Flywheel Inverted Pendulum

instituto superior de engenharia de lisboa

Collaborative online international learning

Amsterdam University of Applied Sciences

Introductions

Our team is composed of two groups: the Portuguese team and the Amsterdam team.

From Portugal, we have Artur Matos and Tiago Bernardo, both Physics Engineering students at ISEL, as well as Hollo Millan, an Erasmus student from Mechanical Engineering.

From Amsterdam, the team includes Casper van Schaardenburg, Silvan van der Leij and Ashley Marsman, all students from the Amsterdam University of Applied Sciences.

Project objectives

- **Design the wheel** in SolidWorks and manufacture it using 3D printing, ensuring an optimized geometry for performance and stability.
- Use the **AS5600 sensor** to accurately measure the wheel's angular position (0–360°) and provide real-time feedback to the control system.
- **Implement a PID control system** using an Arduino to ensure precise and stable control of the wheel's position.
- **Stabilize the wheel** at the equilibrium point on top of an inverted pendulum by controlling its rotation and varying the angular velocity to generate the required torque.

Hardware

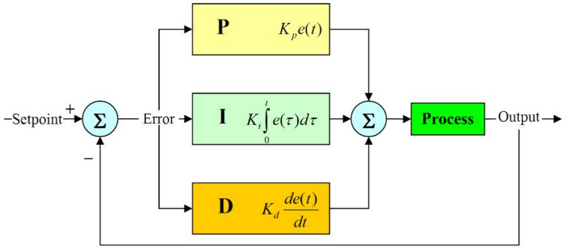
Mechanical Setup Pendulum arm: 3D-printed arm that freely rotates around its pivot axis. Angle sensor: a rotary encoder to measure the arm's tilt.

Reaction wheel: a 3D-printed flywheel attached to the end of the arm, which is accelerated or decelerated by the motor to stabilize the pendulum.

Drive DC motor: JGA25-370, 12 V DC motor with an integrated encoder. The encoder signals are calculate the wheel's rotational speed (RPM). The gear reduction ratio of the motor should be considered in the measurements.

Electronic Setup Microcontroller: Arduino UNO Motor driver: L298N motor driver, which controls the JGA25-370 motor via PWM.

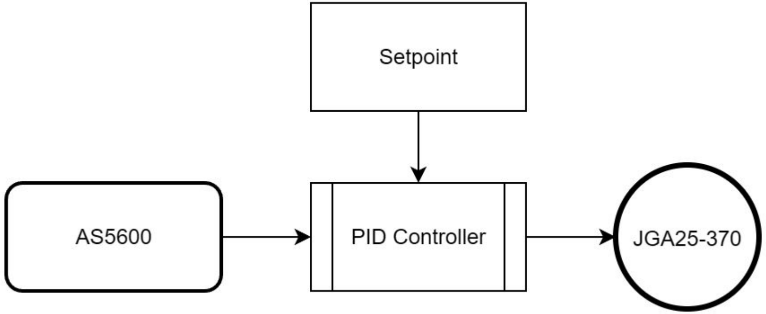
Power supply: The motor is powered by an external 12 V DC supply The Arduino receives power through USB from the computer



Control System

The inverted pendulum is naturally unstable in the upright position if left alone, it will fall over. To keep it balanced, we use a reaction wheel. By accelerating or braking the wheel, we generate a torque that counteracts the pendulum's motion and keeps it upright.

A controller continuously reads the pendulum's angle and angular velocity, and decides how much the motor should accelerate or decelerate the reaction wheel. In this way, the system can maintain balance even if small disturbances occur.



Software

Data acquisition: The AS5600 sensor continuously measures the wheel/pendulum angle via I2C, using a fixed sampling period (~5 ms). Angular velocity is estimated from the time derivative of the measured angle.

Control strategies:

- **Single PID control:** One PID controller directly regulates the angle, converting the error into a PWM signal for the motor.
- **Cascaded PID control (dual PID):**Outer loop PID controls the angle and generates a speed reference. Inner loop PID controls the angular speed and generates the motor PWM command.
- **Upside-down pendulum control:** An extension of the cascaded PID approach, with additional logic for large angular deviations, enabling recovery from the inverted position and convergence to the upright equilibrium.

Motor actuation: The control signal sets the motor rotation direction (IN1/IN2) and the actuation level via PWM (ENA), including a deadzone to overcome static friction.

Monitoring and logging: Key variables (angle, speed, setpoints, and PWM output) are transmitted via the serial interface for debugging, performance evaluation, and data analysis.

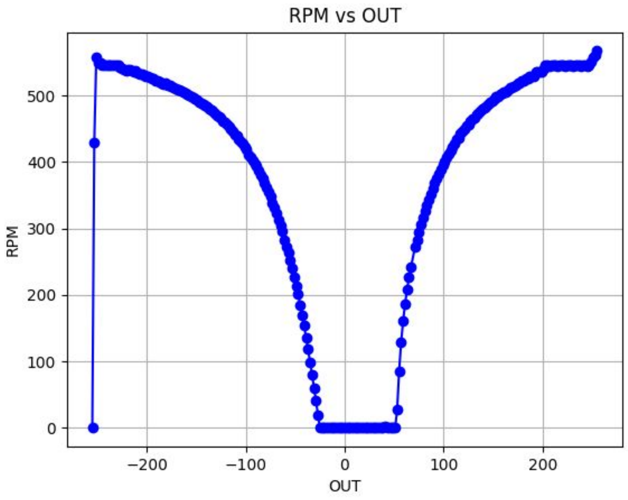
Results

The pendulum has shown significant improvement on both sites. In Lisbon, the wheel is now able to move very quickly from the bumper to the setpoint and remain stable for long periods, solving the issue related to stabilizing it in the center.

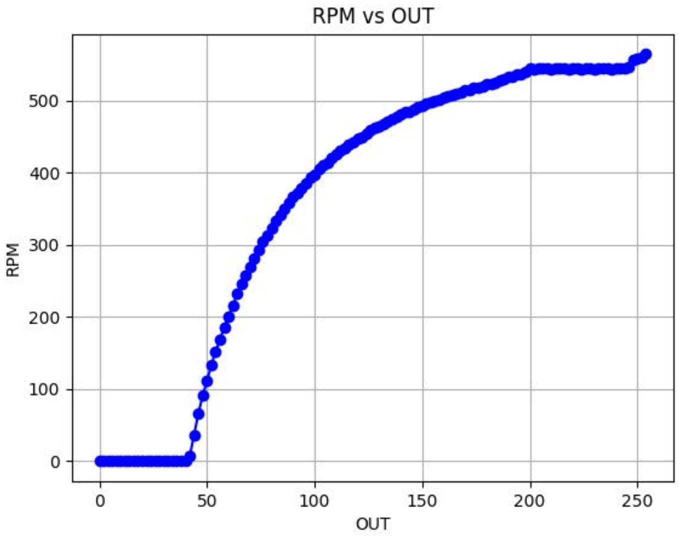
In Amsterdam, the wheel can start from a low position (-180° relative to the equilibrium position), reach the equilibrium position, and maintain stability, making the system almost fully functional.

The main remaining challenge on the Lisbon side is the unreliability of the AS5600 sensor, which occasionally outputs significant errors in angle measurements. Overall, wheel stabilization and setpoint achievement have been successfully accomplished on both sites.

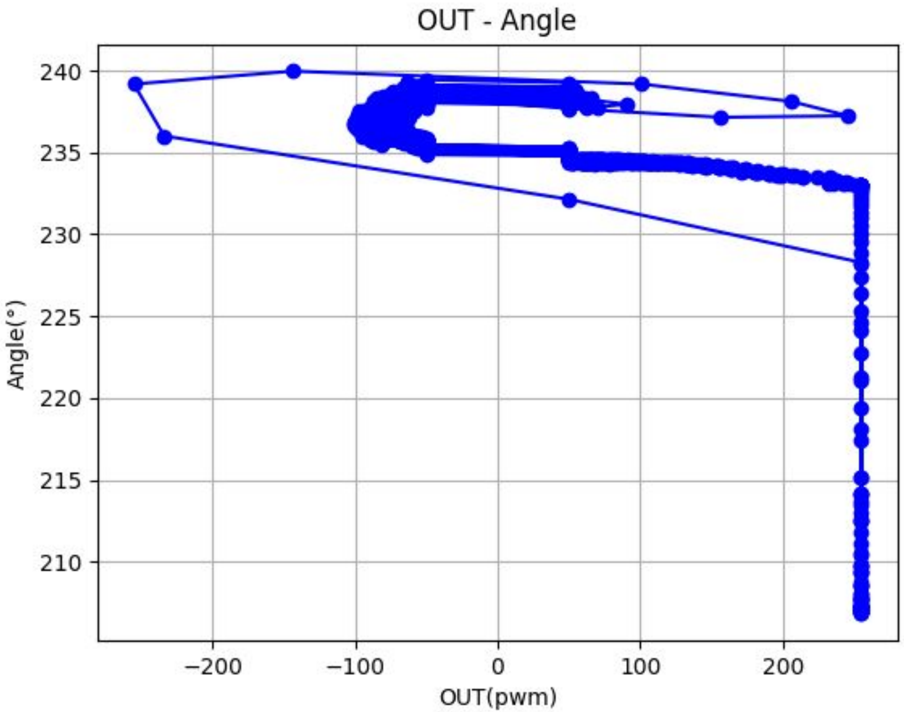
Graphs



RPM vs OUT
RPM
OUT
500
400
300
200
100
0
−200
−100
0
100
200



RPM vs OUT
RPM
OUT
500
400
300
200
100
0
0
50
100
150
200
250


OUT - Angle
240
235
230
225
220
215
210
Angle(°)
−200
−100
0
100
200
OUT(pwm)

Reflections

Throughout the project, the main difficulties were related to physical inconsistencies in the system and the reliability of the measurements. Differences in mechanical behavior and initial instability affected repeatability, while tuning the PID controllers required multiple iterations to achieve stable performance. A significant challenge was the limited reliability of the AS5600 sensor, which occasionally produced incorrect angle readings, negatively impacting control stability.

As an aspect for improvement, an earlier validation of sensor accuracy and the use of signal filtering techniques would have increased the robustness and reliability of the control system.