MECHATRONICS APPROACH FOR THE DEVELOPMENT OF A NANO-ACTIVE-STABILIZATION-SYSTEM

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Abstract

With the growing number of fourth generation light sources, there is an increased need of fast positioning end-stations with nanometric precision. Such systems are usually including dedicated control strategies, and many factors may limit their performances. In order to design such complex systems in a predictive way, a mechatronics design approach also known as "model based design", may be utilized. In this paper, we present how this mechatronics design approach was used for the development of a nano-hexapod for the ESRF ID31 beamline. The chosen design approach consists of using models of the mechatronics system (including sensors, actuators and control strategies) to predict its behavior. Based on this behavior and closed-loop simulations, the elements that are limiting the performances can be identified and re-designed accordingly. This allows to make adequate choices regarding the design of the nano-hexapod and the overall mechatronics architecture early in the project and therefore save precious time and resources. Several test benches were used to validate the models and to gain confidence on the predictability of the final system's performances. Measured nano-hexapod's dynamics was shown to be in very good agreement with the models. Further tests should be done in order to confirm that the performances of the system match the predicted one. The presented development approach is foreseen to be applied more frequently to future mechatronics system design at the ESRF.

INTRODUCTION

With the new 4th generation machines, there is an increasing need of fast and accurate positioning systems [1]. These systems are usually including feedback control loops and therefore their performances are not only depending on the quality of the mechanical design, but also on its correct integration with the actuators, sensors and control system.

In order to optimize the performances of such system, it is essential to consider a design approach in which the structural design and the control design are integrated. This approach, also called the "mechatronics approach", was shown to be very effective for the design many complex systems [2, 3]. Such design methodology was recently used for the development of several systems used by the synchrotron community [4–6].

The present paper presents how the "mechatronic approach" was used for the design of a Nano Active Stabilization System (NASS) for the ESRF ID31 beamline.

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NASS - MECHATRONICS APPROACH

The ID31 Micro-Station

The ID31 micro-station is used to position samples along complex trajectories [7]. It is composed of several stacked stages (represented in yellow in Fig. 1) which allows an high mobility. This however limits the position accuracy to tens of micrometers.

The Nano Active Stabilization System

The NASS is a system whose goal is to improve the positioning accuracy of the micro-station. It is represented in Fig. 1 and consists of three main elements:

- A nano-hexapod located between the sample to be positioned and the micro-station
- An interferometric metrology system measuring the sample's position with respect to the focusing optics
- A control system (not represented), which based on the measured position, properly actuates the nano-hexapod in order to stabilize the sample's position.

This system should be able to actively stabilize the sample position down to tens of nanometers while the micro-station is performing complex trajectories.

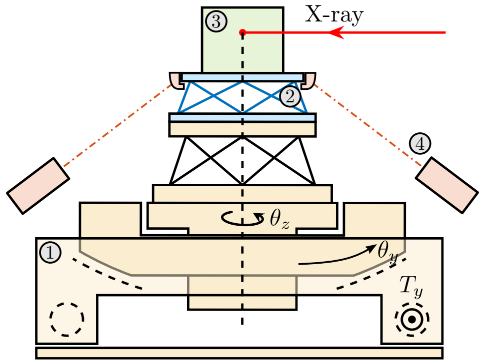


Figure 1: NASS - Schematic representation. 1) Micro-station, 2) Nano-hexapod, 3) Sample, 4) Metrology system.

Mechatronics Approach - Overview

In order to design the NASS in a predictive way, a mechatronics approach, schematically represented in Fig. 2, was used. It consists of three main phases:

1. *Conceptual phase*: Simple models of both the micro-station and the nano-hexapod are used to first evaluate the performances of several concepts. During this

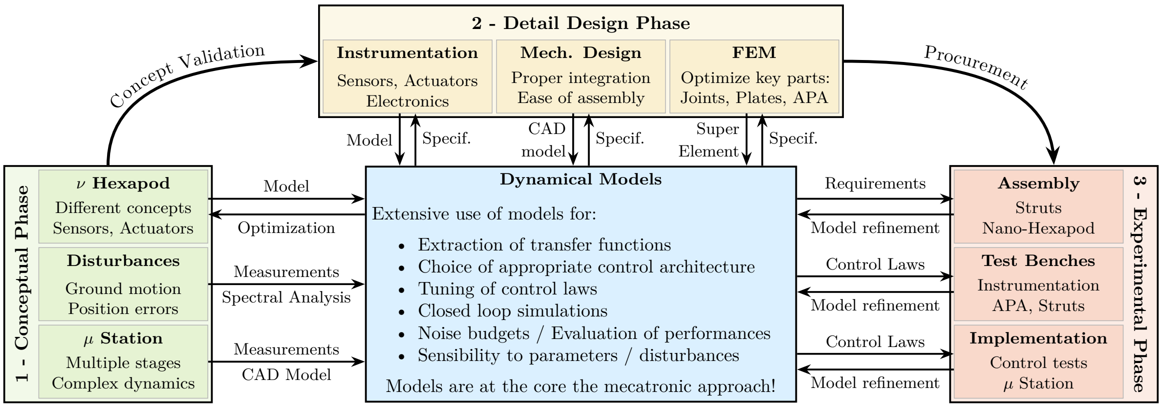


Figure 2: Overview of the mechatronics approach used for the design of the NASS.

phase, the type of sensors to use and the approximate required dynamical characteristics of the nano-hexapod are determined.

2. *Detail design phase*: Once the concept is validated, the models are used to list specifications both for the mechanics and the instrumentation. Each critical elements can then be properly designed. The models are updated as the design progresses.

3. *Experimental phase*: Once the design is completed and the parts received, several test benches are used to verify the properties of the key elements. Then the hexapod can be mounted and fully tested with the instrumentation and the control system.

Models

As shown in Fig. 2, the models are at the core of the mechatronics approach. Indeed, several models are used throughout the design with increasing level of complexity (Fig. 3).

At the beginning of the conceptual phase, simple "mass-spring-damper" models (Fig. 3a) were used in order to easily study multiple concepts. Noise budgeting and closed-loop simulations were performed, and it was concluded that a nano-hexapod with low frequency "suspension" modes would help both for the reduction of the effects of disturbances and for the decoupling between the nano-hexapod dynamics and the complex micro-station dynamics. I was found that by including a force sensor in series with the nano-hexapod's actuators, "Integral Force Feedback" (IFF) strategy could be used to actively damp the nano hexapod's resonances without impacting the high frequency disturbance rejection. The overall goal was to obtain a system dynamics which is easy to control in a robust way.

Rapidly, a more sophisticated and more realistic multi-body model (Fig. 3b) using Simscape [8] was used. This model was based on the 3D representation of the micro-station as well as on extensive dynamical measurements. Time domain simulations were performed with every stage of the micro-station moving and the nano hexapod actively stabilizing the sample against the many disturbances. The multi-body model permitted to study effects such as the coupling between the actuators and the sensors as well as the effect of the spindle's rotational speed on the nano-hexapod's dynamics [9]. The multi-input multi-output control strategy could be developed and tested.

During the detail design phase, the nano-hexapod model was updated using 3D parts exported from the CAD software as the mechanical design progressed. The key elements of the nano-hexapod such as the flexible joints and the APA were optimized using a Finite Element Analysis (FEA) Software. As the flexible modes of the mechanics are what generally limit the controller bandwidth, they are important to model in order to understand which modes are problematic and should be addressed. To do so, a "super-element" can be exported using a FEA software and imported into the multi-body model (Fig. 3c). Such process is described in [10]. The multi-body model with included flexible elements can be used to very accurately estimate the dynamics of the system. However due to the large number of states included, it becomes unpractical to perform time domain simulations.

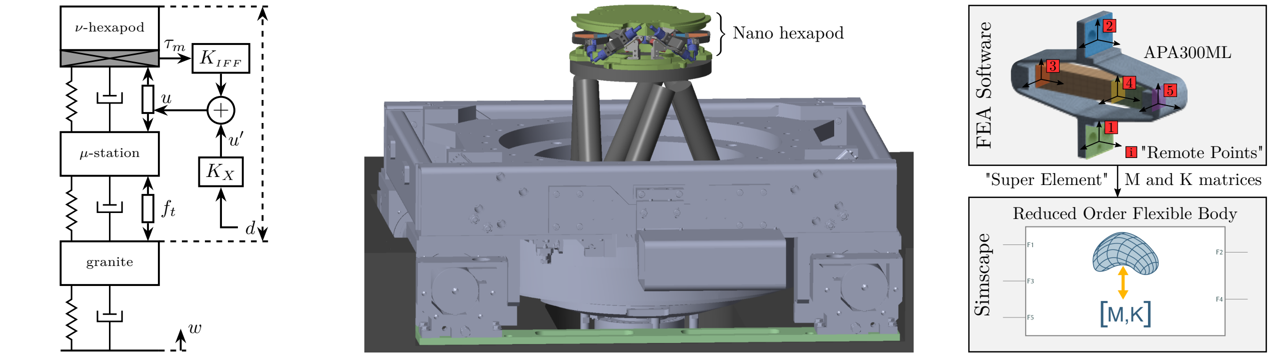
Finally, during the experimental phase, the models were refined using experimental system identification data. At this phase of the development, models are still useful. They can help with the controller optimization, to understand the measurements, the associated performance limitations and to gain insight on which measures to take in order to overcome these limitations.

For instance, it has been found that when fixing the encoders to the struts, as in Fig. 4a, several flexible modes of the APA were appearing in the dynamics which would render the control using the encoders very complex. Therefore, an alternative configuration with the encoders fixed to the plates was used instead.

NANO-HEXAPOD DESIGN

Nano-Hexapod Specifications

The nano-hexapod is a "Gough-Stewart platform", which is a fully parallel manipulator composed of few parts as shown in Fig. 4a: only two plates linked by 6 active struts.



(a) Mass Spring Damper Model. (b) Multi Body Model. (c) Finite Element Model.

Figure 3: Schematic of several models used during all the mechatronics design process.

Each strut has one rotational joint at each end, and one actuator in between (Fig. 4b).

The main benefits of this architecture are its compact design, good dynamical properties, high load capability over weight ratio, and to possibility to control the motion in 6 degrees of freedom. The nano-hexapod should have a maximum height of 95 mm, support samples up to 50 kg, have a stroke of $\approx$ 100 μm and be fully compliant to avoid any wear, backlash, play and to have predictable dynamics.

Based on the models used throughout the mechatronics approach, several specifications were added in order to maximize the performances of the system:

- Actuator axial stiffness $\approx$ 2 N/µm as it is a good trade-off between disturbance filtering, dynamic decoupling from the micro-station and insensibility to the spindle's rotational speed.
- Flexible joint bending stiffness $<$ 100 Nm/rad as high bending stiffness can limit IFF performances [11].
- Flexible joint axial stiffness $>$ 100 N/µm to maximize the frequency of spurious resonances.
- Precise positioning of the b_i and $\hat{s}_i$ to accurately determine the hexapod's kinematics.
- Flexible modes of the top-plate as high as possible as it can limit the achievable controller bandwidth.
- Integration of a force sensor in series with each actuator for active damping purposes.

Parts Optimization

During the detail design phase, several parts were optimized to fit the above specifications.

The flexible joint geometry was optimized using a finite element software while the top plate geometry was manually optimized to maximize the frequency of its flexible modes.

Amplified Piezoelectric Actuators (APA) were found to be the most suitable actuator for the nano-hexapod due to its compact size, large stroke and adequate stiffness. The chosen model was the APA300ML from Cedrat Technologies (Fig. 4b). It is composed of three piezoelectric stacks, a lever mechanism increasing the stroke up to $\approx$ 300 µm and decreasing the axial stiffness down to $\approx$ 1.8 N/µm. One of the three stacks can be used as a force sensor, at the price of loosing 1/3 of the stroke. This has the benefits of providing good "collocation" between the sensor stack and the actuator stacks, meaning that the active damping controller will be robust [12].

Nano-Hexapod Mounting

Using the multi-body model of the nano-hexapod with the APA modeled as a flexible element, it was found that a misalignment between the APA and the two flexible joints was adding several resonances to the dynamics that were difficult to control. Therefore, a bench was developed to help the alignment the flexible joints and the APA during the mounting of the struts.

A second mounting tool was used to fix the six struts to the two plates without inducing too much strain in the flexible joints. The mounted nano-hexapod is shown in Fig. 5.

TEST-BENCHES

Flexible Joints and Instrumentation

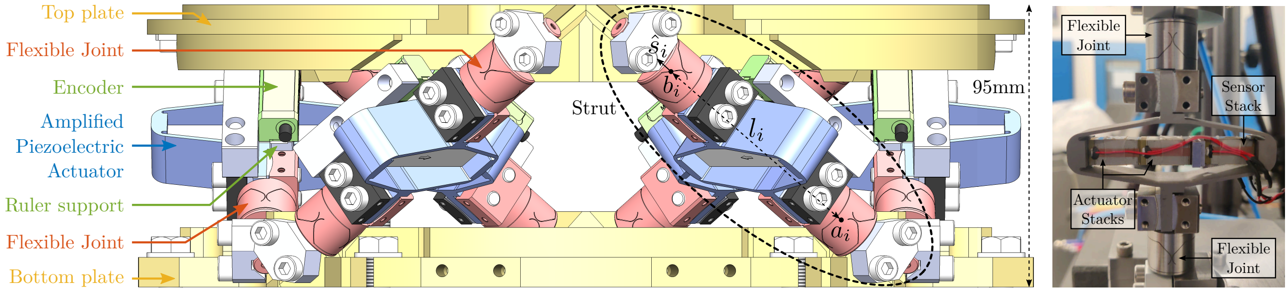
Before mounting the nano-hexapod and performing control tests, several test benches were used to characterize the individual elements of the system.

The bending stiffness of the flexible joints was measured by applying a controlled force to one end of the joint while measuring its deflection at the same time. This helped exclude the ones that were not compliant with the requirement and pair the remaining ones.

The transfer function from the input to the output voltage of the voltage amplifier[1] as well as its output noise were measured. Similarly, the measurement noise of the encoders[2] was also measured.

These simple measurements on individual elements were useful to refine their models, to found any problem as early as possible, and to help analyzing the results obtained when the the nano-hexapod is mounted and all the elements combined.

[1] PD200 from PiezoDrive
[2] Vionic from Renishaw



(a) CAD view of the nano-hexapod with key elements.

(b) Mounted strut.

Figure 4: Nano-hexapod: A Stewart platform architecture.

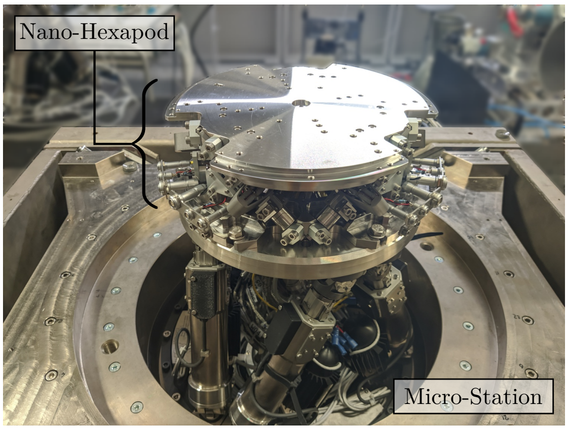


Figure 5: Nano-hexapod on top of the micro-station.

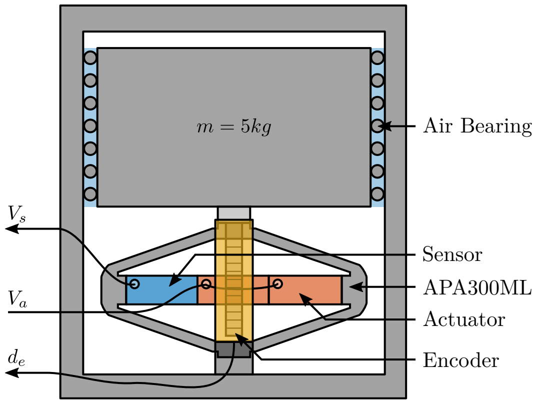


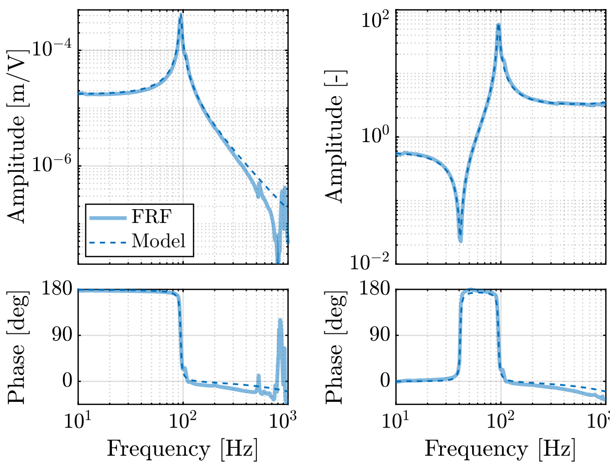
Figure 6: Schematic of the bench used to identify the APA dynamics.

APA and Struts Dynamics

A test bench schematically shown in Fig. 6 was used to identify the dynamics of the APA. It consist of a 5 kg granite fixed on top of the APA and vertical guided with an air bearing. An excitation signal (low pass filtered white noise) was generated and applied to two of the piezoelectric stacks. Both the voltage generated by the third piezoelectric stack and the displacement measured by the encoder were recorded. The two obtained frequency response functions (FRF) are compared with the model in Fig. 7.

The piezoelectric constants describing the conversion from the mechanical domain (force, strain), easily accessible on the model, to the electrical domain (voltages, charges) easily measured can be estimated. With these constants, the match between the measured FRF and the model dynamics is very good (Fig. 7).

The same bench was also used with the struts in order to study the added effects of the flexible joints.



(a) Encoder d_e/V_a.

(b) Force sensor V_s/V_a.

Figure 7: Measured Frequency Response functions compared with the Simscape model. From the actuator stacks voltage to the encoder (a) and to the force sensor stack (b).

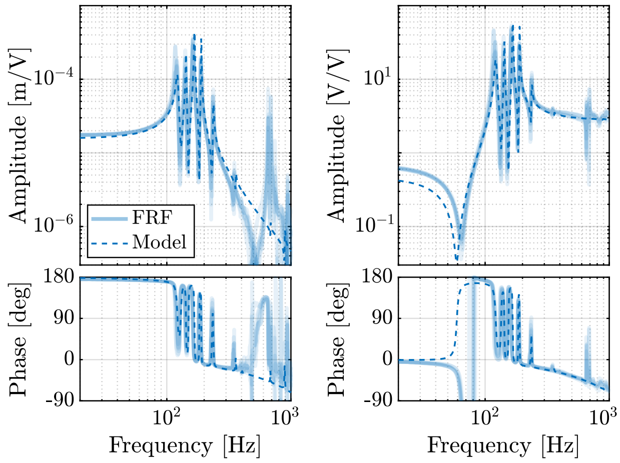
Nano-Hexapod

After the nano-hexapod has been mounted, its dynamics was identified by individually exciting each of the actuators and simultaneously recording the six force sensors and six encoders signals. Two 6 by 6 FRF matrices were computed. Their diagonal elements are shown in Fig. 8 and compared with the model.

In Fig. 8a one can observe the following modes:

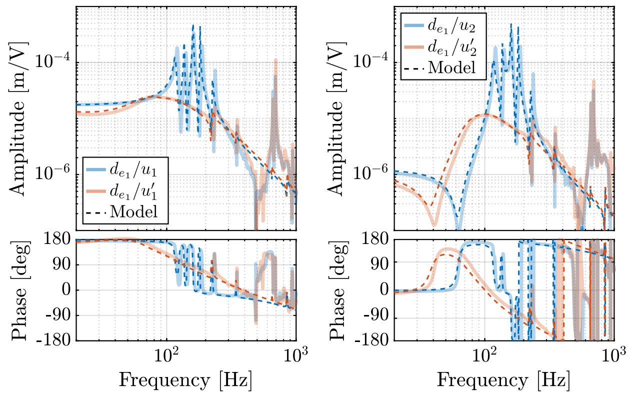
- From 100 Hz to 200 Hz: six suspension modes.
- At 230 Hz and 340 Hz: flexible modes of the APA, also modeled thanks to the flexible model of the APA.
- At 700 Hz: flexible modes of the top plate. The model is not matching the FRF because a rigid body model was used for the top plate.

The transfer functions from the actuators to their "collocated" force sensors have alternating poles and zeros as expected (Fig. 8b). IFF was then applied individually on each pair of actuator/force sensor in order to actively damp the suspension modes. The optimal gain of the IFF controller was determined using the model. After applying the active damping technique, the 6 by 6 FRF matrix from the actuator to the encoders was identified again and shown in Fig. 9. It is shown that all the suspension modes are well damped, and that the model is able to predict the closed-loop behavior of the system. Even the off-diagonal elements (effect of one actuator on the encoder fixed in parallel to another strut) is very well modeled (Fig. 9b).



(a) Encoder d_{e_i}/u_i.   (b) Force sensor V_{s_i}/u_i.

Figure 8: Comparison of the measured Frequency Response functions (FRF) with the Simscape model. From the excitation voltage to the associated encoder (a) and to the associated force sensor stack (b).



(a) Diagonal term.   (b) Off-Diagonal term.

Figure 9: Transfer functions from actuator to encoder with (input u) and without (input u') IFF applied.

CONCLUSION

The mechatronics approach used for the development of a nano active stabilization system was presented. The extensive use of models allowed to design the system in a predictive way and to make reasonable design decisions early in the project.

Measurements made on the nano-hexapod were found to match very well with the models indicating that the final performances should match the predicted one. The current performance limitation is coming from the flexible modes of the top platform, so future work will focus on overcoming this limitation.

This design methodology can be easily transposed to other complex mechatronics systems and are foreseen to be applied for future mechatronics systems at the ESRF.

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