AI-Enabled Control Engineering

Laboratory Report 1: Dual-Loop PID Control and Sim-to-Real Evaluation

Group:	XX
Students:	Student A, Student B, Student C
Student IDs:	ID A, ID B, ID C
Submission date:	YYYY-MM-DD

Target report length: in 10 pages, including the title page and references.
Raw CSV logs and original figures are submitted separately in the same ZIP package.

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Submission Requirements - Remove Before Final Submission

Before submitting, change `\instructionstrue` to `\instructionsfalse` near the beginning of this file. This removes all requirement pages automatically. The final report should contain only your own report.

Required submission package
Submit one ZIP file named:

`GroupXX_LabReport1.zip`

It must contain:

```
GroupXX_LabReport1.zip
|-- GroupXX_LabReport1.pdf
|-- data/
|   `-- all original CSV logs
`-- figures/
    `-- one original PNG figure for every CSV log
```

The PDF, CSV logs and PNG figures must open correctly. Do not submit screenshots of CSV files.

One-to-one file correspondence
Every run must have exactly one CSV log and one original figure with the same identifier. Use naming convention like this:

- Part 1 hardware: `P1_HW_BEST_R1.csv` and `P1_HW_BEST_R1.png`
- Part 1 simulation: `P1_SIM_BEST_R1.csv` and `P1_SIM_BEST_R1.png`
- Part 2 example: `P2_KPA_LOW_R2.csv` and `P2_KPA_LOW_R2.png`

Use `R1`, `R2`, and `R3` for the three repeated trials. The identifiers used in the report, figure captions, tables, CSV files and PNG files must agree exactly.

Experimental repetition
Do not report only the best run. Report all 10 successful runs and calculate the mean and standard deviation across the 10 runs.
For the Sim-to-Real comparison, the controller parameters and experimental settings used in the simulation must be exactly the same as those used on the physical system. Only with matched parameters can the difference between simulation and real-world performance be meaningfully evaluated.

Template usage
The provided report template is only a formatting reference. All instructions, placeholder texts, examples, and guidance notes in the template must be removed before submission.
Students should replace the template contents with their own experimental results, analysis, and discussion. Simply filling in the blank fields without removing the provided instructions will not be considered a complete report.
Please note that this template is only a minimum structure to help organize the report. It does not provide all possible figures, plots, or analysis methods. Students are encouraged to improve the presentation and include additional visualizations, diagrams, data analysis plots, or illustrations when appropriate.
Well-designed figures that clearly explain experimental results, reveal important trends, or improve the readability of the report are highly encouraged. High-quality scientific presentation and additional meaningful analysis will be considered positively during grading.

Group submission

Each group should submit only one report zip file, submitted by one designated group representative.
Although the report is submitted as a group, each member is expected to actively participate in the experiments, data analysis, and report preparation. It is strongly discouraged that a group assigns only one member to complete the entire experimental report. Such an arrangement should only be considered in special circumstances, such as when a group member was unable to attend the corresponding lab session due to a valid reason.
The report must clearly specify the contribution of each group member, including the approximate contribution percentage (e.g., experiment setup, simulation, data analysis, writing, and editing). This information will be used to ensure fair grading among group members.
In case of any disagreement regarding the division of work or individual contributions, the teaching assistants will not participate in determining or arbitrating the internal task allocation within the group. Students should resolve such issues within their own group.

Formatting and grading expectations

The provided font, spacing, margins, table style, caption style and section hierarchy should be retained as closely as possible. Formatting quality is part of the assessment. Figures must be readable, numbered, discussed in the text and accompanied by units. Tables must not contain unexplained symbols.
Grading reference:

Item	Weight
Formatting, organization and file completeness	10%
Method and controller description	10%
Part 1 hardware results and repeated-trial analysis	25%
Part 1 digital-twin comparison and sim-to-real discussion	25%
Part 2 parameter-sensitivity experiments	25%
Critical discussion, limitations and conclusion	5%

Contents

Groups may consist of two, three, or four members. The number of group members will not affect the grading criteria or the total score of the group. However, the individual scores of group members may be adjusted according to their reported contribution percentages to reflect their relative effort and participation.

The following table should be completed and included in the final report.

Table 1: Contribution of each group member

Member	Name	Main Contribution	Contribution (%)
Member 1			
Member 2			
Member 3			
Member 4			

1 Method and Controller Description

Before conducting physical experiments, first introduce the control strategy used in this laboratory. The rotary inverted pendulum is an underactuated nonlinear system. The controller contains two main stages:

1. Energy-based swing-up control, which increases the pendulum energy and moves the pendulum from the hanging-down position to the upright region.
2. Dual-loop PID stabilization, which stabilizes the pendulum after it enters the neighbourhood of the upright equilibrium.

explain the working principles of both controllers and discuss how the controller parameters affect the system performance.

1.1 Energy-based Swing-up Control

The pendulum cannot be stabilized directly when it starts from the downward position because the upright equilibrium is unstable and the available motor torque is limited. Therefore, an energy-based controller is first used to inject energy into the pendulum.

The mechanical energy of the pendulum can be written as

$$E = \frac{1}{2}J\dot{\alpha}^2 + mgl(1 - \cos\alpha),$$

where J is the equivalent rotational inertia, m is the pendulum mass, l is the pendulum length, and α is the pendulum angle.

The desired energy corresponding to the upright position is denoted as E_d. The energy error is

$$e_E = E_d - E.$$

A typical energy-based swing-up controller has the form

$$u_{\text{swing}} = k_E e_E \,\text{sign}(\dot{\alpha}\cos\alpha),$$

where k_E is the energy control gain.

Explain why the term

$$\text{sign}(\dot{\alpha}\cos\alpha)$$

is required. Discuss how this term determines the direction of the motor torque.

Theory questions:

(a) Explain why the energy-based controller alone is not suitable for precise stabilization.

(b) Assume the pendulum starts from the downward position. Describe the energy variation during one swing cycle and explain how repeated control actions finally move the pendulum into the upright region.

1.2 Dual-loop PID Stabilization

After the pendulum enters the capture region around the upright equilibrium, the controller switches to a dual-loop PID controller.

The inner loop controls the pendulum angle:

$$u_\alpha = K_{p\alpha} e_\alpha + K_{i\alpha} \int e_\alpha dt + K_{d\alpha} \dot{e}_\alpha,$$

where

$$e_\alpha = \alpha_{\text{ref}} - \alpha.$$

The outer loop controls the rotary arm position:

$$u_\theta = K_{p\theta} e_\theta + K_{i\theta} \int e_\theta dt + K_{d\theta} \dot{e}_\theta.$$

The final control input is obtained by combining the two loops:

$$u_{\text{PID}} = u_\alpha + u_\theta.$$

Students should explain the purpose of using two control loops instead of only controlling the pendulum angle.

Theory questions:

(a) Explain the role of each PID term:

$$K_p, \qquad K_i, \qquad K_d.$$

(b) Discuss the expected influence of increasing $K_{p\alpha}$ on:

- stabilization speed;
- oscillation amplitude;
- motor PWM variation.

(c) Explain why an excessively large integral gain K_i may cause poor performance or actuator saturation.

(d) Explain the purpose of the velocity low-pass filter and the possible trade-off between noise reduction and control delay.

1.3 Simulation and Physical Implementation

Before physical experiments, the controller should be tested in the simulation environment developed in the previous laboratory session.

Discuss:

- why simulation is useful before hardware deployment;
- possible reasons why the physical system may perform differently from the simulation.

2 Part I: Best Physical Controller and Sim-to-Real Comparison

2.1 Best Physical Controller Parameter Set

First, find a controller parameter set that provides the best overall performance on the physical rotary inverted pendulum system.

The selected parameter set should provide a good balance between:

- reliable energy-based swing-up;
- fast transition into the PID stabilization region;
- small pendulum angle error;
- limited rotary-arm movement;
- smooth PWM output without excessive saturation.

Report all parameters entered in the Python control panel.

Table 2: Best physical controller and calibration parameters.

Parameter	Value	Unit	Parameter	Value	Unit
Duration	0	s	PWM maximum	0	PWM
Swing-up PWM	0	PWM	PID entry angle	0	deg
PID exit angle	0	deg	Soft blend λ	0	–
$K_{p\alpha}$	0	–	$K_{i\alpha}$	0	–
$K_{d\alpha}$	0	–	$K_{p\theta}$	0	–
$K_{i\theta}$	0	–	$K_{d\theta}$	0	–
α integral limit	0	–	θ integral limit	0	–
Velocity LPF	0	–	Calibration values	0	–

Explain the parameter tuning procedure. Discuss why the selected parameter set was considered the best compromise rather than simply the parameter set with the fastest swing-up or the smallest instantaneous angle error.

2.2 Repeated Physical Experiments

Using the selected best parameter set, perform **ten independent physical experiments**. These ten trials will be used as the final hardware performance evaluation.

Do not select only the best trial. Report all ten experimental results.

For each trial, save:

- one original CSV log file;
- one original PNG figure generated from the log file.

The CSV and PNG files must have exactly matching identifiers.

Recommended naming convention:

```
dual_pid_real_best_01.csv
dual_pid_real_best_01.png
```

and similarly for trials 02–10.

Table 3: Ten repeated physical experiments using the best controller parameters.

Trial	Stable time/s	Mean $\|\alpha\|$/rad	Std $\|\alpha\|$/rad	Mean $\|PWM\|$	Std $\|PWM\|$	Max overshoot/rad
1	–	–	–	–	–	–
2	–	–	–	–	–	–
3	–	–	–	–	–	–
4	–	–	–	–	–	–
5	–	–	–	–	–	–
6	–	–	–	–	–	–
7	–	–	–	–	–	–
8	–	–	–	–	–	–
9	–	–	–	–	–	–
10	–	–	–	–	–	–

Define the following evaluation metrics:

- **Stable time**: the time when the pendulum first enters the PID stabilization region and remains stable until the end of the trial.
- **Mean $|\alpha|$**: average absolute pendulum angle error during the final stable stage.
- **Std $|\alpha|$**: standard deviation of the absolute angle error during the final stable stage.
- **Mean and Std $|PWM|$**: describe the average control effort and PWM fluctuation during the stable stage.
- **Maximum overshoot**: after the final transition into the PID region, record the maximum deviation of the pendulum angle from the upright position.

2.3 Simulation Twin Experiments with Matched Controller Parameters

Use the simulation twin to reproduce the best physical experiment as closely as possible.

All controller and experimental parameters must remain identical to those used on the physical system, including:

- experiment duration;
- pendulum and rotary-arm PID gains;
- swing-up PWM;
- PWM limit;
- PID entry and exit angles;
- soft-blend coefficient λ;
- integral limits;
- initial pendulum condition.

Save every simulation trial as one matched CSV/PNG pair using:

```
dual_pid_sim_best_01.csv
dual_pid_sim_best_01.png
```

and continue the numbering from 02 to 10.

Calculate the same metrics used for the physical experiments.

Table 4: Ten repeated simulation-twin experiments using matched controller parameters and one fixed noise configuration.

Trial	Stable time/s	Mean $\|\alpha\|$/rad	Std $\|\alpha\|$/rad	Mean $\|PWM\|$	Std $\|PWM\|$	Max overshoot/rad
1	–	–	–	–	–	–
2	–	–	–	–	–	–
3	–	–	–	–	–	–
4	–	–	–	–	–	–
5	–	–	–	–	–	–
6	–	–	–	–	–	–
7	–	–	–	–	–	–
8	–	–	–	–	–	–
9	–	–	–	–	–	–
10	–	–	–	–	–	–

Report the mean and standard deviation across the ten simulation runs. Compare the distribution of the simulation results with the ten physical results rather than comparing only one simulation run with one physical run.

The controller parameters must not be retuned specifically for the simulation. The only simulation-specific parameters that may be adjusted are the noise parameters.

Select one set of simulation noise parameters that makes the simulated responses reproduce the physical responses as closely as possible. The noise model may include:

- rotary-arm observation-noise mean and standard deviation;
- pendulum-angle observation-noise mean and standard deviation;
- PWM output-noise mean and standard deviation.

Report the selected noise parameters in Table 5.

Table 5: Noise parameters used in the simulation twin.

Noise parameter	Value	Unit
μ_θ	–	rad
σ_θ	–	rad
μ_α	–	rad
σ_α	–	rad
μ_{PWM}	–	PWM
σ_{PWM}	–	PWM

Explain how the noise parameters were selected. The objective is to reduce the Sim-to-Real gap in several metrics simultaneously rather than matching only one individual physical trial.

After fixing the noise parameters, do not change them again. Run the simulation twin ten independent times using different random-noise realizations.

2.4 Sim-to-Real Analysis

Compare the mean results obtained from the ten physical experiments and the ten simulation experiments.

For each performance metric m, calculate the absolute difference

$$\Delta m = |\bar{m}_{\text{real}} - \bar{m}_{\text{sim}}| , \tag{1}$$

and the Sim-to-Real gap ratio

$$G_m = \frac{|\bar{m}_{\text{real}} - \bar{m}_{\text{sim}}|}{\max\left(|\bar{m}_{\text{real}}|, \varepsilon\right)} \times 100\%, \tag{2}$$

where ε is a small positive value used to avoid division by zero.

The stable time t_s is the time at which the pendulum enters the final continuous stable stage and remains within 15° of the upright position until the end of the experiment. It may also be interpreted as the swing-up time.

Table 6: Quantitative Sim-to-Real comparison using the mean values from ten trials.

Metric	Real system	Simulation twin	Difference Δm	Sim-to-Real gap G_m / %
Stable time t_s / s	–	–	–	–
Mean $\|\alpha\|$ / rad	–	–	–	–
Std. $\|\alpha\|$ / rad	–	–	–	–
Mean |PWM|	–	–	–	–
Std. |PWM|	–	–	–	–
Maximum stable-stage overshoot / rad	–	–	–	–

Briefly discuss which metrics show the smallest and largest Sim-to-Real gaps. Possible causes include friction, mechanical backlash, motor dead zone, sensor noise, calibration error, voltage variation and unmodelled dynamics.

3 Part II: Controller Parameter Sensitivity Analysis

Starting from the best parameter set obtained in Part I, investigate how different controller parameters influence the physical control performance.

Only change one parameter at a time and keep all other parameters unchanged.

Each selected parameter value should first be tested in simulation before being deployed to the physical system.

Suggested parameters:

- pendulum proportional gain $K_{p\alpha}$;
- pendulum derivative gain $K_{d\alpha}$;
- soft-blend coefficient λ;
- velocity low-pass filter coefficient.

For each parameter:

- select at least three different values;
- perform repeated physical experiments;
- save all CSV and PNG files;
- explain the influence on stability, angle error and PWM behaviour.

3.1 Parameter Influence Discussion

For each parameter, discuss:

- How does increasing the parameter change the transient response?
- Does it improve stability or introduce oscillation?
- Does it increase PWM fluctuation or saturation?

- Is the observed behaviour consistent with PID theory?

4 Data-driven Parameter Investigation

Choose one parameter that you consider most important for rotary inverted pendulum control.

Collect multiple tuning attempts and analyse the relationship between the parameter value and control performance.

The analysis should include:

- parameter value;
- CSV data;
- control performance metrics;
- explanation of the observed trend.

The goal is to demonstrate a systematic tuning process rather than trial and error.

5 Discussion, Limitations Optional Extension and Conclusion

Synthesize Parts I and II rather than repeating individual observations. Address repeatability, failure cases, reliability of the selected metrics and whether the digital twin is sufficiently accurate for safe pre-tuning.

Optional extension ideas include sensitivity to $K_{d\alpha}$, $K_{p\theta}$ or the velocity-LPF coefficient; comparison of capture-time distributions; or a simple calibrated correction to reduce one observed sim-to-real gap. Optional experiments should not replace any required experiment.State the best physical parameter set, the main sim-to-real discrepancy, the parameter with the strongest observed influence and one concrete recommendation for future controller deployment.