Master of Science Thesis in Mechatronics
Department of Electrical Engineering, Linköping University, 2016

# Investigation of Control Approaches for a High Precision, Piezo-actuated Rotational Stage Operating in Noisy Environments at CERN

**Niklas Ericson**

LINKÖPING
UNIVERSITY

Master of Science Thesis in Mechatronics

**Investigation of Control Approaches for a High Precision, Piezo-actuated Rotational Stage Operating in Noisy Environments at CERN**

Niklas Ericson

LiTH-ISY-EX--YY/NNNN--SE


Supervisor: **Mark Butcher**
CERN, Geneva, Switzerland
**Måns Klingspor**
ISY, Linköpings University, Sweden

Examiner: **Proffesor Svante Gunnarsson**
ISY, Linköpings University, Sweden

*Division of Automatic Control*
*Department of Electrical Engineering*
*Linköping University*
*SE-581 83 Linköping, Sweden*

# Abstract

The Equipment Controls and Electronics section at CERN is developing a high precision piezo-actuated rotational stage for the UA9 crystal collimation project. Several control-related issues arising with the complexity and operational environment of the system make it difficult to design a controller that achieves the desired performance. This thesis aims to identify different control approaches that can be applicable to this rotational stage and similar high precision systems.

# Contents

# Notation

### Abbreviations

| Abbreviation | Meaning |
|---|---|
| CERN | European Organization for Nuclear Research |
| STM | Scanning Tunneling Microscope |
| AFM | Atomic Force Microscope |
| LHC | Large Hadron Collider |
| PEA | Piezoelectric actuator |
| PID | Proportional, Integral, Differential (regulator) |
| DOF | Degrees of Freedom |
| PBRS | Pseudo Random Binary Sequence |
| TF | Transfer Function |
| QFT | Quantitative Feedback Theorem |

# 1 Introduction

## 1.1 Background

The piezoelectric effect is a phenomenon that arises in certain solid materials when an electric potential is generated in response to applied mechanical stress. The effect was first discovered by Jacques and Pierre Curie in 1880 when they found that applying pressure to a quarz crystal generates electrical potential. Today, the effect is commonly encountered in daily life and utilized in for example lighters, buzzers and loudspeakers.

Smart materials such as piezoelectric and magnetostrictive materials are nowadays commonly used in precision actuators due to their ability to convert electrical energy into mechanical energy. Piezoelectric materials have been commercially available for almost 45 years and have become indispensable for the nanopositioning industry [5]. In cases where a relatively small displacement range is required (travel ranges up to 500 μm) a piezo electric device is the actuator of choice due to its fast response, high resolution and its ability to generate large mechanical forces for small amounts of power in compact designs [4].

High precision positioning systems are vital in e.g. scanning tunneling microscopes (STM), atomic force microscopes (AFM) and in semiconductor lithography. In AFM, for instance, high precision positioning is required to control the vertical position of the scanning probe to keep the force constant between the sample surface and the probe tip. An topographical image of the sample is obtained by raster-scanning the probe over the sample surface and plotting the vertical displacement against the probe's x-y position. A positioning system that keeps the force constant down to an atomic-scale resolution is thus inevitable in order to obtain a high resolution image without damaging the sample [4].

The Equipment Controls and Electronics section in the Engineering Department at CERN (European Organization for Nuclear Research) is developing a high precision positioning system for the control of a piezo-actuated rotational stage used in the UA9 Crystal Collimation study. The stage uses a piezo electric linear stack actuator to displace a flexible lever arm mechanism which generates the rotational movement.

## 1.2 Purpose and Goal

Crystalline solids have the ability to constrain the directions that particles take as they pass through, this is commonly called the "channelling" property. The UA9 collaboration at CERN is investigating how tiny bent crystals can help to steer particle beams in modern hadron colliders such as the Large Hadron Collider (LHC) [7]. In high energy colliders, such as the LHC, particles tends to drift outwards creating a beam halo. These particles surrounding the beam, can be lost and cause damage to sensitive parts in the accelerator. By using bent crystals, halo particles can be efficiently extracted from the beam and collected by absorbers further away, reducing the complexity of the system. One major difficulty that aries is that the higher the energy of the particle, the lower the angular acceptance for channeling. Hence, a high precision positioning mechanism with a high angular accuracy is required. The rotational stage (with a range of 20 mrad) is of necessity to be able to track reference trajectories at ramp rates of 100 µrad/s and reject external disturbances to maintain a maximum tracking error of ±1 µrad.

This project aims to identify the possible control approaches that could be applicable to this problem to achieve the desired performance.

## 1.3 Prospective challenges

First of all, piezoelectric actuators show strong nonlinear properties such as hysteresis and creep (drift), which have to be compensated for. Moreover, the mechanical flexural structure in combination with the piezo electric characteristics leads to a highly resonant structure, making it difficult to achieve the desired performance while operating the rotational stage within noisy environments with external disturbances such as ground vibrations.

Furthermore this rotational stage is attached to a linear stage which is composed by a leadscrew, a stepping motor and an axel. The linear movement adds additional perturbation to the rotational stage due to imperfections in the leadscrew and detent torque and stepping nature of the motor.

Finally the system dynamics also show linear position dependence requiring a controller that is robust to such variations.

## 1.4 Related work

One attempt to achieve the desired performance has already been made. The proposed controller, presented in [3] delivers reasonable performance but does not fulfill the requirements during movement. The authors proposes a PID controller in combination with a pre-filter, and a hysteresis compensator. The controller has shown high disturbance rejection at the first resonance peak as well as good tracking performance.

## 1.5 Outline

This thesis plan presents an overview of the thesis, including method, literature base and expected results. The method and work flow of the thesis as well as a comprehensive literature review is given in Chapter 2. In Chapter 3 the results that can be expected half way through the project is discussed while a brief summary of the thesis can be found in Chapter 4.

# 2

# Method

This thesis will identify possible control approaches that could be applicable to the rotational stage at CERN in order to meet the performance requirements. First of all, a brief analysis of the already developed controller will be done in order to point out the drawbacks and determine which controller qualities that have to be improved in order to achieved the desired performance during linear movement of the rotational stage. The main work will then consist of investigating different control approaches such as feedforward, H-infinity, iterative or state feedback control. The most promising approaches will be benchmarked in simulations and compared to the existing algorithm. Finally, the most promising alternative will be implemented and tested on the real rotational stage.

## 2.1 Literature review

Here follows a review of the preliminary literature base that will be used in this thesis. It will most likely be extended with more articles, papers and books during the work with this thesis.

### [1] *- Memory characteristics of hysteresis and creep in multi-layer piezoelectric actuators: An experimental analysis*

The aim of this article is to provide an explanation of peculiar features of the piezoelectric actuator (PEA) response. It presents an experimental characterization of the nonlinear effects i.e. hysteresis and creep in a PEA. The authors find that both the instantaneous and delayed response of the PEA have hysteric dependence on the applied voltage level. Moreover, they present experimental evidence for that the two observed hysteretic relationships share a common memory structure i.e. they are not truly independent nonlinear phenomenas.

### [2]- *On the identification of Hammerstein systems in the presence of an input hysteretic nonlinearity with nonlocal memory: Piezoelectric actuators – an experimental case study*

This paper discusses the identification procedure of the linear dynamic part of piezo based actuators. A Hammerstein structure, consisting of a static (rate independent) hysteresis model with nonlocal memory (the current output does not only depend on the current input voltage but also on its history) and a linear dynamic model, is employed in order to model the hysteretic and dynamic behavior of the actuator.

The authors state that for the identification of the linear part of the actuator, a careful choice of the driving signal has to be made to avoid modifying the characteristics of the excitation. They show that a choice of a PBRS signal allows the decoupling of the identification of the linear and nonlinear part, since the nonlinear part only transforms the PBRS signal into another PBRS.

### [3] - *Controller Design and Verification for a Rotational Piezo-based Actuator for Accurate Positioning Applications in Noisy Environments*

This paper presents the modeling and controller design of a piezo actuated rotational stage operating in a noisy environment at CERN. The authors have adopted a Hammerstein structure, allowing them, in principal, to decouple the nonlinear hysteresis from the linear system dynamics. The extracted linear dynamics is identified as an OE system using several pseudo random binary signals (PBRS) as excitation signals. By adding different voltage biases to the PBRS it is also verified that the operating voltage point influences the identified transfer function (TF). The DC gain and the first resonance frequency and amplitude is affected due to the nonlinear piezo properties.

A 2-DOF controller (feedback and prefilter) and a hysteresis compensator are adopted in order to obtain the desired tracking and disturbance rejection. The proposed controller is designed as a series combination of a PID controller, a lead network and a $4^{th}$ order notch filter according to the quantitative feedback theorem (QFT). The proposed controller is experimentally tested and shows both disturbance rejection and good tracking capability.

### [4] - *A survey of control issues in nanopositioning*

This paper reviews the control-related research in nanopositioning, covering nanopositioning applications, actuators and sensors as well as control challenges. It focuses on piezoelectric actuators discussing both issues in control and different control techniques. Modeling techniques for the nonlinear effects i.e. creep and hysteresis as well as issues such as vibrations and modeling errors are presented in this work. Finally, different control schemes to mitigate the impact from these issues are reviewed such as feedback, forward, iterative and sensor less control.

### [5] - *Piezoelectrics in Positioning, Tutorial on Piezotechnology in Nanopositioning Applications*

This tutorial by Physik Instrumente (PI) gives the reader an overview of the fundamentals of piezoelectricity, piezomechanics and piezo actuators as well as detailed information regarding control approaches, environmental dependencies and design of piezoelectric positioning drives/systems. The electrical, mechanical and thermal behavior of piezoelectric actuators is described by basic equations presented in this paper. Several methods to improve the piezo dynamics are also discussed, such as linearization, signal preshaping and InputShaping® which is a patented real-time feedforward technology.

### [6] - *Design, Modeling and Control of Nanopositioning Systems*

This book covers the complete design cycle of nanopositioning systems. Some relevant chapters with respect to this thesis are Hysteresis Modeling and Control, Noise in Nanopositioning and Mechanical Design: Flexure-Based Nanopositioners.

## 2.2 Timeplan

Figure 2.1 shows the timeplan for the master thesis project. *HP* and *FP* stands for halftime presentation and fulltime presentation, respectively. In addition to the master thesis work, some hardware testing will be carried out from time to time, throughout the whole thesis period.

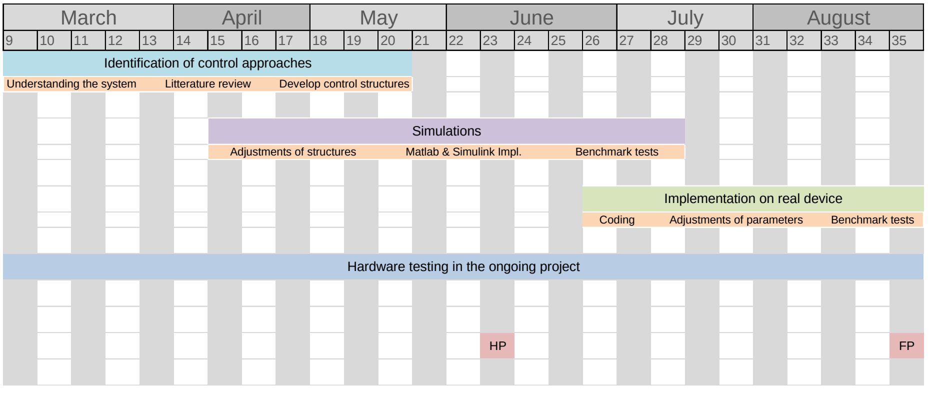


**Figure 2.1:** *Master Thesis timeplan*

# 3 Result

This section describes future results that could be expected half way through the project.

## 3.1 Control Approaches

Half way through the project, all control approaches that have been identified should be presented here. Furthermore, all control approaches that at the time have been simulated will be presented with a schematic structure, transfer functions or state space model, a bode plot of the closed loop system and additional plots for illustration of the trajectory tracking capability and the robustness.

## 3.2 Benchmark tests

Benchmark tests will be carried out on all simulated control approaches and presented here. Comparisons between the new control approaches and the existing algorithm with respect to disturbance rejection, trajectory tracking and closed loop bandwidth will be illustrated in this section with plots and tables.

# 4 Conclusion

This thesis aims to identify, simulate and implement a suitable control approach for a piezo actuated rotational stage at CERN. The rotational stage is to be used within the UA9 project to position a tiny bent crystal (which will steer particle beams) with a high accuracy. Several control approaches will be simulated in order to find a controller that meet the requirements.

# Bibliography

[1] Giustiniani A. Masi A. Biggio M., Butcher M. and Storace M. Memory characteristics of hysteresis and creep in multi-layer piezoelectric actuators: An experimental analysis. *Physica B: Condensed Matter*, 435:40–43, 2014. Cited on page 5.

[2] Giustiniani A. Butcher M. and Masi A. On the identification of hammerstein systems in the presence of an input hysteretic nonlinearity with nonlocal memory: Piezoelectric actuators – an experimental case study. *Physica B: Condensed Matter*, pages 1—-5, 2015. Cited on page 6.

[3] Losito R. Butcher M., Giustiniani A. and Masi A. Controller design and verification for a rotational piezo-based actuator for accurate positioning applications in noisy environments. *Iecon 2015*, 2015. Cited on pages 2 and 6.

[4] Eleftheriou E. Devasia S. and Moheimani R. A survey of control issues in nanopositioning. *IEEE Transactions on Control Systems Technology*, 15(5): 802—-823, 2007. Cited on pages 1 and 6.

[5] Eleftheriou E. Devasia S. and Moheimani R. Piezoelectrics in positioning. tutorial on piezotechnology in nanopositioning applications. *Physik Instrumente (PI) GmbH and Co. KG.*, Retreived in January 2008. URL `http://www.physikinstrumente.com/en/pdf_extra/2009_PI_Piezo_University_Designing_with_Piezo_Actuators_Tutorial.pdf`. Cited on pages 1 and 7.

[6] Fleming A. J. and Leang K. K. *Design, Modeling and Control of Nanopositioning Systems*. Springer International Publishing, first edition, 2014. Cited on page 7.

[7] Website. The ua9 experiment is investigating how crystals could help to steer particle beams in high-energy colliders, Retreived in January 2016. URL `http://home.cern/about/experiments/ua9`. Cited on page 2.

# Index