updates to the controller.

REFERENCES

[1] P. Li, D. Liu, and S. Baldi, "Plug-and-play adaptation in autopilot architectures for unmanned aerial vehicles," in *IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society*, pp. 1–6, 2021.

[2] E. A. Niit and W. J. Smit, "Integration of model reference adaptive control (mrac) with px4 firmware for quadcopters," in *2017 24th International Conference on Mechatronics and Machine Vision in Practice (M2VIP)*, pp. 1–6, 2017.

[3] S. Marcellini, J. Cacace, and V. Lippiello, "A px4 integrated framework for modeling and controlling multicopters with til table rotors," in *2023 International Conference on Unmanned Aircraft Systems (ICUAS)*, pp. 1089–1096, 2023.

[4] P. Ghignoni, N. Buratti, D. Invernizzi, and M. Lovera, "Anti-windup design for directionality compensation with application to quadrotor uavs," *IEEE Control Systems Letters*, vol. 5, no. 1, pp. 331–336, 2021.

[5] F. Marzagalli, P. Ghignoni, G. Gozzini, and D. Invernizzi, "Experimental validation of an anti-windup design trading off position and heading direction control performance for quadrotor uavs," *IFAC-PapersOnLine*, vol. 55, no. 22, pp. 117–122, 2022. 22nd IFAC Symposium on Automatic Control in Aerospace ACA 2022.

[6] D. Asadi, "Partial engine fault detection and control of a quadrotor considering model uncertainty," *Turkish Journal of Engineering*, vol. 6, no. 2, p. 106–117, 2022.

[7] J. Jaramillo, K. Wilcher, T. Yucelen, and M. Pakmehr, "Development of a model reference adaptive control architecture in a hexarotor simulation environment," in *AIAA SCITECH 2024 Forum*, 2024.

[8] T. Bresciani, "Modelling, identification and control of a quadrotor helicopter," Master's thesis, Lund University, 2008.

[9] PX4, "Development environment," 2023. [Accessed: June 16, 2023].

[10] T. M. Inc., "Quaternion multiplication." `https://www.mathworks.com/help/aeroblks/quaternionmultiplication.html`, 2023.