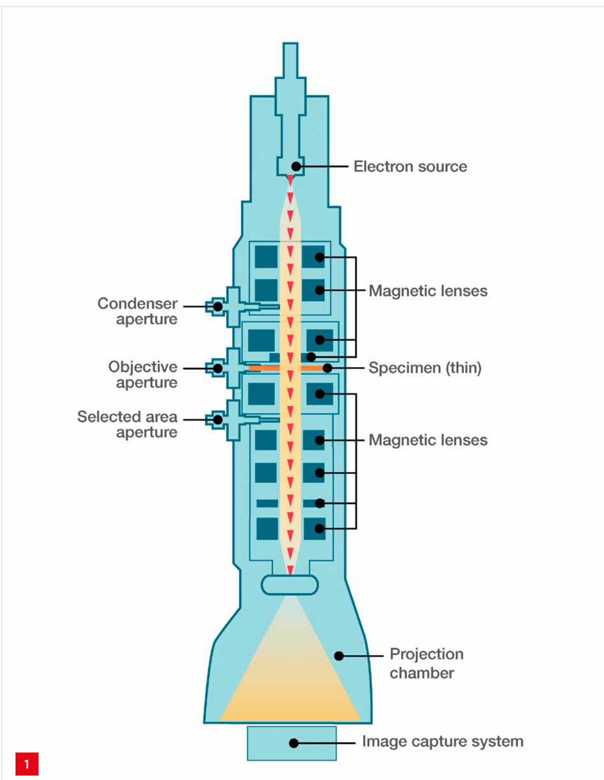
HIGH-PRECISION SAMPLE POSITIONING IN ELECTRON MICROSCOPES

Piezo stepper actuators are used in many nanopositioning systems because of their high resolution, high stiffness and fast response, and their ability to position a mover over an infinite stroke by means of a motion reminiscent of walking. A major drawback of employing piezoelectric actuators is their hysteretic behaviour. The history dependence of hysteresis prevents the application of a trivial compensating feedforward controller for existing hysteresis models. The method presented here exploits a new hysteresis modelling approach that allows for a straightforward feedforward controller that can be manually tuned, reminiscent of industry-standard tuning approaches for mechanical feedforward components.

NARD STRIJBOSCH, EDWIN VERSCHUEREN, KOEN TIELS AND TOM OOMEN

Introduction

High-tech electron microscopes, as designed and manufactured by Thermo Fisher Scientific, use beams of electrons to create images, magnifying micrometer and nanometer structures up to ten million times, thus providing a spectacular level of detail. These microscopes even allow researchers and scientists to view columns of atoms in crystal structures. The images acquired are a key enabler for advances in nanotechnology, life science, material science and semiconductor technology.



General overview of an electron microscope.

The working principle of an electron microscope resembles that of an ordinary light microscope or slide projector, except that it uses an electron beam instead of a light beam; see Figure 1. The electron beam first passes through a set of lenses before it reaches the sample. Several phenomena occur that distort the electron beam when it passes through a sample, including energy losses and quantum-mechanical phase shifts. After the beam goes through the sample, another set of lenses guides the electron beam to a detector. The data from the distorted electron beam is translated, using image processing techniques, to an image of the sample.

An important aspect of obtaining high-resolution images is the positioning of the sample. Any disturbances acting on the sample have an impact on the image quality. One of the recent advances is cryogenic transmission electron microscopy (Cryo-EM), which can be used to make 3D reconstructions of macromolecules such as viruses; see Figure 2. These 3D reconstructions require a significant number of tilted 2D images. This leads to increasing positioning velocity requirements to decrease the time between consecutive images, thereby increasing the throughput.

AUTHORS' NOTE

Nard Strijbosch (Ph.D. candidate), Koen Tiels (assistant professor) and Tom Oomen (full professor) are all associated with the Control Systems Technology group within the department of Mechanical Engineering at Eindhoven University of Technology in Eindhoven (NL). Edwin Verschueren works as a mechatronic design engineer at Thermo Fisher in Eindhoven.
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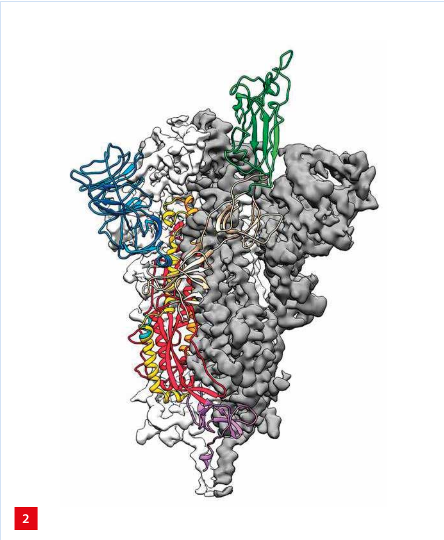
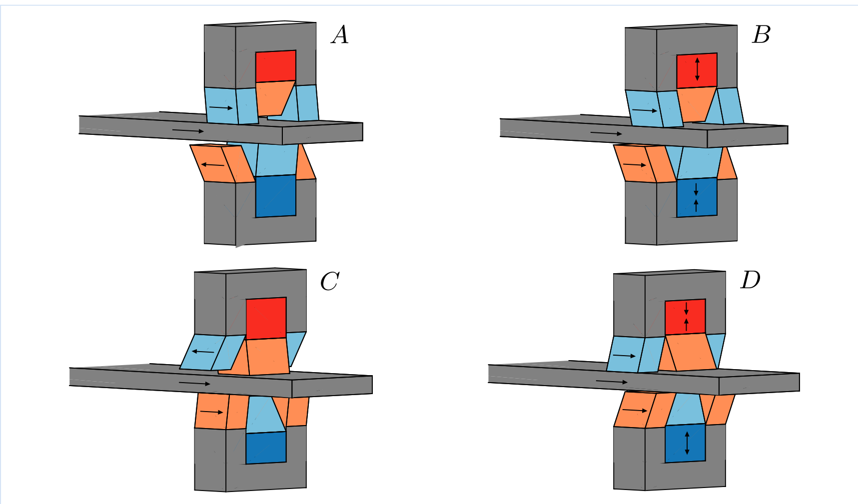
n.w.a.strijbosch@tue.nl
www.tue.nl/cst
www.thermofisher.com
www.toomen.eu



SARS-CoV-2 spike protein. Cryo-EM density data in white and grey [2].

Piezo stepper actuators enable the increasing accuracy and velocity requirements for sample positioning to be met. Individual piezoelectric elements provide high accuracy, high stiffness and fast responses times, albeit within a limited range. Combining several piezoelectric elements and exploiting them to propel a mover through walking leads to an actuator with a potentially infinite range, while maintaining the favourable properties of the individual piezoelectric elements.

The use of piezo stepper actuators for future high-accuracy and high-velocity electron microscopes creates two major challenges that require advanced control techniques. Firstly, it is well known that individual piezoelectric elements exhibit hysteretic effects. Hysteresis is a history-dependent nonlinear effect that is typically hard to model and compensate for. Secondly, the walking of a piezo stepper involves impact at contact, which must take place carefully to ensure smooth walking behaviour in order to avoid unwanted disturbances. Approaches to compensate for the disturbances introduced by the walking behaviour have been developed in e.g. [3] [4]. These approaches assume no history dependency, which is violated due to the hysteresis phenomena. The remainder of this article addresses the first challenge of compensating for the hysteretic behaviour. The main aim is to achieve this by extending well-known motion control techniques used in the high-tech industry, including semiconductor, printing systems and additive manufacturing.



Schematic representation of a piezo stepper actuator in each of its four phases, A to D, of a stepping motion. The different piezo elements are: longitudinal piezo of group 1 (blue); longitudinal piezo of group 2 (red); shear piezo of group 1 (light blue); and shear piezo of group 2 (orange).

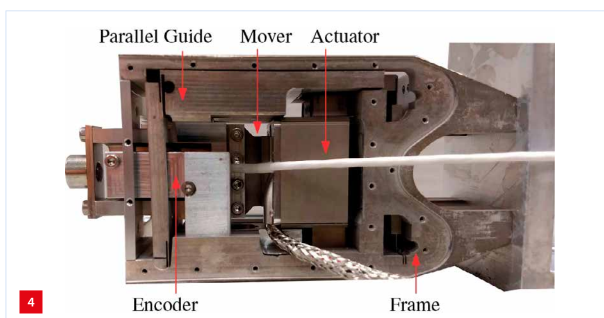
Piezo stepper actuators

Piezo stepper actuators consist of multiple piezoelectric elements in varying configurations that propel a mover; see e.g. [3] [4]. The piezo stepper actuator considered here is schematically depicted in Figure 3. This piezo stepper consists of two groups of piezo elements, each containing a longitudinal element that can extend perpendicularly to the mover, and three shear elements that can extend in the direction of the movement. When the longitudinal element of a group is extended, the corresponding shear elements are in contact with the mover, thereby dictating the position of the mover. Alternating between the two piezo groups results in a walking motion, which leads to an unlimited stroke of the mover. An experimental set-up that includes a piezo stepper actuator is shown in Figure 4.

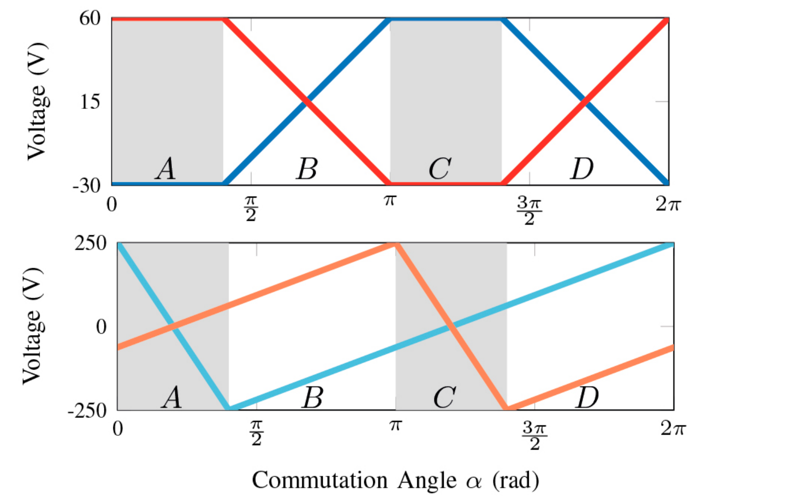
A set of waveforms is chosen judiciously to specify the relation between the inputs of the individual piezo elements, which in turn achieves the walking behaviour. The design of these waveforms is crucial in achieving high performance. The waveforms are mappings from the commutation angle α to the input voltages for the longitudinal piezo elements, c_1 and c_2, and shear piezo elements, s_1 and s_2. The waveforms are defined on the interval $\alpha \in [0,2\pi)$. A full cycle from $\alpha = 0$ to $\alpha = 2\pi$ includes a step from each piezo group.

The waveforms depicted in Figure 5 are designed to obtain four distinct phases, A to D, as shown in Figure 3:

A. Group 1 shear piezo elements in contact with the mover; group 2 shear piezo elements, not in contact with the mover, are retracting.
B. Transition phase. Shear piezo elements of both groups possibly in contact with the mover.
C. Group 2 shear piezo elements in contact with the mover; group 1 shear piezo elements, not in contact with the mover, are retracting.
D. Transition phase. Shear piezo elements of both groups possibly in contact with the mover.



Piezo stepper actuator made by Heinmade [5].



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Top: waveforms applied to longitudinal piezo elements.
Bottom: waveforms applied to shear piezo elements.
The colours of each line correspond to the colours of the piezoelectric elements in Figure 3.
The intervals A, B, C and D correspond to the four phases depicted in Figure 3.
Interval A: the longitudinal piezo element of group 2 is fully extended and the shears of group 1 are not in contact with the mover.
Interval C: the longitudinal piezo element of group 1 is fully extended and the shears of group 2 are not in contact with the mover.
B and D are the transition intervals.

Experiments reveal that the walking behaviour introduces disturbances that are highly reproducible in the commutation angle domain. These disturbances can be explained by physical sources, such as misalignment between the piezo elements or the contact dynamics between the shear piezoelectric elements and the mover. These disturbances can effectively be compensated for through learning-based techniques [3] [4], which exploit past error data to update the waveforms to compensate for the disturbances. These techniques are based on the assumption that the behaviour of the piezo stepper actuator is not history dependent. This assumption is not valid due to the hysteretic behaviour of the individual piezoelectric elements. Here, the aim is to compensate for this hysteretic effect using a feedforward controller that can be tuned during experiments.

Hysteresis

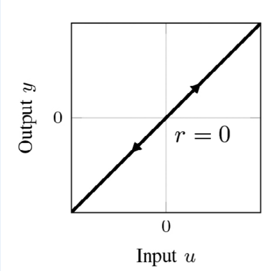
Piezoelectric actuators consist of a piezoelectric material that expands or contracts when placed inside an electric field. The internal energy losses in the piezoelectric material cause hysteretic phenomena [6]. This implies that the current position depends not only on the current input voltage, but also on its history, in particular the last instance in which the input direction changed. In other words, the hysteresis phenomenon is a memory-based nonlinearity. This behaviour can have a significant effect on the tracking performance of a piezoelectric actuator and should therefore be considered carefully.

Many models have been suggested to capture the hysteretic behaviour in piezoelectric actuators. The Prandtl-Ishlinskii model is a widely accepted one. It is a linear weighted superposition of a finite number of play operators, i.e.:

$$y(t) = \sum_{j}^{N} w_j H_{r_j}(u(t))$$

Here, N is the number of play operators and w_j the weight corresponding to the play operator H_{r_j}, as in Figure 6, with threshold r_j. In mechanical systems, a single play operator is often used to model the backlash or play between gears.

Results of a simulation study using the Prandtl-Ishlinskii model are given in Figures 7 and 8. A triangular input signal is applied to a Prandtl-Ishlinskii model that consists of four play operators. In the hysteresis loop in Figure 8, it can be observed that this leads to a piecewise linear approximation of the hysteresis loop. The inner and outer loop in Figure 8 indicate the history-dependent behaviour of hysteresis. Increasing the number of play operators allows the possibility of the model mismatch to decrease.



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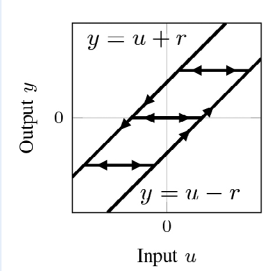

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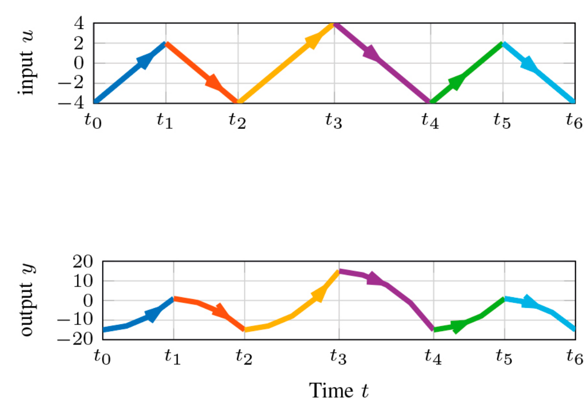
Schematic representation of a play operator.
(a) $r = 0$.
(b) $r > 0$.



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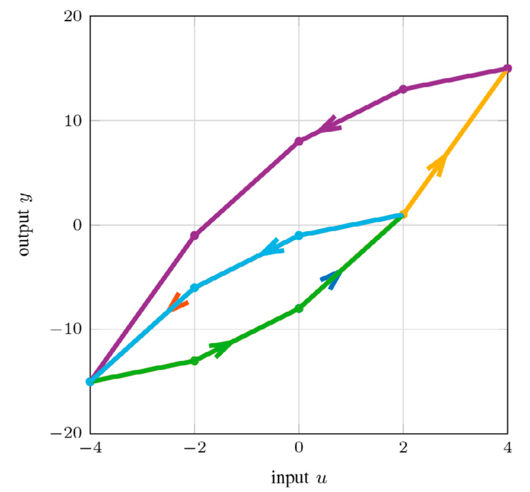
Input (top) and corresponding output (displacement) of the Prandtl-Ishlinskii hysteresis model.



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Hysteresis loop corresponding to the input and output (displacement) signals as depicted in Figure 7.

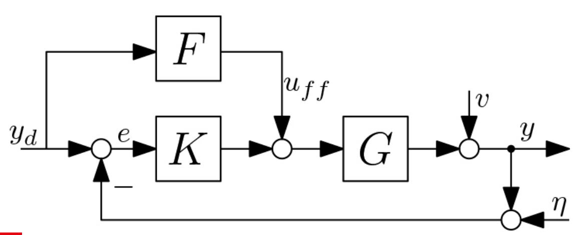
Motion control feedforward

Before moving to hysteresis feedforward, we will investigate traditional feedforward for general linear motion systems. A typical control architecture for motion systems is shown in Figure 9 (see e.g. [7]), where K and F are the feedback and feedforward controllers. When all systems are linear time invariant (LTI), then:

$$e = \underbrace{S\,(1 - \mathrm{GF})\,y_d}_{\text{feedforward}} - \underbrace{S}_{\text{feedback}}\,v - \underbrace{S}_{\text{feedback}}\,\eta$$

Here, $S = (1 + GK)^{-1}$, v is a disturbance affecting the system and η is the measurement noise. The goal of feedforward is to obtain an input signal u_{ff} for the plant G, such that the desired trajectory y_d is followed. This is achieved if the feedforward controller is an exact inverse of G. The goal of the feedback controller is to attenuate the unknown disturbances v and η, and a possible residual $(1 - GF)y_d$ caused by incomplete knowledge of G in the design of F.

Industrial practice is to design the feedback controller in the frequency domain using loop-shaping techniques and subsequently manually tune the feedforward controller.



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Typical control architecture for servo control.

This systematic manual tuning technique is used to determine the feedforward controller F during experiments without the need for accurate knowledge of the system. The case study (see text box) outlines the manual feedforward tuning procedure for an H-drive.

Case study: Manual feedforward tuning for mechanical systems

To illustrate a typical manual feedforward tuning approach, consider a general H-drive. The aim is to reduce the positioning error along a prescribed trajectory y_d. The model of the H-drive at low frequencies is simply given by its rigid body behaviour, i.e.:

$$y(s) = \frac{1}{ms^2}$$

Here, m corresponds to the mass of the system. Therefore, a candidate feedforward controller is $F = k_{fa}s^2$, which leads to the feedforward signal $u_{ff}(s) = k_{fa}s^2y_d(s)$ and, by the inverse Laplace transform, to $u_{ff} = k_{fa}\cdot d^2y_d(t)/dt^2$. This feedforward is therefore also referred to as acceleration feedforward. Then, the error signal is given by:

$$e = S(1 - GF)y_d = S\left(1 - \frac{k_{fa}}{m}\right)y_d$$

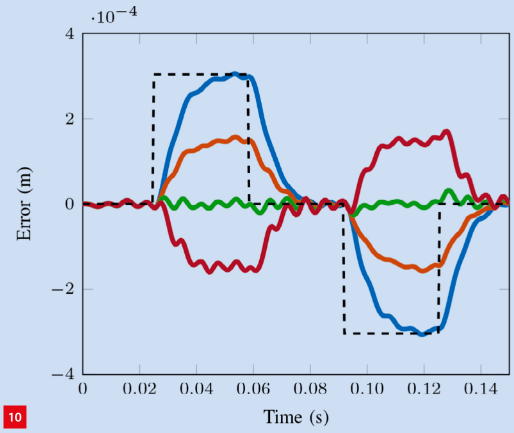
This feedforward structure clearly minimises the error if $k_{fa} = m$. However, accurate knowledge of m is not typically available. The main idea of a manual feedforward tuning approach is to tune the parameter k_{fa} during experiments, while evaluating the error for an appropriate reference signal y_d.

To this end, a stabilising feedback controller K, typically in the form of a lead filter, is implemented, without integral action. This implies that at low frequencies $|GK| >> 1$, for some constant c:

$$S = \frac{1}{1 + GK} \approx \frac{1}{GK} \approx cs^2$$

Combining with the error signal, this leads to:

$$e(s) = cs^2\left(1 - \frac{k_{fa}}{m}\right)y_d$$



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Tuning the feedforward parameter k_{fa} for an H-drive in an experiment where $d^2y_d(t)/dt^2$ is given by the dashed line (--). The error signals correspond to experiments with $k_{fa} = 0$ (blue), $k_{fa} = 10$ (orange), the optimal value $k_{fa} = 21$ (green), and $k_{fa} = 31$ (red).

Applying the inverse Laplace transform, this becomes:

$$e = c\left(1 - \frac{k_{fa}}{m}\right)\frac{d^2 y_d(t)}{dt^2}$$

This directly reveals how to determine the feedforward controller: choose k_{fa} such that the error is not correlated with the acceleration signal. This can be done by performing experiments under normal operating conditions. Tuning of the value of k_{fa} can be done in a straightforward manner, since the error depends affinely on k_{fa}; see Figure 10.

This idea is adopted widely in industry and applied in a very similar way to manually tune many feedforward components, including viscous friction or snap feedforward, or possibly nonlinear components such as Coulomb friction [7]. A key point is that all of these feedforward elements are memoryless. However hysteresis depends on the history of the system, thereby preventing the use of these memoryless feedforward elements. In the next section, we outline how manual feedforward can be achieved for hysteresis. The key idea is the use of a new memory model.

Feedforward for hysteresis

The history dependency of the hysteretic behaviour in piezoelectric actuators prevents a straightforward inverse that can be used for feedforward. A fundamentally new way to model these hysteresis phenomena is through memory (MEM) elements; see [8] for a recent overview. The key idea is described below; for more details, see [9].

A variable p is introduced, which can be interpreted as a variable that keeps track of the history.

Exploiting this variable, the Prandtl-Ishlinskii model is rewritten as:

$$\dot{y}(t) = M\big(p(t)\big)\dot{u}(t)$$

An example of a typical function $M(p)$ is given in Figure 11. This $M(p)$ is rather straightforward, where the number of levels corresponds to the number of play operators, and is constant for each level.

This new notation of the hysteresis model allows for a straightforward inverse, leading to the following feedforward controller:

$$\dot{u}_{ff}(t) = \frac{1}{M\big(p(t)\big)}\dot{y}_d(t)$$

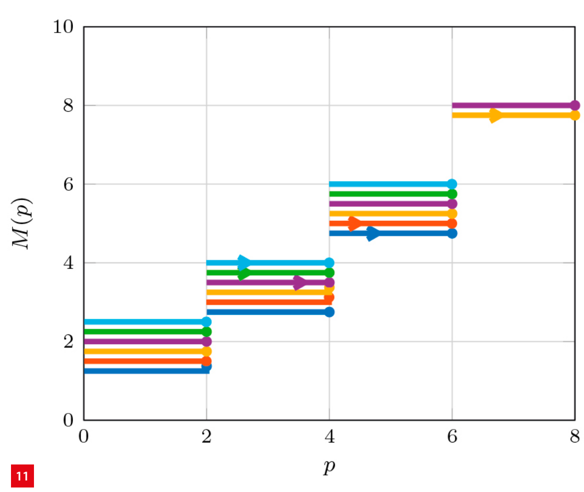
Tuning the feedforward controller now boils down to finding the constants in the mapping $M(p)$. In each of the ranges of p where the mapping $M(p)$ is constant, the hysteresis model behaves as a linear spring, i.e.:

$$y(t) = c_p u(t)$$

With c_p a constant, the corresponding feedforward controller is given by:

$$u_{ff}(t) = \frac{1}{k_s} y_d(t)$$

Hence, in each of these ranges the constant value of the mapping $M(p)$ can be tuned as if it were a linear system; this is similar to the tuning approach in Figure 10.



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Function M(p) for a Prandtl-Ishlinskii model that consists of four play operators. Each colour corresponds to a branch generated by the input signal from Figure 7. To visualise the start and end point of each line, all lines have a slight offset with respect to each other; in reality, all lines perfectly overlap.

Tuning the feedforward parameter k_s is done typically by applying a constant reference, i.e. $y_d = c$, leading to the error signal:

$$e = c\left(1 - \frac{c_p}{k_s}\right)$$

This error signal is affine in the unknown parameter k_s.

Changing the amplitude of the reference y_d will change the history and consequently change the variable p. Hence, a suitable reference signal to tune all of the constants that constitute the hysteresis feedforward is a piecewise constant signal with varying amplitudes, as depicted in Figure 12. Each change of the amplitude leads to a different history and thereby another level of the mapping $M(p)$ can be tuned.

This leads to the following procedure:
1. Select N play operators and their corresponding thresholds.
2. Choose a piecewise constant reference with low amplitude to tune the first weight, i.e. the first level in $M(p)$.
3. Increase the amplitude to tune the next level of $M(p)$.
4. Repeat step 3 until all levels are tuned perfectly. If the desired performance is not achieved, return to step 1 and increase the number of play operators.

This procedure is applied to the shear piezo elements in the piezo stepper actuator. The error data of this experiment is given in Figure 12.

Results

Applying this feedforward controller in a normal servo task to the piezo set-up given in Figure 4, shows a significant performance improvement compared to only feedback; see Figure 13. A factor of ten improvement is achieved in terms of the maximum error value.

The remaining error after applying the compensating feedforward is caused mainly by an error in modelling the hysteric behaviour in the Prandtl-Ishlinkskii model, with only four weights. Higher performance levels can be achieved by exploiting this approach with an increasing number of weights or with a different hysteresis model, see e.g. [10], although tuning a feedforward controller with a different model can be significantly more complex.

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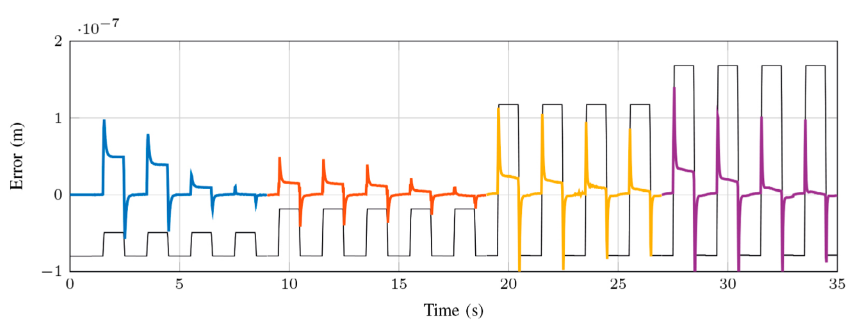

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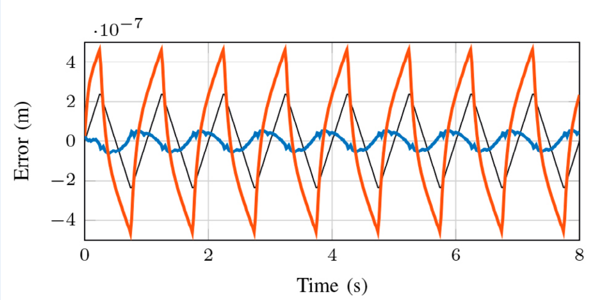
Manual tuning procedure for hysteresis feedforward applied to a piezoelectric actuator. The desired trajectory (scaled and shifted in black) is piecewise constant with four different amplitudes; each amplitude ensures a different range of p is active. The four tuning steps:
- *blue: decreasing c_{p1};*
- *orange: decreasing c_{p2};*
- *yellow: decreasing c_{p3};*
- *purple: decreasing c_{p4}.*



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Closed-loop experiment with a piezoelectric actuator following a triangular desired trajectory (scaled and in black).
Two different cases are studied:
- *in red: only feedback;*
- *in blue: with feedforward compensation determined using the manual feedforward tuning procedure of Figure 12.*