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Editors

# Robot 2023: Sixth Iberian Robotics Conference

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## Preface

This book contains a selection of papers accepted for presentation and discussion at ROBOT2023, the Sixth Iberian Robotics Conference, held in Coimbra, Portugal, during November 22–24, 2023. ROBOT2023 is part of a series of conferences that are jointly organized by Sociedade Portuguesa de Robótica (SPR)/Portuguese Society for Robotics and by Sociedad Española para la Investigación y Desarrollo en Robótica (SEIDROB)/Spanish Society for Research and Development in Robotics. The conference organization had also the collaboration of several universities and research institutes, including Institute for Systems and Robotics, University of Coimbra (ISR-UC); Polytechnic Institute of Bragança; University of Minho; University of Zaragoza; and Universidad Politécnica de Madrid.

ROBOT2023 builds on several previous events held in Zaragoza 2022, Porto 2019, Seville 2017, Lisbon 2015, and Madrid in 2013. The conference is focused on presenting research results, new developments, and applications in the field of Robotics in the Iberian Peninsula, although open to contributions from all over the world. ROBOT2023 featured four plenary talks on state-of-the-art subjects on robotics, the first one by **Paloma de la Puente** from the Universidad Politécnica de Madrid, Spain, on “Understanding the environment and the users: towards mobile robot navigation and interaction in the real world”, followed by **Denis Fernando Wolf** from the University of São Paulo, Brazil, on “Intelligent Vehicles: from autonomy to interaction”; **António Pedro Aguiar** from the University of Porto, Portugal, on “Model based control design combining Lyapunov and optimization tools to empower trusted autonomy of robotic vehicles”; and **Sven Behnke** from the University of Bonn, Germany, on “From Intuitive Immersive Telepresence Systems to Conscious Service Robots”.

ROBOT2023 included ninety scientific papers presented in fourteen thematic sessions organized in three parallel tracks. Some of these were Special Sessions organized by members of the Program Committee, to whom we are thankful for their hard work by promoting the conference and helping to make it a successful event. We also express our gratitude to the members of all the Program Committees and additional reviewers, as they were crucial for ensuring the high scientific quality of the event and to all the authors and delegates that, with their research work and participation, made this event a huge success.

Finally, we would like to express our gratitude to the local organization members, Sedat Dogru, Paulo Menezes, Cristiano Premebida, Hélder Araújo, Dylan Denizon, Vera

Baptista, and João Leite, for their hard and valuable work on the local arrangements, publicity, proceedings publication, financial issues, and website management.

November 2023

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# A Comparison of PID Controller Architectures Applied in Autonomous UAV Follow Up of UGV

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**Abstract** The cooperation between Unmanned Aerial Vehicles (UAVs) and Unmanned Ground Vehicles (UGVs) has brought new perspectives and effectiveness to production and monitoring processes. In this sense, tracking moving targets in heterogeneous systems involves coordination, formation, and positioning systems between UGVs and UAVs. This article presents a Proportional-Integral-Derivative (PID) control strategy for tracking moving target operations, considering an operating environment between a multirotor UAV and an indoor UGV. Different PID architectures are developed and compared to each other in the Gazebo simulator, whose objective is to analyze the control performance of the UAV when used to track the ground robot based on the identification of the ArUco fiducial marker. Computer vision techniques based on the Robot Operating System (ROS) are integrated into the UAV's tracking system to provide a visual reference for the aircraft's navigation system. The results of this study indicate that the PD, Cascade, and Parallel controllers showed similar performance in both trajectories tested, with the Parallel controller showing a slight advantage in terms of mean error and standard deviation, suggesting its suitability for applications that prioritize precision and stability.

**Keywords:** UAVs tracking moving targets, UAV simulation, UAV-UGV cooperation, PID controller, Cascade PID, Parallel PID

## 1 Introduction

Unmanned Aerial Vehicles (UAVs) have brought new possibilities to automate different tasks due to their ability to perform activities involving different levels of complexity, environment dynamicity, and need for motion [1]. Several works in the literature have reported different strategies for heterogeneous cooperation among robots. [2].

An interesting review is presented by Ding et al. [3], which describes various applications involving cooperation between Unmanned Aerial Vehicles and Unmanned Ground Vehicles. As part of the [3] research, the complexity of the precision landing procedure is elucidated, which involves a preliminary step where the UAV must follow the UGV before proceeding with the landing procedures.

In this sense, the UAV has to dynamically adjust its velocity to reach the landing spot while the UGV is in motion. Achieving this landing procedure involves using either a vision-based approach or a sensor fusion technique [4]. It is important to highlight that the detection and tracking of the UGV is challenging for the UAV [5]. Over the years, the vision-based approach for this joint motion has been extensively reported, especially in GPS-denied environments [5].

For instance, Respass et al. [6] presented a vision-based control strategy for the UAV to take off and land into the UGV, where the UAV has to track it. The authors used a color-based detection algorithm and Kernelized Correlation Filters (KCF) for tracking. A challenge in their approach is that the detection and tracking algorithms may not be robust enough to handle UGV appearance, shape, or size variations.

The central focus of this work is the implementation and comparison of different Proportional-Integral-Derivative (PID) control architectures on a multi-rotor UAV, whose main objective is its application in the precise tracking of a moving object. The UAV's localization and positioning system is based on the tracking and detecting an ArUco fiducial marker positioned on top of a UGV.

The main contributions can be summarized as follows:

- Implementation of a PID control system based on the visual reference of an ArUco marker to enable precise and stable flight control during a tracking process of a moving object in a simulated environment.
- Comparison between different architectures of linear controllers used for tracking operations of moving targets by a UAV.
- Experimental evaluation of the proposed strategy in the Software-in-the-Loop (SITL) approach using ROS and Gazebo software.

The structure of this paper is as follows: [section 2](#) provides background information to understand the proposed work fully and discusses related literature. [section 3](#) details the methodology of the proposed approach. The experimental results in the specific scenario are presented in [section 4](#). Finally, [section 5](#) concludes with remarks and outlines future directions for research.

## 2 Background and Related Works

Effective collaboration and cooperation among agents in an autonomous task involving multiple agents are crucial for leveraging their capabilities [2]. For this cooperation, computer vision-based localization tasks are vital in determining the robots' positions without relying solely on Global Navigation Satellite Systems (GNSS).

The importance of accurate localization becomes even more pronounced when UAVs and UGVs interact and collaborate in dynamic environments [2]. Seamless coordination between these robotic systems is essential to ensure safe and efficient operations [7]. Therefore, reliable localization information facilitates effective navigation and interaction between robots. Computer vision systems can detect and analyze artificial features such as fiducial markers using cameras and sophisticated algorithms [8].

Fiducial markers act as reference points, allowing the extraction of their unique characteristics. Through this process, the position and relative orientation of the robot, whether it's a UAV or UGV, can be accurately estimated. For instance, Lebedev et al. [9] shows a vision-based detection of ArUco marker for UAV autonomous landing. Another interesting work is presented in Eriki et al. [10]. Their paper showed a system that used virtual fiducial markers to accurately predict the position of a drone in a warehouse and count items on the rack. About the cooperation between UGV and UAV, [11] presented a real-time autonomous tracking and landing of a UAV on a moving UGV. Their approach estimated the relative pose and velocity between a UAV and a UGV. Then, they used a model predictive control for UAV trajectory planning.

As can be seen, the tracking approach based on fiducial markers provides a robust and reliable solution for UAVs to track and land onto UGVs. As cited by Jurado et al. [12], fiducial markers are robust and easy to detect, even in devices with low computing power. It enables accurate relative position and orientation estimation, facilitating smooth and coordinated interactions between the robotic platforms. In this sense, using fiducial markers as visual cues, UAVs can autonomously track and align themselves with UGVs [13]. This can enhance collaborative tasks' overall efficiency, safety, and effectiveness. Therefore, this study focuses on integrating ArUco fiducial markers as visual references to enhance the performance of a PID control system for optimizing UAV trajectories.

PID controllers' state of the art reflects an extensive exploration of various approaches. For instance, the category of application-based research is represented by works like that of [14], which applies a Genetic Algorithm tuned PID controller to reduce energy consumption in an office building, and [15], which conducts a simulation model of a conventional PID controller for a DC Servo Motor.

Additionally, [16] and [17] present examples of improvements over traditional PID controllers, with the former enhancing the operational stability of a maintenance robot using a hybrid GA-PSO-PID controller and the latter optimizing the drying process through an improved Neural Network PID controller. Hybrid controllers integrating different control strategies with the PID controller are

also emerging, as exemplified by the improved Differential Evolution Adaptive Fuzzy PID control method introduced by [18].

Moreira et al. [19] gives a valuable methodological contribution. The authors provided strategies to tune the speed and position controllers and suggested various methodologies such as PID, Cascade, and feedforward combination with dead zone compensation, which our current work will employ to some extent. Lastly, the category of advanced controllers is exemplified by the work of Mohd et al. [20], which showcases a sophisticated data-driven Neuroendocrine-PID controller for a multi-input-multi-output gantry crane system, demonstrating a clear move towards more intelligent and adaptive control systems.

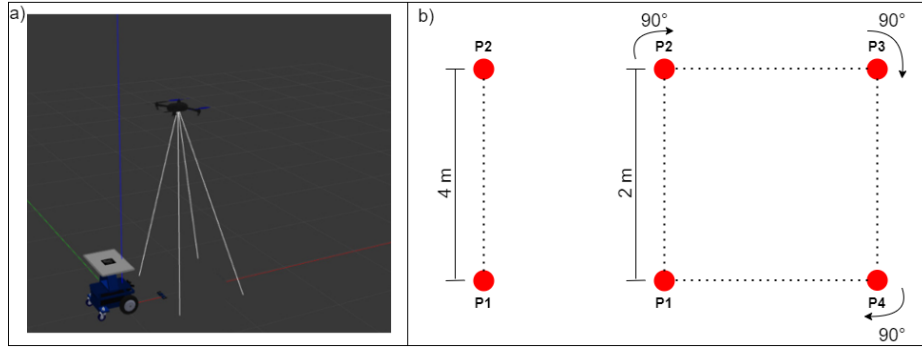
### 3 Materials and Methods

As previously mentioned, this work aims to compare and evaluate different control architectures applied to simulated operations of tracking moving targets, considering an operating environment between a multirotor UAV and a UGV in an indoor environment. In this sense, the Gazebo robotic simulation environment is used to validate the experiments conducted in this work, considering its native integration with ROS.

The robotic platforms chosen to be used in the virtual environment are constituted by the UAV 3DR iris, which is integrated with the MAVROS PX4 framework, and the UGV Magni by Ubiquity Robots, which also has a control structure based on the ROS framework. The iris UAV has an RGB camera pointing downwards with a resolution of 320x240 px to locate the ArUco fiducial marker.

The intrinsic camera parameters defined in the iris model were used to detect and measure the fiducial markers. A landing platform with an ArUco marker measuring 12x12 cm was modeled and added to the top of the Magni UGV, making it approximately 53 cm high. The fiducial marker aims to estimate the aircraft's position and pitch relative to the UGV. In this way, the aircraft has a visual reference to assist in pursuing the UGV along the routes proposed in this work.

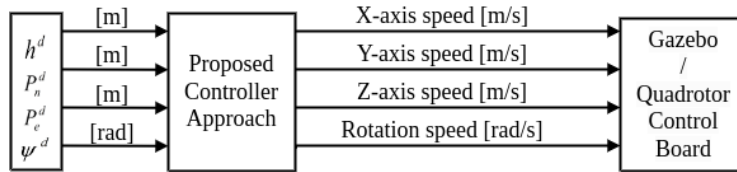
Two routes were predefined to evaluate the control architectures used, where the UAV must follow the UGV and stay at 2 meters in height. The first route executed by the robotic platforms consists of a straight line of four meters, performing forward and backward movements, while in the second route, the robotic platforms cover a section whose shape is square of two meters side, adding more complexity to the UAV movement during the tracking operation. The different control architectures, i.e. PD, cascaded PD-PI, and parallel PD-PI, are applied and compared on each route defined by the experiments. The speed of the UGV is constant in both test scenarios. [Figure 1](#) illustrates the robotic units used in the virtual Gazebo environment and the routes used to analyze and validate the tests presented in this work.



**Figure 1.** a) UAV Iris and UGV Magni are used in the Gazebo virtual environment; b) Predetermined routes are chosen to evaluate the different controllers.

### 3.1 Proposed Controller Approaches

The proposed control system regulates the UAV's attitude ( $h$ ), inertial position ( $P_n$  and  $P_e$ ), and trajectory, ensuring stable and precise flight control during the process. The overall control structure is presented in [Figure 2](#):



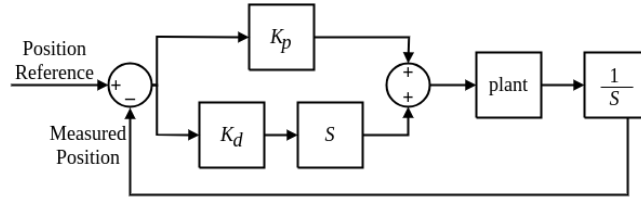
**Figure 2.** Schematic of the proposed controller approach.

This paper will present different results for three other control structures, which are: PD Controller ([Figure 3](#)), PD-PI Cascade Controller ([Figure 4](#)) and PD-PI Parallel Controller ([Figure 5](#)), inspired from the research work presented in [\[21\]](#). These figures [\(3, 4, 5\)](#) show the diagram of the blocks tested in the specific placement shown in [Figure 2](#)

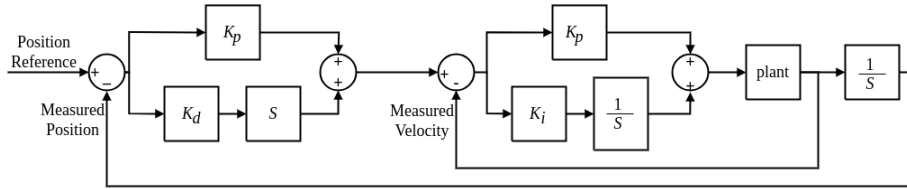
From the figure above, it is possible to see that a position variable is a setpoint for the PD controller, where the respective velocity is the output driven to the Gazebo environment.

[Figure 4](#) illustrates a PD-PI cascade controller where the outer loop receives a position variable and drives a velocity variable as a setpoint for the inner one. The output of the whole control structure is also a velocity variable. The last proposed control approach is a PD-PI parallel structure, as seen in [Figure 5](#).

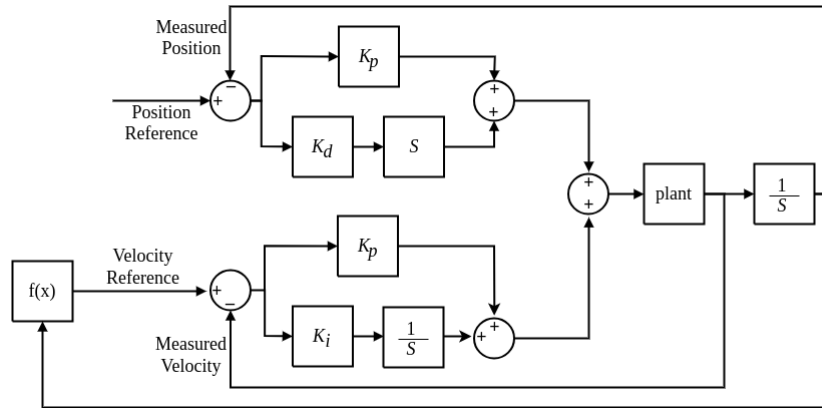
Then, the position and speed must be entered as set points, one for the PD and one for the PI controller. Finally, the respective velocities are added



**Figure 3.** Proportional and Derivative controller.



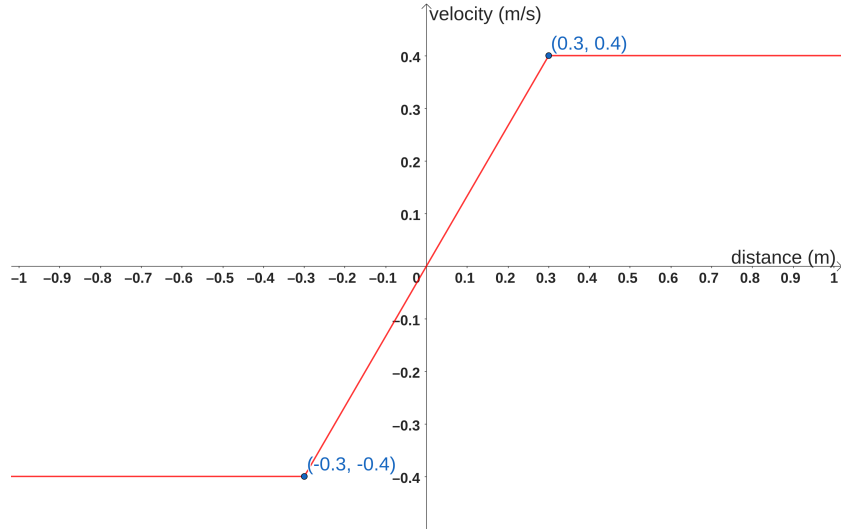
**Figure 4.** Proportional and Derivative - Proportional Integral cascade controller



**Figure 5.** Proportional and Derivative - Proportional Integral parallel controller

and directed towards the Gazebo environment. For a speed reference, we use a curve, represented by  $f(x)$  in [Figure 5](#), based on the distance between the UAV and the UGV acquired with the fiducial marker measurement, thus establishing a relationship between the speed and position reference. The curve used for the four axes is in [Figure 6](#), only for the yaw command, the speed axis is in radians per second.

Finally, all three PID architectures employed for drone control utilized the conditional integration anti-windup approach. This method effectively manages integral wind-up during boundary constraints.



**Figure 6.** PD-PI parallel controller speed reference.

This strategy integrates the error based on the current controller output's position relative to its limits.

### 3.2 Definition of controller's gain

To achieve a satisfactory result when using the controllers, it is first necessary to define the gains used by each of them. It used a controller for each UAV motion axis (x, y, z, and yaw), so each was calibrated separately, following the same criteria. We first approximated the UAV's transfer function for each motion axis to define the gains. To do this, we measured the step response of each axis by sending a constant velocity and maintaining it until it reached a stationary state. Using the step response, it is possible to approximate the transfer function using Matlab's system identification tool. By using two poles and a zero to estimate the functions [Equation 1](#), [Equation 2](#), [Equation 3](#), [Equation 4](#) are obtained.

$$H_x(s) = \frac{0.541s + 3.400}{s^2 + 5.258s + 3.394} \quad (1)$$

$$H_y(s) = \frac{-1.419s + 13.656}{s^2 + 11.416s + 14.577} \quad (2)$$

$$H_z(s) = \frac{2.373s + 0.768}{s^2 + 2.252s + 0.697} \quad (3)$$

$$H_{yaw}(s) = \frac{2.503s + 0.017}{s^2 + 2.826s + 3.758 \times 10^{-7}} \quad (4)$$

To define the gains, we used Matlab’s Autotuning system, which returns a gain value from a value of transient behavior and response time. For this purpose, the closed loops of the speed PI controller and the position PD controller were assembled separately.

Both controllers used the transfer function already presented, but the PD controller had to integrate it to obtain the position response. For each transfer function, the values of the transient behaviour and the response time were changed so that the system remained stable, minimizing the overshoot and the settling time for the step response. As a result, all the gains required for the architectures in [section 3](#) were defined and are shown in table [Table 1](#).

	PD				PI			
	RT	TB	KP	KD	RT	TB	KP	KI
<b>X</b>	2.909	0.495	0.93	0.11	1.348	0.550	1.28	2.78
<b>Y</b>	2.48	0.586	0.97	0.15	2.58	0.9	0.74	0.74
<b>Z</b>	1.819	0.667	1.02	0.087	0.9507	0.9	0.906	1.67
<b>YAW</b>	1.759	0.6	1.40	0.014	0.832	0.9	1.017	2.651

**Table 1.** PD and PI Controller Gains

## 4 Results and Discussion

As mentioned in the [section 2](#), two trajectories were analyzed, one straight and one square. [Figure 7](#) shows the path the two robotic platforms take in these two trajectories for each control architecture.

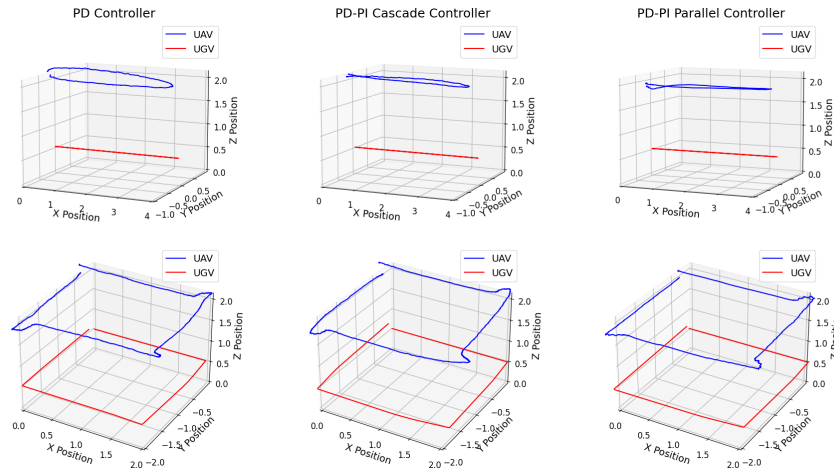
Regarding the position of the Z axis, the Iris UAV must maintain a height of 1.5 meters above the top of the Magni. Since the UGV measures approximately 53 cm, the UAV must hover approximately 2 meters above the ground. [Figure 7](#) shows that the cascade controller and the parallel controller have a low variance, while the PD controller has a high variance. This observation is further confirmed by the error analysis presented in [Table 2](#), which shows that the standard deviation of the PD controller is higher than that of the others. Comparing the average error of the parallel controller and the cascade controller, we see that the cascade has a lower error in both trajectories, concluding cascade PD-PI controller performed better in this axis.

In figure [Figure 7](#), the trajectory of the UGV is represented in red, while the trajectory of the UAV is represented in blue. Focusing on the X and Y axes, that the UAV was able to follow the entire trajectory of the UGV with only a slight deviation while the Magni made a rotation, which is expected because the IRIS camera is on at the front of the UAV, not at the center. This effect is also seen in the [Figure 8](#), which shows that the iris can correctly imitate the rotations made by the Magni, but during this movement, the X and Y axes are affected.

In terms of the average error in the linear trajectory, see [Table 2](#). As the UGV’s movement is only in the direction of the X axis, alignment in Y becomes

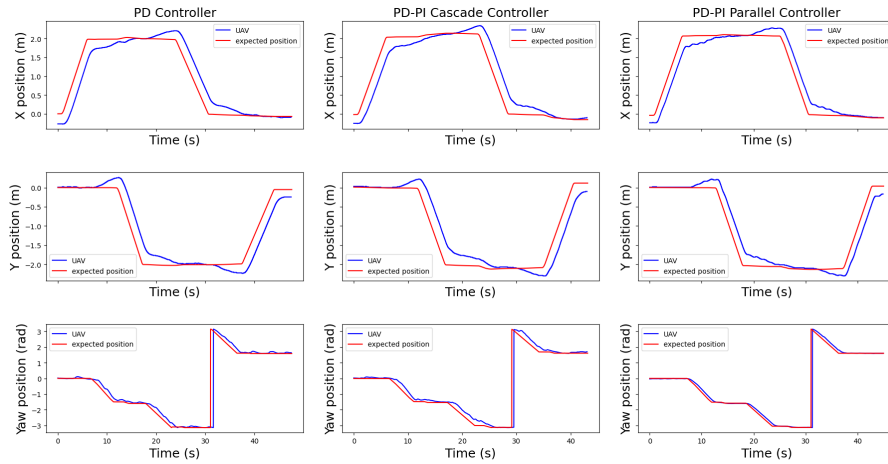
**Table 2.** Standard Deviation and Mean error of the Z-axis position in each control architecture.

		Z		X		Y	
		mean	std	mean	std	mean	std
line trajectory	pd	0.1	0.11	0.39	0.38	0.02	0.01
	cascade	0.03	0.03	0.38	0.38	0.02	0.02
	parallel	0.14	0.03	0.29	0.28	0.02	0.01
square trajectory	pd	0.05	0.06	0.23	0.32	0.23	0.32
	cascade	0.05	0.05	0.25	0.34	0.25	0.35
	parallel	0.13	0.02	0.2	0.27	0.2	0.27

**Figure 7.** UGV and UAV trajectories. The PD controller is shown on the left, the cascade PD-PI controller in the center and the PD controller on the right.

easier, meaning that the average error in the Y axis is lower. In contrast, the error is much higher for the X-axis, so it can be concluded that the UAV could not stay aligned with the UGV while it was moving in this direction, always staying slightly behind the Magni. In this case, the parallel controller seems to have performed better, with an error close to 30 centimeters, and the other controllers had an error of 40 centimeters. Furthermore, analyzing the standard deviation, we see that the pattern repeats, with a good value on the Y axis but a worse value on the X axis.

In the square trajectory, we see that the two axes, X and Y, have a high average error and a high standard deviation because the UGV moves in both axes in this trajectory. This is confirmed by observing [Figure 8](#) in which the Iris position is always behind the Magni position during movements. It is also clear that this delay is slightly less in the case of the parallel PD-PI controller.



**Figure 8.** Comparison of UAV and UGV position with the three controllers, PD, PD-PI Cascade, and PD-PI Parallel, on the quadrangle trajectory.

## 5 Conclusions and Future Work

This study contributes to the continued advancement of autonomous robotics and control systems, offering insights for researchers and professionals working at the intersection of UAVs and UGVs, computer vision and process automation. The SITL tests performed on the Gazebo software, implemented using ROS, showed that the proposed approach is a suitable solution, presenting effectiveness and robustness.

It also shows that PID control architectures based on fiducial marker detection successfully performed the tracking task, keeping the UAV coordinated with the ground robot’s movement in a simulated environment. The results showed that all the architectures tested performed satisfactorily, allowing them to move synchronously. However, the parallel PD-PI performed slightly better among the three architectures investigated than the other two.

For future work, in order to further improve the findings derived from simulated environments, it is important to conduct comparative experiments in real-world scenarios. This approach will not only extend the reliability and applicability of the system, but also provide a comprehensive understanding of its adaptability to real-world conditions.

In addition, a crucial factor that significantly affects the performance of the tested controllers is the adjustment of gains. Importantly, implementing adaptive systems for gain adjustment can offer greater robustness to the system. Future research should also include exploring and testing non-linear controllers to verify their applicability compared to PID controllers. These avenues for future

research are key to bridging the gap between simulation and practical application, advancing the field of autonomous robotics and control systems.

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