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Closed-Loop Control and Sensor Noise Reduction in a Low-Cost Aerodynamic Pendulum Using Digital PID and Kalman Filtering on Arduino Mega

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Abstract. This work presents the design, construction, and validation of a cost-effective aerodynamic pendulum as an alternative to commercial systems. It uses a digital PID controller for real-time angular position regulation and a Kalman filter to reduce sensor noise. The modular design allows for easy integration of hardware and software, promoting replication and experimentation without compromising accuracy.The prototype features affordable components including an Arduino Mega 2560, DC motor, precision potentiometer, and an L298N H-bridge. A closed-loop system with PID control minimizes error relative to a 90° reference angle, while the Kalman filter enhances measurement reliability. The mechanical structure, built from plywood and plastic, offers stability. Motor voltage is adjusted using a PWM signal. Results show a fast dynamic response and resistance to disturbances. Overall, the project confirms the feasibility of developing effective, low-cost alternatives for control systems and educational applications.

Keywords: Modular Design, Precision Potentiometer, Mathematical Model, Educational Prototype, Replicability

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1 Introduction

Educational prototypes are viewed as experimental devices designed to demonstrate and test concepts in control systems. In research and educational settings, these devices are often used to visualize system dynamics, which in turn facilitates the observation of system behavior under the application of various control laws, such as PID control. In addition, it is intended to use them as a platform to validate control algorithms in real or simulated environments, allowing parameters to be adjusted and results to be evaluated in a practical way. Although didactic prototypes are essential to understand the theory of control in physical systems, acquiring them through commercial suppliers is very expensive. For example, systems such as the inverted pendulum, ball and beam, temperature controllers or even mobile robots are marketed at prices ranging from 3,600 to 6,170 dollars (USD) in industrial or academic versions offered by companies such as Quanser, Intec Automation or ServoCity. There are also more affordable options in semi-industrial kits, with prices between 770 and 1,800 dollars (USD). However, these amounts remain high for many educational institutions and research projects with limited budgets.

In order to respond to this problem, it is proposed to build and program a low-cost Aero Pendulum. This system, widely used to study stability, with the aim of demonstrating the feasibility of employing economic alternatives in experimentation and training in control systems.

To support the rationale of this proposal, a review of the existing literature is carried out, highlighting the experimental validation of various methodologies both through simulated environments and field tests. Multiple studies have demonstrated the feasibility of employing didactic prototypes for the control of aeropendulums using economical and robust solutions. For example, combining a ZVDD shaper with a robust PID controller has been reported to reduce overshoot from 15% to 4% and stabilize the system within 6 seconds (Marashian, 2020). Similarly, the speed control of a DC motor has been verified by a PID controller and the L298N controller, demonstrating effective performance under different load conditions (Peerzada, 2021). The literature also highlights the application of frequency domain identification combined with a Kalman filter to refine control strategies (Marashian, 2021). In addition, a comprehensive approach to modelling and parameter estimation based on Newton's second law has been presented (Lucena, Luiz, & Lima, 2021). Recognize the realization of a didactic prototype implemented in MATLAB and Arduino, in which an LQR controller with integrator is incorporated to achieve an approximate accuracy of 90.59% (Yamanaka et al., 2022), and the optimization of a PID controller through Particle Swarm Optimization (PSO), which reduces tracking error by 85% compared to other approaches (Barros and Lima, 2022). They also include the presentation of a hybrid framework based on Lagrangian Neural Networks and Energy Shaping, which stabilizes the system in approximately 4.1 seconds with an overshoot of 4.6% (Araújo, 2023), and describe the validation of a nonlinear model applied to systems that integrate a beam with propeller and counterweight through simulations in MATLAB and Simulink (Carraro, 2023). Consider the proposal of a modular PID-based system that uses 3D printing, Arduino, and LabView for its implementation (Jiménez López et al., 2023), as well as the integration of a PID controller complemented with an advanced network to achieve a 3-second response in angular control (Díaz García et al., 2023). To recognize the comparison made between the performance of an LPV-H controller versus a conventional PID for angular position regulation (Valdés, Zoulagh, & Barbosa, 2023) and the refinement of the aaeropendulum mathematical model by analyzing the thrust force using the WSINDy algorithm (Oliveira, Lima, & Lima, 2023). Likewise, to present the construction of a low-cost open-source prototype, called AeroShield, whose price is reduced to 23 euros and integrates interfaces in Arduino IDE, MATLAB and Simulink (Vargová et al., 2023).

Similarly, research exploring H-loop shaping control to stabilize the system with minimum overshoots (Oliveira, Aguiar, & Vargas, 2023) and studies documenting the design of angular position control systems based on PID and LabVIEW, which mitigate destabilization under variable loads (Romadhon & Endryansyah, 2023) were identified. Highlight the hardware-software integration that allows the implementation of an L298 H-Bridge, managed by Arduino PWM and calibrated to operate in the optimal range (0–5 V) in order to avoid actuator saturation (Carraro, 2023), and the real-time execution of the Kalman filter to compensate for the limitations of economic sensors without relying on complex analytical models (Araújo, 2023), as well as the system's demonstrated ability to tolerate transient disturbances without resorting to more sophisticated control solutions (Marashian, 2021; Oliveira et al., 2023).

To further support the proposal, several recent works have implemented and experimentally validated prototypes of aeropendulums with novel approaches in design, instrumentation and control. For example, Morales-Narciso et al. (2023) presented a propeller-driven rocker system, designed in SolidWorks and manufactured using 3D printing, whose angular position was measured with a potentiometer characterized by least squares; the dynamics were identified by step response and PID control was fine-tuned with Ziegler–Nichols, demonstrating the feasibility of combining low cost and accuracy in physical platforms. In a complementary way, Alvarado-Hernández et al. (2025) integrated a fuzzy PID-controller with state estimation in an aeropendulum, enriching the robustness against external uncertainties and disturbances using fuzzy logic and a flexible sensor, and compared its performance in real time with purely crisp methods. Likewise, Hernández-Pérez et al. (2024) validated, on an Arduino UNO platform, the application of a Kalman filter to attenuate measurement noise and compared a classic PID against a gravity-compensated LQR (LQR+G), evidencing significant improvements in disturbance rejection and energy efficiency. Incorporate the implementation of an adaptive PID controller through a "Hunting Search" algorithm to improve angular tracking (Rojas-Galván et al., 2024) and the comparison between PID and MPC controllers, concluding that MPC offers greater stability, while PID provides faster response times and fewer overshoots (Pamuji et al., 2024).

This compilation of background reinforces the idea that the development of economic didactic prototypes allows for experimentation and practical validation of control strategies. In this project, a Kalman filter is integrated to reduce the noise present in the potentiometer measurements and a PID controller whose parameters, obtained by assigning poles, will allow quantifying the system's ability to reject disturbances and optimize energy consumption. In this way, a theoretical and experimental basis is established that supports the viability of the proposed aeropendulum. Likewise, economical and easily acquired materials are chosen, which makes it possible to replicate the system without significant investments. Finally, the implementation of the PID controller will be carried out on the Arduino platform, discarding the standard libraries provided for that purpose.

To provide an overview of the topics addressed, the structure of this study is detailed below:

Section 2: describes the methodological development of the project, starting with the construction of the aero-pendulum, for which accessible materials and key components were selected. The mathematical model that represents the dynamic behavior of the system is presented, as well as the implementation of the Kalman filter, used to improve the quality of the sensory signal. Finally, the programming of the PID controller on the Arduino platform is detailed, explaining its logical structure and its integration with the physical system.

Section 3: the experimental results obtained after the implementation of the system are presented and analyzed. The performance of the PID controller in conjunction with the Kalman filter is evaluated, highlighting its effectiveness in stabilizing the angular position of the aero-pendulum at 90°. Graphs showing error evolution, angular trajectory, and PWM control signal are included. Likewise, improvements to the prototype are proposed, focused on optimizing its performance and facilitating its scalability.

Section 4 presents the general conclusions of the study, which confirm the feasibility of building a functional control system. The developed mathematical model is validated and the effectiveness of the implemented control algorithms is checked. In addition, the educational value of the prototype, its replicable nature and its usefulness as a didactic tool for teaching automatic control systems in contexts with limited resources are highlighted.

2 Methodology

In the field of theory and application, the pendulum is used as a classical dynamic system to study and design control strategies. It consists of a mass suspended from a fixed point by means of a rod or rope, generating an oscillatory movement described by differential equations and allowing the stability and behavior of nonlinear systems to be studied.

Also, describe the Aero pendulum as a device that combines a traditional pendulum with an actuator. Forming the actuator with a direct current motor coupled to a propeller, driving the rotational movement on an axis and having sensors to measure the position of the arm in real time. Include a PID-based electronic controller that, through feedback, adjusts the voltage to increase or decrease the speed of the motor, stabilize an arbitrary position, and respond to external disturbances. To highlight the great relevance of the Aeropendulum in the field of modern control, by modeling important challenges of real systems, such as the compensation of nonlinear disturbances, the management of delays in response and the optimization of energy. The device was applied in areas such as the control of drones during wind gusts and the manipulation of robotic arms that require millimetric precision. Likewise, it contributes to the research and development of control systems applied to aerial vehicles and aircraft, by allowing the modeling of turbulence-like scenarios. In addition, it serves as a tool to teach and experiment with classical control strategies, such as PID, and to explore innovative techniques such as adaptive control, predictive control and advanced methods that incorporate artificial intelligence. Its mechanical simplicity and low cost were used to facilitate the learning of fundamental concepts such as stability, robustness and adaptability.

2.1 Mathematical Model

The aero-pendulum consists of a rotating arm of length L, the near end of which is connected to a potentiometer to measure its angular position. At the opposite end, a DC motor coupled to a gear drives a propeller that generates a thrust T, producing a TL torque that modifies the angular position of the system (angle and relative to the vertical axis). This displacement induces a perpendicular component of the weight force (mgsin(y)), acting on the center of mass of the assembly (arm, motor, gear, propeller), located at a distance "L" from the potentiometer.

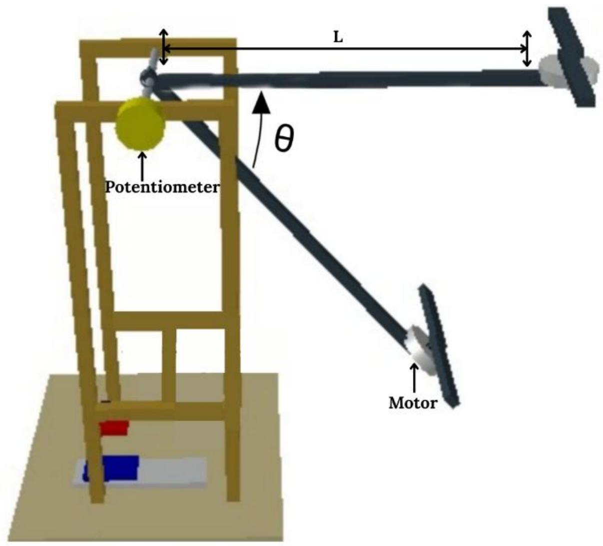

Figure 1. Schematic representation of the aeropendulum.

The angular velocity will be directly related to the speed of the motor. Therefore, the differential equation describing the armature current (ia) is formulated in (1), as established by Franklin et al. (2001). Additionally, the dynamics of the rotor speed is represented by equation (2) of the same study, where the electromagnetic torque is given by Kiia, the torque due to viscous friction by Fω1, and the mechanical torque imposed by the gears and the propeller by T1. (Lucena et al., 2021)

$$\frac{d\omega_1}{dt}=\frac{K_i}{Jm}i_a-\frac{F}{Jm}\omega_1-\frac{1}{Jm}T_1 \quad \textbf{(1)}$$

$$\frac{di_a}{dt}=-\frac{R_a}{L_a}i_a-\frac{K_w}{L_a}\omega_1+\frac{1}{L_a}v_a \quad \textbf{(2)}$$

The rotor applies a T1 torque to the driving gear (with N1 teeth), transmitting a T2 torque to the propeller by the driven gear (with N2 teeth). According to the gear ratio, the angular velocity of the propeller is ω2=(=(N1/N2)ω1, while the torque over the propeller is adjusted as T2 = (N2/N1)T1 . From Newton's second law for rotational systems, the differential equation describing the motion of the pendulum, given in (3) (Lucena et al., 2021), is obtained.

$$J\frac{\partial^2 y}{\partial t^2}+C\frac{\partial y}{\partial t}+mgd\sin(y)=LT \quad \textbf{(3)}$$

For the simplification of some calculations, some assumptions were made, such as the dynamics of the engine (1) and (2) turn out to be negligible compared to the dynamics of the engine (3), the moment of inertia of the propellers (Jh) is also neglected and the transient response is faster than that of the pendulum arm, therefore, the velocity is assumed to be constant ω2=ω2SS. The angular velocity of the motor shaft does not take negative values. Under these assumptions, the dynamic between the work cycle u and the thrust T can be neglected. (Lucena et al., 2021).

2.2 System Construction

The aeropendulum platform was conceived as a compact and portable assembly, with a square base of 0.30 × 0.30 m made of plywood to ensure a robust and uniform support surface. On top of it rise two parallel towers, spaced 0.15 m apart and centred, which provide rigidity and structural stability. The pendulum consists of a rigid rod mounted on a horizontal axis, supported by low-friction bearings, whose movement is transmitted to a precision potentiometer (model WDD35D-4 of 10 kΩ) installed at one of its ends. At the same point, the brushless motor and propeller generate the necessary thrust force to counteract gravity and position the pendulum exactly.

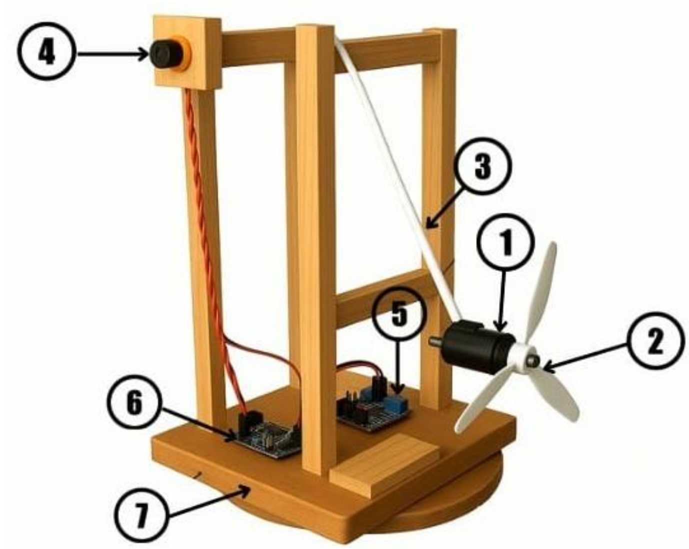

Figure 2. Components of the aerodynamic pendulum

1. DC motor model 2CCW
2. Clockwise rotation propeller 10 x 4.5"
3. Plastic tube of the structure (length= 0.6 m)
4. Potentiometer (model WDD35D-4 of 10 kΩ)
5. H-bridge (L298N)
6. Arduino Mega 2560 board
7. Wooden structure (base 0.3 x 0.3 m, height 0.4 m)

The mechanical design process was developed entirely in SolidWorks, which allowed for interference validation and sizing of elements prior to manufacturing. After cutting and assembling the plywood parts, the team installed the potentiometer on a bracket that ensures it is aligned with the shaft. In addition, the brushless motor was fixed by means of an adapter that maintains concentricity with the propeller. The Arduino Mega 2560 board centralizes data acquisition and control: it reads the analog signal from the potentiometer, executes the control algorithm, and generates the PWM signal. To drive the motor, an L298N H-bridge was incorporated, calibrated in the optimal range of 0–12 V to avoid saturation of the ESC. Finally, all wiring and power electronics are housed in the base so that the assembly retains a clean profile and minimizes vibrations and electromagnetic interference.

Below is a table with the materials used in the development of the prototype and the cost of each:

Table 1. Total Model Budget

Amount	Material Used	Price(USD)
1 piece	18 mm plywood structure	2.48
1 piece	Wood adhesive	3.23
1 piece	1/8 screws	0.99
4 piece	1/8 nuts	0.15
5 piece	*Straps*	0.50
2.2 mt	*22 AWG wire*	0.50
1 piece	*Precision potentiometer*	10.68
1 piece	*Arduino MEGA 2560 board*	25.34
1 piece	*H Bridge L298*	3.38
1 piece	*Breadboard*	4.97
1 piece	*6-volt DC motor*	2.48
1 piece	*Propeller and its coupling (gearbox)*	1.49
	Cost =	56.19

2.3 The Kalman filter

The Kalman filter is applied in order to eliminate unwanted variations, calculating the optimal estimate of the state (angular position).
The "clean" signal is optimized to provide the control system (in this case, the PID controller) with the necessary parameters to reach the rest (or reference) position in an accurate and stable way, dynamically adjusting the estimate to any change in the environment.

It is emphasized that the implementation of the Kalman filter allows overcoming the inherent measurement limitations, guaranteeing greater reliability of the signal in the aeropendulum control system.

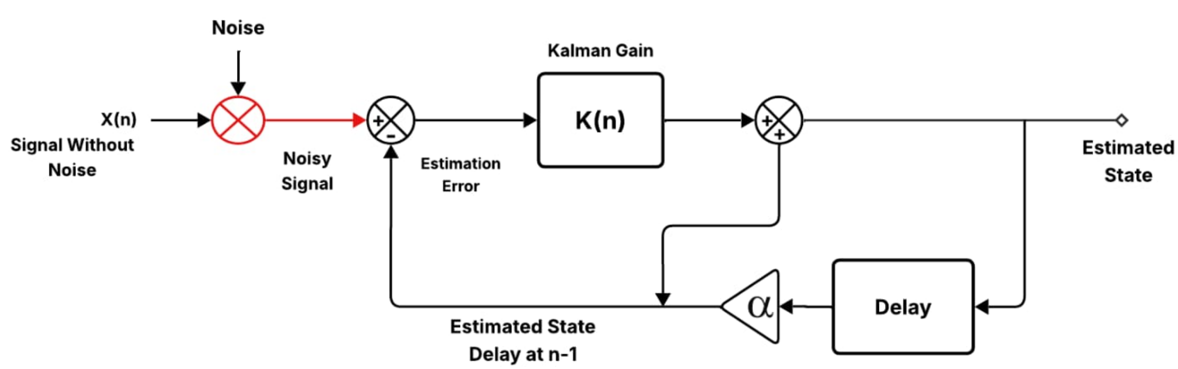

Figure 3. Block diagram of the Kalman Filter implemented.

The following block diagram illustrates the control flow of the Kalman Filter implemented for the Aero-pendulum system. The design reflects the algorithm's structure, clearly showing the interaction between the measured signal and the system's internal model, enabling the estimation of the pendulum's true state from noisy signals.

The diagram comprises the following stages:

Estimation error: Calculated as the difference between the measured signal (which includes noise) and the previous state estimate.

Kalman Gain (K[n]): Adjusts the weight assigned to the estimation error in the state correction.

Updated state estimation: The weighted error is added to the previous prediction to obtain the new state estimate.

Feedback: The updated state is delayed to be used as input for the estimator in the next iteration.

This control flow graphically represents the internal logic of the Kalman Filter implemented on the Arduino platform, significantly enhancing the accuracy of the pendulum's angular position measurement, even in the presence of noise.

2.4 Implementation of a PID Controller in Arduino for the Aeropendulum System

A PID (Proportional, Integral, Derivative) controller is used with the aim of precisely regulating the angular position of an aeropendulum, minimizing the error between the desired value and the value measured by an analog sensor. This type of controller is characterized by its efficient and stable responsiveness, being widely used in automatic control systems. The algorithm is programmed on an Arduino Mega 2560 board, taking as a reference the signal coming from a potentiometer, which represents the angular position of the pendulum.

The process is started by reading the analog input from the A0 pin, to which a precision potentiometer is connected. This signal, represented by a digital readout between 0 and 1023, is converted to voltage by a linear proportionality rule that considers the range from 0 to 5 volts. A desired reference position of 2.7 V is set, corresponding to the target angular position of the system. Error is defined as the difference between the desired value (xdes) and the measured value (xmed). From this difference, the three fundamental actions of the PID controller are calculated:

- Proportional Action (P): The current error is multiplied by a constant kp, generating an immediate response to deviations.
- Integral Action (I): The cumulative sum of the error over time is calculated, using the trapezium rule for a better numerical approximation. This action allows you to eliminate the steady-state error.
- Derivative Action (D): The change in the error with respect to time is determined by a discrete derivative, which anticipates the trend of the system and helps to stabilize the response to rapid disturbances.
- The three actions are combined by a weighted sum, where the constants kp, ki and kd define the degree of influence of each on the control signal.

The control signal is constructed as the sum of the three components (P, I, D), and is continuously updated within the main program cycle. This signal is used, in the complete system, to modify the behavior of the aeropendulum actuator (e.g. a motor), correcting the position of the pendulum according to the error detected. The control signal and measurement value are printed by the serial port, in order to monitor the behavior of the system in real time.

The value of the previous error (errorant) is updated at the end of each cycle, thus allowing the correct calculation of the derivative in the next iteration. This procedure is repeated in each execution cycle (loop()), allowing the system to respond continuously and adaptively to any change or disturbance in the input.

2.5 Actuator Operation

When an angle measurement is made, the potentiometer sends a signal to the Arduino, where it is processed by a Kalman filter (to reduce noise) and the PID controller. The latter generates a PWM control signal proportional to the discrepancy between the desired position (90°) and the current position (θ): the greater the error, the greater the adjustment in the signal's duty cycle. The PWM signal is directed to an H-bridge, which regulates the voltage that is applied to the DC motor terminals. When this voltage is increased or decreased, the speed of the motor is modified, whose shaft is mechanically coupled to a propeller. The aerodynamic force generated by the propeller raises or lowers the arm of the Aero pendulum, thus correcting (θ). The closed feedback loop ensures that the system dynamically converges to any specified angular position.

The following describes the complete implementation, without dependence on Arduino libraries, of a Kalman filter and a PID controller (with its P, I and D gains) to ensure the correct performance of the system.

```
START

Define pins:
   pinPWM ← 10
   IN1 ← 8
   IN2 ← 7
   pot ← A0

Initialize constants and variables:
   xdes ← 1.98      // desired position
   kp ← 5500.3
   ki ← 50000.0
   kd ← 300.0
   h ← 0.001        // time step
   ac ← 1.0
   sigma_uc ← 0.0005

Initialize dynamic variables:
   xmed, error, errorant, trapezoid, integral, derivative, control ← 0
   shat, M, numc, meanC, restC, errorC, Kc ← 0
   kc ← 1
   var_nc, sigma_nc ← 0

SETUP:
   Set pinPWM as output
   Begin serial communication at 9600 baud

MAIN LOOP (executed continuously):
```

This section is responsible for estimating the real signal of the sensor by means of an adaptive Kalman-type filter. It starts with reading the potentiometer and ends with getting your already filtered position signal.

```
Read potentiometer signal → xmedc
   Convert to real voltage: xnc ← (xmedc / 1024) * 5

   Compute mean and variance (adaptive filter):
      Accumulate value: var_nc ← var_nc + xnc
      meanC ← var_nc / kc
      restC ← (xnc - meanC)^2
      numc ← numc + restC
      sigma_nc ← numc / kc

   Apply adaptive filter:
      shat ← ac * shat
      errorC ← xnc - shat
      M ← (ac^2) * (M + sigma_uc)
      Kc ← M / (sigma_nc + M)
      shat ← shat + (Kc * errorC)
      M ← (1 - Kc) * M

   Estimate filtered signal: xmed ← shat
```

This section takes the filtered value (xmed) and calculates the control signal based on the error, the integral and the derivative which is the PID (Proportional-Integral-Derivative Controller).

```
   Compute control error:
      error ← xdes - xmed
      trapezoid ← h * (error + errorant) / 2
      integral ← integral + trapezoid
      derivative ← (error - errorant) / h

   Compute PID control signal:
```

```
    control ← kp * error + ki * integral + kd * derivative

  Increment sample counter: kc ← kc + 1
  Store previous error: errorant ← error
```

Finally, we have the writing of data on the output that includes both the sending of the signal to the actuator (via PWM), and the printing of data by the serial monitor, and sends it to the actuator.

```
  Scale control signal to PWM range:
    pwmValue ← map(control, 0, 30000, 120, 255)
    Write PWM output to actuator: analogWrite(pinPWM, pwmValue)

  Print data to serial monitor:
    Print shat, pwmValue, error, control

END LOOP
```

The image depicts the functional design of a control system applied to the aero-pendulum. The prototype was successfully built and is currently operating with a PID controller implemented on the Arduino UNO platform. The diagram also includes an adaptive Kalman filter, used to improve the estimation of the sensor's noisy signal. By continuously feeding back measurements, computing the control law, and actuating the motor, the system achieves stabilization of the pendulum around the desired position.

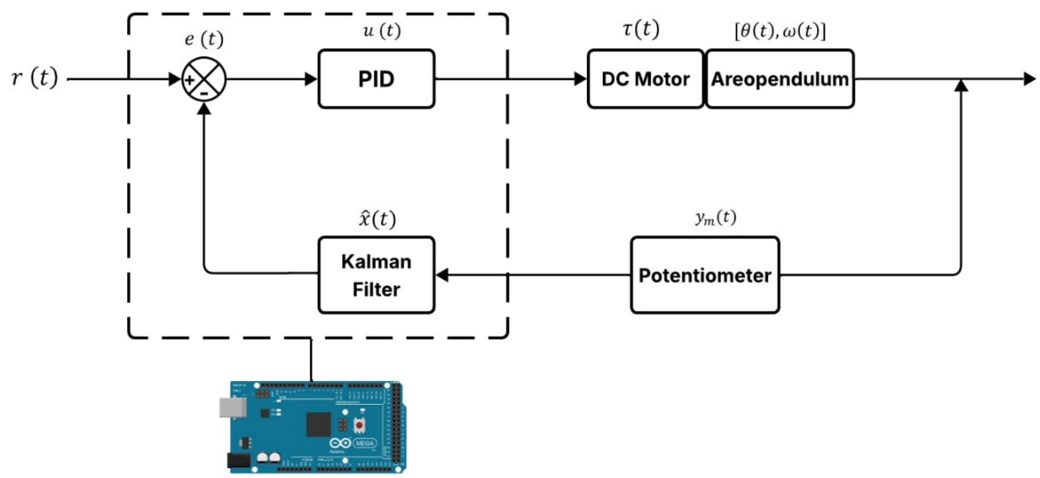

Figure 4. Diagram of the Automatic Operation of the Aero-Pendulum

Where:

- $r(t)$ Desired angle
- $e(t)$ Position error
- $u(t)$ Control signal produced by PID
- $\tau(t)$ Torque generated by the DC motor
- $[\theta(t), \omega(t)]$ The propeller and the dynamics of the pendulum produce the position and velocity
- $y_m(t)$ Noisy angle measurement
- $\hat{x}(t)$ Optimal condition estimation

2.6 Prototype Performance

The aeropendulum shows a behavior in accordance with what was planned: it corrected the position errors that it presented at the beginning of its tests (t=0), as the tests progressed, it managed to stabilize at the desired angle of 90°. At the same time, the Kalman filter fulfills its critical role by suppressing interference in the potentiometer signal, thus protecting its quality from the data fed to the PID controller. The H-bridge regulated the voltage applied to the motor based on the PWM signal sent by the Arduino, and guaranteed the structure – in design, mechanical robustness and economic efficiency – its operation was stable, with no operational failures during its tests. The performance of the aeropendulum can be viewed at the following link: https://youtube.com/shorts/eaBiwqKWQgg

3 Results and discussions

A working prototype of an Aero-pendulum was successfully developed using materials of modest cost for both its mechanical assembly and its electronic components. The control system implemented a Kalman filter to filter out the noise produced by the precision potentiometer to the analog input of the Arduino Mega 2560 board, which could affect the accuracy of the angular position managed by the PID controller.

The PWM signal generated by the Arduino was connected to an H-bridge (L298), responsible for supplying the power by means of an additional power supply that the programming board cannot generate for the electromagnetic torque that the motor requires to propel itself, maintain and make the angular position control. Necessary to the motor, the propeller was coupled with its respective gearbox that allows the movement of the Aero-pendulum arm and with it the objective position of 90° is obtained.

The prototype showed a rapid dynamic response, both during system initialization (t=0) and in steady-state operation (θ=90°). In addition, it demonstrated robustness against transient disturbances caused by environmental factors or human intervention. This efficiency is attributed to the synergistic work between the PID controller and the Kalman filter, which managed to compensate for the inherent limitations of the materials while keeping it at an affordable price.

(Figure 5) shows the evolution of the error between the initial position (t=0) and the steady state. The control system will detect the discrepancy between the desired position (90°), defined by a potentiometer that will convert the angle into an analogue voltage signal (0-5 V. The Arduino MEGA 2560 processes this reference signal through its analog input and adjusts the voltage applied to the motor using pulse-width modulation (PWM). The closed feedback loop progressively reduced the error, which tends asymptotically to zero as the system reaches the target position.

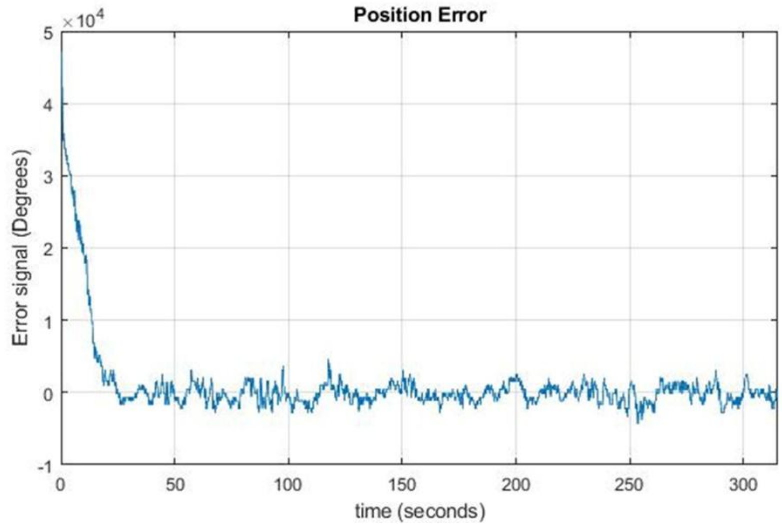

Figure 5. Position Error

(Figure 6) shows the angular trajectory of the aeropendulum as a function of time, showing how the error described in (figure 5) converges towards zero. This behavior confirms that the PID controller is correctly calibrated, as it effectively regulates the position of the system until the desired equilibrium point (θ = 90°) is reached and maintained, despite external disturbances.

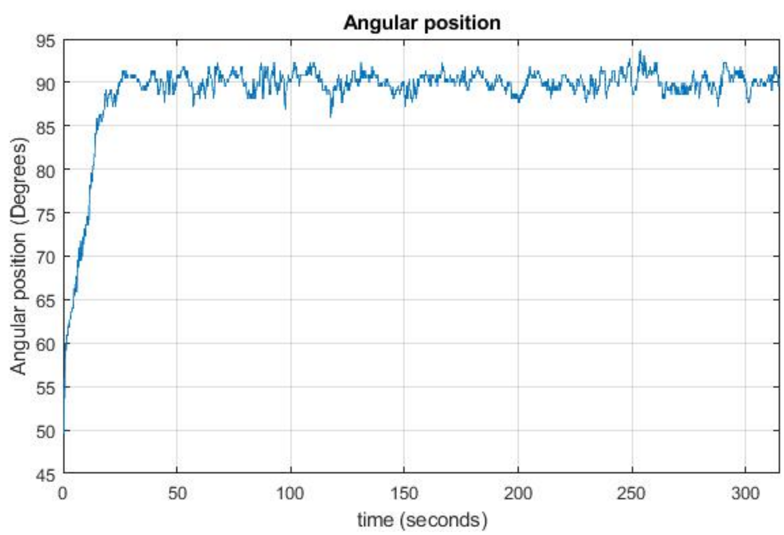

Figure 6. Angular position of the system with the PID controller

(Figure 7) shows the initial rapid response of the PID control for error correction

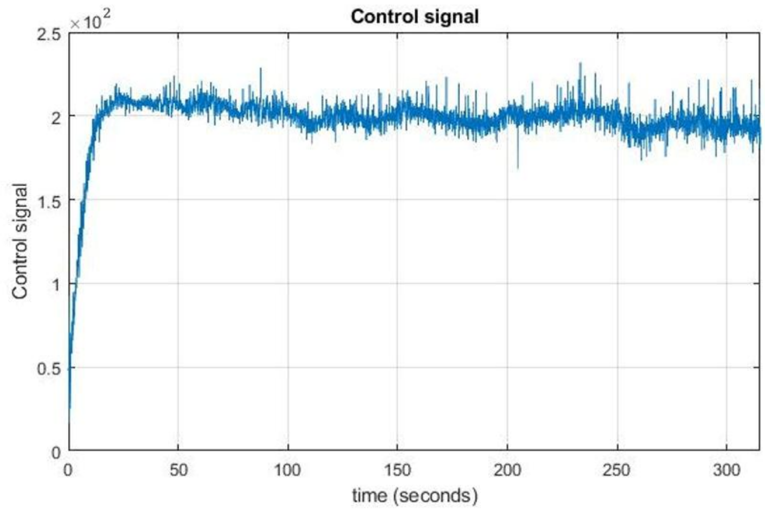

Figure 7. Control signal provided by PID control

(Figure 8) Illustrates the dynamics of the PWM signal generated by the PID controller as a function of time. In the initial phase (t=0), a significantly high value of the PWM signal is observed, the expected response of the control algorithm to the large discrepancy between the current angular position of the aero-pendulum and the desired reference (90°). This increase in the PWM signal duty cycle allows a high voltage to be applied to the motor, facilitating the rapid movement of the arm towards the target position. As the system approaches the steady state (θ=90°), the amplitude of the PWM signal progressively decreases, adjusting to maintain stability with reduced control effort. This behavior is consistent with the evolution of the position error shown in (figure 5)

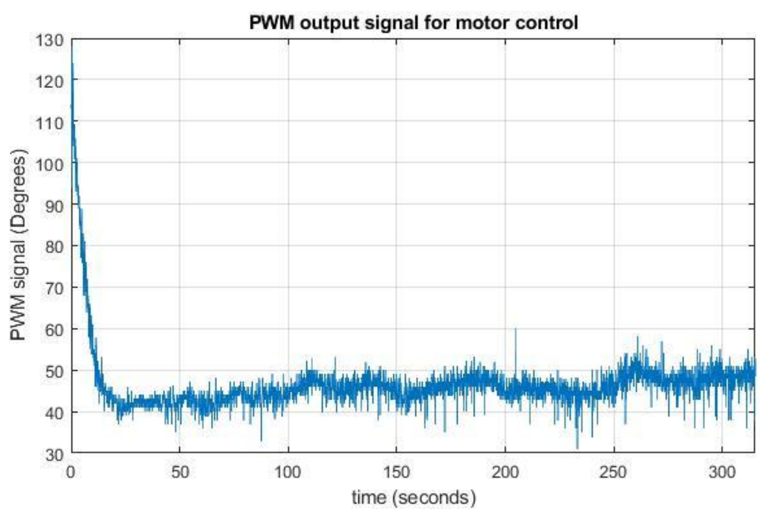

Figure 8. PWM Signal for Motor Control

4 Conclusions

To conclude the validation of the design and implementation of the Aero pendulum system built and programmed with low-cost materials, demonstrating the feasibility of developing a semi-professional prototype adapted to reduced budgets without compromising its functional performance. The successful integration of the Kalman filter and PID controller into the Arduino platform stands out, which allows to eliminate disturbances in the analog signals and precisely regulate the angular position until the 90° target is effectively reached.

Likewise, it is concluded that the system developed for the analysis and control of the aerodynamic pendulum has satisfactorily met the proposed objectives, validating both the mathematical model and the control algorithms implemented. The design, construction and implementation process has made it possible to corroborate the adequate performance of the prototype in real conditions, evidencing a consistent and robust dynamic response to disturbances, without the need to make additional modifications once the control gains have been estimated. This behavior underlines the robustness of the proposed methodology, in addition to demonstrating the applicability of the knowledge of automatic control in the effective regulation of nonlinear systems.

It has been proven that it is possible to obtain good initial estimates of control gains, either from the transfer functions previously described, which validates the adjustment and corroboration strategy of the system. The use of accessible materials and a modular process facilitates the replication of the prototype in academic and experimental environments, contributing to the democratization of access to study and teaching tools in the field of automatic control and virtual instrumentation.
Proposed improvements include upgrading the H-bridge to a model with higher current capacity, adding a cooling fan, and implementing a larger heat sink to counteract temperature rise during extended operations. It is also recommended to replace the breadboard with a custom printed circuit board (PCB), which would reduce the size of the system, improve its aesthetic appeal, and increase electrical reliability. These modifications would not only increase the efficiency of the device, but also facilitate its scalability for applications that require greater operational demands.

Finally, it concludes by reaffirming that the harmonious integration of electronic and mechanical components not only meets the proposed technical objectives, but also expands the dissemination and application of this knowledge in the field of automatic control.

References

Alvarado-Hernandez, J.-R., et al. (2025). *Fuzzy-PID control with state estimation for the regulation of an aero-pendulum system*. In *2025 11th International Conference on Mechatronics and Robotics Engineering (ICMRE)* (pp. 187–192). IEEE. https://doi.org/10.1109/ICMRE64970.2025.10976289

Araújo, R. T. (2023). *Modeling and control of an aeropendulum through Lagrangian neural networks* (Final paper). Federal University of Campina Grande, Campina Grande, Paraíba, Brazil.

Aris, B., & Romadhon, D. (2023). *Design of the aeropendulum angular position control system using a LabVIEW-based PID controller*. Semarang State University.

Barros, S. N., & Lima, R. B. C. (2022). *Optimal PID controller based on PSO applied to an aeropendulum*. Annals of the Brazilian Congress of Automatics, 2(1), 1–6.

Carraro, S. A. (2023). *Study and design of automatic control for an aeropendulum system* (Final paper). São Paulo State University "Júlio de Mesquita Filho", Faculty of Engineering of Ilha Solteira, Ilha Solteira, SP, Brazil.

Castillo, G., Gómez, E., Gonzaga, E., & Reyes, I. (2020). *Tuning and comparing controllers for an aeropendulum*. *Journal of Electrical Engineering*, 1(3), 16–26.

Díaz García, J. D., Prieto Jiménez, D. E., & Blanco Cañón, R. A. (2023). *Design and implementation of PID controller and advance net for angle control in an aerodynamic rocker*. *Mutis*, 13(2), 1–26.

Hernández Pérez, J., Gutiérrez Moreno, E., Ordaz Oliver, J. P., & Ordaz Oliver, M. O. (2024). *LQR-based control with gravity compensation for a wind turbine pendulum system*. *International Journal of Combinatorial Optimization Problems and Informatics*, 15(5), 161–180. https://doi.org/10.61467/2007.1558.2024.v15i5.428

Jiménez López, A., Sánchez Saquín, C. H., Gómez Hernández, A., Contreras Calderón, M. G., & Donjuán Carreño, M. E. (2023). *Methodology for controlling a demountable aeropendulum with a PID*. En *Kaizen and Mechatronics* (cap. 32, pp. 411–422). ISBN 978-607-9394-28-8.

Kagami, R. M., Angonese, M., Pereira, R. M., Von Ganter, S. P., Reynoso-Meza, G., & Freire, R. Z. (2020). *Multiobjective optimization applied in the control of a nonlinear aeropendulum system*. *Annals of the Brazilian Congress of Automation*, 2020. https://doi.org/10.48011/asba.v2i1.1173

Lamatenggo, M., Wiranto, I., & Ridwan, W. (2020). *Design of balancing two-wheeled robots with an Arduino Nano-based PID control method*. *Jambura Journal of Electrical and Electronics Engineering*, 2(2), 39–43. https://doi.org/10.37905/jjeee.v2i2.6906

Lucena, E. R., Luiz, S. O. D., & Lima, A. M. N. (2021). *Modeling, parameter estimation, and control of an aero-pendulum*. In *XV Brazilian Symposium on Intelligent Automation (SBAI 2021)* (pp. 1984–1988). Brazilian Society of Automatics.

Marashian, A. (2020). *Modeling and control of mechatronic aeropendulum*. Dynamical Systems & Control (DSC) Research Lab., Department of Electrical Engineering, Persian Gulf University.

Morales-Narciso, L.-M., et al. (2023). *Design, construction and control of a seesaw system driven with a thrust propeller*. In *2023 XXV Robotics Mexican Congress (COMRob)* (pp. 122–127). IEEE. https://doi.org/10.1109/COMRob60035.2023.10349707

Oliveira, A., Aguiar, L., & Vargas, R. (2023). *Loop-shaping H∞H_\inftyH∞ control of an aeropendulum model*. *Journal of Control Engineering*, 12(2), 8–14.

Paesani, M., & Sosa Visconti, A. (2020, June 21). *Modelling, identification and control of the aeropendulum system* [Practical work n.º 1]. National University of La Pampa, Balseiro Institute, Faculty of Engineering.

Pamuji, A. T., Hapsari, R. R., Tjahyaningtijas, A., Kholis, N., & Zuhrie, M. S. (2024). *The design of the pendulum aero angle setting system using the PID and MPC methods*. *Journal of Electrical Engineering*, 13(3), 219–226.

Romadhon, A. D., & Endryansyah. (2023). *Design of the aero pendulum angle position adjustment system using a LabVIEW-based PID controller*. *Journal of Electrical Engineering*, 1(1), 1–10.

Souza, W. A., Teixeira, M. C. M., Cardim, R., & Assunção, E. (2020). *On switched regulator design of uncertain nonlinear systems using Takagi–Sugeno fuzzy models*. *IEEE Transactions on Fuzzy Systems*, 22(6), 1720–1727.

Valdés Olivares, A., Zoulagh, T., & Barbosa, K. A. (2023). *LPV modeling and control for the aeropendulum system*. In 2023 IEEE Chilean Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON) (pp. 1–6). IEEE. https://doi.org/10.1109/CHILECON60335.2023.10418622

Yamanaka, H. F., Bispo, C. A. de S., Breganon, R., Ribeiro, F. S. F., Almeida, J. P. L. S. de, & Alves, U. N. T. (2022). *Construction and follower control via LQR of an aeropendulum system*. Annals of the XXIV Brazilian Congress of Automatics, 137–140.