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A Low-Cost Dual-Rotor Platform for Control Systems Education and Digital Twin Integration

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Abstract. Control of mechanical systems is a fundamental topic in undergraduate engineering curricula, and practical laboratory experiments are often employed. These experiments rely on commercial test benches; however, such equipment is often expensive, thus prohibitive. Low-cost boards and sensors have become widely available, enabling the development of affordable facilities. This study aims to develop a digital twin for a dual-rotor setup with two degrees of freedom. The system will integrate sensing, actuation, and control techniques in a more accessible manner. Instrumentation will include an Inertial Measurement Unit (IMU), such as the MPU6050, with data acquisition handled via the Arduino platform and processed in MATLAB. Control algorithms will be implemented and tested using both classical techniques (*e.g.*, PID control) and modern control methods (*e.g.*, Full State Feedback and Kalman filtering) to evaluate the system's dynamic response. Experimental data will also be used to feed and validate a computational model of the prototype, establishing an integration between physical and mathematical models within the framework of a digital twin. The application of digital twin technology to test bench systems with two degrees of freedom represents a significant advancement compared to conventional commercial setups, making it a valuable resource for undergraduate education.

Keywords: affordable experiments, control systems education, prototype validation.

1 Introduction

The teaching of control systems in engineering courses often relies on highly abstract mathematical tools, combined with a solid theoretical foundation and laboratory practices that enable the understanding of the dynamics of real physical systems (Caldeira *et al.* [1]). However, the reliance on expensive commercial benches imposes significant limitations, especially for universities with budget constraints (de Castro Lobato *et al.* [2]). Accessible technologies, such as Arduino microcontrollers and low-cost sensors, for example, the MPU6050, open new possibilities for economical and versatile experimental platforms (Llamas Bello *et al.* [3]). Although these innovations hold great potential, there is still a gap in the practical application of digital twins in low-cost educational environments, particularly in platforms with multiple degrees of freedom and dynamic control (Bachmann *et al.* [4]). Digital twins establish a bridge between industry and academia by integrating computational simulations with physical systems, promoting interactive environments that facilitate both learning and model validation, in addition to driving digital transformation (Tabunshchyk *et al.* [5]). In light of this, this work proposes the creation of a low-cost aerodynamic platform with two degrees of freedom, using brushless motors, IMU sensors, MATLAB-based control, and a digital twin for validation. The objective is to expand access to advanced technologies in engineering education and to stimulate pedagogical innovation in resource-limited environments. Furthermore, the implementation of classical (PID) and modern (state feedback, Kalman filter) techniques is anticipated for the analysis and control of the system, as well as the construction of a digital twin for computational validation. The proposal aims to democratize access to advanced technologies in engineering education, aligning with the demands of Industry 4.0 and offering a cost-effective alternative to traditional commercial benches, equipping graduates with essential skills and meeting the needs of the manufacturing sector (Jeganathan *et al.* [6]).

2 Test bench descriptions

The proposed test bench consists of an arm that can pitch and yaw around a base, as can be inspected in Fig. 1. Specifically, revolute joints between the arm and the base, applied in the middle of the arm, constrain the arm in such a way it can pitch and yaw; in the edges of the arm there are DC motors and propellers able to execute control actions. The free-body diagram of the arm is presented in Fig. 1(a). F and T indicate the front and rear of the device, respectively, where F_p and F_y represent the two main reaction forces from the DC motors and propellers. F_p is applied around the Y-axis, with the angle θ indicating pitch motion (negative in Y-axis), and F_y is applied around the Z-axis, with the angle ψ indicating yaw motion (positive in Z-axis). The combined action of these forces, applied at a distance $L/2$ from the centre of the system, is responsible for generating torques that induce rotational movements around the axes of interest. These effects are considered both as primary actions, in the case of thrust forces, and as secondary actions, due to the resistive moments τ_p and τ_y induced by the system. The accurate representation of these forces and torques is essential for analysing the system's dynamics, as well as for the precise identification of physical parameters and the subsequent development of control strategies.

(a) (b)



Figure 1. (a) Model used for the Dual-Rotor Platform (b) Prototype

The experimental prototype used for the implementation of the digital twin in this study is depicted in figure 1(b) together with the main components built-in. This physical system represents an aerodynamic structure with two rotational pitch and yaw degrees of freedom, designed to simulate the behavior of dual-rotor aircraft. The structure is primarily composed of 3D-printed PLA parts, forming a model mounted on a fixed base and actuated by DC motors.

The system exhibited excessive vibration during operation. This compromised the stability of the system and the reliability of the data collected by the MPU6050, which is capable of measuring acceleration and rotation along the three coordinate axes (x, y, z), transmitting the data to an Arduino Uno R3.

The standard transfer function for this type of system is $\mathrm{T(s)} = \omega_n^2 \Big/ \left(s^2 + 2\zeta\omega_n s + \omega_n^2 \right)$, where $\zeta = -\ln\left(M_p \ / \ 100\right) \Big/ \sqrt{\ln\left(M_p \ / \ 100\right)^2 + \pi^2}$ and $\omega_n^2 = K_{py} W_{yy} / J_y$ are estimated for the prototype under controllable conditions. Note that M_p, K_{py}, W_{yy} and J_y stands for system overshoot, the proportional controller gain, thrust torque and moment of inertia related to the yaw axis, respectively.

The unit step response of the simulated controlled system is depicted in Fig. 2(a), revealing an underdamped behaviour, with transient oscillations that converge to a value around $\theta = 0.6$. From the perspective of the digital twin of an aerodynamic system, this response reflects the integration of sensing data and the performance of the actuation and control algorithms. The reference line set at $\theta = 1$ corresponds to the desired input in the virtual environment, while the observed deviation, characterized as a steady-state error, typical of type 0 systems without integral action, indicates a discrepancy between the virtual model and the ideal behaviour of the physical prototype. This error highlights the need to improve the controller, suggesting the inclusion of integral action to eliminate the deviation and enhance reference tracking, ensuring greater fidelity in both the simulation and implementation of the digital twin. The step response of ψ, shown in Fig. 3(b), demonstrates that the control system of the digital twin operates with high precision. A small overshoot is observed, followed by an exact convergence to the reference value (1), with no steady-state error. This behaviour indicates effective tuning between sensing, actuation, and control, ensuring that the digital model accurately replicates the real dynamics of the aerodynamic system. Such a result reinforces the reliability of the digital twin for implementing advanced simulations and control strategies under critical operating conditions.

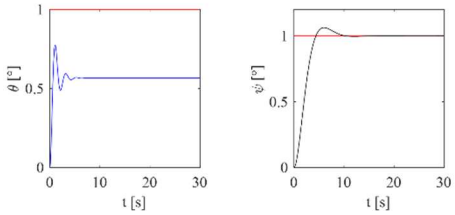


Figure 2. (a) Unit step response of a controlled system. The blue curve represents the angular response $\theta(t)$ of the system under the action of the controller. The red line represents the unit step input ($\theta = 1$). (b): Unit step response of the variable ψ in the digital twin of the aerodynamic system. The black curve represents the response of the controlled system.

3 Initial Results

This section presents the results of tests carried out under static conditions and with manual movement, aiming to evaluate the performance of the MPU-6050 inertial sensor during normal operation, without the use of smoothing filters. The following analysis focuses on the responses obtained with the application of the Kalman Filter. The main purpose of these experiments was to assess the stability of the measurements at rest and in motion, identifying the presence of background noise during prototype operation, crucial factors for ensuring the good response of the sensing system and, consequently, the output of the digital twin. Figure 3 shows some initial results.

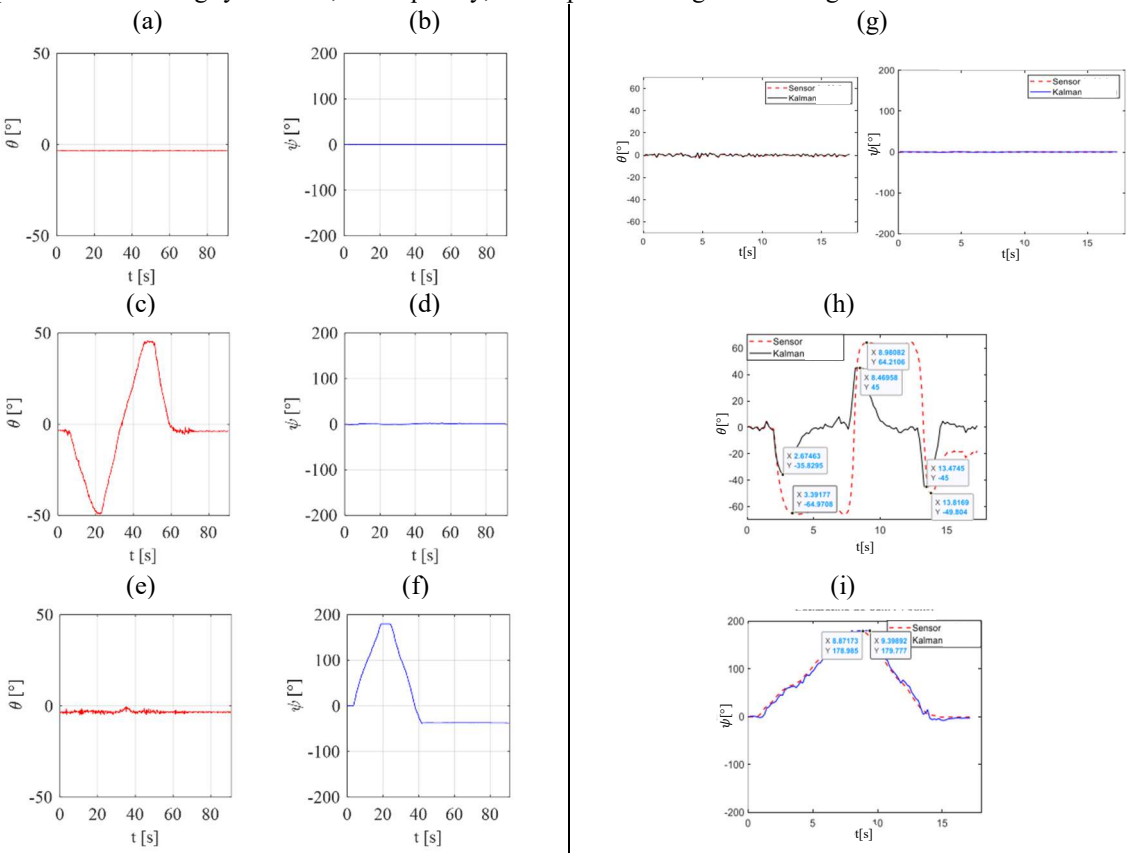


Figure 3: Results of static and manual tests with the MPU-6050 sensor. (a) and (b): Pitch and yaw angles under static conditions; (c) and (d): Yaw angle in motion and pitch in static condition; (e) and (f): Pitch angle in motion and yaw in static condition.

Figures 3(a) and (b), the behavior of the sensor at rest is observed, showing minimal background noise and signals centered near zero, indicating stability in the measurements in the absence of external movement. Figures 3(c) and (d) correspond to manually induced variations along the pitch axis, with the yaw axis kept static. These graphs reveal good sensor sensitivity to the application of actual physical angles, with smooth variations and consistent responses reaching amplitudes close to the expected limits $\pm 45°$. Meanwhile, Fig 3(e) and (f)

correspond to manually induced variations along the yaw axis, while the pitch axis remains at rest. These also demonstrate good sensor sensitivity to the application of physical angles, with smooth variations and consistent responses reaching amplitudes close to the expected limits of of $\pm 180°$. Figure 3(g) presents a comparison between the raw data obtained from the sensor, represented by the red dashed line, and the data estimated by the Kalman Filter, shown as the solid black line at rest. Figure 3(h) presents a comparison between the raw data obtained from the sensor, represented by the red dashed line, and the data estimated by the Kalman Filter, represented by the solid black line. It can be observed that the signal coming directly from the sensor is characterized by significant noise, which compromises the accuracy of the instantaneous measurement of θ. In contrast, the estimate provided by the Kalman Filter shows a noticeably more stable behavior, resulting in a smooth and continuous curve that effectively attenuates the peaks and valleys characteristic of the noisy signal, providing a more accurate and reliable representation of the observed variable. Figure 3(i) presents a comparison between the raw sensor data, represented by the red dashed line, and the estimate filtered by the Kalman Filter, represented by the solid blue line, applied to ψ. It can be observed that the signal provided by the sensor is of good quality, with a low noise level, allowing for an accurate approximation through the filtered estimate. The high degree of overlap between the two signals demonstrates the filter's efficiency in tracking the real dynamics of the variable, faithfully preserving both the temporal trend and the maximum and minimum values (peaks and valleys), with minimal time lag. These results reinforce the integration between sensing and control in the digital twin of the aerodynamic system, ensuring that the digital model accurately replicates the behavior of the prototype.

4 Conclusions

This paper presents an alternative test bench designed to simulate dual-rotor conditions. A brief introduction to the mathematical model is provided, followed by a description of the main components of the test bench. The overall architecture of the controller is also outlined, with initial results demonstrating good stability. Preliminary prototype tests were carried out, showing strong performance under static conditions and reasonable results when the Kalman filter was applied. The digital twin approach will be discussed in detail during the conference presentation.

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