Nano Active Stabilization System - Introduction

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Contents

1 Context of this thesis

1.1 Synchrotron Radiation Facilities

Accelerating electrons to produce intense X-ray

- Explain what is a Synchrotron: light source
- Say how many there are in the world (~50)
- Electron part: LINAC, Booster, Storage Ring ??
- Synchrotron radiation: Insertion device / Bending magnet
- Many beamlines (large diversity in terms of instrumentation and science)
- Science that can be performed:
  - structural biology, structure of materials, matter at extreme, ...

Figure 1.1: European Synchrotron Radiation Facility

[scale=1,width=0.7]figs/introduction$_{e}srf_{s}chematic$

Figure 1.2: Schematic of the ESRF - Over 40 beamlines. Booster, Linac, storage ring

The European Synchrotron Radiation Facility

3rd and 4th generation Synchrotrons

- 4th generation light sources

– [1]

Picture of 3rd generation "beam source" vs 4th generation?

Picture showing Synchrotron "moore's law"

1.2 The ID31 ESRF Beamline

Beamline Layout

Beamline layout (OH, EH)

- ID31 and Micro Station (Figure 1.4) Check https://www.esrf.fr/UsersAndScience/Experiments/StructMaterials/ID31 https://www.wayforlight.eu/beamline/23244
- X-ray beam + detectors + sample stage (Figure ??)
- Focusing optics
- Optical schematic with: source, lens, sample and detector. Explain that what is the most important is the relative position between the sample and the lens.
- Explain the XYZ frame for all the thesis (ESRF convention: X: x-ray, Z gravity up)

  Add XYZ on figure 1.3

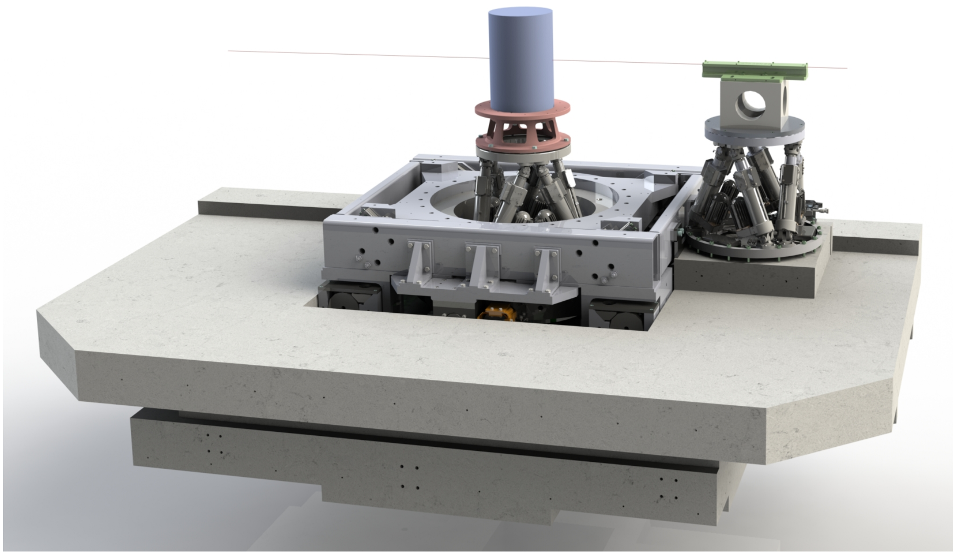


Figure 1.3: CAD view of the optical hutch with the nano-focusing optics, the micro-station

Positioning End Station: The Micro-Station Micro-Station:

- DoF with strokes: Ty, Ry, Rz, Hexapod

- Experiments: tomography, reflectivity, truncation rod, ... Make a table to explain the different "experiments"
- Explain how it is used (positioning, scans), what it does. But not about the performances
- Different sample environments
- Alternative: `id31_microstation_cad_view.png` (CAD view)

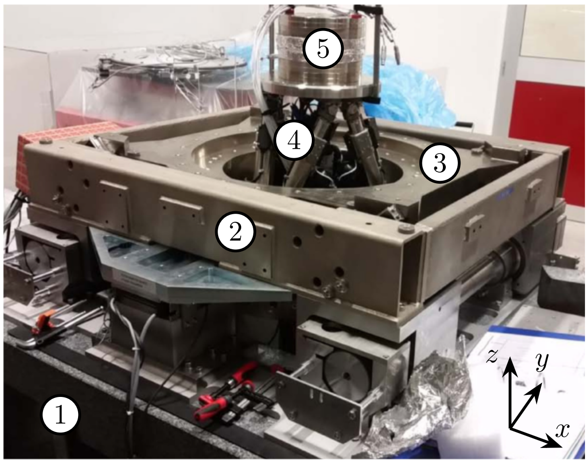


Figure 1.4: Picture of the ID31 Micro-Station with annotations

Science performed on ID31

- Few words about science made on ID31 and why nano-meter accuracy is required
- Typical experiments (tomography, ...), various samples (up to 50kg), sample environments (high temp, cryo, etc..)
  - Alignment of the sample, then
  - Reflectivity
  - Tomography
  - Diffraction tomography: most critical
- Example of picture obtained (Figure 1.5) with resolution

`introduction_exp_scanning` and `introduction_exp_scanning_image`

1.3 Need of accurate positioning end stations with high dynamics

A push towards brighter and smaller beams... Improvement of both the light source and the instrumentation:

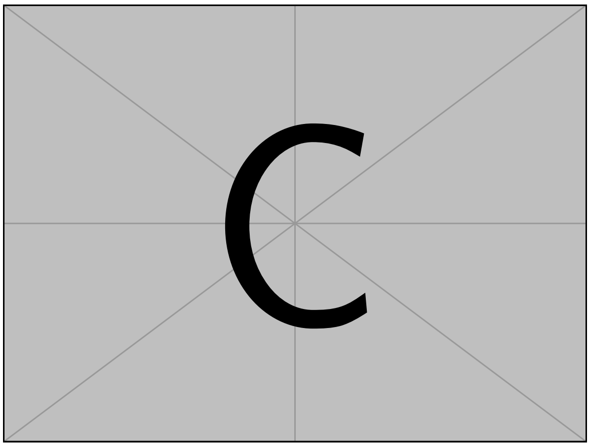


Figure 1.5: Image obtained on the ID31 beamline

- EBS: smaller source + higher flux
- Better focusing optic (add some links): beam size in the order of 10 to 20nm FWHM (reference)

  Show picture or measurement of the beam size

  crossed silicon compound refractive lenses, KB mirrors [17], zone plates [18], or multilayer Laue lenses [19] [2]

Higher flux density (+high energy of the ID31 beamline) => Radiation damage: needs to scan the sample quite fast with respect to the focused beam

- Allowed by better detectors: higher sampling rates and lower noise => possible to scan fast [3]

...Requires the use of dynamical positioning "from traditional step by step scans to *fly-scan*"

Fast scans + needs of high accuracy and stability => need mechatronics system with:

- accurate metrology
- multi degree of freedom positioning systems
- fast feedback loops

Shift from step by step scan to *fly-scan* [4]

- Much lower pixel size + large image => takes of lot of time if captured step by step. Explain what is step by step scanning: move motors from point A to point B, stops, start detector acquisition, open shutter , close the shutter, move to point C, ...

[5]

> n traditional step scan mode, each exposure position requires the system to stop prior to data acquisition, which may become a limiting factor when fast data collection is required. Fly-scanning is chosen as a preferred solution that helps overcome such speed limitations [5, 6]. In fly-scan mode, the sample keeps moving and a triggering system generates trigger signals based on the position of the sample or the time elapsed. The trigger signals are used to control detector exposure.

Make picture representing a typical experiment (maybe YZ scan?) with: Probably already shown earlier `introduction_exp_scanning`

- nano focusing optics (see the beam focused)
- positioning stage with displayed YZ motion (pixel by pixel in the YZ plane)
- detector

Subject of this thesis: design of high performance positioning station with high dynamics and nanometer accuracy

2 Challenge definition

2.1 Multi DoF, Highly accurate, and Long stroke positioning end station?

Performance limitation of "stacked stages" end-stations Typical positioning end station:

- stacked stages
- ballscrew, linear guides, rotary motor

Explain the limitation of performances:

- Backlash, play, thermal expansion, guiding imperfections, …
- Give some numbers: straightness of the Ty stage for instance, change of 0.1^oC with steel gives x nm of motion
- Vibrations
- Explain that this micro-station can only have ~10um of accuracy due to physical limitation
- Possibility to have linear/rotary encoders that correct the motion in the considered DoF, but does not change anything to the other 5DoF

Talk about flexure based positioning stations? Advantages: no backlash, etc… But: limited to short stroke Picture of schematic of one positioning station based on flexure

The ID31 Micro-Station Presentation of the Micro-Station in details **??**:

- Goal of each stage (e.g. micro-hexapod: static positioning, Ty and Rz: scans, …)
- Stroke
- Initial design objectives: as stiff as possible, smallest errors as possible

New positioning requirements

- To benefits from nano-focusing optics, new source, etc… new positioning requirements
- Positioning requirements on ID31:

  - Maybe make a table with the requirements and the associated performances of the micro-station

  - Make tables with the wanted motion, stroke, accuracy in different DoF, etc..

- Sample masses

The goal in this thesis is to increase the positioning accuracy of the micro-station to fulfil the initial positioning requirements.

Goal: Improve accuracy of 6DoF long stroke position platform

2.2 The Nano Active Stabilization System

NASS Concept Briefly describe the NASS concept. 4 parts:

- Micro Station
- multi-DoF positioning system with good dynamics
- 5DoF metrology system
- Control system and associated instrumentation

6DoF vibration control platform on top of a complex positioning platform that correct positioning errors based on an external metrology

Add the control system in the schematic

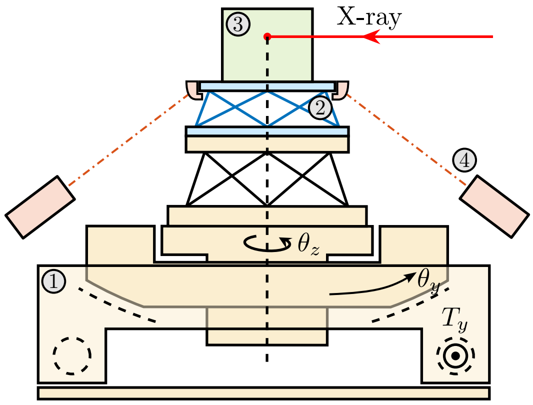


Figure 2.1: Nass Concept. 1: micro-station, 2: nano-hexapod, 3: sample, 4: 5DoF metrology

Metrology system Requirements:

- 5 DoF

- long stroke
- nano-meter accurate
- high bandwidth

The accuracy of the NASS will only depend on the accuracy of the metrology system.

Concept:

- Fiber interferometers
- Spherical reflector with flat bottom
- Tracking system

Complex mechatronics system on its own.

This metrology system is not further discussed in this thesis as it is still under active development.

In the following of this thesis, it is supposed that the metrology system is accurate, etc..

- Say that there are several high precision sensors, but only interferometers for long stroke / high accuracy?

Multi-DoF Positioning stage for error compensation

- 5 DoF
- High dynamics
- nano-meter capable (no backlash,)
- Accept payloads up to 50kg

MIMO robust control strategies Explain the robustness need?

- 24 7/7 …
- That is why most of end-stations are based on well-proven design (stepper motors, linear guides, ball bearing, …)
- Plant uncertainty: many different samples, use cases, rotating velocities, etc…

Trade-off between robustness and performance in the design of feedback system.

2.3 Predictive Design

- The performances of the system will depend on many factors:
  - sensors
  - actuators
  - mechanical design
  - achievable bandwidth
  - ...
- Need to evaluate the different concepts, and predict the performances to guide the design
- The goal is to design, built and test this system such that it work as expected the first time. Very costly system, so much be correct.

2.4 Control Challenge

High bandwidth, 6 DoF system for vibration control, fixed on top of a complex multi DoF positioning station, robust, ...

- Many different configurations (tomography, Ty scans, slow fast, ...)
- Complex MIMO system. Dynamics of the system could be coupled to the complex dynamics of the micro station
- Rotation aspect, gyroscopic effects, actuators are rotating with respect to the sensors
- Robustness to payload change: very critical. Say that high performance systems (lithography machines, etc...) works with calibrated payloads. Being robust to change of payload inertia means large stability margins and therefore less performance.

3 Literature Review

3.1 Nano Positioning end-stations

End Station with Stacked Stages Stacked stages:

- errors are combined

To have acceptable performances / stability:

- limited number of stages
- high performances stages (air bearing etc…)

Examples:

- ID16b [6]
- ID13 [7]
- ID11 [8]
- ID01 [9]

  Maybe make a table to compare stations

Explain limitations => Thermal drifts, run-out errors of spindles (improved by using air bearing), straightness of translation stages, …

Online Metrology and Active Control of Positioning Errors The idea of having an external metrology to correct for errors is not new.

- To have even better performances: online metrology are required.
- Several strategies:
  - only used for measurements (post processing)
  - for calibration
  - for triggering detectors
  - for real time positioning control

HXN [5] Laser interferometers on reference ring (on top of rotary stage). Used to trigger the detectors (ptychography, microscope) Similar to [10]

Table 3.1: Table caption

Architecture	Sensors and measured DoFs	Actuators and controlled DoFs
XYZ, Spherical retroreflector, Sample	3 interferometers[1], Y,Z	YZ piezo stages
Spindle / Metrology Ring / XYZ Stage / Sample	3 Capacitive, Y,Z,Rx	
Hexapod / Spindle / Metrology Ring / Sample	12 Capacitive[2], X,Y,Z,Rx,Ry	Piezo (Hexapod)
XYZ, Rz, XY, Cylindrical reference	5 interferometers[3], X,Y,Z,Rx,Ry	XYZ linear motors
XYZ, Rz, XYZ Spherical reference	3 Interferometers[4], Y,Z,Rx	XYZ parallel piezo stage
XYZ, mirrors/sample	3 interferometers[3], XYZ	XYZ piezo stage
Rz, Parallel XYZ stage	3 interferometers[1]	3xVCM parallel stage
Parallel XYZ stage	3 interferometers[4], XYZ	3xVCM parallel stage

Figure with different stages

Compared to the existing stages (see table), what are the challenges here? Rotation, large stroke, light to heavy payloads, lots of DoF (5 to be controlled)

Comparison with NASS?

Architecture	Sensors	Actuators	Institute, BL	OL/CL (bandwidth)	Stroke, DoF
Ty,Ry,Rz,Hexapod,Sample	6+ Interferometers		ESRF, ID31	CL	Ty, Ry, Rz, Hex

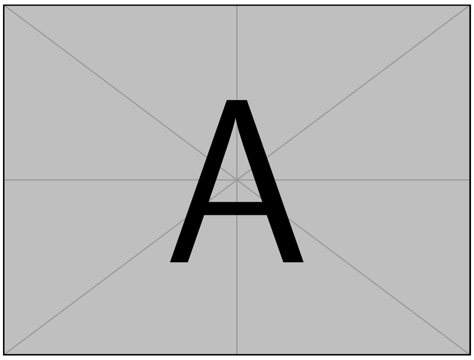
Long Stroke - Short Stroke architecture Speak about two stage control?

- Long stroke + short stroke
- Usually applied to 1dof, 3dof (show some examples: disk drive, wafer scanner)
- Any application in 6DoF? Maybe new!
- In the table, say which ones are long stroke / short stroke. Some new stages are just long stroke (voice coil)

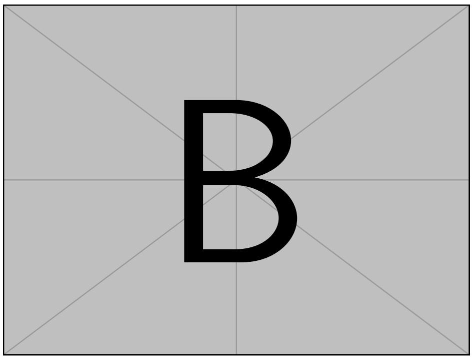
3.2 Multi-DoF dynamical positioning stations

Serial and Parallel Kinematics Example of several dynamical stations:

[1]PicoScale SmarAct Michelson interferometers
[2]Capacitive sensors from Fogale Sensors
[3]Attocube FPS3010 Fabry-Pérot interferometers
[4]Attocube IDS3010 Fabry-Pérot interferometers



(a) Stewart platform based on voice coil actuators



(b) Stewart platform based on piezoelectric actuators

Figure 3.1: Examples of Stewart Platforms

- XYZ piezo stages
- Delta robot? Octoglide?
- Stewart platform

Serial vs parallel kinematics (table?)

Stewart platforms

Explain the normal stewart platform architecture

Make a table that compares the different stewart platforms for vibration control. Geometry (cubic), Actuator (soft, stiff), Sensor, Flexible joints, etc.

3.3 Mechatronics approach

Predicting performances using models

- [21]

> igh 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.

Can use several models:

- Lumped mass-spring-damper models [22]
- Multi-Body Models

- Finite element models Sub structuring?

Closed-Loop Simulations [23]

Say what can limit the performances for a complex mechatronics systems as this one:

- disturbances
- measurement noise
- DAC / amplifier noise (actuator)
- feedback system / bandwidth

Simulations can help evaluate the behavior of the system.

Dynamic Error Budgeting

- [21]

  > igh 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.

- [24]
- [25]

  > rror budgets [23] are frequently used in the design of precision machines, in order to assess the contributions of different factors such as parasitic motions, thermal expansion, and servo accuracy, on the positioning accuracy of a machine. Dynamic Error Budgeting (DEB) or 'Spectral Analysis' extends this concept to the realm of feedback control. Recognizing that the controller can provide only a finite attenuation of disturbance signals interfering with the servo, DEB provides a methodology for predicting the cumulative effect of such signals on the control error as a function of their spectral (frequency) content. The method can be used to predict the control accuracy of a system implemented using a set of certain devices under certain conditions before it is realized. Furthermore, as it is formulated in the frequency domain, it can be used to optimize the controller design as well, typically leading to an H2 - optimal control framework. In DEB, the disturbance signals are modeled with their power spectral density (PSD), assuming that they are stationary stochastic processes which are not correlated with each other. Then, these PSD's are transmitted to the performance goal, most often the positioning error, using linear time invariant (LTI) system theory. The transmitted PSD's are summed up into the variance of the performance goal, which constitutes a comparative measure of performance. Most importantly, the influence of different dynamic factors and disturbance sources, which have the greatest impact on the achievable performance (e.g.,

> accuracy) can be easily spotted and improved, through this kind of analysis. An approach similar to DEB was followed to decompose the contribution of different noise sources on the hard disk position error in [1], [2], [45]. DEB has been used to assess the performance of a geophone and a vibration isolation system in [75]. Jabben [49] has used DEB in the mechatronic design of a magnetically suspended rotating platform. Aguirre et al. [3] have analyzed the performance of active aerostatic thrust bearings using DEB.

3.4 Control architecture

Maybe make a simple review of control strategies for Stewart platform control. Based on file:///home/thomas/Cloud/work-projects/ID31-NASS/matlab/stewart-simscape/org/bibliography.org

Broad subject (MIMO control), maybe talk only about vibration control based on external metrology.

- Active Damping
- Decentralized
- Centralized
- Manually tuned: PID, lead lag, etc…
- Automatic / Optimal: LQG, H-Infinity

4 Original Contributions

This thesis proposes several contributions in the fields of Control, Mechatronics Design and Experimental validation.

Active Damping of rotating mechanical systems using Integral Force Feedback [26], [27]

> his paper investigates the use of Integral Force Feedback (IFF) for the active damping of rotating mechanical systems. Guaranteed stability, typical benefit of IFF, is lost as soon as the system is rotating due to gyroscopic effects. To overcome this issue, two modifications of the classical IFF control scheme are proposed. The first consists of slightly modifying the control law while the second consists of adding springs in parallel with the force sensors. Conditions for stability and optimal parameters are derived. The results reveal that, despite their different implementations, both modified IFF control scheme have almost identical damping authority on the suspension modes.

Design of complementary filters using $\mathcal{H}_\infty$ Synthesis and sensor fusion [28] [29] [30]

- Several uses (link to some papers).
- For the NASS, they could be use to further improve the robustness of the system.

Multi-body simulations with reduced order flexible bodies obtained by FEA [31]

Combined multi-body / FEA techniques and experimental validation on a Stewart platform containing amplified piezoelectric actuators Super-element of amplified piezoelectric actuator / combined multibody-FEA technique, experimental validation on an amplified piezoelectric actuator and further validated on a complete stewart platform

> e considered sub-components in the multi-body model as *reduced order flexible bodies* representing the component's modal behaviour with reduced mass and stiffness matrices obtained from finite element analysis (FEA) models. These matrices were created from FEA models via modal reduction techniques, more specifically the *component mode synthesis* (CMS). This makes this design approach a combined multibody-FEA technique. We validated the technique with a test bench that confirmed the good modelling capabilities using reduced order flexible body models obtained from FEA for an amplified piezoelectric actuator (APA).

Robustness by design

- Design of a Stewart platform and associated control architecture that is robust to large plant uncertainties due to large variety of payload and experimental conditions.
- Instead of relying on complex controller synthesis (such as $\mathcal{H}_\infty$ synthesis or μ-synthesis) to guarantee the robustness and performance.
- The approach here is to choose an adequate architecture (mechanics, sensors, actuators) such that controllers are robust by nature.
- Example: collocated actuator/sensor pair => controller can easily be made robust
- This is done by using models and using HAC-LAC architecture

Mechatronics design Conduct a rigorous mechatronics design approach for a nano active stabilization system [32], [33]

Approach from start to finish:

- From first concepts using basic models, to concept validation
- Detailed design phase
- Experimental phase

Complete design with clear choices based on models. Such approach, while not new, is here applied This can be used for the design of future end-stations.

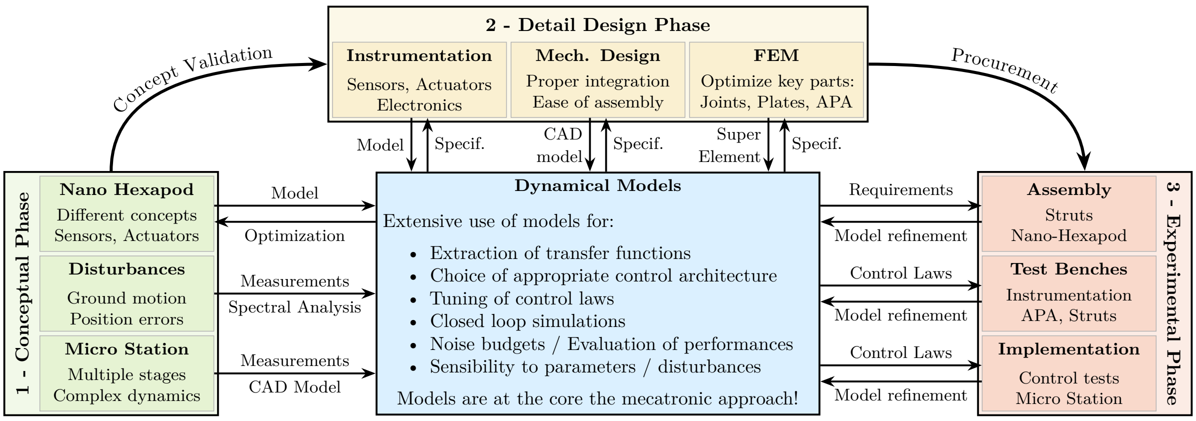


Figure 4.1: Overview of the mechatronic approach used for the Nano-Active-Stabilization-System

6DoF vibration control of a rotating platform Vibration control in 5DoF of a rotating stage To the author's knowledge, the use of a continuously rotating stewart platform for vibration control has not been proved in the literature.

Experimental validation of the Nano Active Stabilization System Demonstration of the improvement of the the positioning accuracy of a complex multi DoF (the micro-station) by several orders of magnitude (Section ...) using ...

5 Thesis Outline - Mechatronics Design Approach

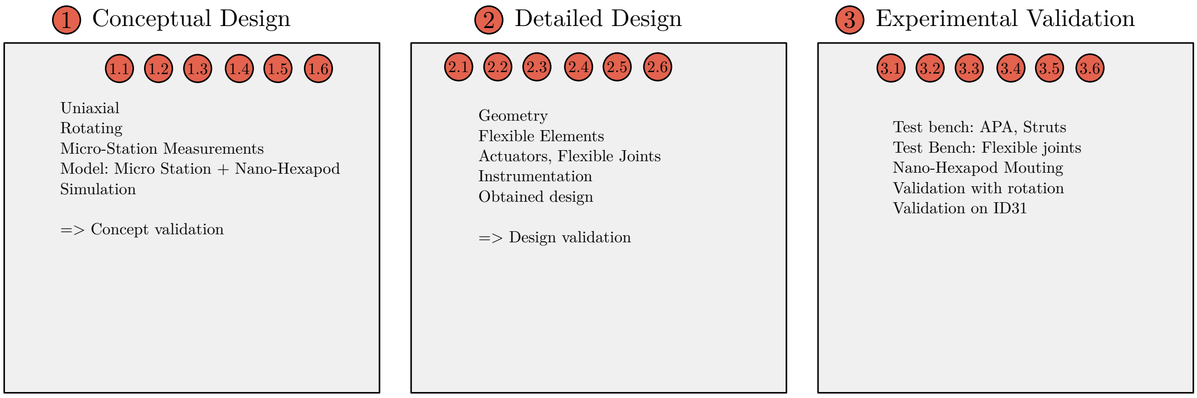


Figure 5.1: Overview of the sections

This thesis

- has a structure that follows the mechatronics design approach

Is structured in three chapters that corresponds to the three mains parts of the proposed mechatronics approach.

A brief overview of these three chapters is given bellow.

Conceptual design development

- Start with simple models for witch trade offs can be easily understood (uniaxial)
- Increase the model complexity if important physical phenomenon are to be modelled (cf the rotating model)
- Only when better understanding of the physical effects in play, and only if required, go for higher model complexity (here multi-body model)
- The system concept and main characteristics should be extracted from the different models and validated with closed-loop simulations with the most accurate model
- Once the concept is validated, the chosen concept can be design in mode details

Detailed design

- During this detailed design phase, models are refined from the obtained CAD and using FEM
- The models are used to assists the design and to optimize each element based on dynamical analysis and closed-loop simulations
- The requirements for all the associated instrumentation can be determined from a dynamical noise budgeting
- After converging to a detailed design that give acceptable performance based on the models, the different parts can be ordered and the experimental phase begins

Experimental validation

- It is advised that the important characteristics of the different elements are evaluated individually Systematic validation/refinement of models with experimental measurements
- The obtained characteristics can be used to refine the models
- Then, an accurate model of the system is obtained which can be used during experimental tests (for control synthesis for instance)

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