# 1 Introduction

Learning control is a key research topic within the Control Systems Technology Section, and currently, we are very active in research in this area (see e.g. [1, 2]). The aim of this course is to address open challenges in the field. In the first weeks, you followed a tutorial on learning control, made exercises, and implemented several of your own ILC controllers in experiments with an A3 printer. During the rest of the course, you are going to develop a learning-based approach to accurately control piezo-stepper actuators.

Piezo-electric elements enable highly accurate actuation with high stiffness and a fast response, at the cost of offering only a limited stroke. Piezo-stepper actuators employ piezo-electric elements to generate a 'walking' motion, overcoming the limitation of short strokes, see [3]. This results in highly precise and power-efficient devices with sub-nanometer accuracy that convert electrical energy into mechanical motion, making them a popular choice for various industrial and scientific applications. The performance of these actuators is highly dependent on the control system used to drive them. Therefore, the control of piezo-stepper actuators is an important area of research that has significant practical implications in many fields, including aerospace, robotics, and biomedical engineering. Example applications include nano-motion stages [4] and scanning probe microscopy [5].

The working principle of a piezo-stepper actuator from Thermo Fisher Scientific is depicted in Figure 1.1a. The clamps can be moved vertically to press the shears onto a mover. These shears can be actuated to move in a direction parallel to the mover, pushing or pulling the mover in the process. By coordinating the movement of the individual shears and clamps, a 'walking' motion can be achieved, see Figure 1.1b. The control aim is to actuate the shears and clamps such that the mover performs a desired motion.

Control of piezo-stepper actuators is uniquely challenging because of their multi-input nature and interesting input-output characteristics. Indeed, four sets of actuators (see S1, S2, C1, C2 in Figure 1.1a) need to perform a coordinated motion to position the mover. This coordination is typically done through user-defined commutation functions that are driven by a scalar commutation signal $\alpha$, see Figure 2.1. Note that the input-output behavior from $\alpha$ to mover position therefore directly depends on the design of these commutation functions, see also [6]. Also, because of the piezo actuation principle, a voltage change applied to the four piezo elements in the setup leads to a movement of the shears and clamps almost instantly when compared to the time scale of typically desired motions. That is, dynamics in many cases are ignored and the voltage-position relationship can be approximated by a static function, i.e. a position-dependent gain. Lastly, the voltage-position relationship of the shear elements is hysteretic: it is dependent on history [7]. These challenges call for smart control solutions to achieve good tracking performance.

In open-loop clamping and walking experiments, the piezo-stepper actuator's walking motion causes disturbances in the mover's position, which repeat at the period of the actuating waveform. These disturbances coincide with the moments of engagement and release between the mover and the piezo elements. Imperfect alignment of the piezo elements in the actuator may explain these disturbances, as suggested by previous research [8].

Therefore, the aim of this challenge is to apply learning control techniques taught in this course to the control of piezo-stepper actuators, to accurately track a desired reference. This challenge is detailed in Section 2, and some initial suggestions are provided in Section 3. Finally, practical details are given in Section 4.

# 2 Problem Description

Consider the control scheme in Figure 2.1. The physical inputs to the system are four voltages $u_i(t)$, $i = 1, 2, 3, 4$: one for each clamp and set of shears. Typically, the required input voltage profiles for walking are constructed through a parametrization in terms of a so-called commutation angle

$\alpha(t) \in \mathbb{R}$ by means of commutation functions, or waveforms. These functions $F_i(\alpha) : \alpha \rightarrow u_i$ with $u_i(t) = F_i(\alpha(t))$ are typically periodic with $2\pi$, i.e., a step of $2\pi$ in $\alpha$ corresponds to one full walking step, see Figure 2.2.
The aim is to let the mover position $y$ track the periodic reference $r$ depicted in Figure 2.3 as accurately as possible, in the sense that $\|r - y\|_2$ is minimized over a period of $r$. To achieve this, the inputs to the system must be adapted, since there are disturbances present that need to be counteracted. The fewer periods it takes for your approach to converge to a small tracking error, the better. Note that, with the aforementioned parametrization using commutation functions, there are multiple degrees of freedom for control:

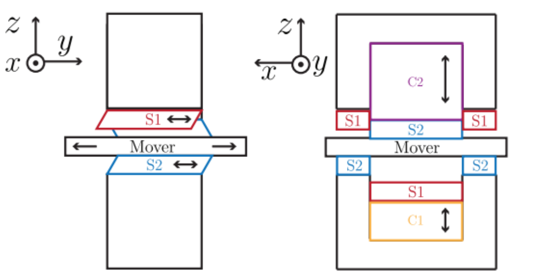
- the commutation signal $\alpha(t)$,
- and the commutation functions $F_i(\alpha),\ i \in \{1, 2, 3, 4\}$.

Your approach might consist of applying learning-based control to either one or both of these control variables. We require that your control solution is related to at least one learning technique covered in this course, i.e., repetitive control or iterative learning control. Finally, there is no single right approach; we encourage original solutions. Feel free to get creative!

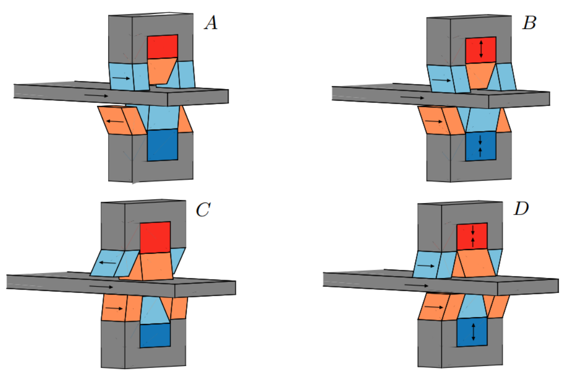
# 3 Suggestions

This section provides some questions/points to help you get started.

- First, familiarize yourself with piezo-stepper systems, using the references in this document. Try to answer the following questions within your group: why is it necessary to use commutation functions? What requirements do they need to satisfy (continuous/periodic/parallel to each other, etc)? Once commutation functions are chosen, can you sketch a plot of the input-output behavior, i.e., $y$ as a function of $\alpha$? What can you say about stability?
- Study the simulation example posted on Canvas and follow the instructions in the comments. What does this example teach you about the invertibility and monotonicity of the $(y, \alpha)$ relationship? How can it happen in practice that a simple commutation function leads to a non-invertible $(y, \alpha)$ relationship? Hint: think of the disturbances and nonlinearities that may be present in the real setup. Finding commutation functions that lead to a monotone/invertible $(y, \alpha)$ relationship might prove to be an important aspect of the challenge.
- If piezo-stepper systems are effectively static functions, as opposed to dynamic systems, what consequences does that have for learning control? What is the impulse response matrix? What about the state(s)? What does it mean for the state(s) to reset, and what does this mean for




(a) Side view (left) and front view (right) of the piezo-stepper actuator, showing the clamp ('C') and shear ('S') elements of the first group (S1, C1) and second group (S2, C2) [6].




(b) Through coordinated movement of the clamp and shear elements, walking can be achieved.

Figure 1.1: Schematic illustrations of piezo-stepper actuator.

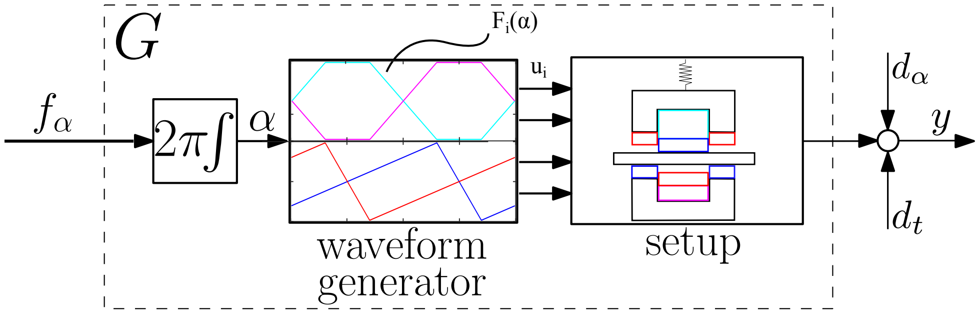



Figure 2.1: Open-loop implementation of waveforms to actuate the piezo-stepper actuator. From the input $f_\alpha$ (drive frequency) to the output y (mover position) [9].

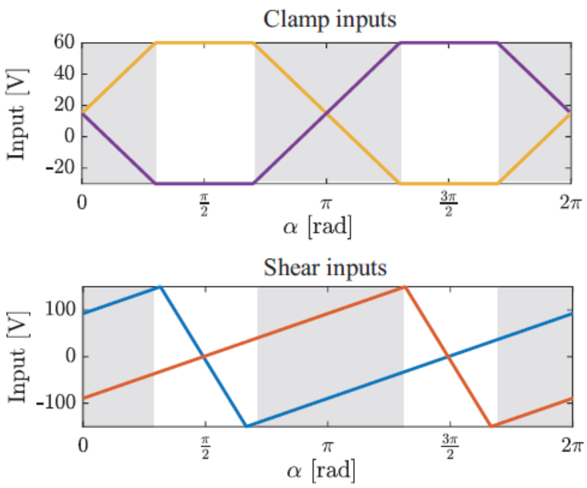



Figure 2.2: Example of commutation functions $F_i(\alpha)$ [6]: the functions for the clamps (top plot) contain regions where both clamps could be in contact with the mover, indicated in gray. In these regions, the inputs for the shear elements (bottom plot) have equal derivatives.

differences/equivalences between repetitive control and iterative learning control? Could you also implement an LTI feedback controller?

- If you decide that you want to change the commutation functions, how will you parameterize them? Piece-wise linear like the functions implemented by default, or some other nonlinear continuous functions?
- As mentioned before, hysteresis affects the walking motion, i.e., the movement not only depends on the instantaneous voltage applied but also on the history of the applied voltages. Think about this effect; can you mitigate the effect using smart initiation, e.g., ignore the first period of $r$ to ensure that the history is the same in all subsequent periods given a periodic reference? Advanced hysteresis compensation methods are out of the scope of this course.
- Since the reference consists of a back-and-forth motion across multiple steps, you can think about what period you choose to consider for learning. Do you consider your ILC trial length / RC period to be this whole range of motion? Or do you assume each step in the same direction to be identical, and thus consider the ILC trial length / RC period to be only one step? What are the pros and cons of either approach?

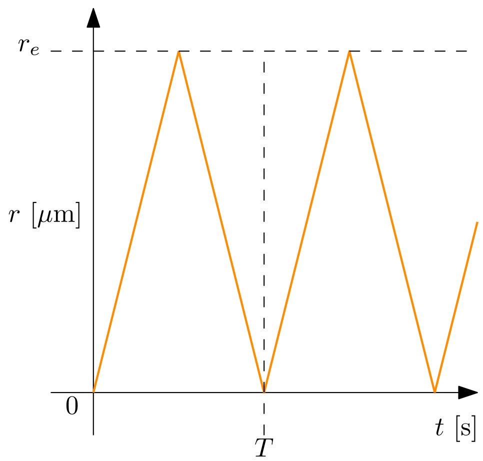



Figure 2.3: Schematic overview of the periodic reference to be tracked. The values of the period $T$ and distance $r_e$ will be announced in due time. The value of $r_e$ is several times larger than the stroke of one step of the piezo-stepper.

# 4 Practical details

## 4.1 Material

You will receive the following:

1. A simple simulation example in Matlab, where the commutation functions can not be changed individually, but the commutation angle signal $\alpha(t)$ can be designed by you.
2. A periodic reference $r$ that is to be tracked, see Figure 2.3.
3. Files needed to run experiments on the piezo-stepper.
4. A list of useful sources, see the end of this document.

## 4.2 Experiments

We recommend that you use Git for version control for this course, but this is up to you; just make sure you think about version control. For the experiments in this course, we will use the setup in the DCT lab in Gemini-South, floor -1. When you want to do experiments on the piezo-stepper, you can reserve a time slot in the Excel sheet in Teams (which will be available in due time). During the experiments, a TA needs to be present, preferably your own TA, so please discuss the planning with them. The files needed for the experiments, along with an explanation of the experimental setup, will be provided in due time.

## 4.3 Deliverables

The following deliverables are expected. Please see the Canvas page for deadlines for each deliverable.

- A 10-minute midterm presentation in which you present your ideas to receive feedback. Please refer to the planning on Canvas. This is informal, and intended for discussion and alignment. It is a challenge, there is not one right answer!
- An algorithm with which the piezo-stepper can accurately track a given periodic reference.
- A report on your approach, using the distributed template. This report should include at least a theoretical framework, an explanation of the design and implementation, and an evaluation of the experimental results.
- A short ($\pm$ 5 min.) movie, explaining your approach. We discourage pre-recorded PowerPoint presentations. Other than that, the format is free, use your creativity!

# References

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[8] Nard Strijbosch, Paul Tacx, Edwin Verschueren, and Tom Oomen. Commutation angle iterative learning control: Enhancing piezo-stepper actuator Waveforms. *IFAC-PapersOnLine*, 52(15):579–584, 2019.

[9] Nard Strijbosch, Paul Tacx, Edwin Verschueren, and Tom Oomen. Commutation Angle Iterative Learning Control: Enhancing Piezo-Stepper Actuator Waveforms. *IFAC-PapersOnLine*, 52(15):579–584, 2019.