הטכניון – מכון טכנולוגי לישראל, הפקולטה להנדסת מכונות

TECHNION—Israel Institute of Technology, Faculty of Mechanical Engineering

# Introduction to Control (00340040)

LABORATORY

## 1 Overview and safety rules

### Experiment objectives

Become acquainted with the experimental setup, software, and basic tools in the control lab. Observe the behavior of a DC motor controller in closed-loop via a P and PI controller, compare the results with those obtained for the simplified LTI model in the project.

### Lab safety rules

A safe distance from the system must be kept during the experiment to prevent hair or other body parts being caught. Pay attention to the following:

- have instructor's approval before running any real time code,
- keep the main power switch in the OFF position while not performing the experiment,
- make sure that the removable pendulum is *detached* from the motor arm.

### Experiment overview

The experiment involves reading from the encoder in real time, determining the factor required to convert encoder readings to degrees, and activating the DC motor in the closed-loop fashion. The experimental results are then compared simulation results based on the simplified model derived in the project. For the latter use $J = 0.0047$ and $f = 0.007$, assume the perfect motor efficiency, calculate the gear ratio $n_{\mathrm{g}}$ from the experiment, and take the other motor parameters from the datasheets published on the course website. Use the motor model in the form

$$P_\theta(s) = \frac{k_{\mathrm{s}}}{s(\tau s + 1)}, \tag{1}$$

for comparison, do not forget to use the correct physical units for the parameters. The closed-loop system operates in the form shown in Fig. 1, where the prefilter $F$ (its goal is to smoothen the input signal) has the transfer function

$$F(s) = \frac{30^2}{s^2 + 1.6 \cdot 30s + 30^2}.$$

The resulting closed-loop system $T_{\theta r} : r \mapsto \theta$ has the transfer function

$$T_{\theta r}(s) = \frac{P_\theta(s)C(s)}{1 + P_\theta(s)C(s)} F(s).$$

Measure its response to $r = 30^\circ \mathbb{1}$ and compare the results with simulations of the identified model.

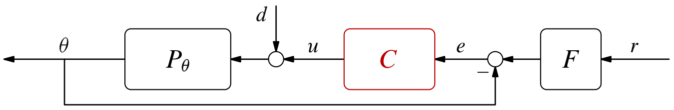

Fig. 1: Closed-loop system with prefilter

Note that this guide does not always explicitly separate between the tasks that should be completed during the lab and those to be done afterwards, while working on the report. In general, complete only the experimental tasks during the lab class, collect the results properly, and process them afterwards, during your later work on the report.

# 2 Experiment procedure

## 2.1 Encoder readings

In this stage you will be running a pre-made Simulink file which is used to read encoder measurements through the data acquisition (DAQ) board and display the related signals in real-time.

1. Check the version of the DAQ at your station, either `6221` or `6321`, and download the appropriate ZIP file from Moodle. Extract its contents to your work folder. Make sure the folder name contains no white spaces and only English characters.

2. Open the Simulink file `encoders.slx`.

3. Connect blocks in order to obtain the encoder readings (you may use the given blocks such as Encoder Input, Display, Scope, etc). Run the simulation via the "Play" button.

4. Manually rotate the arm to be sure that the sensor functions correctly and that you indeed get the encoder readings in real-time. Answer the following questions in your report.
   - What is the positive direction of the encoder?
   - Are the readings discrete or continuous (value-wise, not time-wise)? Why?
   - What may be inferred from this fact regarding measurement errors and the expected behavior of the control system? (consider for example a control system stabilizing an inverted pendulum under current setup)

5. Determine the scaling factor that converts the encoder readings into the arm angle *in degrees*. One way of doing so is to analyze the reading obtained for a complete arm round (360° degrees). Note that the arm is connected to the encoder (which in turn is connected to the rotor of the DC motor) through *a gear with some unknown ratio*. Use the fact that the number of slits per round is 1000 for workstations `1, 5, 6, 7, 9, 10` and 500 for the others. Each slit correspond to 4 pulses, hence this number is multiplied by 4 when evaluated by the Simulink Encoder Input block. Find the unknown gear ratio. In case you want to reset the encoders reading, you may do so by stopping the simulation (stop button) and rerunning it.

6. Using $J = 0.0047$ and $f = 0.0077$, the gear ratio you identified, and the parameters from the motor data sheet write down your estimate of the motor transfer function $P_\theta(s)$ in form (1).

## 2.2 Proportional Controller

7. Open the Simulink file named `closed_loop_step.slx`.

8. Connect blocks to implement the feedback loop depicted in Fig. 1.

9. Enter the block `Plant` (by double clicking it), and modify the gain block in it with the conversion factor obtained in item 5.

10. Connect scopes (so that you can view results in real-time) to the following signals:
    - the arm angle $\theta$,
    - the control signal $u$,
    - the reference signal $r$.
11. In what range of the P controller parameter the closed-loop system is stable? Use your estimates of plant parameters and do not forget to correctly adjust the units (we are working in *degrees*).
12. Execute the response of the closed-loop system to the reference input $r = 30^\circ \mathbb{1}$ for the controller gains $k_\mathrm{p} \in \{0.05, 0.36\}$ (set $k_\mathrm{i} = 0$). For each value of $k_\mathrm{p}$ repeat the experiment three or four times, to observe possibly different responses. Stop the execution when the arm stops moving. Save the results by using the `To Workspace` blocks (one recording per gain is sufficient). Observe the following quantities from the plots of the arm angle $\theta$ and the motor input voltage $u$:
    - steady-state error,
    - time it takes to reach the steady state (i.e. the moment when the signal value becomes constant),
    - overshoot,
    - rise time (from 10% to 90% of the steady-state value),
    - settling time (under the settling level 2%),
    - the maximal value of the input voltage in the DC motor.

    In the final report, you will need to calculate accurate numerical values for these characteristics. During the experiment, you should only observe them qualitatively by using the scope plots.
13. What is the effect of $k_\mathrm{p}$ on each of the characteristics above?
14. Qualitatively (and using former items): how do the responses for different gains compare to each other? How does it confirm with the root-locus analysis?
15. Why is the steady-state error different from zero?
16. Manually tune the gain $k_\mathrm{p}$ so that the observed overshoot is approximately the one you would have obtained for $\zeta = 0.69$ (question 4(c) in the project). Explain the differences between the observed value of $k_\mathrm{p}$ and the theoretical one.

### 2.3 PI controller

17. In what range of the PI controller parameters the closed-loop system is stable? Use your estimates of plant parameters and do not forget to correctly adjust the units (we are working in *degrees*), again.
18. Execute the response of the closed-loop system to the reference input $r = 30^\circ \mathbb{1}$ for the controller gains $k_\mathrm{p} = 0.36$ and $k_\mathrm{i} \in \{0.1, 1.1\}$. For each value of $k_\mathrm{i}$ repeat the experiment three or four times, to observe possibly different responses. Stop the execution when the steady-state error goes to zero, i.e. when arm angle reaches 30° and stops. You may use the Display block to decide when this happens, *this may take a while*. Save the results by using the `To Workspace` blocks (one recording per gain is sufficient). Observe the following quantities from the plots of the arm angle $\theta$ and the motor input voltage $u$:
    - steady-state error,

  - time it takes to reach the steady state (i.e. the moment when the signal value becomes constant),
  - overshoot,
  - rise time (from 10% to 90% of the steady-state value),
  - settling time (under the settling level 2%),
  - the maximal value of the input voltage in the DC motor.

  In the final report, you will need to calculate accurate numerical values for these characteristics. During the experiment, you should only observe them qualitatively by using the scope plots.

19. What is the effect of $k_\mathrm{i}$ on each of the characteristics above?

20. Does the steady-state error go to zero now? How can it be explained and compared to the P controller case?

21. Scale down the reference signal to $r = 15^\circ \mathbb{1}$ and manually tune $k_\mathrm{i}$ so that the system loses stability (do it cautiously, with small steps), trying to find the critical value. Make sure the system oscillates for at least 8 seconds before converging/diverging. How does the actual value compare with your estimates from item 17?

22. Bonus: Can you propose a way to estimate the time constant, $\tau$, of the plant in (1) using only the data you have collected thus far? *Hint: think about the root-locus plot.*

Save all experiment files and relevant information.

## 3 Requirements to prepare the final report

- For each of the closed-loop experiments (including that for the critical $k_\mathrm{i}$), perform a respective simulation with the model with the parameters identified in the lab. Make sure to use the same experiment conditions (i.e., same controller, prefilter and input signal). Provide the following comparison figures for each experiment:
  - The arm angle, *in degrees*, as a function of time. The plots of simulation and experimental results should be on same figure.
  - The control signal, *in volts*, as a function of time. The plots of simulation and experimental results must be on same figure. Present separate figures for each gain case.
- Are there any differences between simulation and experiment results? If there are, what are the differences and how can they be explained?

Answers to the questions in this document should be submitted electronically (in PDF only, typeset, not scanned handwrites) along with the data files and code to the lab instructor. Failure to comply with these guidelines will be penalized in the grade. Answers should be concise and mostly qualitative.