Mechatronic approach for the design of a Nano Active Stabilization System

PhD Thesis

by

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A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy (PhD) in Engineering Science

at

Liège Université

Abstract

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Résumé

Acknowledgments

Contents

List of Tables

List of Figures

1. Introduction

1.1 Context of this thesis / Background and Motivation

- European Synchrotron Radiation Facility (ESRF) (Figure 1.1)

Figure 1.1.: European Synchrotron Radiation Facility

- ID31 and Micro Station (Figure 1.2)

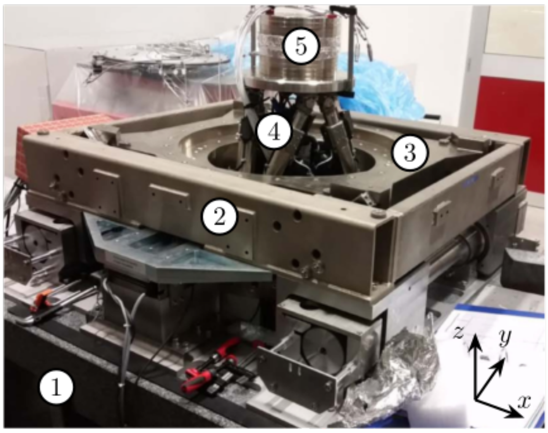


Figure 1.2.: Picture of the ID31 Micro-Station with annotations

Alternative: `id31_microstation_cad_view.png` (CAD view)

- X-ray beam + detectors + sample stage (Figure 1.3)

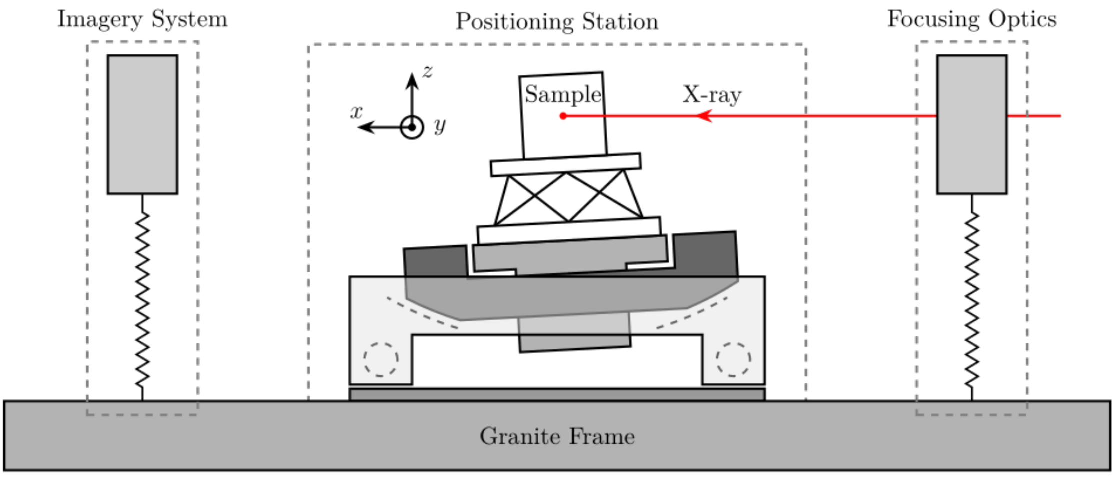


Figure 1.3.: ID31 Beamline Schematic. With light source, nano-focusing optics, sample stage and detector.

- Few words about science made on ID31 and why nano-meter accuracy is required
- Typical experiments (tomography, ...), various samples (up to 50kg)
- Where to explain the goal of each stage? (e.g. micro-hexapod: static positioning, Ty and Rz: scans, ...)
- Example of picture obtained (Figure 1.4)

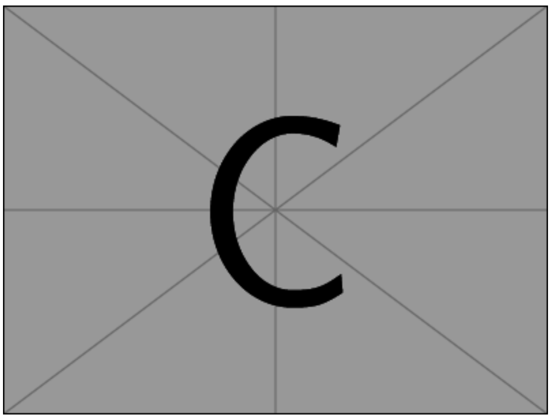


Figure 1.4.: Image obtained on the ID31 beamline

- Explain wanted positioning accuracy and why micro-station cannot have this accuracy (backlash, play, thermal expansion, ...)
- Speak about the metrology concept, and why it is not included in this thesis

1.2 Challenge definition

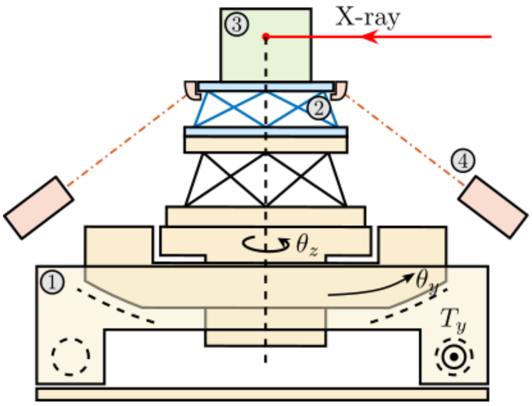


Figure 1.5.: Nass Concept. 1: micro-station, 2: nano-hexapod, 3: sample, 4: 5DoF metrology

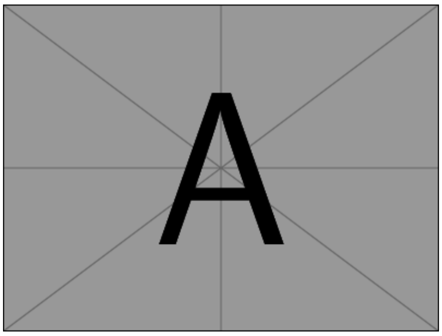
- 6DoF vibration control platform on top of a complex positioning platform
- **Goal**: Improve accuracy of 6DoF long stroke position platform
- **Approach**: Mechatronic approach / model based / predictive
- **Control**: Robust control approach / various payloads. First hexapod with control bandwidth higher than the suspension modes that accepts various payloads?
- Rotation aspect
- Compactness? (more related to mechanical design)

1.3 Literature Review

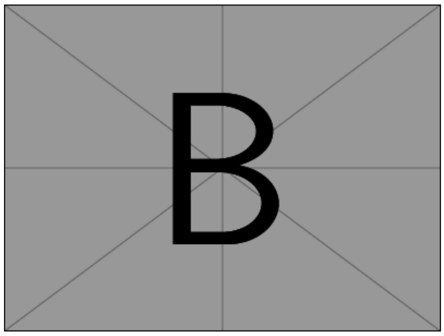
- Hexapods **li01_simul_fault_vibrat_isolat_point bishop02_devel_precis_point_contr_vibrat hanieh03_activ_stewar afzali-far16_vibrat_dynam_isotr_hexap_analy_studies naves20_desig** `file:///home/thomas/Cloud/work-projects/ID31-NASS/matlab/stewart-simscape/org/bibliography.org`
- Positioning stations
- Mechatronic approach? **rankers98_machin monkhorst04_dynam_error_budget jabben07_mechat**

1.4 Outline of thesis / Thesis Summary / Thesis Contributions

Mechatronic Design Approach / Model Based Design:



(a) Stewart platform based on voice coil actuators



(b) Stewart platform based on piezoelectric actuators

Figure 1.6.: Examples of Stewart Platforms

- **monkhorst04_dynam_error_budget** high costs of the design process: the designed system must be **first time right**. When the system is finally build, its performance level should satisfy the specifications. No significant changes are allowed in the post design phase. Because of this, the designer wants to be able to predict the performance of the system a-priori and gain insight in the performance limiting factors of the system.

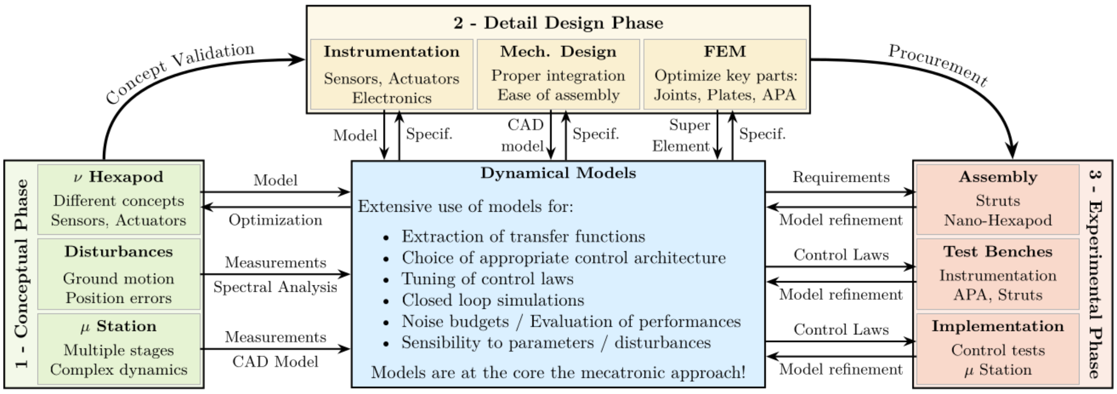


Figure 1.7.: Overview of the mechatronic approach used for the Nano-Active-Stabilization-System

Goals:

- Design Nano Active Stabilization System (NASS) such that it is easy to control (and maintain). Have good performances by design and not by complex control strategies.

Models:

- Uniaxial Model:
  - Effect of limited support compliance
  - Effect of change of payload

- Rotating Model
  - Gyroscopic effects
- Multi Body Model
- Finite Element Models

2. Conceptual Design Development

Contents

Abstract

2.1 Uni-axial Model

- Explain what we want to capture with this model
- Schematic of the uniaxial model (with X-ray)
- Identification of disturbances (ground motion, stage vibrations)
- Optimal nano-hexapod stiffness/actuator: Voice coil VS Piezo (conclusion?)
- Control architecture (IFF, DVF, ...)?
- Conclusion

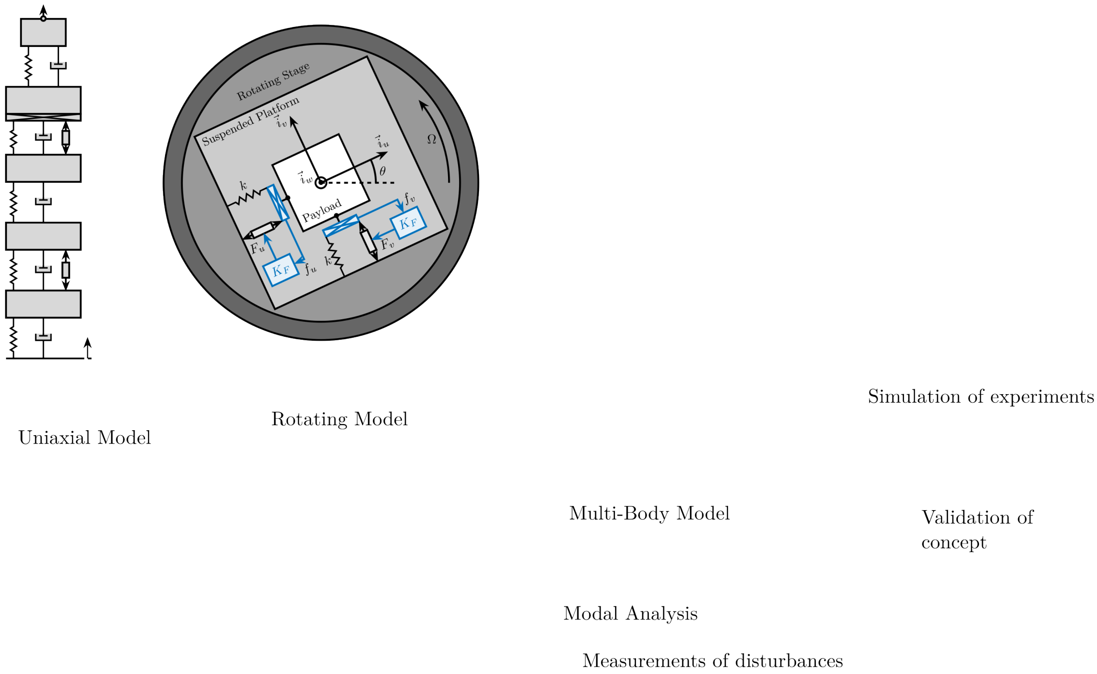


Figure 2.1.: Figure caption

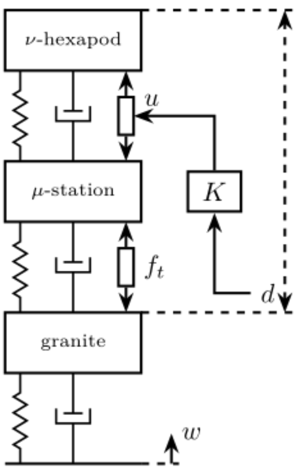


Figure 2.2.: 3-DoF uniaxial mass-spring-damper model of the NASS

2.1.1 Micro Station Model

2.1.2 Nano Hexapod Model

2.1.3 Disturbance Identification

2.1.4 Open Loop Dynamic Noise Budgeting

- List all disturbances with their spectral densities
- Show how they have been measured
- Say that repeatable errors can be calibrated (show measurement of Hans-Peter?)

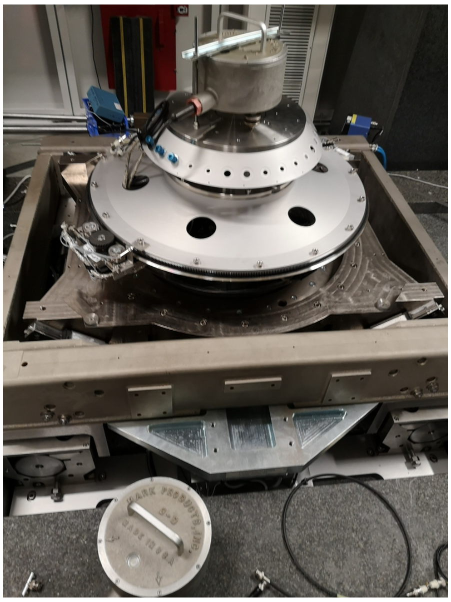


Figure 2.3.: Setup used to measure the micro-station vibrations during operation

2.1.5 Active Damping

Conclusion: IFF is better for this application

Integral Force Feedback

- Mass spring damper model
- Root Locus
- Sensitivity to disturbances

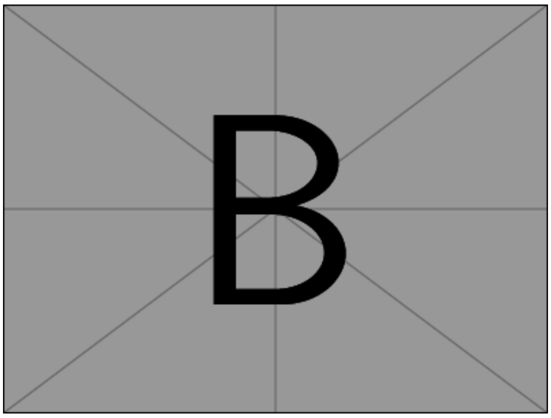


Figure 2.4.: Amplitude Spectral density of the measured disturbance sources

Direct Velocity Feedback

- Mass spring damper model
- Root Locus
- Sensitivity to disturbances

2.1.6 Position Feedback Controller

2.1.7 Effect of support compliance

- **goal**: make the nano-hexapod independent of the support compliance
- Simple 2DoF model
- Generalized to any support compliance
- **conclusion**: frequency of nano-hexapod resonances should be lower than first suspension mode of the support

2.1.8 Effect of payload dynamics

- **goal**: be robust to a change of payload
- Simple 2DoF model
- Generalized to any payload dynamics

2.1.9 Conclusion

2.2 Effect of rotation

Papers:

- **dehaeze20_activ_dampin_rotat_platf_integ_force_feedb**
- [1]

2.2.1 System Description and Analysis

- x-y-Rz model
- explain why this is representing the NASS
- Equation of motion
- Centrifugal forces, Coriolis

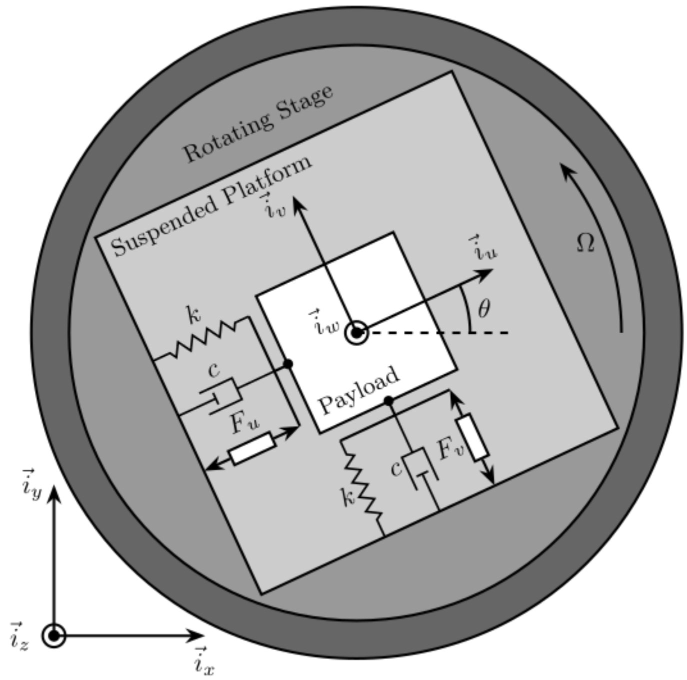


Figure 2.5.: Mass spring damper model of an X-Y stage on top of a rotating stage

2.2.2 Integral Force Feedback

- Control diagram

- Root Locus: unstable with pure IFF

2.2.3 IFF with an High Pass Filter

2.2.4 IFF with a stiffness in parallel with the force sensor

2.2.5 Relative Damping Control

2.2.6 Comparison of Active Damping Techniques

2.2.7 Rotating Nano-Hexapod

2.2.8 Nano Active Stabilization System with rotation

2.2.9 Conclusion

- problem with voice coil actuator
- Two solutions: add parallel stiffness, or change controller
- Conclusion: minimum stiffness is required
- APA is a nice architecture for parallel stiffness + integrated force sensor (have to speak about IFF before that)

2.3 Micro Station - Modal Analysis

Conclusion:

- complex dynamics: need multi-body model of the micro-station to represent the limited compliance...

2.3.1 Measurement Setup

2.3.2 Frequency Analysis

2.3.3 Modal Analysis

2.4 Micro Station - Multi Body Model

2.4.1 Kinematics

`file:///home/thomas/Cloud/work-projects/ID31-NASS/matlab/nass-simscape/org/kinematics.org`

- Small overview of each stage and associated stiffnesses / inertia

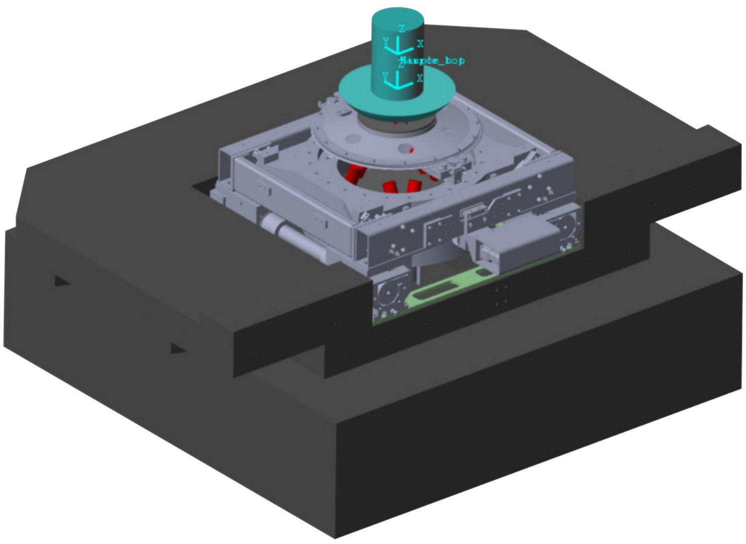


Figure 2.6.: 3D view of the multi-body model of the micro-station

- schematic that shows to considered DoF
- import from CAD

2.4.2 Modal Analysis and Dynamic Modeling

- Picture of the experimental setup
- Location of accelerometers
- Show obtained modes
- Validation of rigid body assumption
- Explain how this helps tuning the multi-body model

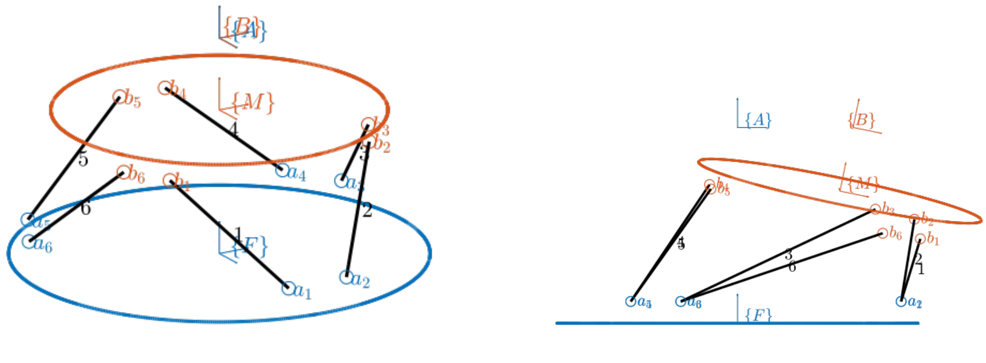
2.4.3 Disturbances and Positioning errors

2.4.4 Validation of the Model

- Most important metric: support compliance
- Compare model and measurement

2.5 Nano Hexapod - Multi Body Model

- What we want to capture with this model



(a) Initial position

(b) After some motion

Figure 2.7.: Stewart Platform Architecture

- Explain what is a multi body model (rigid body, springs, etc...)
- Key elements (plates, joints, struts): for now simplistic model (rigid body elements, perfect joints, ...), but in next section, FEM will be used
- Matlab/Simulink developed toolbox for the study of Stewart platforms

2.5.1 Stewart Platform Architecture

Configurable Simscape Model: `file:///home/thomas/Cloud/work-projects/ID31-NASS/matlab/stewart-simscape/org`

- Explain the different frames, etc...
- Little review
- explain key elements:
  - two plates
  - joints
  - actuators
- explain advantages compared to serial architecture

2.5.2 Kinematics

- Well define elements, frames, ...
- Derivation of jacobian matrices: for forces and for displacement
- Explain this is true for small displacements (show how small)

2.5.3 Model of an Amplified Piezoelectric Actuator

- APA test bench
- Piezoelectric effects
- mass spring damper representation (2dof)
- Compare the model and the experiment
- Here, just a basic 2DoF model of the APA is used

2.5.4 Dynamics of the Nano-Hexapod

- Effect of joints stiffnesses

  The APA model should maybe not be used here, same for the nice top and bottom plates. Here the detailed design is not yet performed

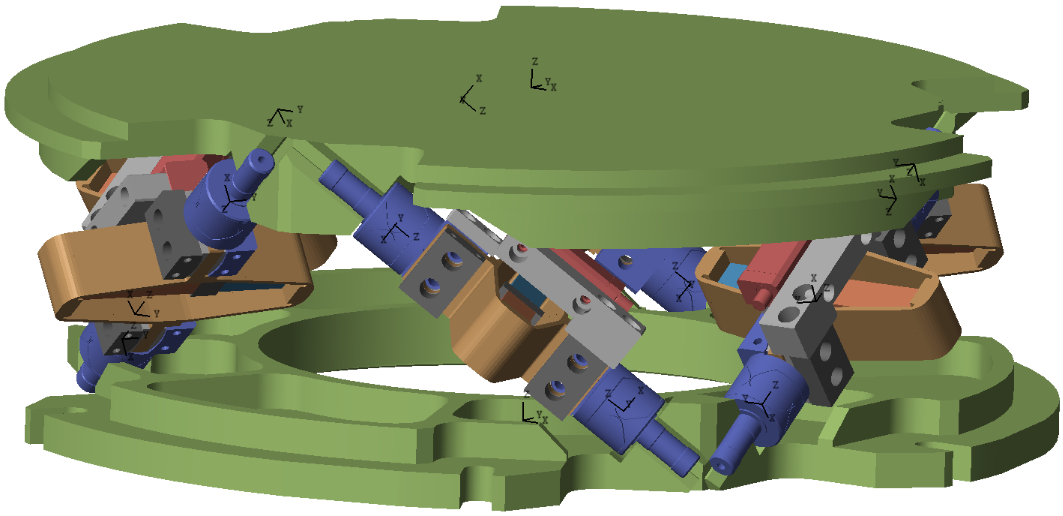


Figure 2.8.: 3D view of the multi-body model of the Nano-Hexapod (simplified)

2.6 Control Architecture - Concept Validation

Discussion of:

- Transformation matrices / control architecture (computation of the position error in the frame of the nano-hexapod)
- Control of parallel architectures

- Control in the frame of struts or cartesian?
- Effect of rotation on IFF? => APA
- HAC-LAC
- New noise budgeting?

2.6.1 Control Kinematics

- Explain how the position error can be expressed in the frame of the nano-hexapod
- block diagram
- Explain how to go from external metrology to the frame of the nano-hexapod

2.6.2 High Authority Control - Low Authority Control (HAC-LAC)

- general idea
- case for parallel manipulator: decentralized LAC + centralized HAC

2.6.3 Decoupling Strategies for parallel manipulators

study

- Jacobian matrices, CoK, CoM, ...
- Discussion of cubic architecture
- SVD, Modal, ...

2.6.4 Decentralized Integral Force Feedback (LAC)

- Root Locus
- Damping optimization

2.6.5 Decoupled Dynamics

- Centralized HAC
- Control in the frame of the struts
- Effect of IFF

2.6.6 Centralized Position Controller (HAC)

- Decoupled plant
- Controller design

2.7 Conceptual Design - Conclusion

3. Detailed Design

Contents

Abstract

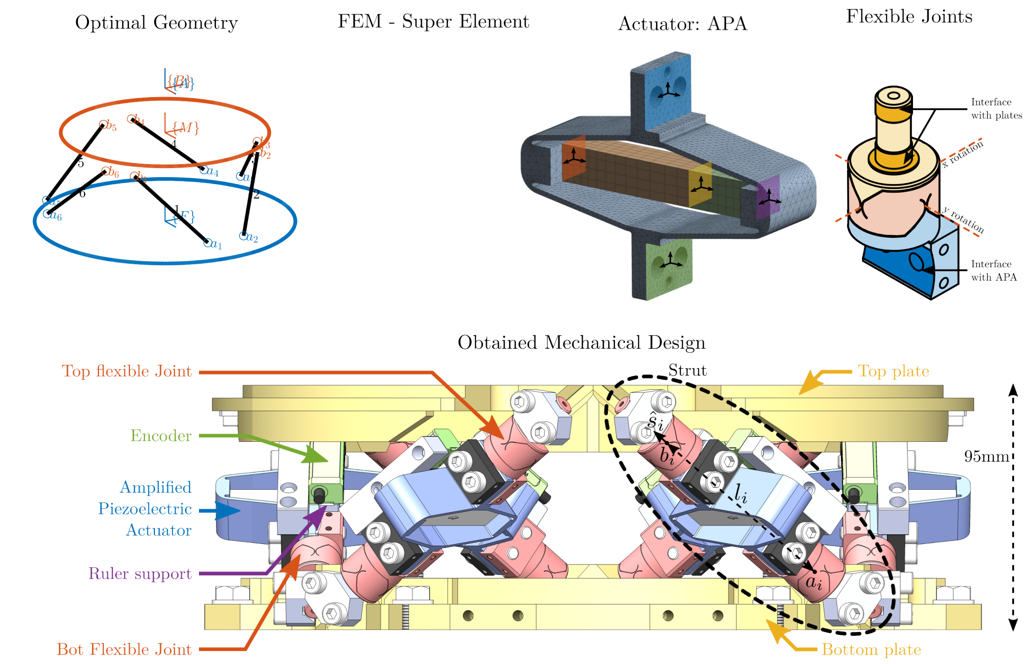


Figure 3.1.: Figure caption

3.1 Nano-Hexapod Kinematics - Optimal Geometry?

Maybe this can be just merged with the last section in this chapter?

3.1.1 Optimal strut orientation

3.1.2 Cubic Architecture: a Special Case?

`file:///home/thomas/Cloud/work-projects/ID31-NASS/matlab/stewart-simscape/org/cubic-configuration.org`

3.2 Nano-Hexapod Dynamics - Including Flexible elements in the Multi-body model

Should this be an appendix?

Reduced order flexible bodies [2]

- Used with APA, Flexible joints, Plates

3.2.1 Reduced order flexible bodies

- Quick explanation of the theory
- Implementation with Ansys (or Comsol) and Simscape

3.2.2 Numerical Validation

- Numerical Validation Ansys VS Simscape (APA)
- Figure with 0 and 1kg mass

3.2.3 Experimental Validation

- Test bench
- Obtained transfer functions and comparison with Simscape model with reduced order flexible body

3.3 Actuator Choice

- From previous study: APA seems a nice choice
- First tests with the APA95ML: validation of a basic model (maybe already presented)
- Optimal stiffness?
- Talk about piezoelectric actuator? bandwidth? noise?
- Specifications: stiffness, stroke, ... => choice of the APA
- FEM of the APA
- Validation with flexible APA in the simscape model

3.3.1 Model

Piezoelectric equations

- FEM
- Simscape model
- (2 DoF, FEM, ...)

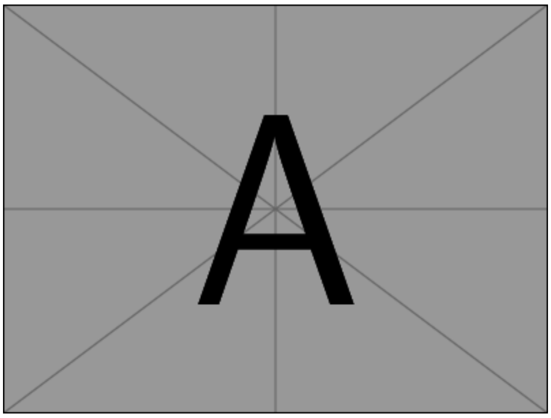


Figure 3.2.: Schematical representation of an Amplified Piezoelectric Actuator

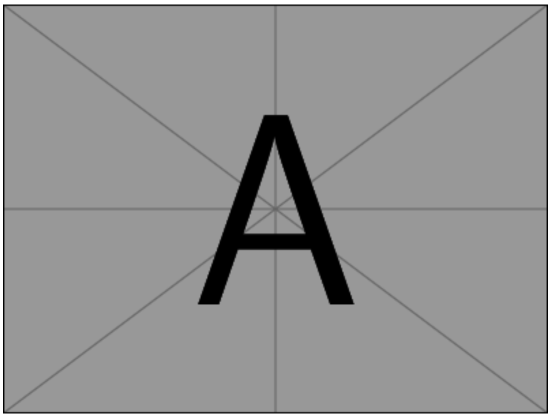


Figure 3.3.: Schematical representation of a 2DoF model of an Amplified Piezoelectric Actuator

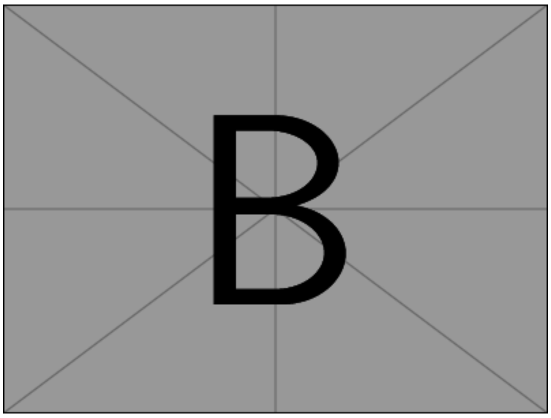


Figure 3.4.: Schematical representation of a FEM of an Amplified Piezoelectric Actuator

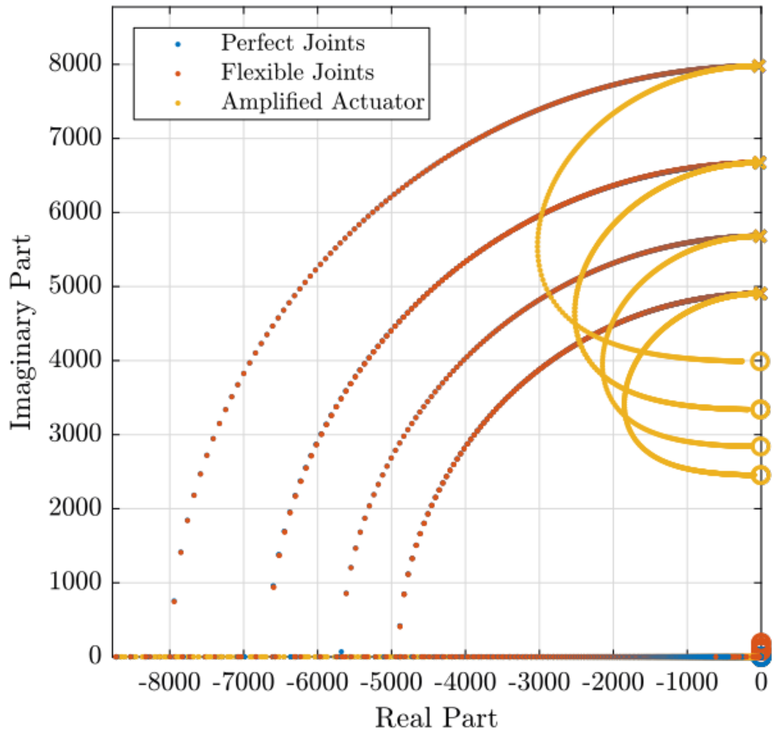


Figure 3.5.: Limitation of the attainable damping due to the APA design

3.3.2 Experimental System Identification

- Experimental validation (granite test bench)
- Electrical parameters
- Required instrumentation to read force sensor?
- Add resistor to include high pass filtering: no risk of saturating the ADC
- Estimation of piezoelectric parameters

3.3.3 Validation with Simscape model

- Tuned Simscape model
- IFF results: OK

3.4 Design of Nano-Hexapod Flexible Joints

- Perfect flexible joint
- Imperfection of the flexible joint: Model

- Study of the effect of limited stiffness in constrain directions and non-null stiffness in other directions
- Obtained Specification
- Design optimisation (FEM)
- Implementation of flexible elements in the Simscape model: close to simplified model

3.4.1 Effect of flexible joint characteristics on obtained dynamics

- Based on Simscape model
- Effect of axial stiffness, bending stiffness, ...
- Obtained specifications (trade-off)

3.4.2 Flexible joint geometry optimization

- Chosen geometry
- Show different existing geometry for flexible joints used on hexapods
- Optimisation with Ansys
- Validation with Simscape model

3.4.3 Experimental identification

- Experimental validation, characterisation (study)
- Visual inspection
- Test bench
- Obtained results

3.5 Choice of Instrumentation

- Discussion of the choice of other elements:
  - Encoder
  - DAC
  - ADC (reading of the force sensors)
  - real time controller
  - Voltage amplifiers
- Give some requirements + chosen elements + measurements / validation

3.5.1 DAC and ADC

- Force sensor

3.5.2 Voltage amplifier (link)

- Test Bench: capacitive load, ADC, DAC, Instrumentation amplifier
- Noise measurement
- Transfer function measurement

3.5.3 Encoder (link)

- Noise measurement

3.6 Obtained Design

- Explain again the different specifications in terms of space, payload, etc..
- CAD view of the nano-hexapod
- Chosen geometry, materials, ease of mounting, cabling, …
- Validation on Simscape with accurate model?

3.7 Detailed Design - Conclusion

4. Experimental Validation

Contents

Abstract Schematic representation of the experimental validation process.

- APA
- Strut
- Nano-hexapod on suspended table
- Nano-hexapod with Spindle

Figure 4.1.: Figure caption

4.1 Amplified Piezoelectric Actuator

4.2 Flexible Joints

4.3 Struts

4.4 Nano-Hexapod

4.5 Rotating Nano-Hexapod

4.6 ID31 Micro Station

4.7 Experimental Validation - Conclusion

5. Conclusion and Future Work

5.1 Alternative Architecture

file:///home/thomas/Cloud/work-projects/ID31-NASS/matlab/nass-simscape/org/alternative-micro-station-architecture.org

Appendix A.

Mathematical Tools for Mechatronics

A.1 Feedback Control

A.2 Dynamical Noise Budgeting

A.2.1 Power Spectral Density

A.2.2 Cumulative Amplitude Spectrum

Appendix B.

Stewart Platform - Kinematics

Bibliography

[1] T. Dehaeze and C. Collette, “Active damping of rotating platforms using integral force feedback,” *Engineering Research Express*, Feb. 2021 (cit. on p. 28).

[2] P. Brumund and T. Dehaeze, “Multibody simulations with reduced order flexible bodies obtained by fea,” in *MEDSI'20*, (Chicago, USA), ser. Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation, JACoW Publishing, 2020 (cit. on p. 36).

List of Publications

Articles

T. Dehaeze and C. Collette, "Active damping of rotating platforms using integral force feedback," *Engineering Research Express*, Feb. 2021.

In Proceedings

P. Brumund and T. Dehaeze, "Multibody simulations with reduced order flexible bodies obtained by fea," in *MEDSI'20*, (Chicago, USA), ser. Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation, JA-CoW Publishing, 2020.

T. Dehaeze, J. Bonnefoy, and C. Collette, "Mechatronics approach for the development of a nano-active-stabilization-system," in *MEDSI'20*, (Chicago, USA), ser. Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation, JACoW Publishing, 2021.

Acronyms

Notation	Description
ESRF	European Synchrotron Radiation Facility
NASS	Nano Active Stabilization System

Glossary

Notation	Description
ϕ	A woody bush