WP-5 Simulation of massively controlled space telescopes

POLITECNICO DI MILANO

Dipartimento di Ingegneria Aerospaziale

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Introduction

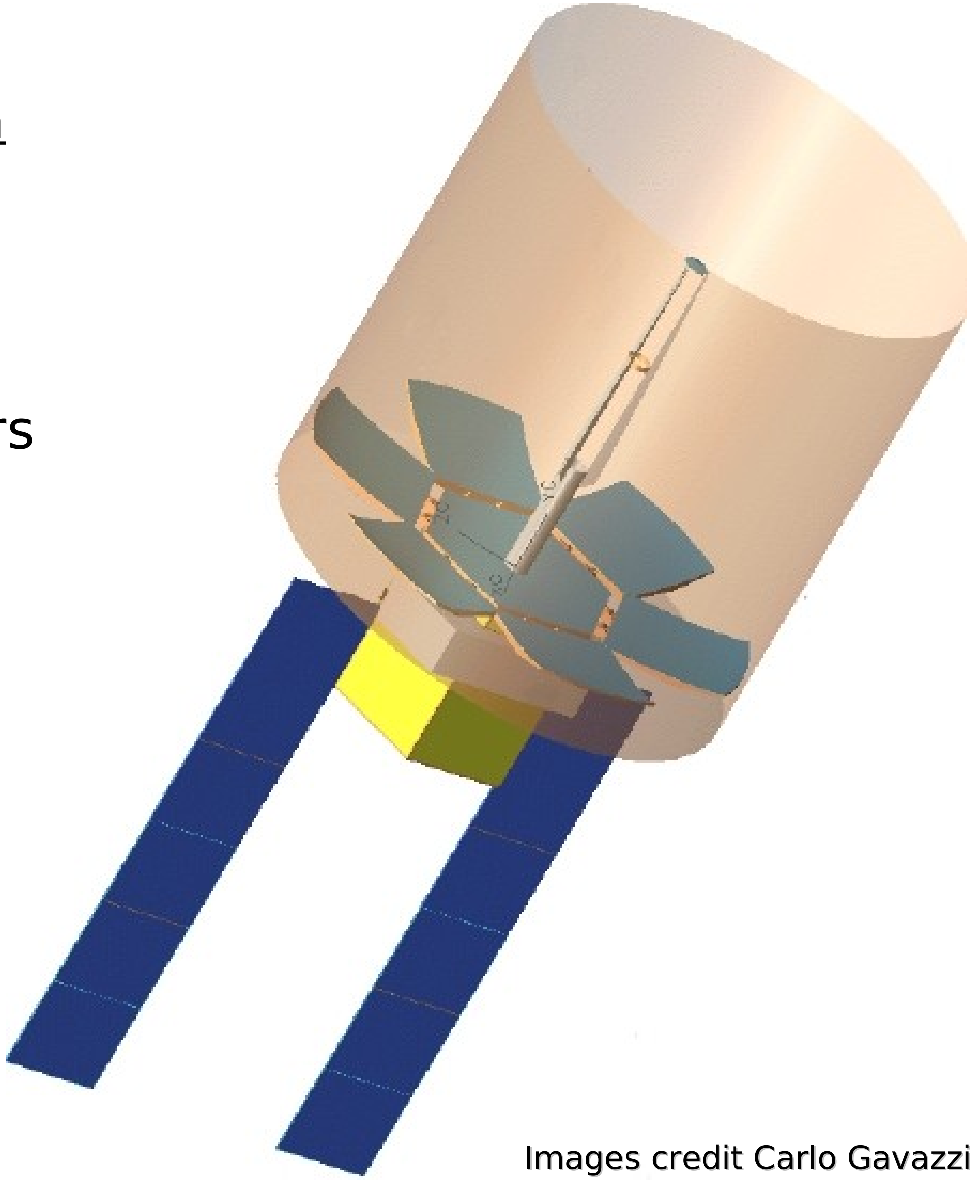
Active mirror technology on ground telescopes → updates → Space telescopes application

The active mirrors should correct:

- manufacturing mirror imprecisions
- structural thermic deformations
- positioning errors after the orbital mirrors deployment

Partnership

- Carlo Gavazzi space Spa
    - Structural design
- A.D.S. International
    - Active mirror actuators
- DIAPM
    - Active mirror control

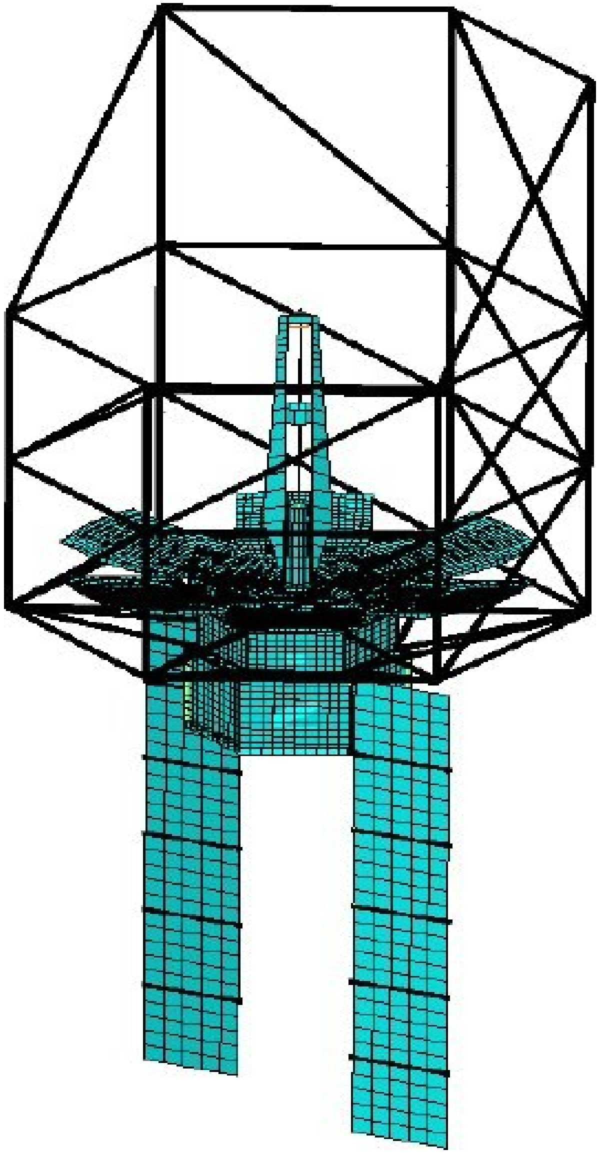


Images credit Carlo Gavazzi Space

Outline

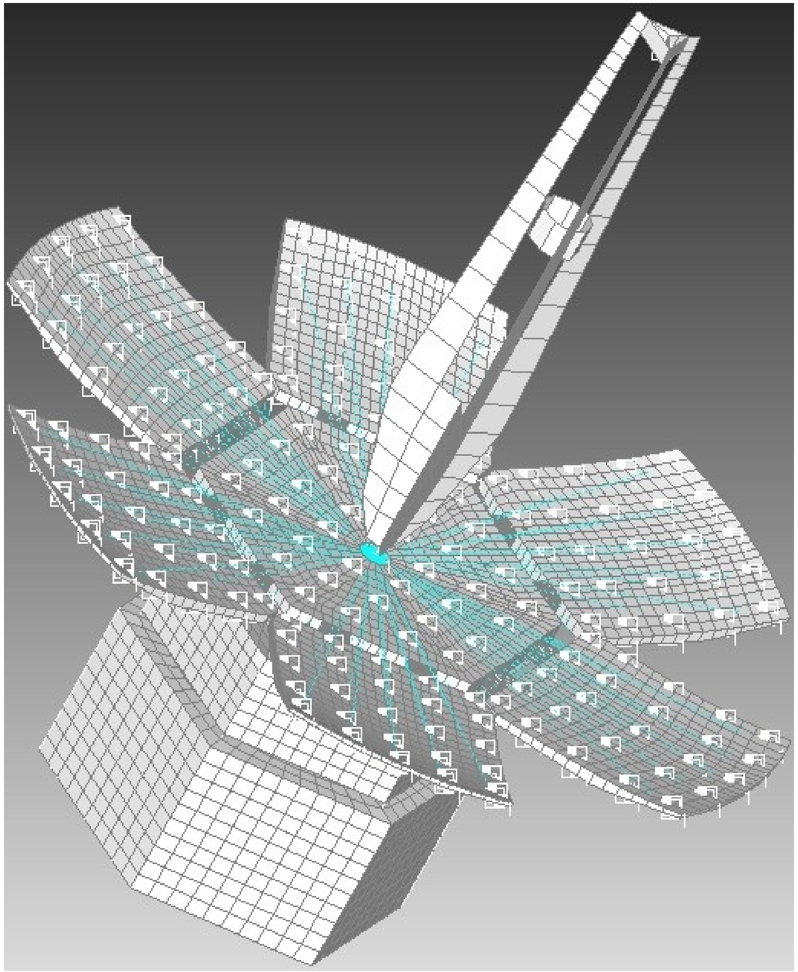
- Problem description
- Model set-up
- Static high frequencies recovery through residualization
- Control law and dynamic feed-forward
- Control law tuning
- Stiffness matrix identification
- Simulation results

Model description



No Baffle

No Power System



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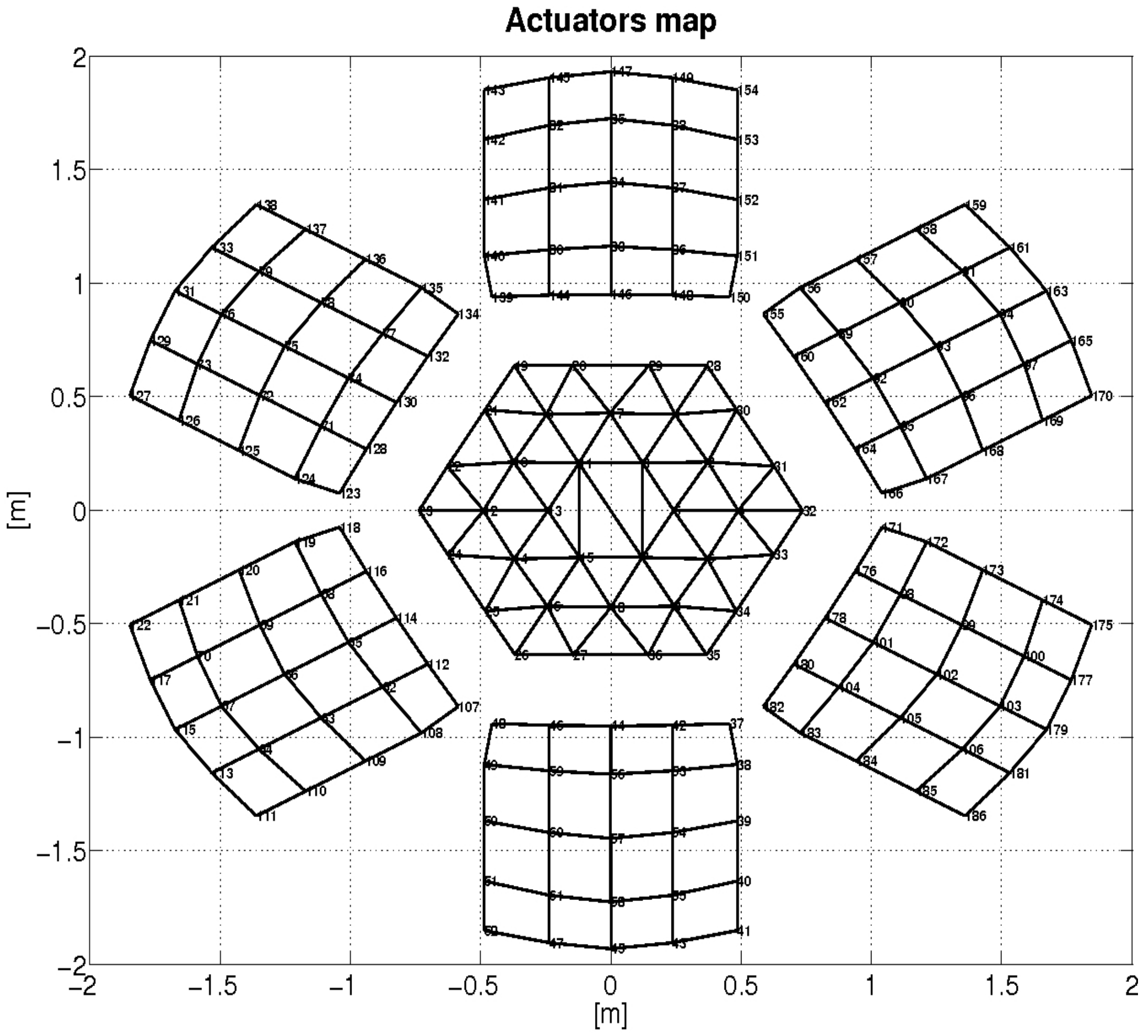
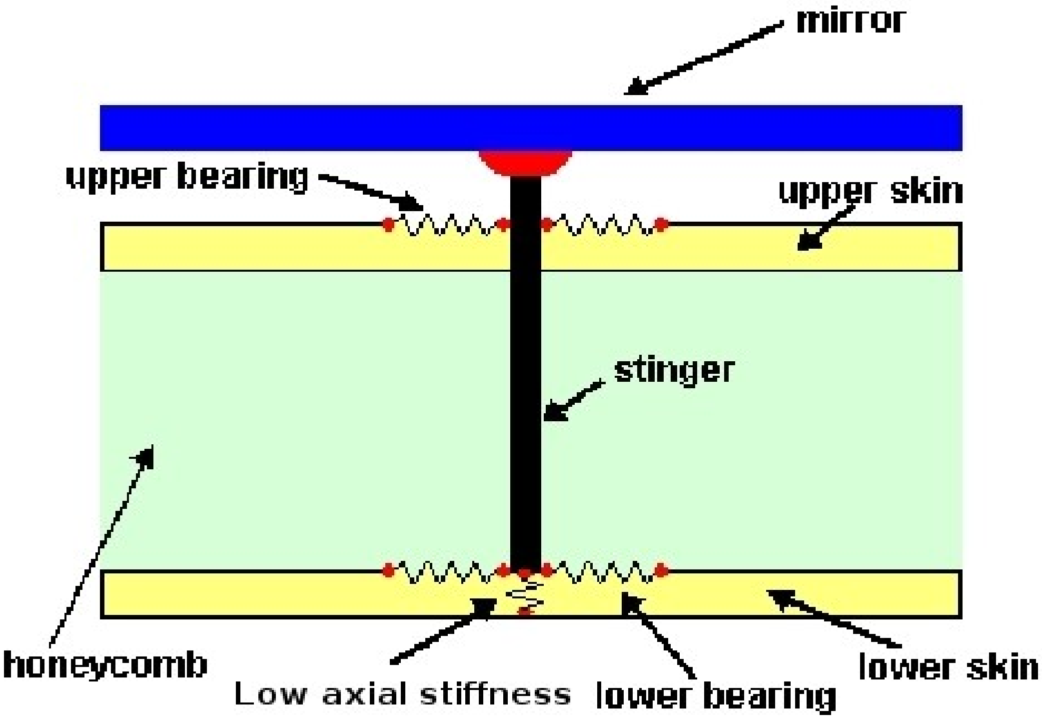
Model description

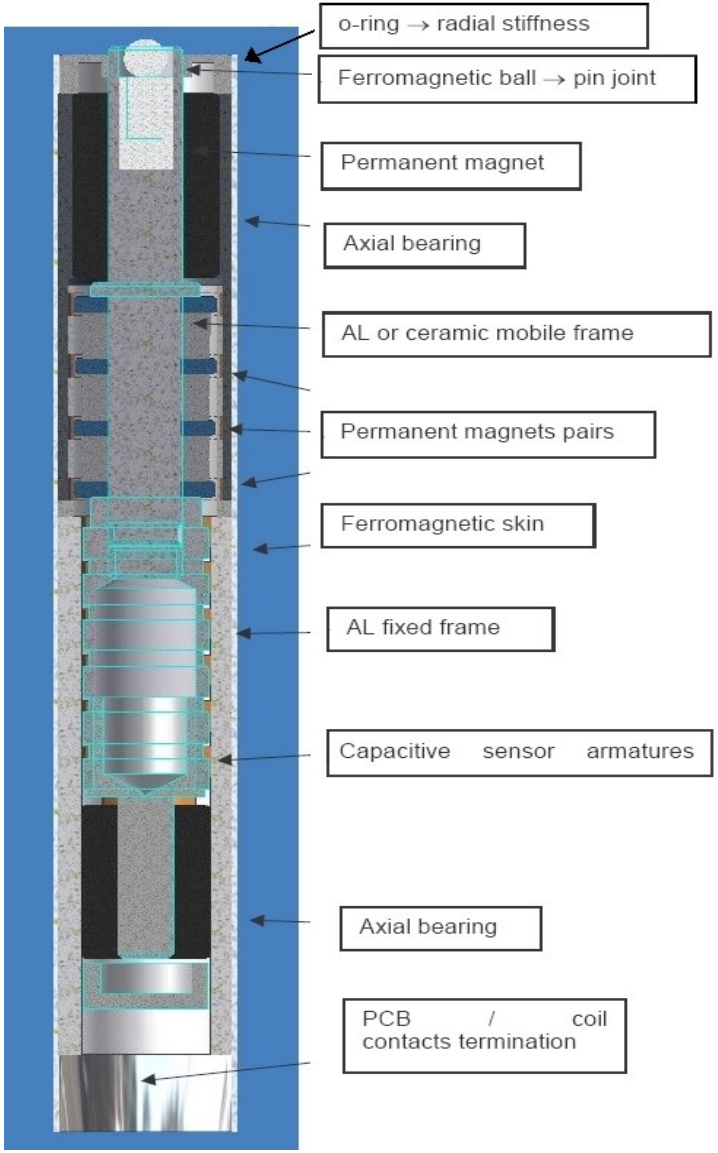


- 186 co-located actuators-sensors pairs
- 7 mirrors
  - 6 petals mirrors (25x6 actuators)
  - 1 central mirror (36x1 actuators)

Model description

- All actuators direction along satellite spin axis
- Mirror-actuator connection through 3D hinges
- Very low fictitious axial control force to remove mirrors rigid displacements

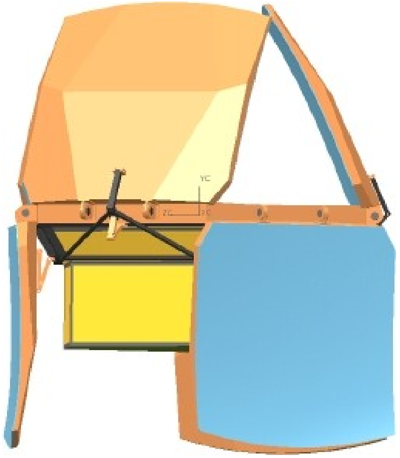




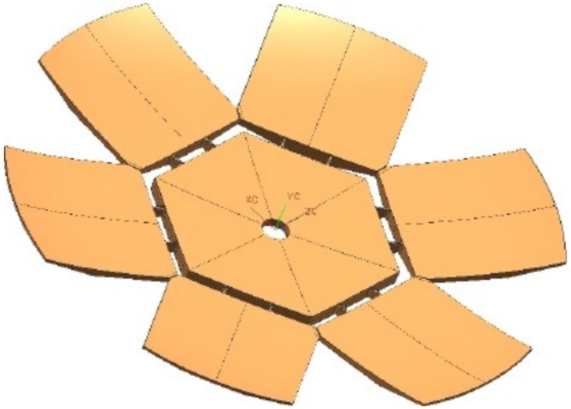
Images credit Carlo Gavazzi Space

Model description

Launch configuration

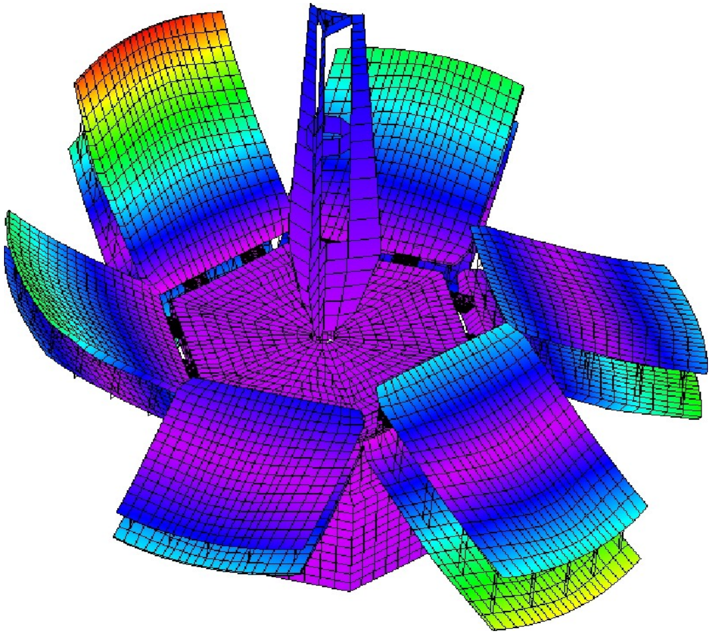


Deployed configuration



Images credit Carlo Gavazzi Space

First petals elastic modal shape



- ➢Modal shape difficult to observe
- ➢Modal shape difficult to control

The petals hinges stiffness must provide a modal frequency of at least 20 Hz

Simulation steps

- Finite elements structure model
- First order filters to approximate the actuators and sensors dynamic
- Modal reduction of dynamic model
  - 3000 modes
  - frequency range 0-1000 Hz (good model description, spillover check)
  - satellite rigid movements removed
- Control forces application through the control law
- Addition of disturbances
  - actuators and sensors noises
  - quantization errors
- Integration of modal equations system
  - transition matrix
  - Runge-Kutta algorithms
- Take into account delays
  - A/D/A conversion
  - computational time

High frequencies recovery

Static high frequencies recovery through residualization technique

↓

Correct forces values once the steady state position is reached

(No reduced modal base approximation)

$$S = \boxed{U_{low\,f}\, q_{low\,f}} + \boxed{\left(\overline{K}^{-1} - K_{low\,f}^{-1}\right) F}$$

Classical modal displacements recovery through a reduced base.

High frequencies recovery through the difference between the real FEM system flexibility and the approximated modal flexibility.

Control law

Control force

$$F^{c} = F^{c}_{PD2} + F^{c}_{Feed}$$

PD2 feedback uncoupled contribution

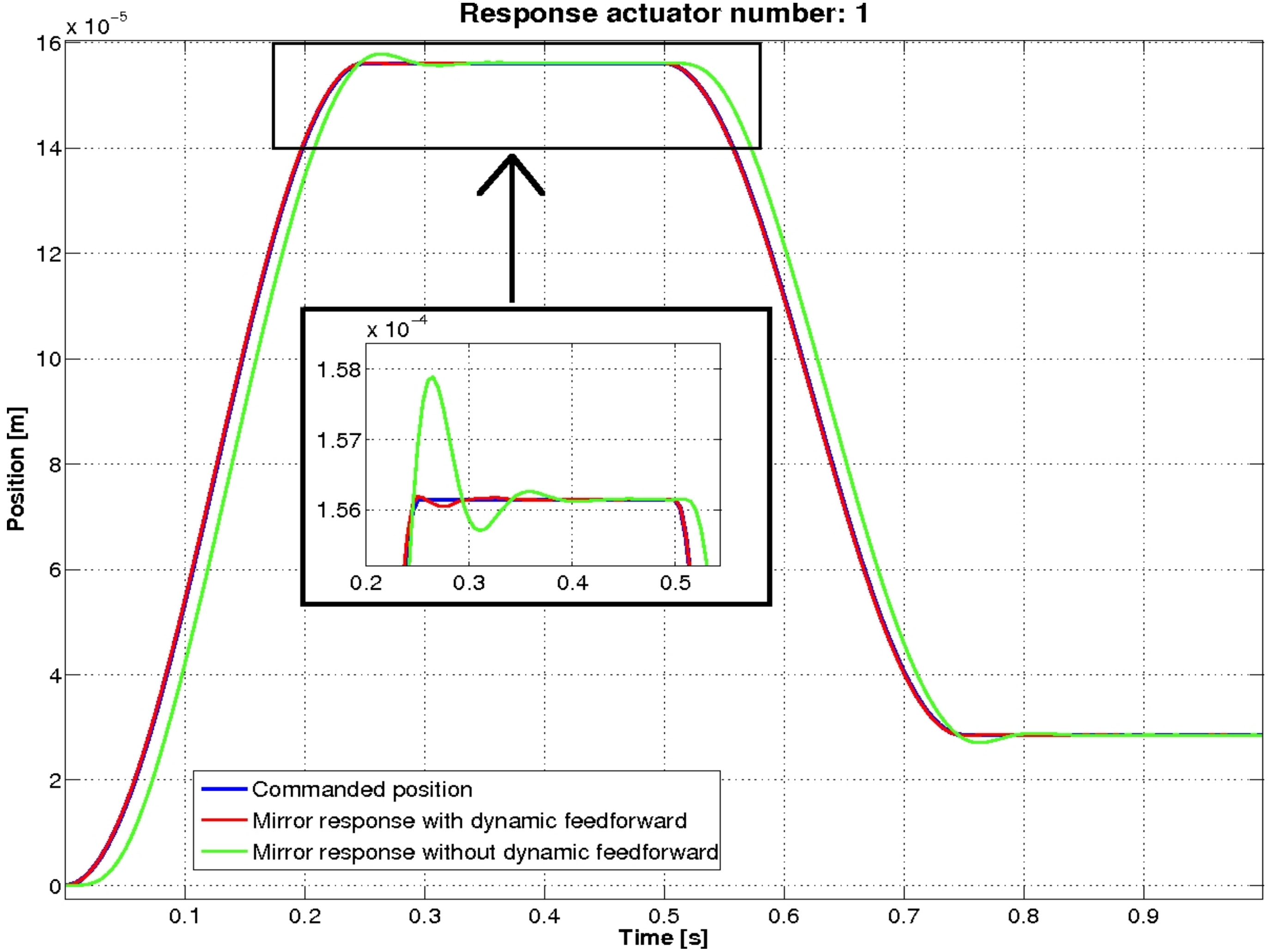
$$F^{c}_{PD2} = K_{P}\left(p^{req} - p^{mes}\right) + K_{Da}\dot{p}^{mes} + K_{D2a}\ddot{p}^{mes}$$

Feed-forward open loop coupled contribution

$$F_{Feed} = \underbrace{\bar{F} + K_{Id}\left(p^{req} - \bar{p}\right)}_{\textbf{Static feed-forward}} + \underbrace{K_{Db}\dot{p}^{req} + K_{D2b}\ddot{p}^{req}}_{\textbf{Dynamic feed-forward}}$$

Control law

Comparison of control performances with and without dynamic feed-forward



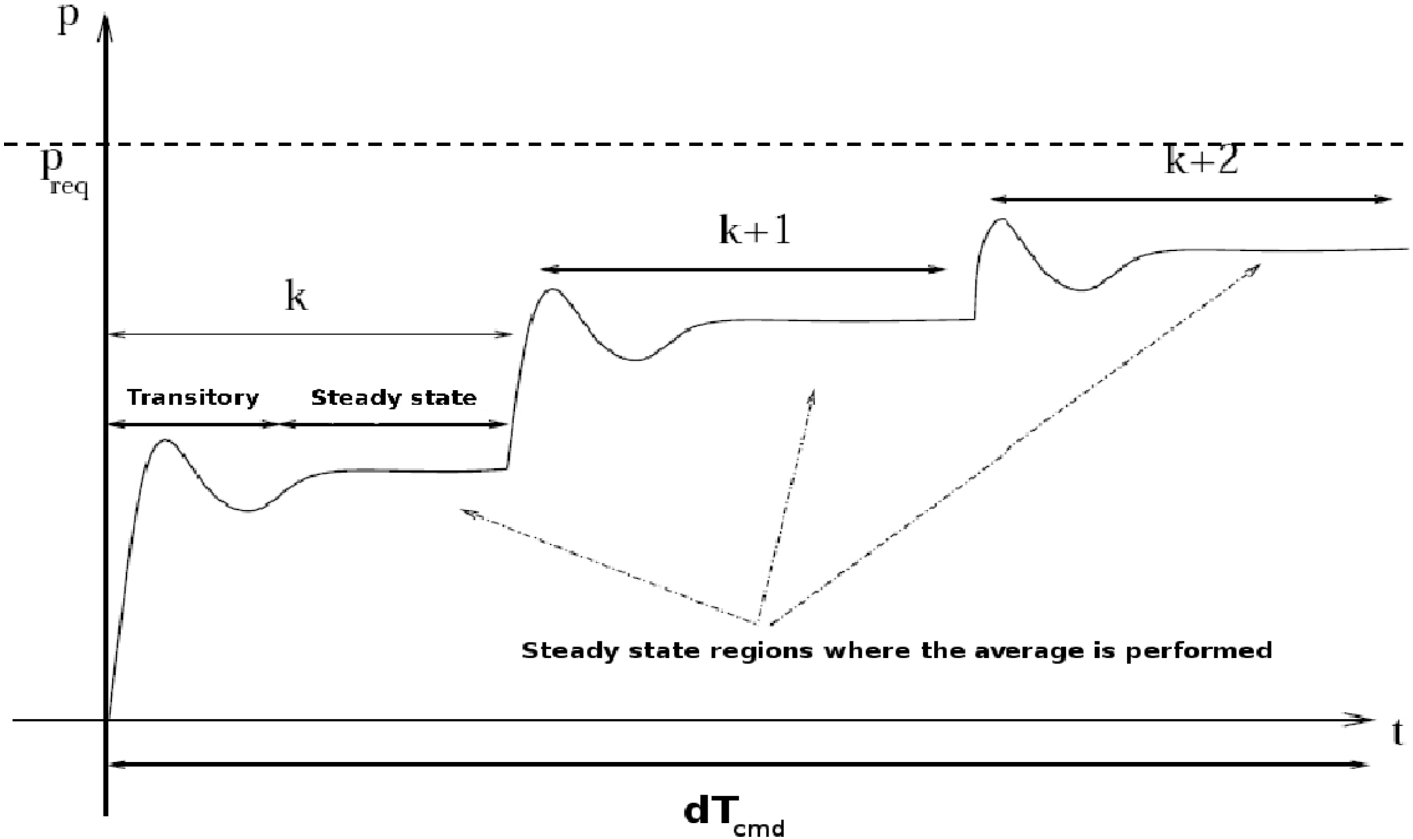
Control law

Control parameters resume

Control frequency	4000 Hz	2800 Hz	1600 Hz
Command frequency	2 Hz	2 Hz	1Hz
Actuators filter frequency	500 Hz	500 Hz	300 Hz
Sensors filter frequency	500 Hz	500 Hz	300 Hz
Derivation filter frequency	500 Hz	500 Hz	300 Hz
Force application delay	0.5 control step length	0.5 control step length	0.5 control step length
K_P	1000	700	350
K_{Da}	12	10	5
K_{D2a}	0.0008	0	0
K_{db} (petals)	5	5	5
K_{D2b} (petals)	0.12	0.12	0.12
K_{db} (central)	12	12	12
K_{D2b} (central)	0.2	0.2	0.2

Control law

Sub-stepping technique



Through sub-steps it is possible to demonstrate the control convergence to the final commanded position even with a roughly estimated stiffness matrices K_{ld}

Control law

System characteristics:

- Low passive damping (only the structural one, no air contribution)
- Control frequency as low as possible to save power consumption and limit possible heat introduction.

- Low PD2 gains to avoid instability.

- Low control damping.
- Poor dynamic controller performances.

- The application of sub-stepping technique requires high dynamic performances to allow the achievement of a steady state position into the sub-step length. So it is not possible to use sub-stepping and the control precision in reaching the final requested position implies a good stiffness identification.

Identification

The identification is performed by retrieving from the local control units a set of averaged position and force commands to set up a least squares system of equation.

Sensible Parameters

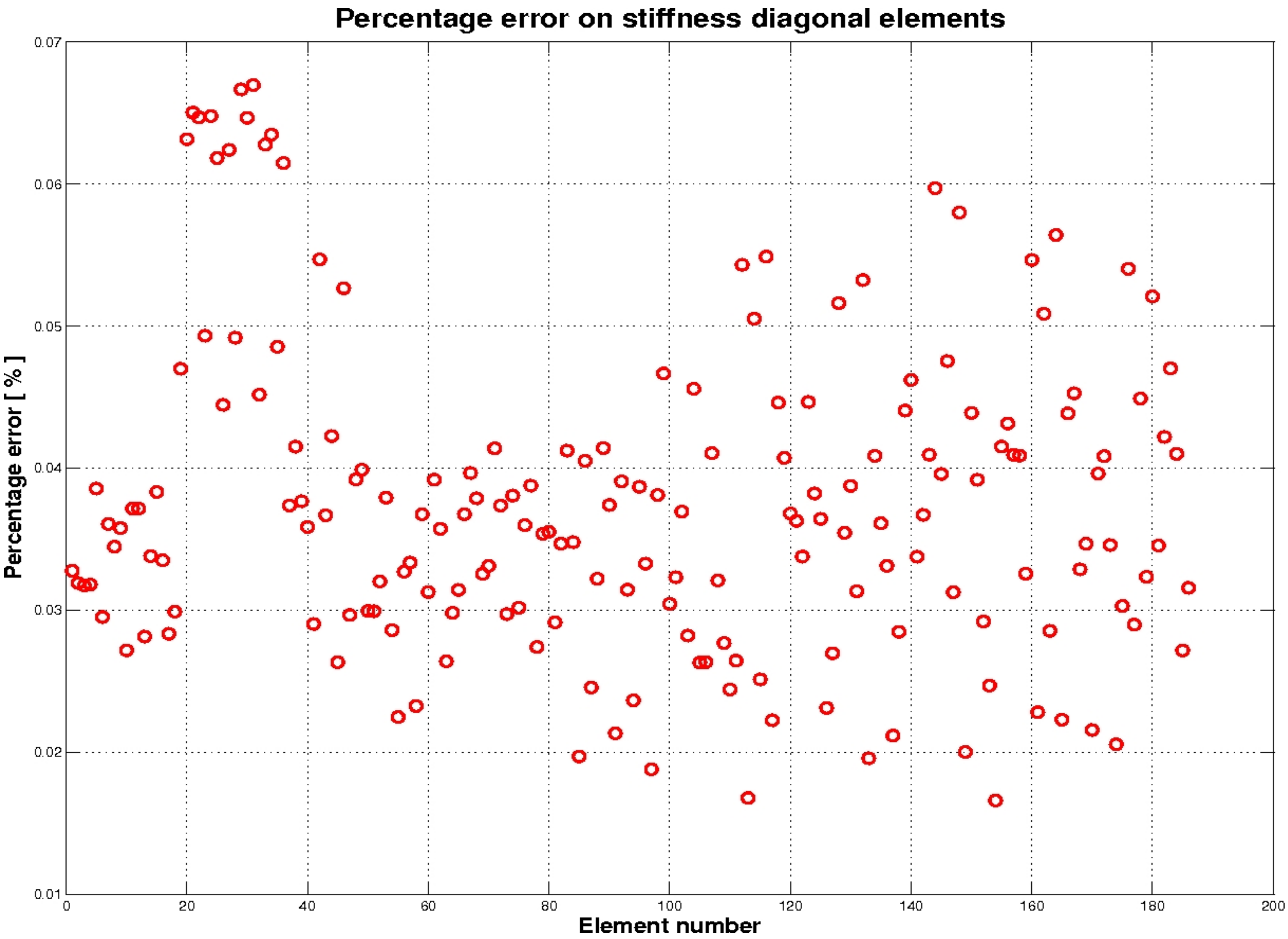
- Actuator and sensor noise levels
- Quantization error entity
- Command step length (link with dynamic system performances)
- Number of command steps of the identification history
- Forces and position range obtained with the identification history respect to noises and errors range

Simulation code

Simulation of real identification history (time expensive)

Static response calculation supposing the controller capability to reach the steady state position (time cheap)

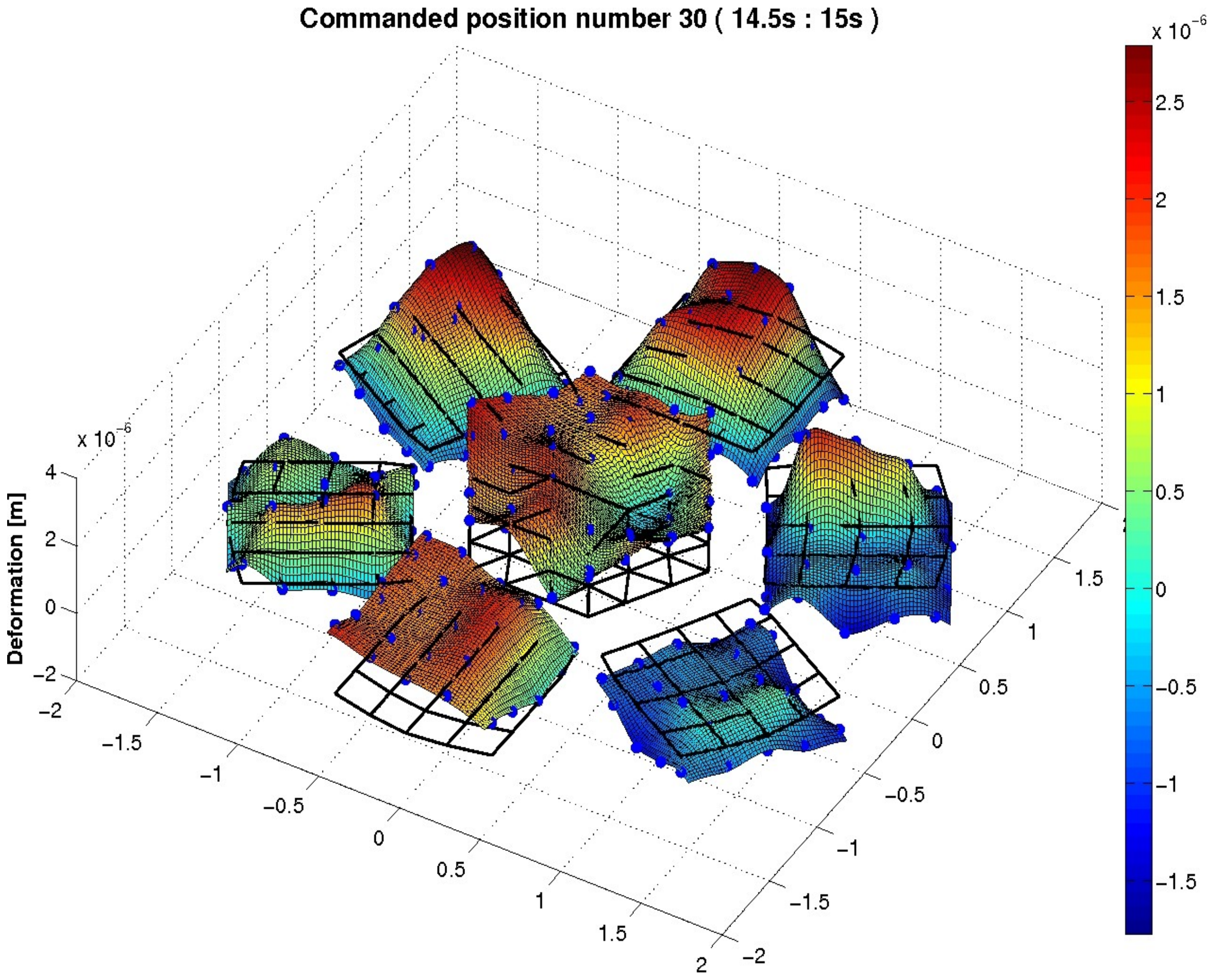
Identification



Simulation results

Simulation 1

- Random history
- Deformations range: +/- 2E-6 m



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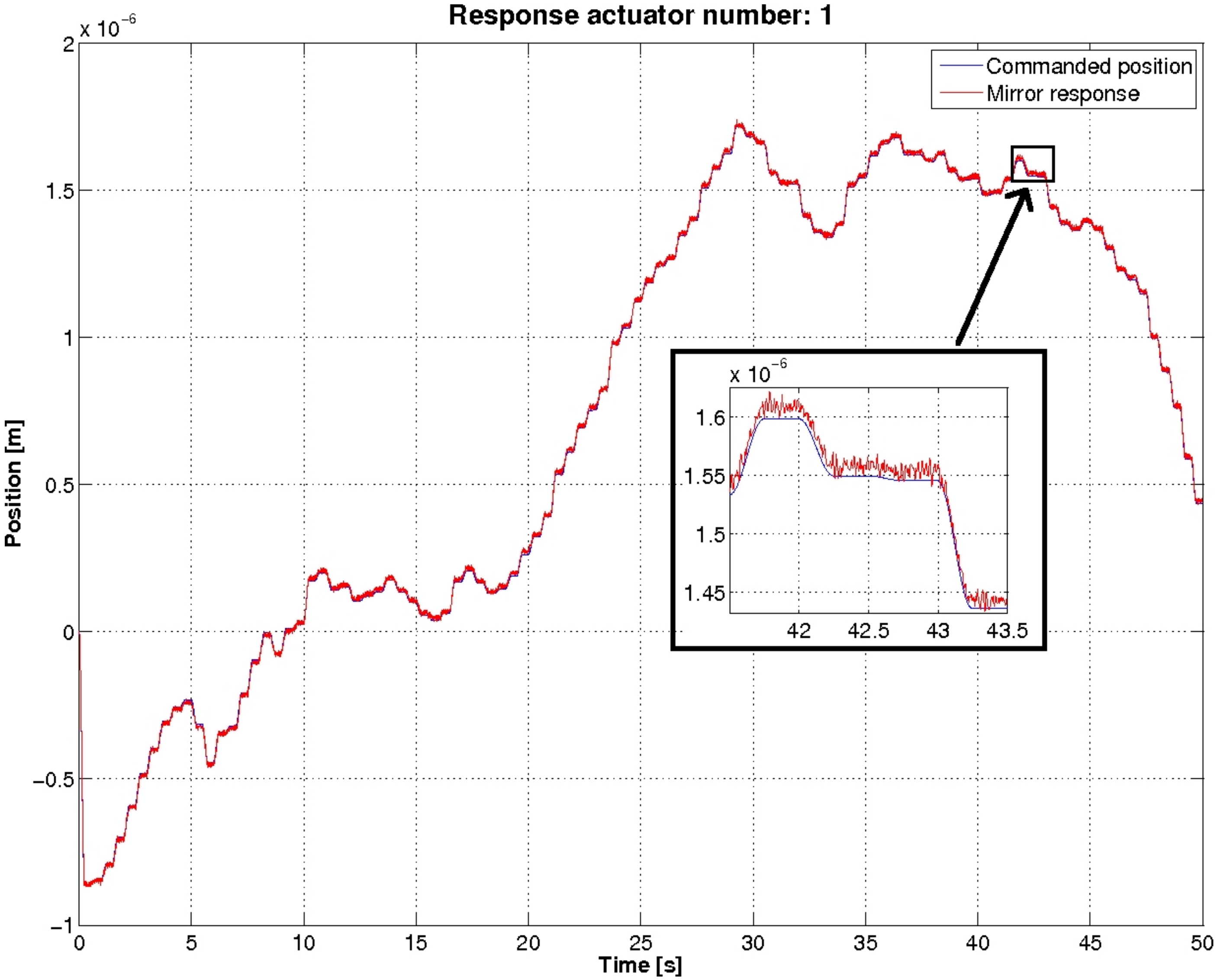

Simulation results

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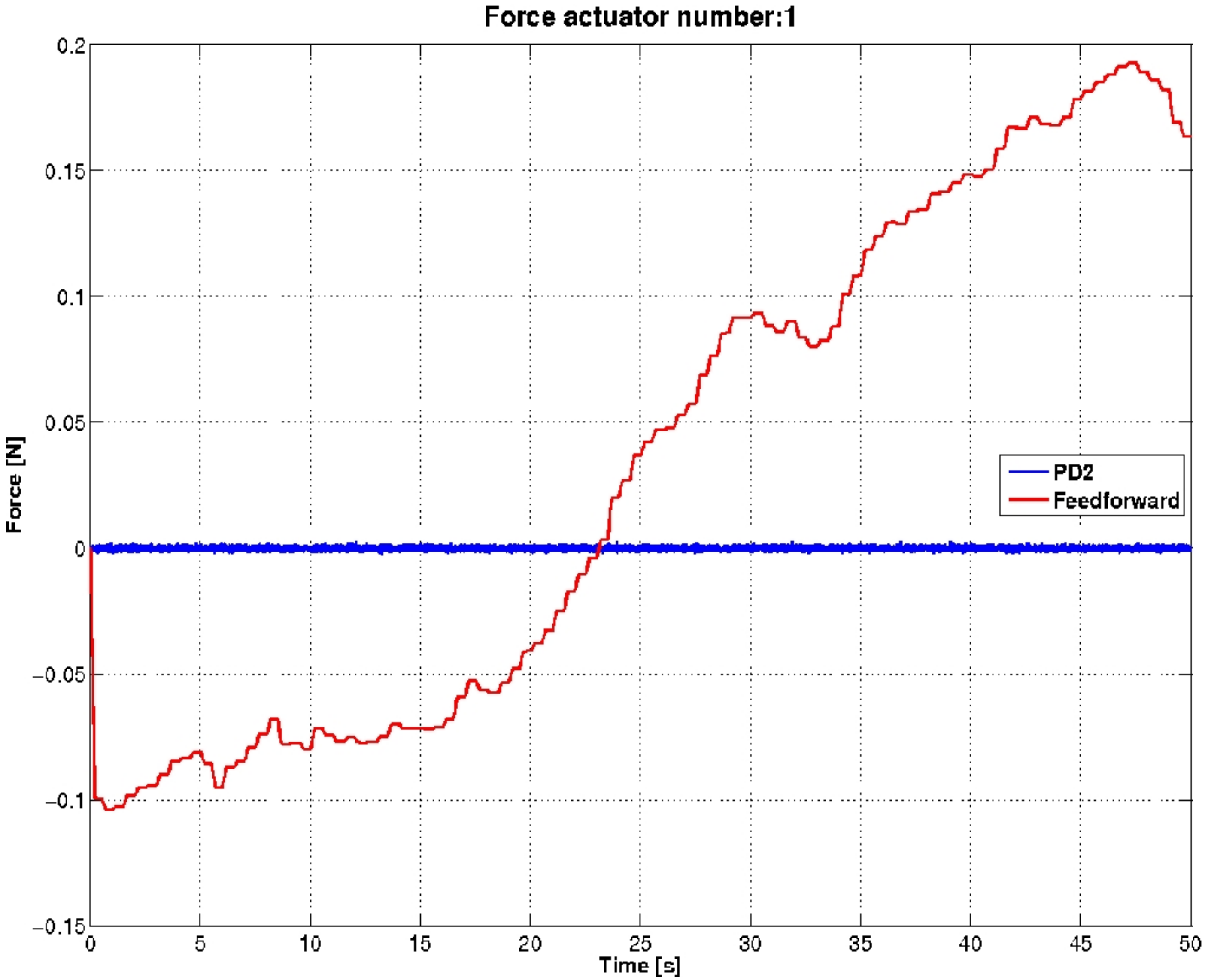
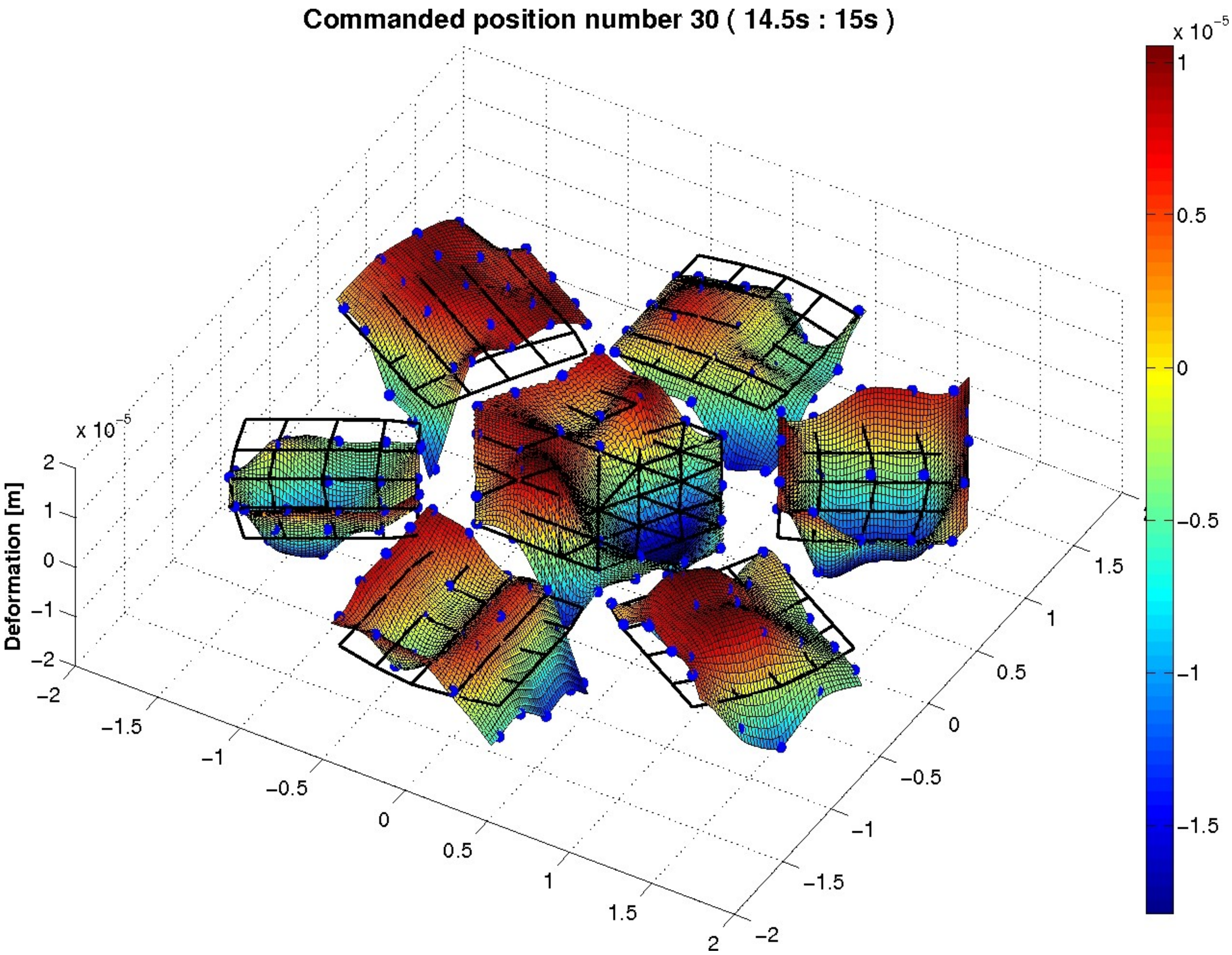


Simulation results

Simulation 2

- Random history

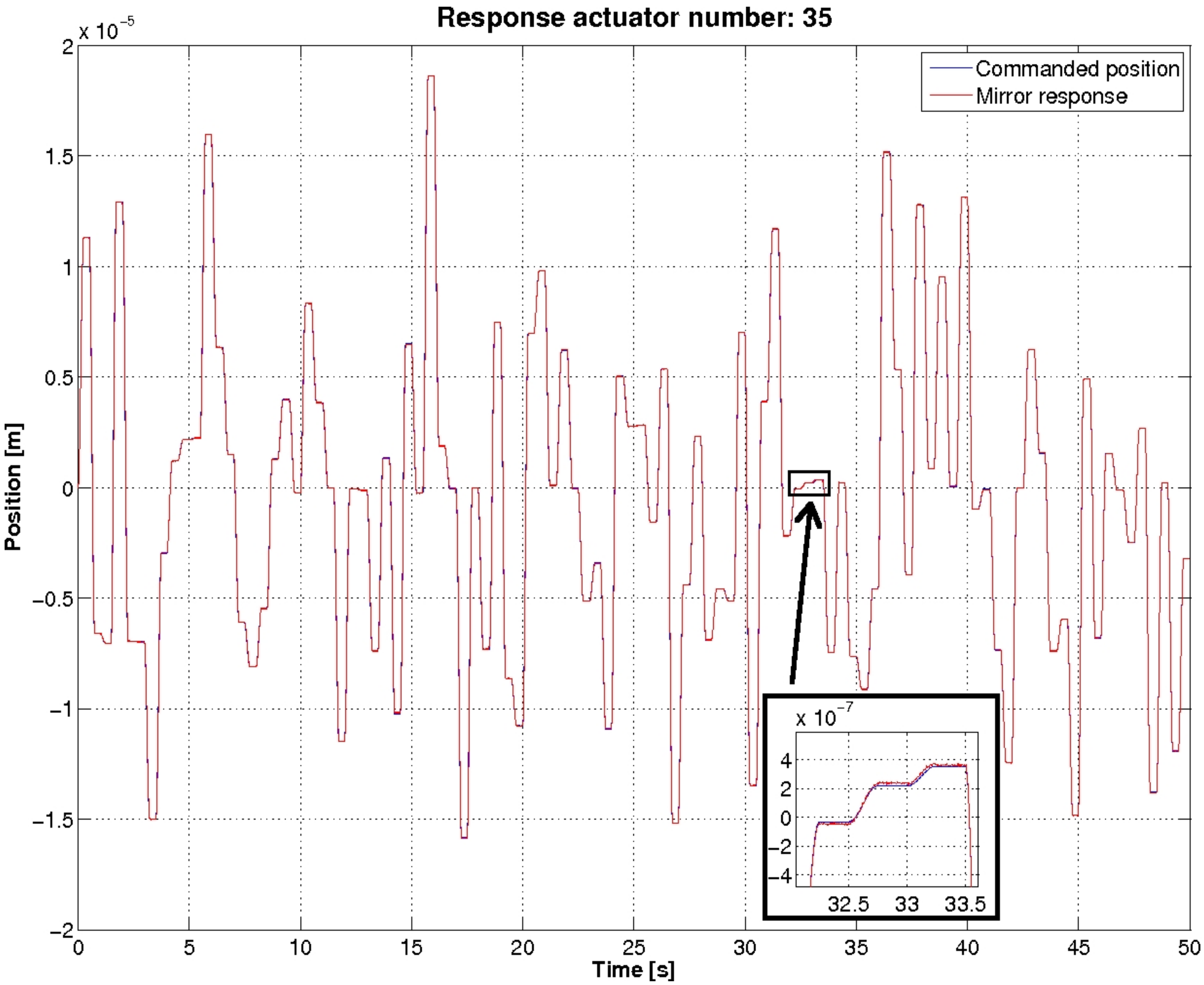
- Deformations range: +/- 25E-6 m



Simulation results

Simulation 2

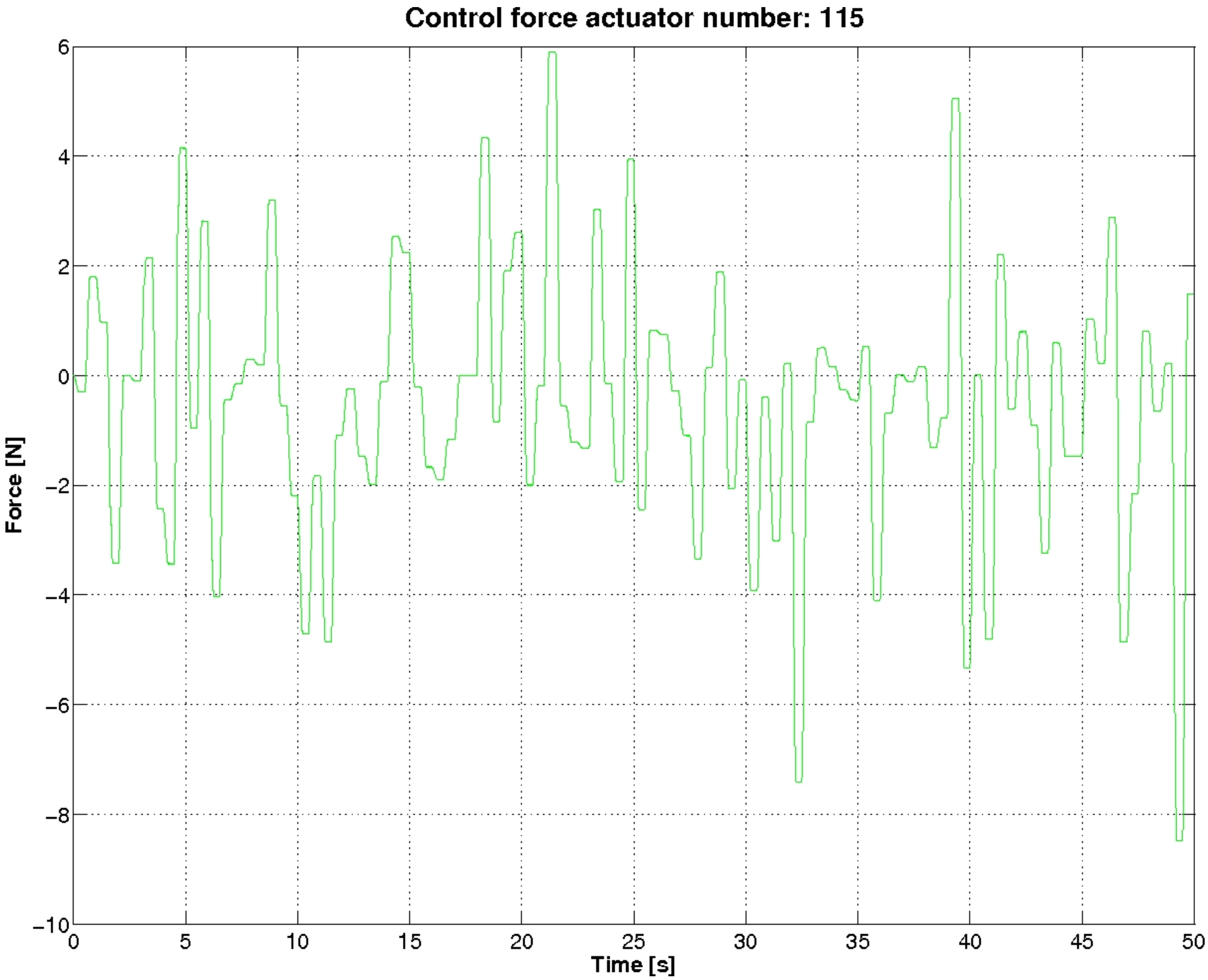
- Random history
- Deformations range: +/- 25E-6 m



Simulation results

Simulation 2

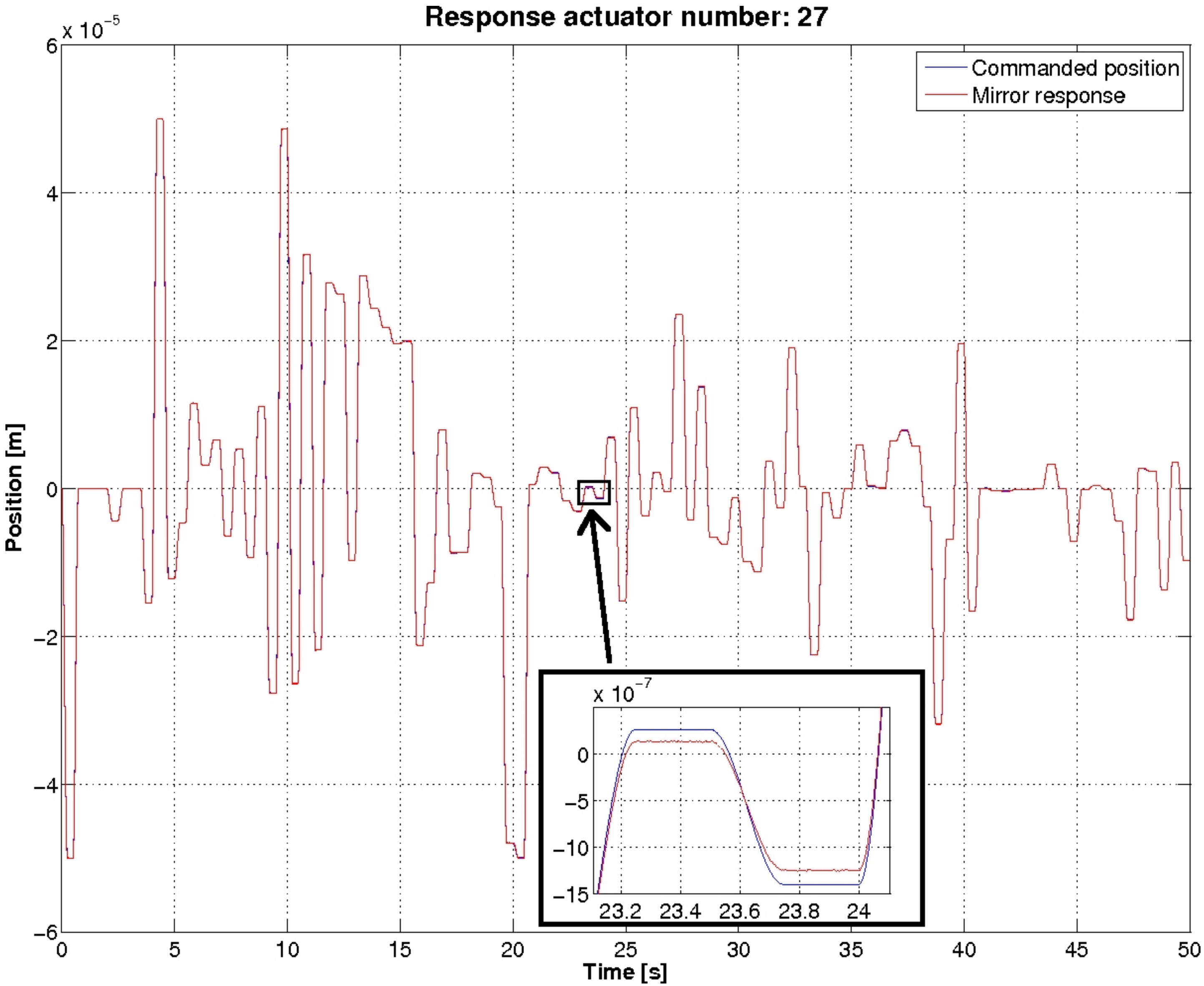
- Random history
- Deformations range: +/- 25E-6 m



Simulation results

Simulation 3

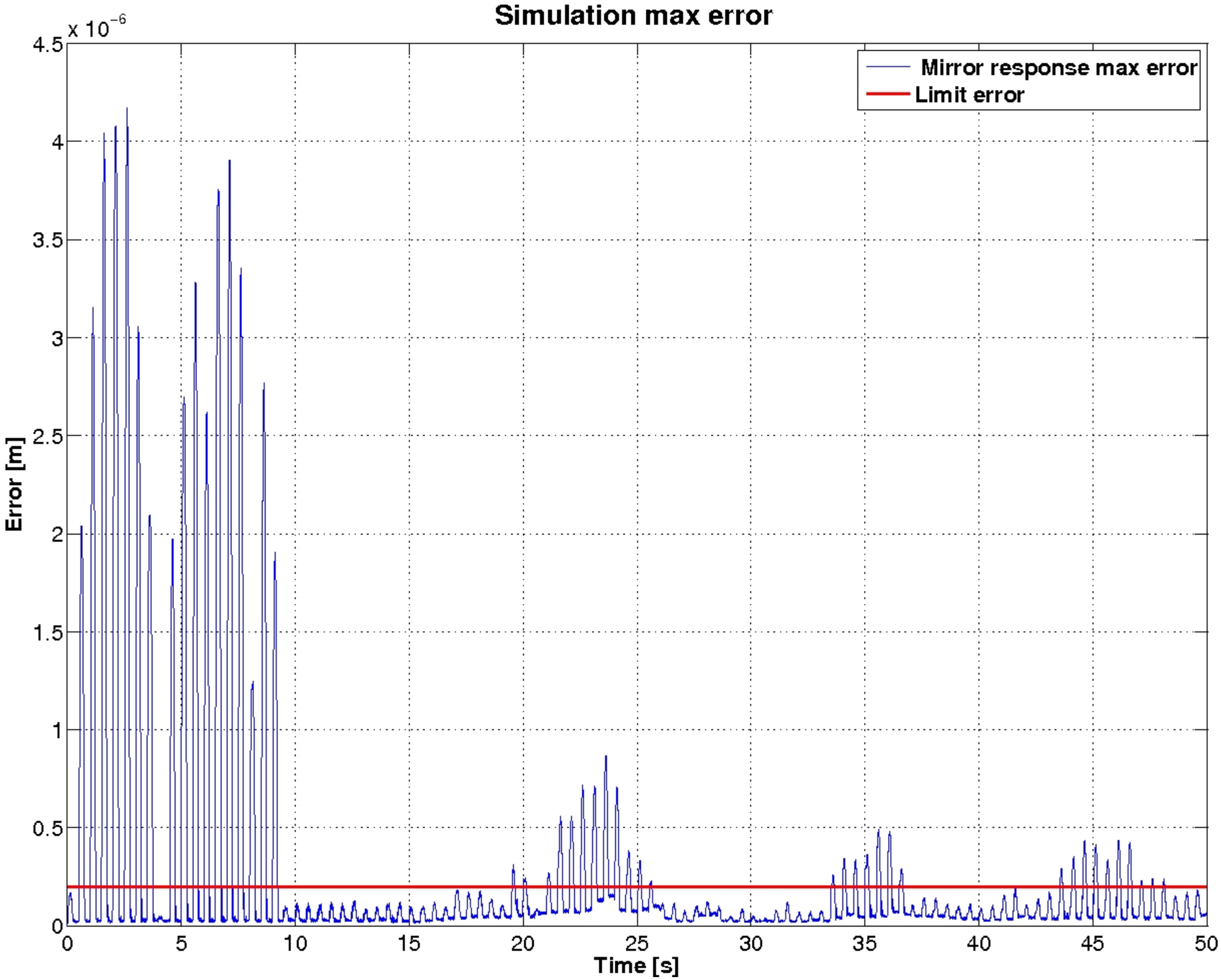
- Modal change history
- Deformations range:
  +/- 50E-6 m



Simulation results

Simulation 3

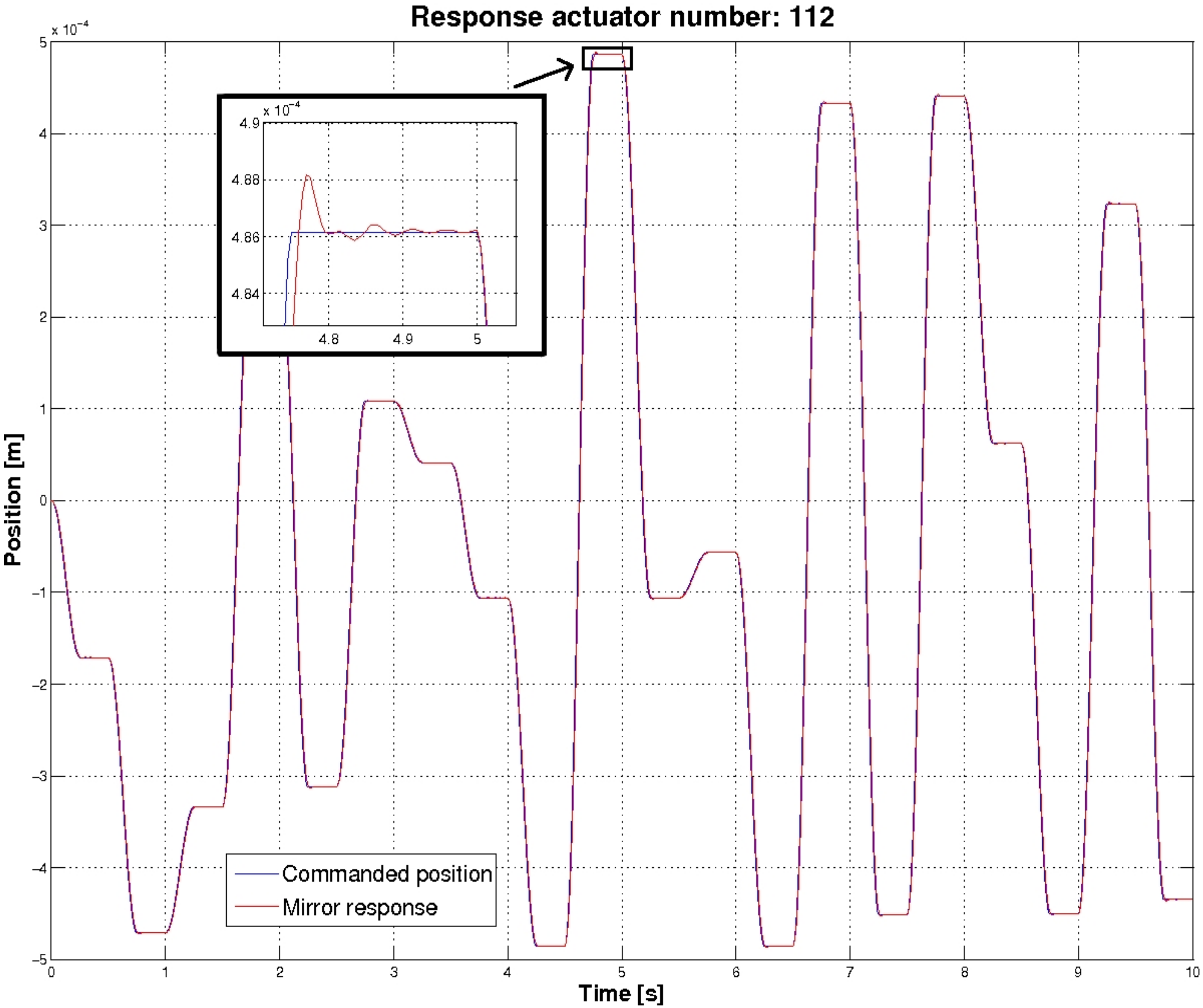
- Modal change history
- Deformations range: +/- 50E-6 m



Simulation results

Simulation 4

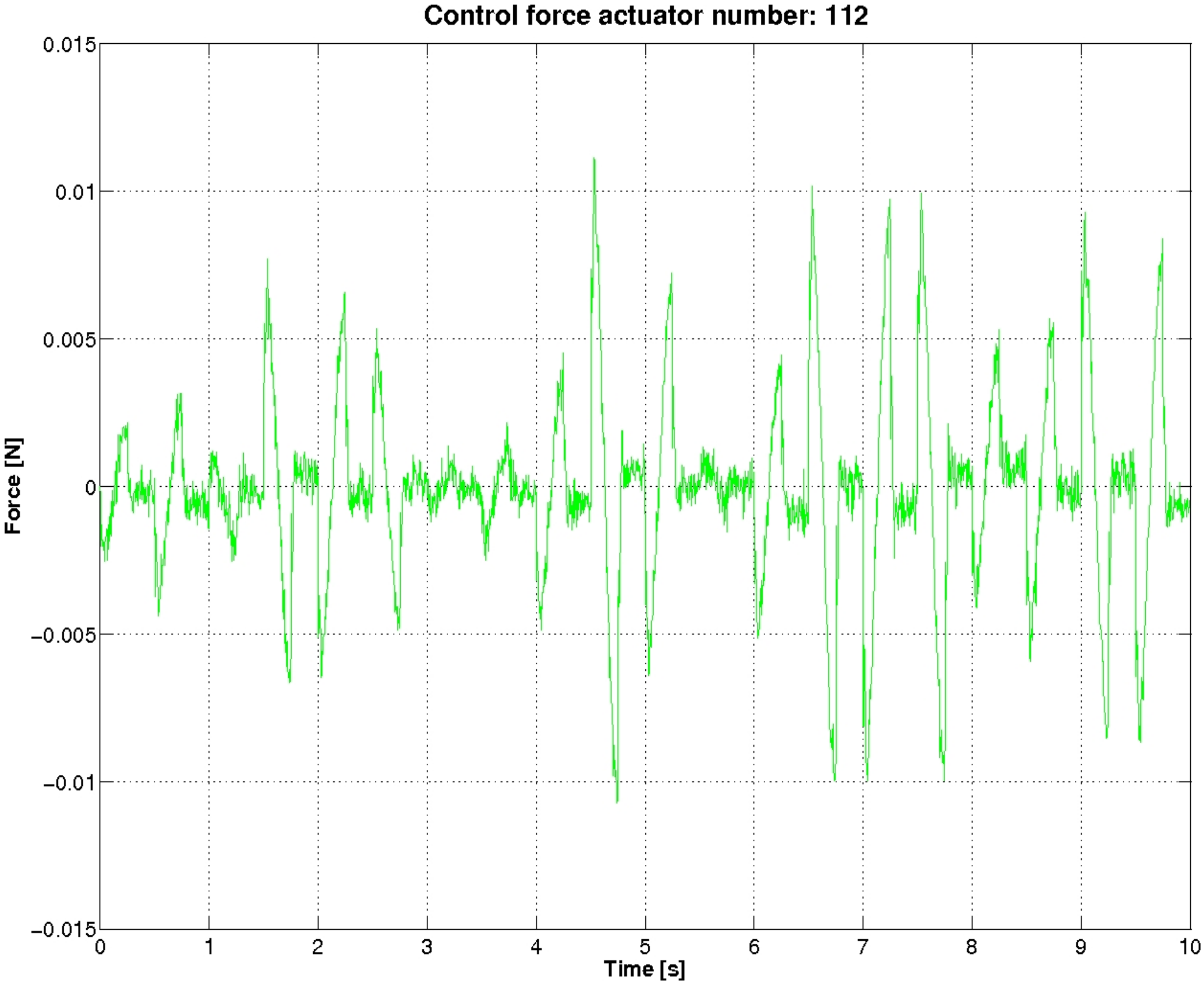
- Rigid mirrors displacement history
- Displacements range: +/- 0.0005 m



Simulation results

Simulation 4

- Rigid mirrors displacement history
- Displacements range: +/- 0.0005 m

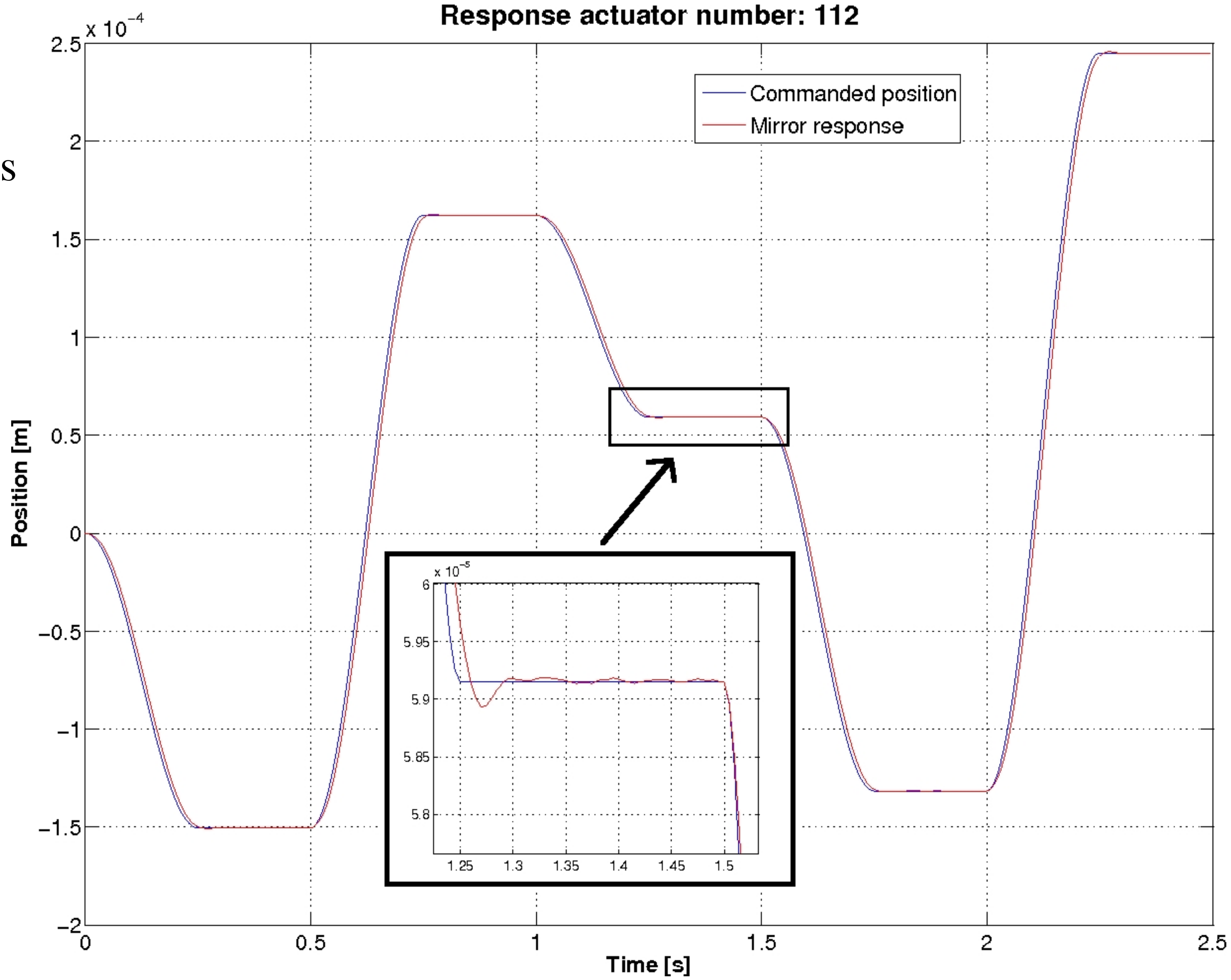


Simulation results

Simulation 5

- Rigid movements + deformations history

- Displacements range: +/- 0.00025 m



Conclusions

- The controller allows the correct achievement of the final commanded positions and satisfies the precision tolerance of +/-200 nm imposed by specification with the following histories:
  - small random deformations (range +/- 2E-6 m)
  - wide random or modal shapes deformations (range +/-50E-6 m)
  - pure rigid motions (range +/-0.0005 m)
  - rigid motions coupled with deformations

- With a command frequency of 2 Hz it is requested a controller frequency of 4000 Hz to assure a good performance with a sufficient safety margin. This frequency is higher than the 500 Hz of initial specifications.

- The forces needed to obtain wide deformations exceed the saturation level (+/-0.2 N), but the actual mirror-actuator connections can add stiffness, moreover the imposed deformation shapes (modal or random) could penalize the force values more than the real one.

- The support structure stiffness play a key role to achieve good controller performances. In particular the petals connection with the central satellite body must be stiff enough to avoid dangerous interaction between mirror rigid motions and petals first elastic modal shapes, that are difficult to observe and to control.

Future developments

- Try different solutions for mirror-actuator connections, and check the resulting control force values and mirrors rigid movements capabilities.

- Update the structural model to improve control performances, and perform simulations taking into account possible disturbances linked with baffle and power system units.

- Evaluation of the satellite attitude control system coupled to the mirrors control to avoid negative interaction.