INVESTIGATION OF ACTIVE DETUMBLING SOLUTIONS FOR DEBRIS REMOVAL

DETUMBLING Final Presentation

18-07-2017

AGENDA

14:00-14:05:   **Project Motivation**
14:05-14:10:   **Project Overview**
14:10-14:25:   **Survey of Detumbling Strategies & Mission baseline**
14:25-14:45:   **GNC design – Guidance**
14:45-15:30:   **GNC design – Control synthesis & Analysis**
15:30-15:45:   **Coffee break**
15:45-16:15:   **Validation campaign – results**
16:15–16:30:   **Conclusions**
16:30   **Questions**

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Project Motivation

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MOTIVATION

- Space debris (defunct man-made objects orbiting Earth):
  - Dead satellites
  - Expendable orbital stages
  - Components or mechanisms released during the spacecraft life
  - Fragments from collisions
- Alarming Space Debris expected evolution!
- We deal with non-cooperative targets for capture and de-orbiting
- Problem of tumbling state (in some cases very large angular velocity)
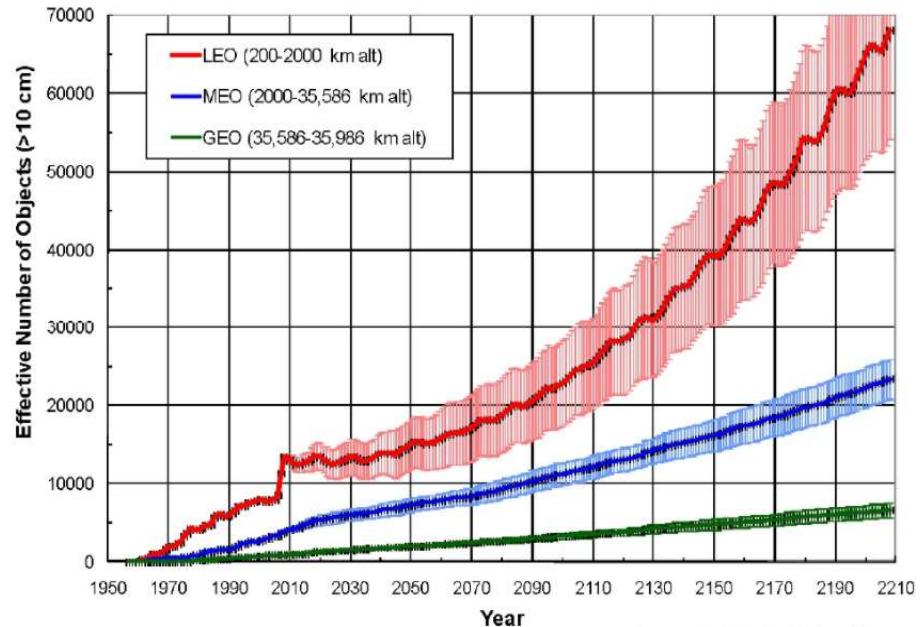
Type	Characteristics	Hazard
Tiny	Not tracked, <1 cm	Shielding exists, damage to satellites may occur
Small	Not tracked, diameter 1 – 10 cm, 98% of lethal objects, ~400.000 objects in LEO	Too small to track and avoid, too heavy to shield against
Medium	Tracked, diameter >10 cm, <2 kg, 2% of lethal objects, ~24.000 objects in LEO, > 99% of mass (incl. large objects)	Avoidance manoeuvres performed most often for this category
Large	Tracked, >2 kg, <1% of lethal objects, > 99% of mass (incl. medium objects)	Primary source of new small debris, 99% of collision area and mass

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DEBRIS DISTRIBUTION

- Debris population
  - Total mass estimated at 6300 tons
  - High concentration at **82-83°** inclination
    - Rocket **upper stages** (large occurrence)
- SSO particularly important for remote sensing and Earth observation
  - SSO **inclination-paired** with 82-83° inclination orbit (orbit precesses in opposite direction)
    - Hightens collision probability
      - Orbit planes may align, leading to head-on collisions

LEO Mass distribution over inclination

Distribution of debris over height and inclination
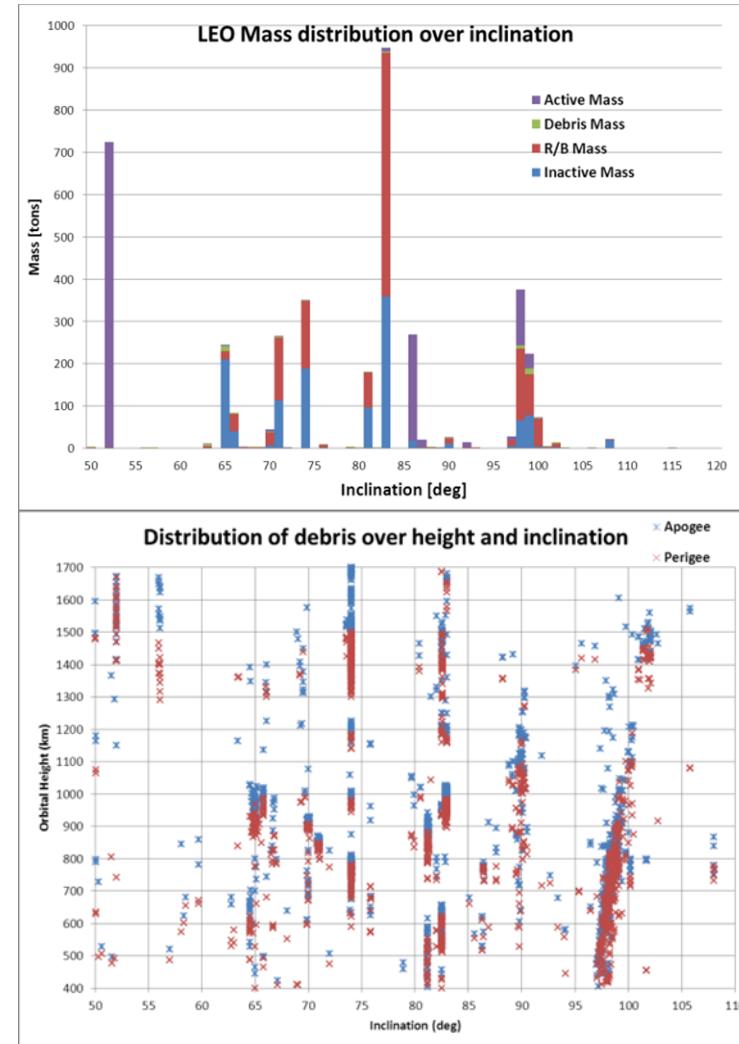
DEBRIS OBJECT SELECTION

Two sets of **debris selection criteria** applied to debris catalogue (for removal):

- European build, high mass, SSO, lifetime greater than 25 years
  - See table →

- Many high mass, similar objects in similar orbits, lifetime greater than 25 years
  - Ariane 4 H-10 upper stages (lifetime < 25 years, m =1780 Kg)
  - 236 COSMOS 3M upper stages (lifetime > 25 years, m=1420 Kg)

Alternative selection criteria (e.g. probability-severity)
= kinetic energy x probability

Sat no.	COSPAR ID	Name	Mass [kg]
27386	2002009A	Envisat	8111
28492	2004049A	Helios IIA	4200
27540	2002048A	Integral	3954
27421	2002021A	SPOT 5	3000
25260	1998017A	SPOT 4	2730.43
25977	1999064A	Helios 1B	2544
23605	1995033A	Helios IA	2514.37
23560	1995021A	ERS-2	2493.56
23715	1995062A	ISO	2475.72
20638	1990049A	ROSAT	2468.78
25023	1997066A	MAQSat-H	2269.57
21574	1991050A	ERS-1	2140.73
22823	1993061A	SPOT 3	1890.98
16613	1986019A	SPOT 1	1813.68
20436	1990005A	SPOT 2	1813.68

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Project Overview

PROJECT OBJECTIVES

- Identification and characterisation of existing **classes of tumbling** objects
- Survey, trade-off and selection of **de-tumbling concepts** and strategies
- Development of mathematical **models** for tumbling debris
  - <u>Prediction</u> models for long term tumbling debris attitude prediction
  - <u>Synthesis</u> models for control design
  - <u>Non-linear</u> models for performance evaluation (both tumbling target and composite multi-body models)
- Baseline of a candidate concept and development of the GNC by means of ROBUST MIMO synthesis and analysis techniques
- Analysis of the applicability/scalability to a wider range of debris classes and contribution to technology Roadmaps

STUDY LOGIC

- Main processes and resources of the activity
  - Identification of candidate concepts
  - LTP modelling
  - Trade-off
  - Synthesis/Analysis models development
  - GNC design
  - Non-linear models development
  - GNC validation (linear + non-linear)

STUDY LOGIC

- Study logic & task sharing

Core activities of the project

STUDY INPUTS

| Statement of Work | Applicable Documents | Reference Documents | Proposal |

KOM

T0 — **Kick Off**

TASK 1: Identification of classes of tumbling objects and survey of de-tumbling strategies

Literature Review

WP 1100 Tumbling classes identification

WP 1300 Survey of Detumbling strategies

WP 1200 Tumbling debris mathematical models development

T0+3m — **Progress Meeting 1**

TASK 2: Trade-off and baseline selection of promising de-tumbling strategies and compound models development

WP 2300 Target-chaser mathematical models development

WP 2100 Detumbling strategies trade-off and Chaser GNC requirements

WP 2400 Detumbling strategy selection and operational sequence identification

WP 2200 System-level requirements for detumbling

T0+8m — **Requirements Review**

TASK 3: Chaser GNC System Design

WP 3200 Chaser GNC design (robust control) and robustness analysis

WP 3100 Robust control design techniques identification and selection

WP 3300 GNC Mission Simulator and GNC design performance assessment and boundaries

WP 3400 Extrapolation of GNC results to a broader scope of classes of tumbling debris and chasers

T0+12m — **Implementation Review**

TASK 4: Finalization, Recommendations and Future Plans

WP 4100 Study conclusions, roadmaps and future plans – GNC and operations

WP 4200 Study conclusions, roadmaps and future plans – system level

T0+15m — **Acceptance Review and Final Presentation**

END

DETUMBLING

Survey of detumbling strategies & Mission baseline

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SURVEY OF DETUMBLING STRATEGIES

■ Detumbling strategies review

Detumbling methods

Contact based

Contactless
- Plume impingement
- Impacting Pellets
- Magnetic torque
- Magnetic eddy current
- Electrostatic

Detumbling package

Passive methods:
- Gravity gradient
- Permanent magnets
- Magnetic hysteresis
- Magnetic eddy currents
- Mechanical dampers

Rigid link
- Robotic arm
- Tentacles
- Nozzle docking

Flexible link
- Net / harpoon + tether
- Foam

Other
- Detumbling subsatellite
- Robotic arm poking
- Airbags

Fixed link

Active chaser

Target design

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WORK PERFORMED: TASK 1

- **Long Term Prediction** (LTP) simulator (for debris rotational state)
  - To include only the strictly relevant effects (for computational efficiency)
    - **Preliminary study of the order of magnitude of each perturbation contribution** for the long term behaviour
    - Use **analytical models** and reasonable assumptions to obtain the estimation of the individual contributions of each perturbation
  - Implemented perturbations: gravity gradient, Earth magnetic torque, eddy currents, sloshing
    - Energy dissipation due to eddy current is important for long term prediction (typically for upper stages)
      - Analytical model available for basic shapes and used to validate numerical model (surface is replaced by thin rods connected at nodes)

ENVISAT study case
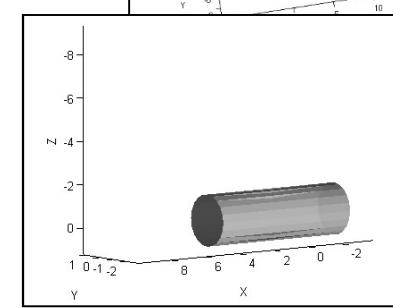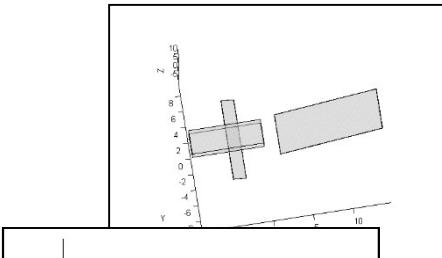
KOSMOS 3M study case
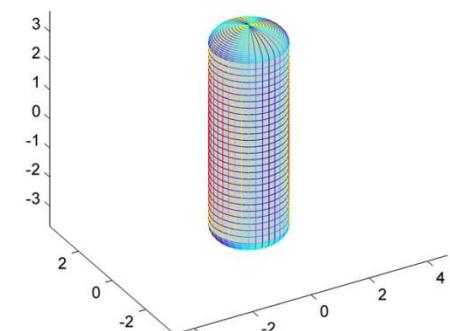
Current flow model on cylindrical tank

WORK PERFORMED: TASK 1

- Target rotational state: **long term prediction** general facts:

  – Dissipative torques must be considered for prediction of the decay rate (<u>eddy currents</u>, magnetic hysteresis, damped mechanical vibration, sloshing).

  – Orienting torques (<u>gravity gradient</u>, <u>magnetic torques</u>, aerodynamic and solar radiation torques) for the prediction of the long term attitude.

  – **LEO** space debris→ Long term motion either coupled to the gravity gradient (1 rev/orbit) or magnetic field (2 rev/orbit)

  – MEO and GEO → mechanical damping + orienting torques → flat spin / spin stabilised objects at high rate.

ENVISAT spin rate prediction using different fit methods

After May 2013
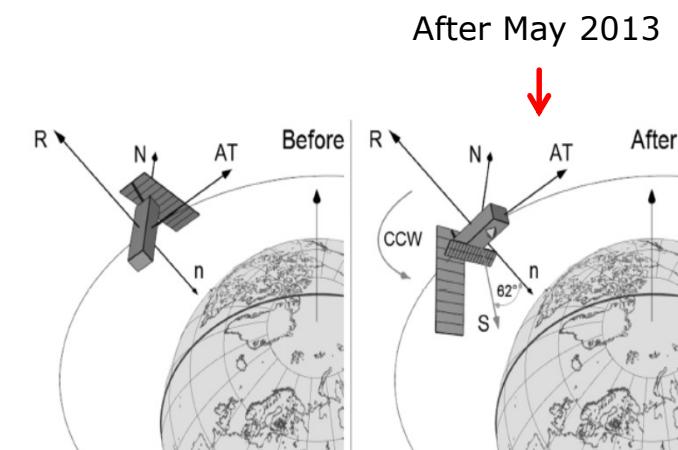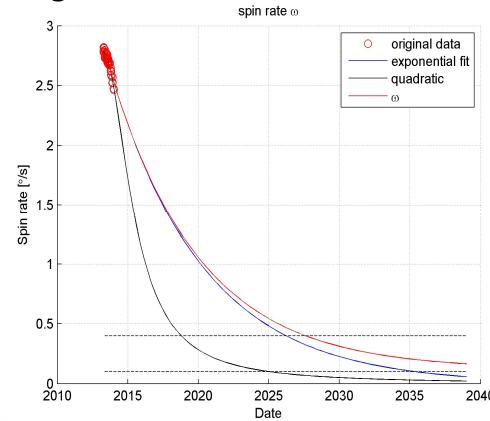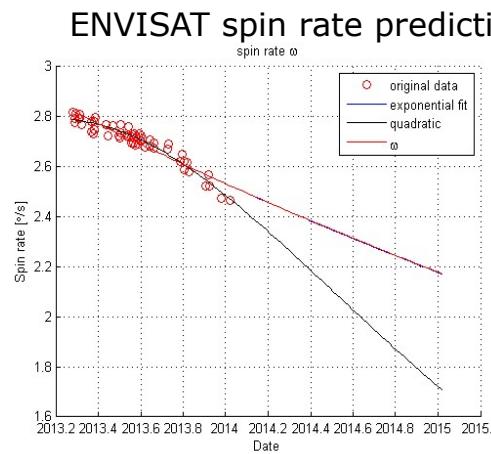
CONCEPTS TRADE-OFF

- Detumbling concepts trade-off
  - Analytical hierarchy process (*Thomas Saaty, 1970s*) was used for the trade-off:
    - Breakdown of the problem into smaller sub-problems that are arranged in a **hierarchy**, and **pair-wise comparison** of elements
  - **Robotic arm capture** is selected as baseline for TASK 3 (GNC development)
    - Performs well across all three criteria (risk, technical, reliability)
    - High TRL (highest TRL of all capture and de-tumbling techniques)
    - Can partially be tested
    - Least amount of development would be required
  - It is observed that **contactless** methods tend to perform well on risk criterion because
    - No physical contact and no attitude synchronization
    - Plume impingement de-tumbling and electrostatic tractor also perform well on technical criteria
    - Contactless methods tend to *score lower in reliability criterion*

SURVEY OF DETUMBLING STRATEGIES – RIGID LINK METHODS

- **Robotic arm precursors and recent past/current activities**
  - Precursor activities dealt with **cooperative** targets (attitude controlled, visual markers, grappling interfaces)
    - ETVS-VII
    - Orbital Express (DARPA program)
  - FREND (DARPA) performed on-ground demonstration of capture of **uncooperative** target debris
  - Other missions/concepts investigated in recent activities:
    - DEOS (passive v.s. active chaser AOCS investigated)
    - eDeorbit (several robotic arm and tentacles configurations proposed)
    - ANDROID (double demonstration of robotic arm and net)

ETS-VII (NASDA/JAXA)
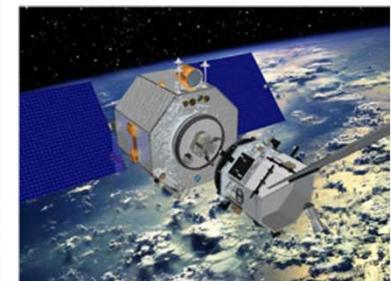
Orbital Express (DARPA)
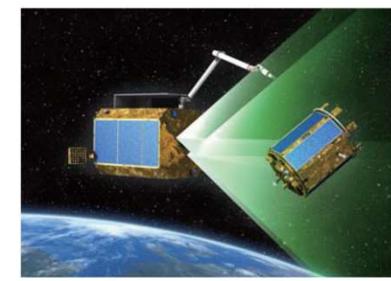
DEOS
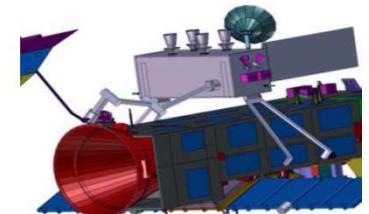
eDeorbit concept from ESA CDF study

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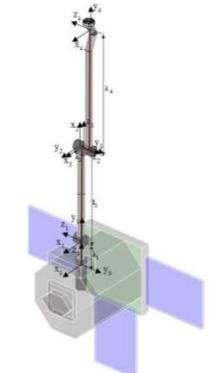
MISSION BASELINE

- **Envisat**
  - De-tumbling mission
    - Arm deployment
    - Close in & Synchronisation up to capture (contact dynamics out of the scope of the activity)
    - Detumbling manoeuvre
  - Purpose of the study is to assess <u>feasibility of MIMO robust control</u> for all phases and point key problems/needs (not to design the GNC for an already defined system)
  - Some eDeorbit facts taken as reference but alternative assumptions/solutions when considered interesting for the study:
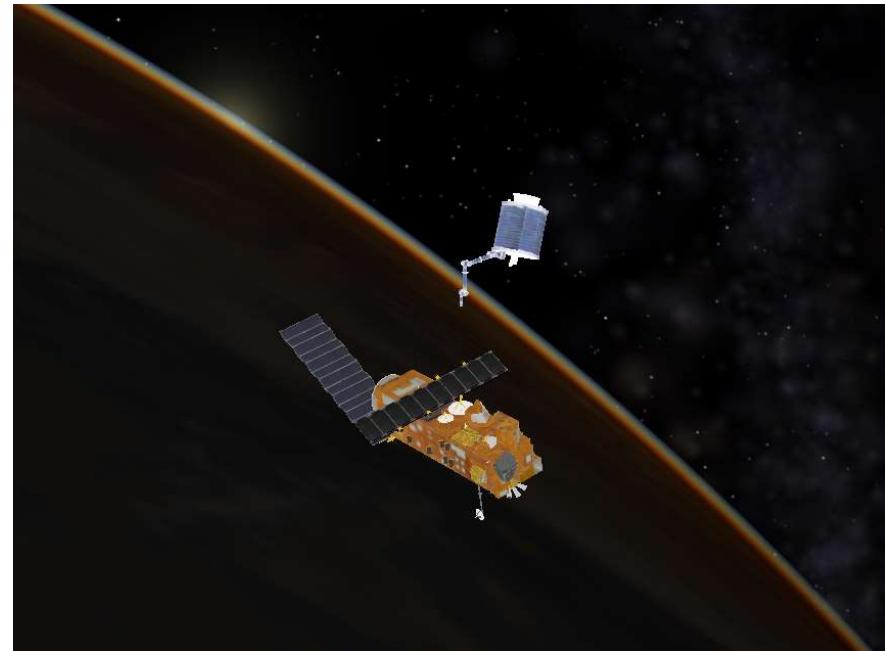
- Higher target rotational rates considered here (3º/s – 5º/s)
- No clamping devices for the braking manoeuvre

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GNC design – Guidance

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SYNCHRONISATION GUIDANCE

Manoeuvre	Final conditions	Duration
Station keeping at Parking Hold Point	100 m on Vbar	
Move closer to target	30 m on Vbar	3 min
Transition to a position on the angular momentum axis of the target & synchronize rotation	30 m from the target on angular momentum axis	5 min
Forced approach in straight line over the angular momentum axis	7 m from the target on angular momentum axis	3 min
Transfer to target body frame		
Fly-around in target body frame	7 m from the target in last approach axis (target body frame)	3 min
Forced approach in straight-line to Mating Point	Mating Point (TBC m) from the target in last approach axis (target body frame)	3 min
Station keeping at Mating Point	Mating Point	TBC
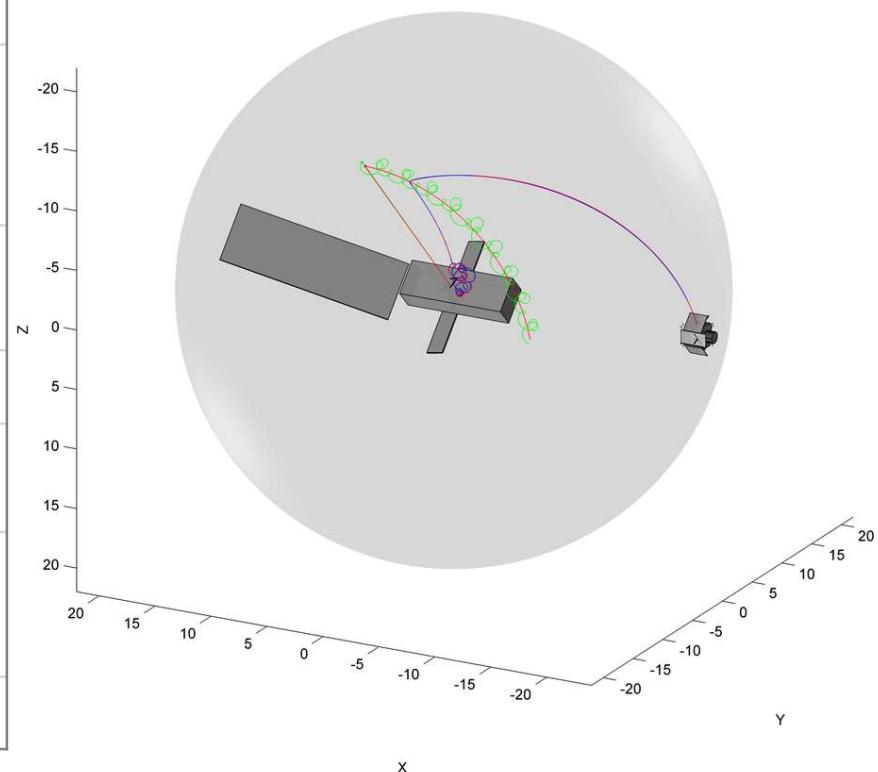
SYNCHRONISATION GUIDANCE

Trajectory types

- Fly-around forced motion trajectories
  - From a point in **LVLH frame** to a point along **angular momentum** direction vector
  - From a point along angular momentum direction vector to target body frame
  - Between two points in **target body** frame
- Forced motion trajectories
  - Linear forced motion in LVLH
  - Linear forced motion along angular momentum vector
  - Linear forced motion in target body frame

- Linear forced motion
  - Constant acc. – constant vel. – constant acc.
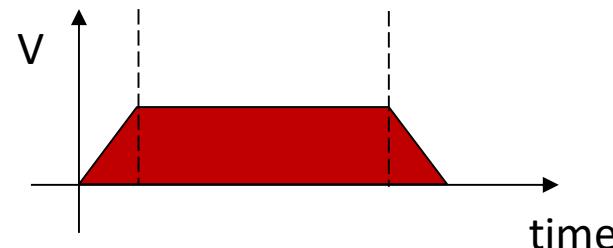
- Fly-around generated using reference frame transformations
  - Interpolation between reference frames leads to $\mathbf{R}(t), \mathbf{\Omega}(t), \dot{\mathbf{\Omega}}(t)$
  - Leads to feed-forward force (see next slide)

SYNCHRONISATION GUIDANCE

- **Fly-around position, velocity accelerations**

$$\mathbf{r}_B = \mathbf{R}_{A \to B} \mathbf{r}_A$$

$$\mathbf{v}_B = \mathbf{R}_{A \to B} \left(\mathbf{v}_A + \boldsymbol{\omega}_{A \to B,A} \times \mathbf{r}_A \right)$$

$$\mathbf{a}_B = \mathbf{R}_{A \to B} \left(\mathbf{a}_A + \boldsymbol{\omega}_{A \to B,A} \times \left(\boldsymbol{\omega}_{A \to B,A} \times \mathbf{r}_A \right) + 2 \cdot \boldsymbol{\omega}_{A \to B,A} \times \mathbf{v}_A + \dot{\boldsymbol{\omega}}_{A \to B,A} \times \mathbf{r}_A \right)$$

- **Acceleration leads to feed-forward force**

$$\mathbf{F}_{rot} = \mathbf{F}_{ine} + \mathbf{F}_{centrifugal} + \mathbf{F}_{Coriolis} + \mathbf{F}_{Euler}$$

- **Simultaneously provides** <u>target-pointing attitude</u>, <u>angular velocity</u> and <u>angular acceleration</u>

$$\mathbf{r} = \mathbf{R} \begin{bmatrix} -D \\ 0 \\ 0 \end{bmatrix}$$

$$\mathbf{v} = \boldsymbol{\omega} \times \mathbf{r}$$

$$\mathbf{R} = \begin{bmatrix} \mathbf{e}_x & \mathbf{e}_y & \mathbf{e}_z \end{bmatrix}$$
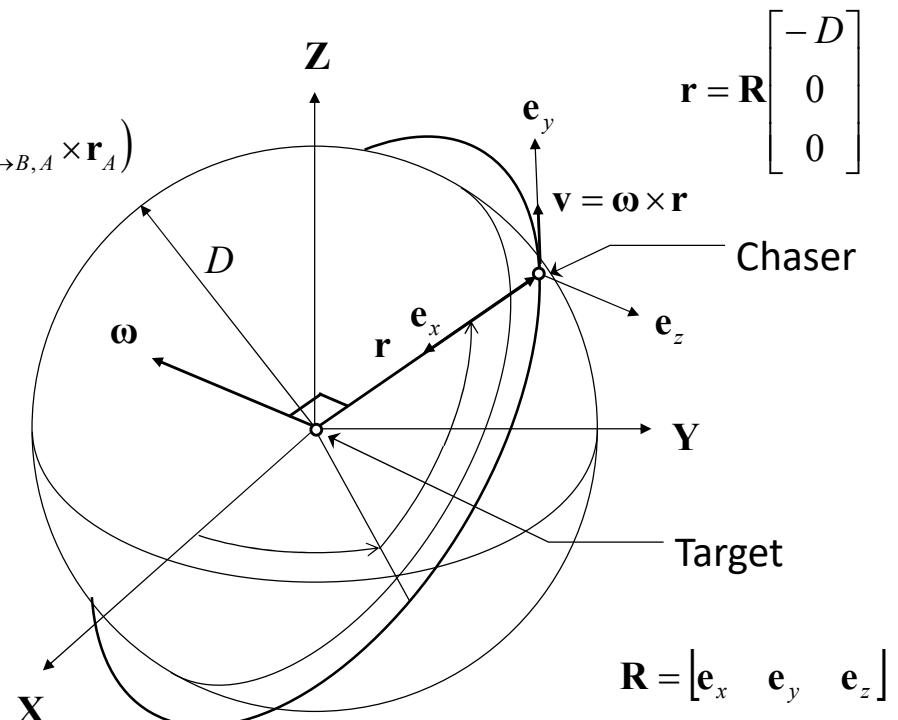
ENVISAT ROTATION AND CONSEQUENCES

- Rotational stability:
  - Rotation around major and minor axis is stable
  - Rotation around intermediate axis unstable
- Energy dissipation with constant angular momentum eventually leads to rotation around major axis
- Torque-free body rotation visualized as inertia ellipsoid rolling over invariable plane perpendicular to angular momentum
  - Chaser position along target angular momentum vector at sufficient distance is safe
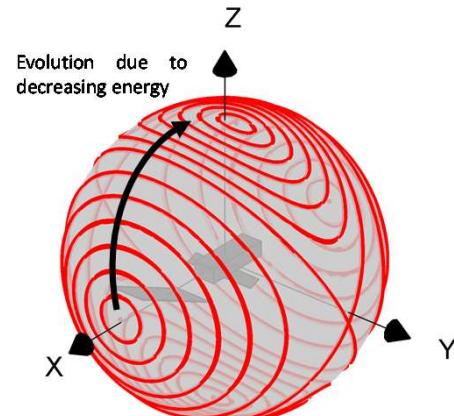
Angular velocity
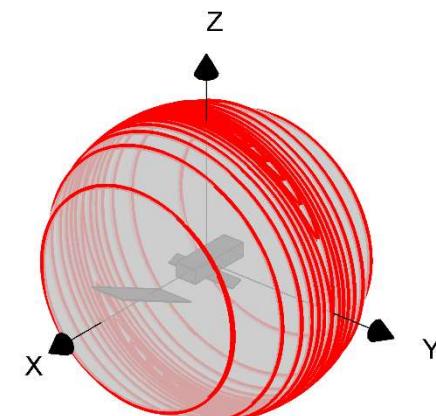
Angular momentum

ENVISAT ROTATION AND CONSEQUENCES

- **Angular momentum vector is a logical choice for approach direction**
  - Fixed in inertial space, meaning there is an easy connection to LVLH frame
    - Low ΔV required for station-keeping
  - Safe approach distance easily determined using invariable plane
  - Slow evolution in target body frame
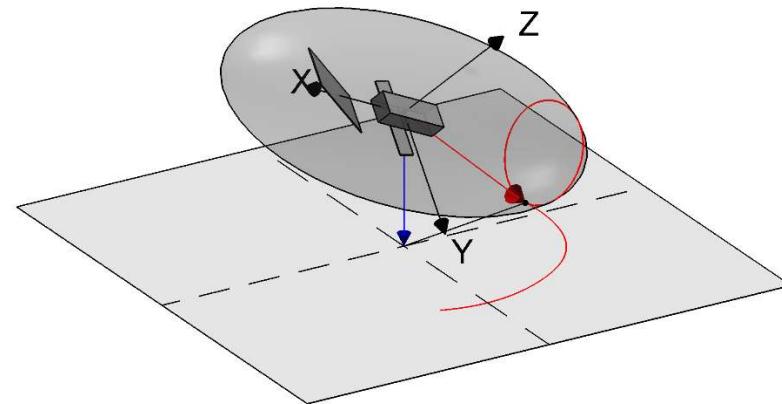
- Appropriately scaled inertia ellipsoid provides stay-out zone
- Scaled inertia ellipsoid never crosses invariant plane
- Invariant plane perpendicular to angular momentum vector

ENVISAT ROTATION AND CONSEQUENCES

■ Station-keeping in target body frame requires compensating centrifugal force

– Limits maximum distance at which station-keeping can be performed

– E.g. (eDeorbit chaser design): max force 88 N, rotation rate 5°/s => maximum distance 8 m

thrust and centrifugal acceleration

— Maximum thrust
—○— Centrifugal force at 90 °
—□— Centrifugal force at 60 °
—◇— Centrifugal force at 45 °

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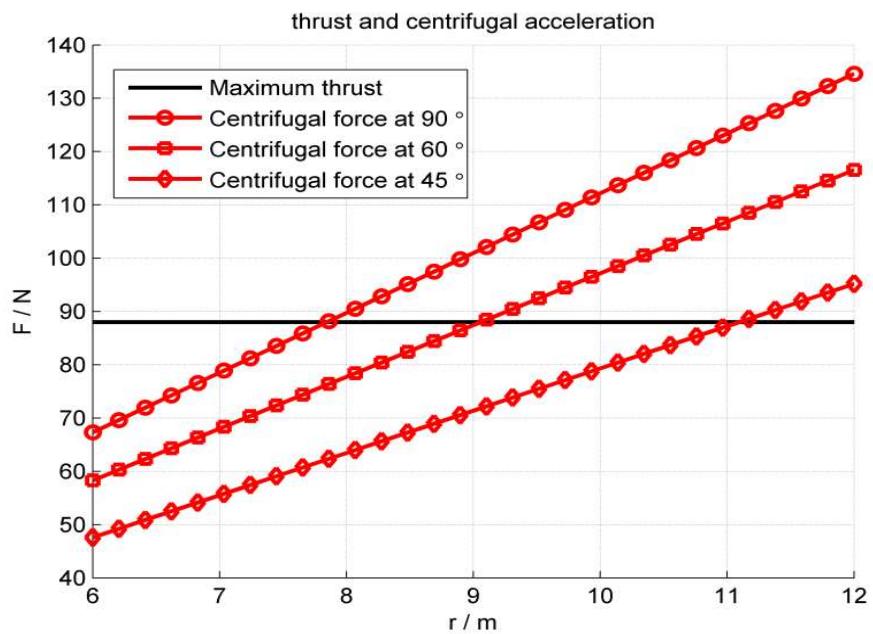
DETUMBLING

GNC Design – Control synthesis & analysis

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GNC IMPLEMENTATION GUIDELINES. CONTROL

- GNC Design guidelines:
  - **MIMO** controllers (6DOF and 10DOF (6+4))
  - Synthesised/analysed by means of modern robust control techniques
  - Linear plant models with uncertainty representation by means of **LFTs** for synthesis and robustness analyses.
  - Different control modes to be designed according to each S/C configuration and control requirements for each phase (e.g. FMC for synchronisation phase v.s. FMCC for detumbling in composite configuration).
  - Main focus of the activity is put into:
    - the control function and in the evaluation of feasibility of the capture and detumbling operation.
    - performances evaluation and derivation of recommendations for later on-board implementation, system design and consolidation.

CONTROL SYNTHESIS & ANALYSIS METHODOLOGY - H∞

■ **H∞ Design** (synthesis method)

- Disturbance and noise rejection formulated in the frequency domain.
- Steady state error requirement and transient response relates with the control bandwidth
- The requirements specification information included within weighting functions used to augment the plant model entering the synthesis process.

■ **µ-Analysis** (analysis method)

- Robust stability – ensure that, with a given controller, the closed-loop system remains stable for all plants in the defined uncertainty set.
- Robust performance – determine the amplification from the exogenous inputs to the performance outputs for all plants in the uncertainty set.

MODELLING – SYNTHESIS/ANALYSIS PLANTS

- Multibody model
- Take into account uncertainty for design and analysis
- Obtain an LFT representation of the linear dynamics of the multi-body systems including:
  - Sloshing (two tanks with 3 modes each)
  - robotic arm with flexibility
  - rigid-body dynamics of the target
  - flexible modes from target appendages

MODELLING – SYNTHESIS/ANALYSIS PLANTS

- Multibody model based on [2-port model Alzard, et all "Two-input two-output port model for mechanical systems", AIAA 2015]
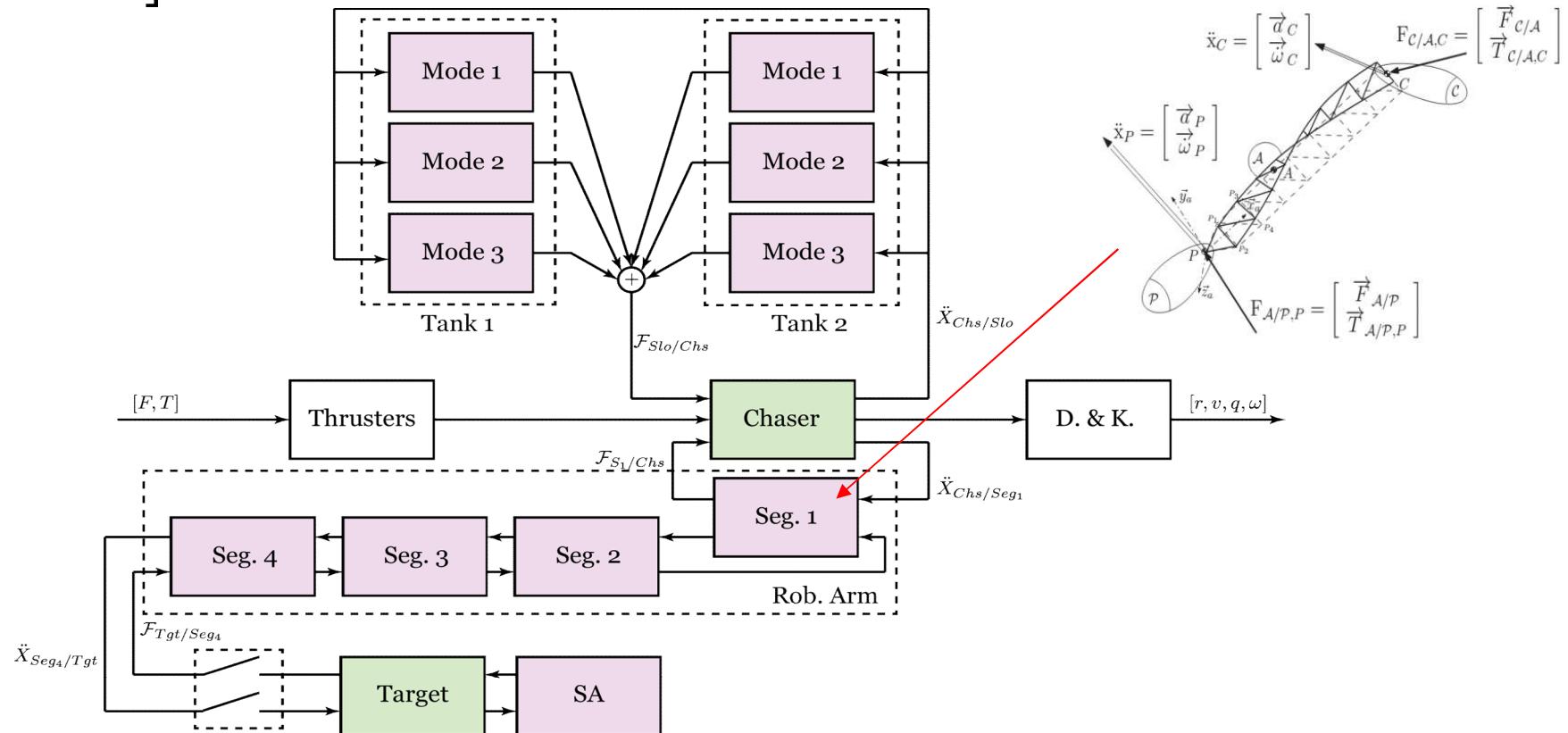
MODELLING – SYNTHESIS/ANALYSIS PLANTS

Interconnection using the TITOP models: Chaser with slosh and flexible modes + 3 segment robotic arm + Target with flexible modes
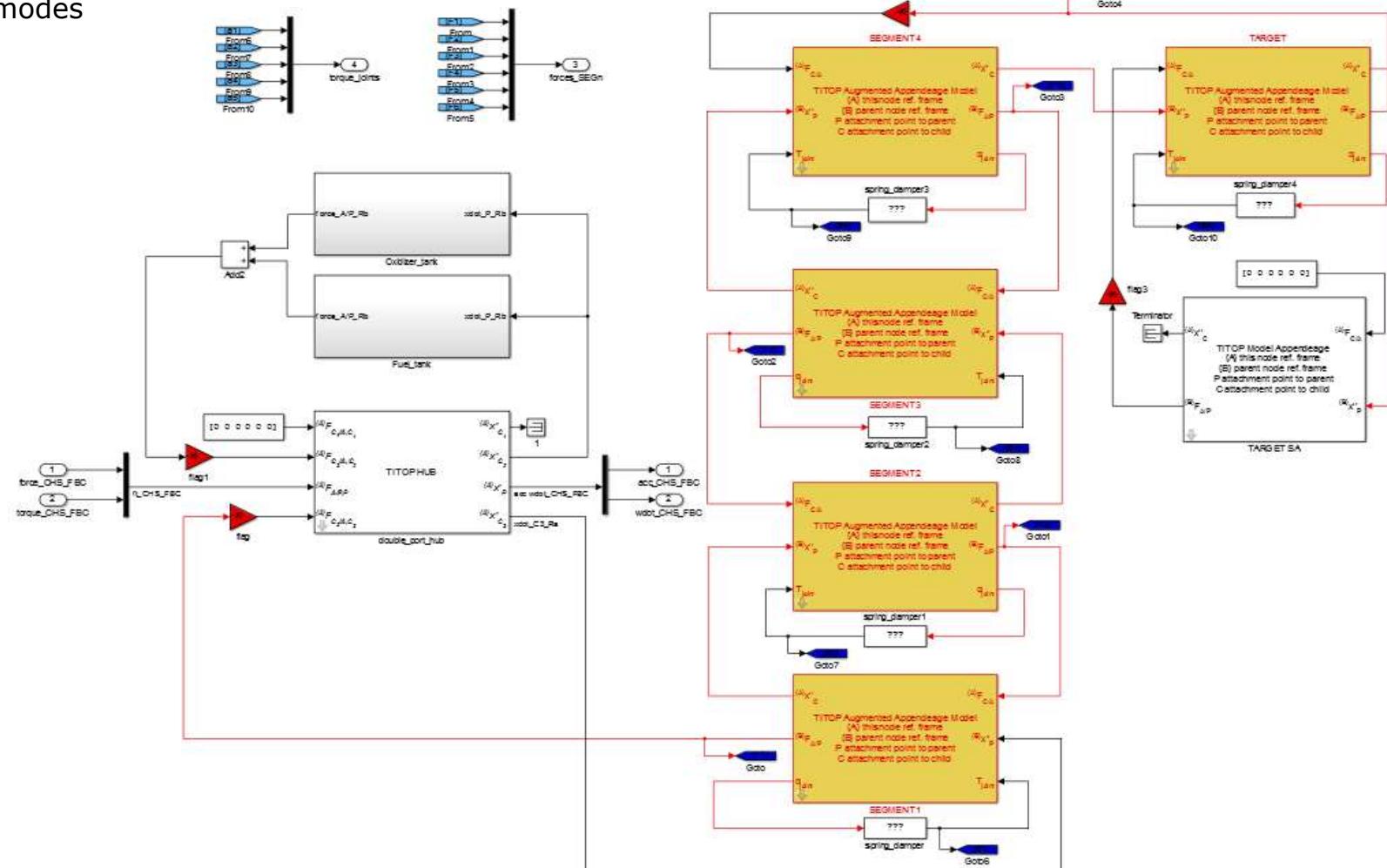
CONTROL MODES CHARACTERISATION

- **Forced motion control mode (FMC):** 6DOF control mode for forced motion
  - Station keeping
  - Forced motion in LVLH
  - Forced motion in target body frame. Mode needs to be robust to:
    - High range of possible debris attitude motions
    - Navigation uncertainties in target attitude and relative state
    - Actuators misalignments/noises/delays
    - Fuel sloshing and flexible modes
  - Forced motion in target body frame with active robotic arm. Mode needs to be robust to:
    - Changing mass, centre of gravity & inertia properties due to robotic arm movement

- **Forced Motion Control of Composite (FMCC):** Forced motion during de-tumbling. Mode needs to be robust to:
  - M.C.I. properties uncertainty
  - Thrusters displacement with respect to centre of gravity of composite
    - Lower controllability during manoeuvre
  - High flexibility of composite satellite
  - Arm motion
    - Impact on dynamics
    - Requires advanced control techniques to cope with inertia matrix and centre of mass variations

CONTROL MODES CHARACTERISATION

- **Forced motion control mode 2 (FMC2):** 10DOF control mode for forced motion. Controls the state of the end-effector of the robotic arm using the thrusters and the joints in an integrated and optimized way.
  - Station keeping
  - Forced motion in LVLH
  - Forced motion in target body frame. Mode needs to be robust to:
    - High range of possible debris attitude motions
    - Navigation uncertainties in target attitude and relative state
    - Actuators misalignments/noises/delays
    - Fuel sloshing and flexible modes
  - Forced motion in target body frame with active robotic arm. Mode needs to be robust to:
    - Changing mass, centre of gravity & inertia properties due to robotic arm movement

CONTROL SYNTHESIS/ANALYSIS - WEIGHTS

- The dynamic model is extended with frequency weights for Hinf design allowing for the characterization of noise, reference, disturbances, tracking error, actuation spectrum and input-output behaviour
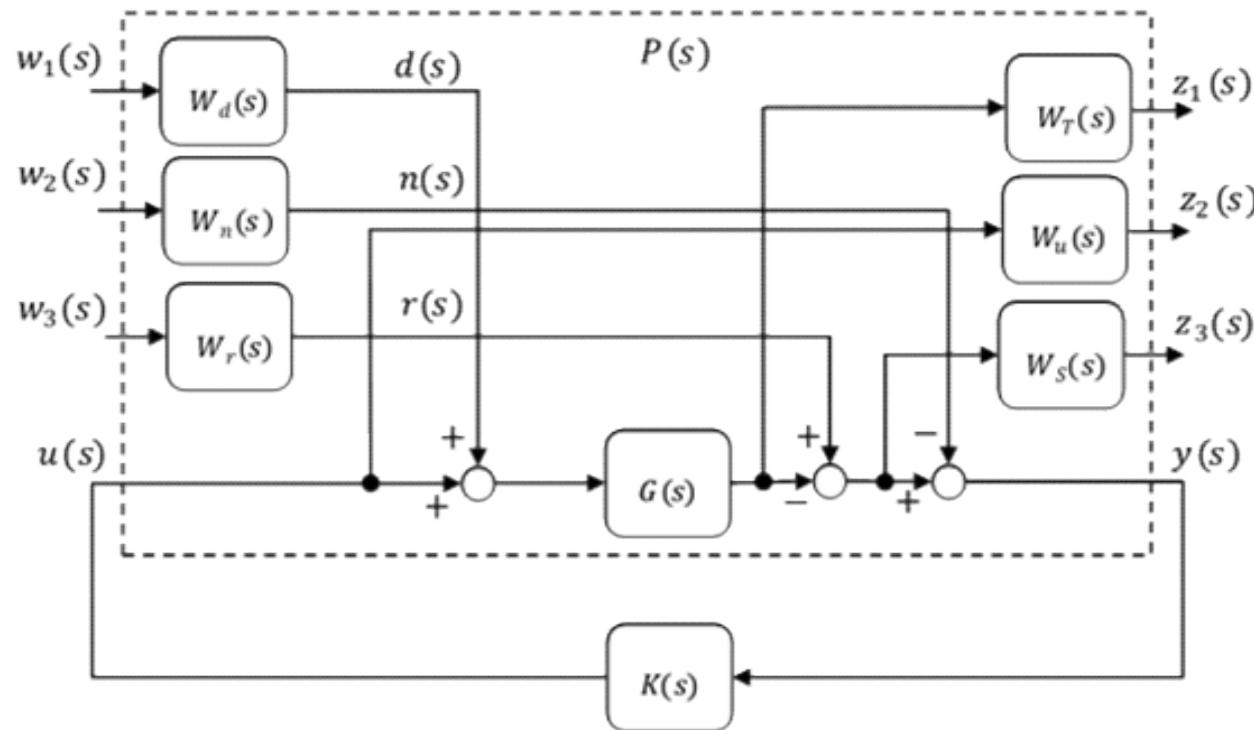
CONTROL SYNTHESIS: FMCC– SIGMA PLOTS
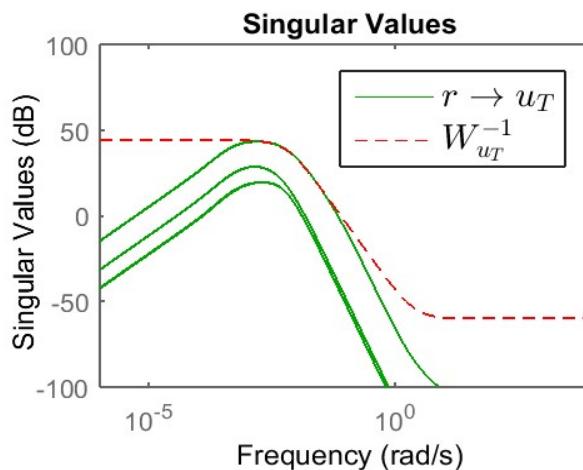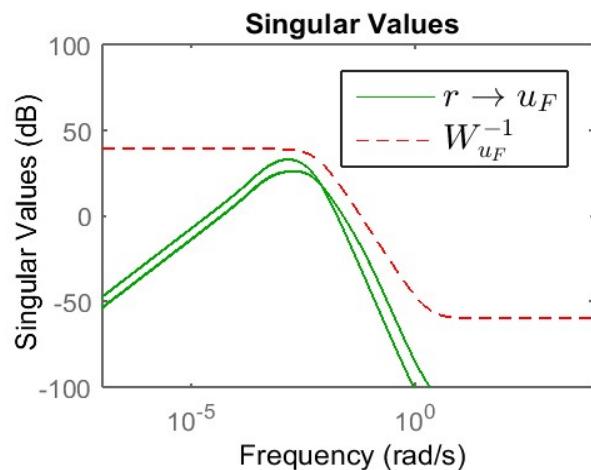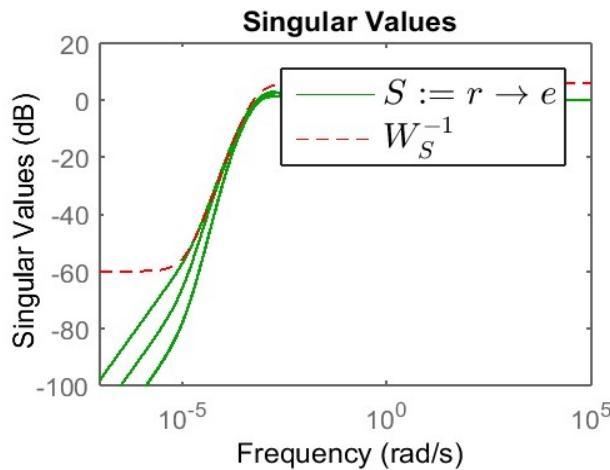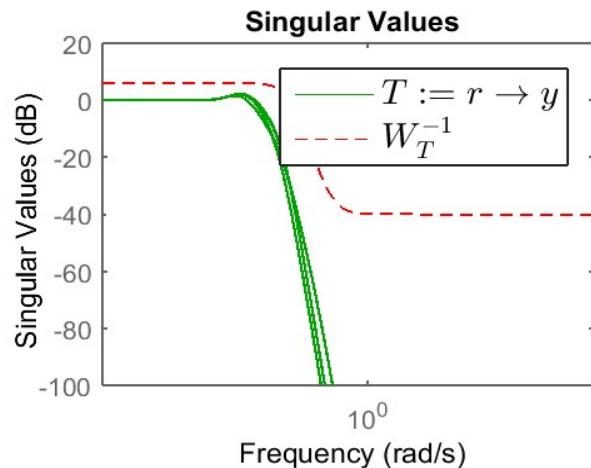
FMCC– SIGMA PLOTS

Sigma plots of the closed-loop system from the unweighted control disturbance input to all unweighted performance outputs
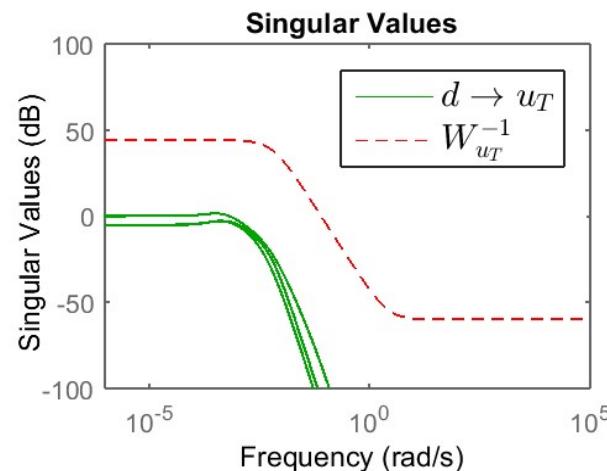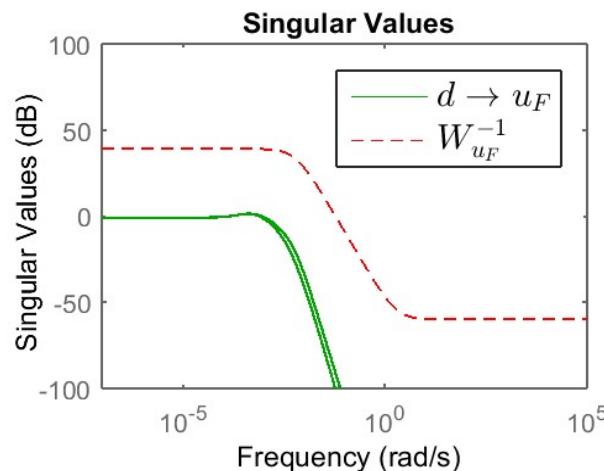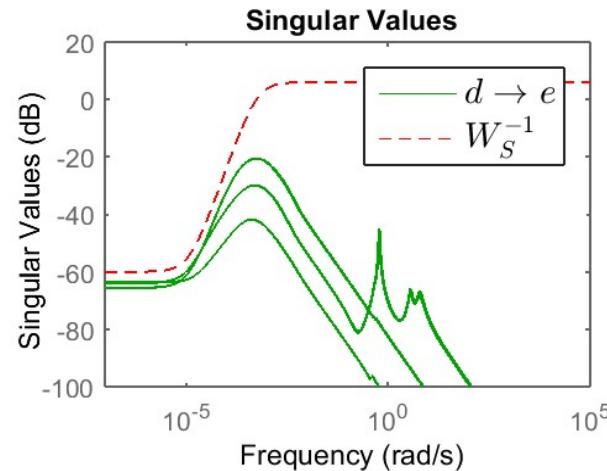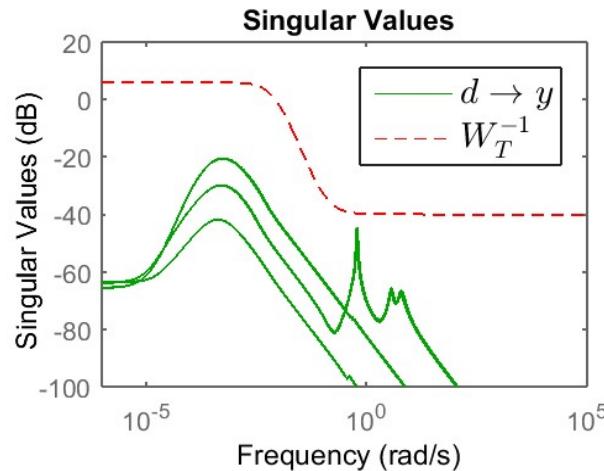
FMCC– SIGMA PLOTS

Sigma plots of the closed-loop system from the unweighted noise disturbance input to all unweighted performance outputs
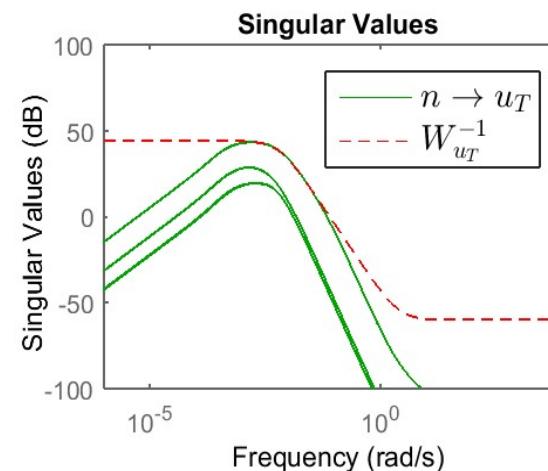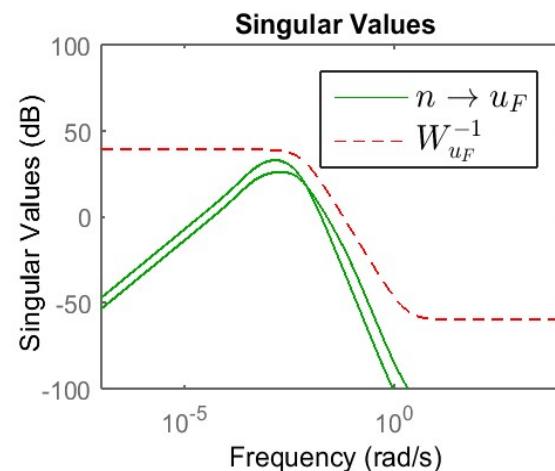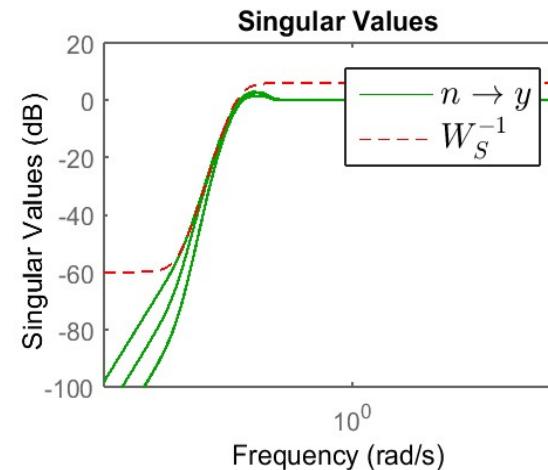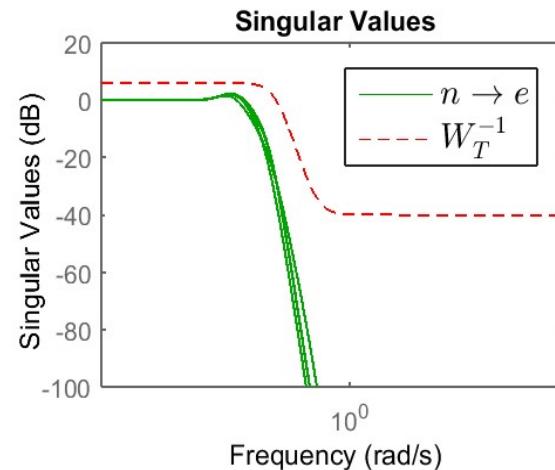
FMCC– CLOSED LOOP STEP RESPONSES

FMCC–ANALYSIS

Robust stability

Wide frequency region (1000 points)

Small region (800 points)
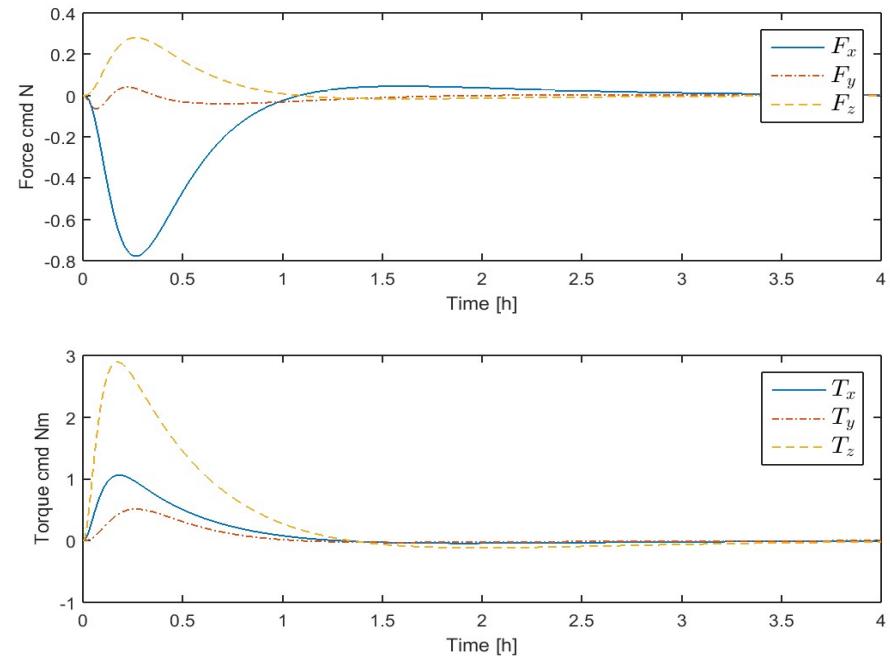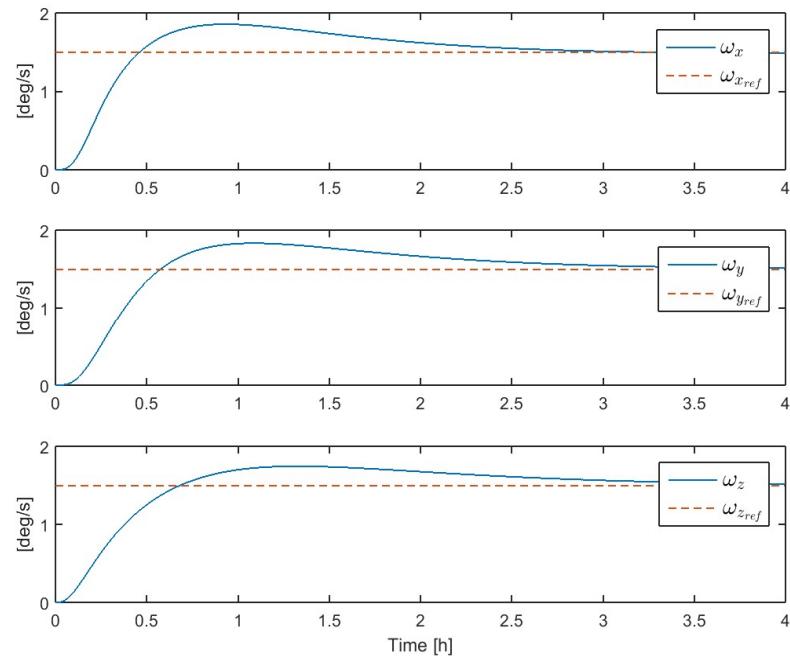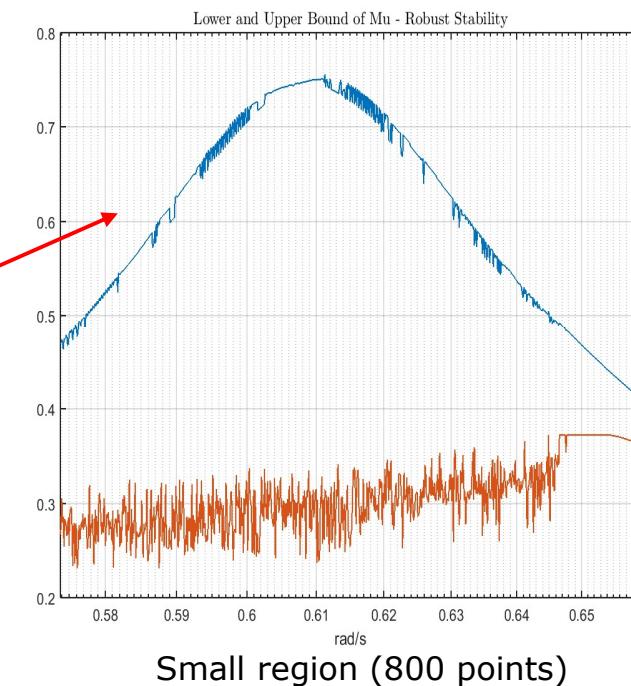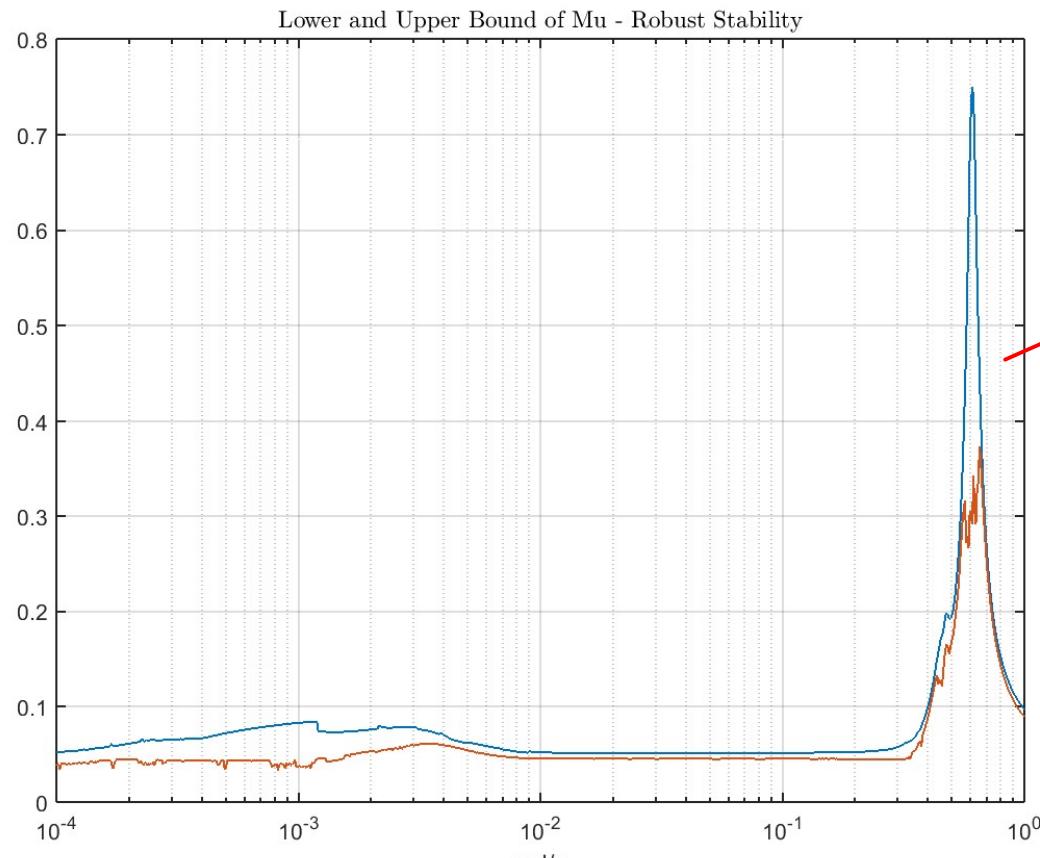
FMCC−ANALYSIS
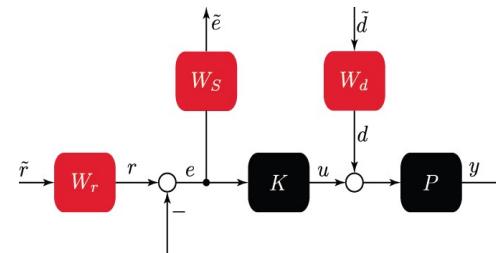
Robust performance
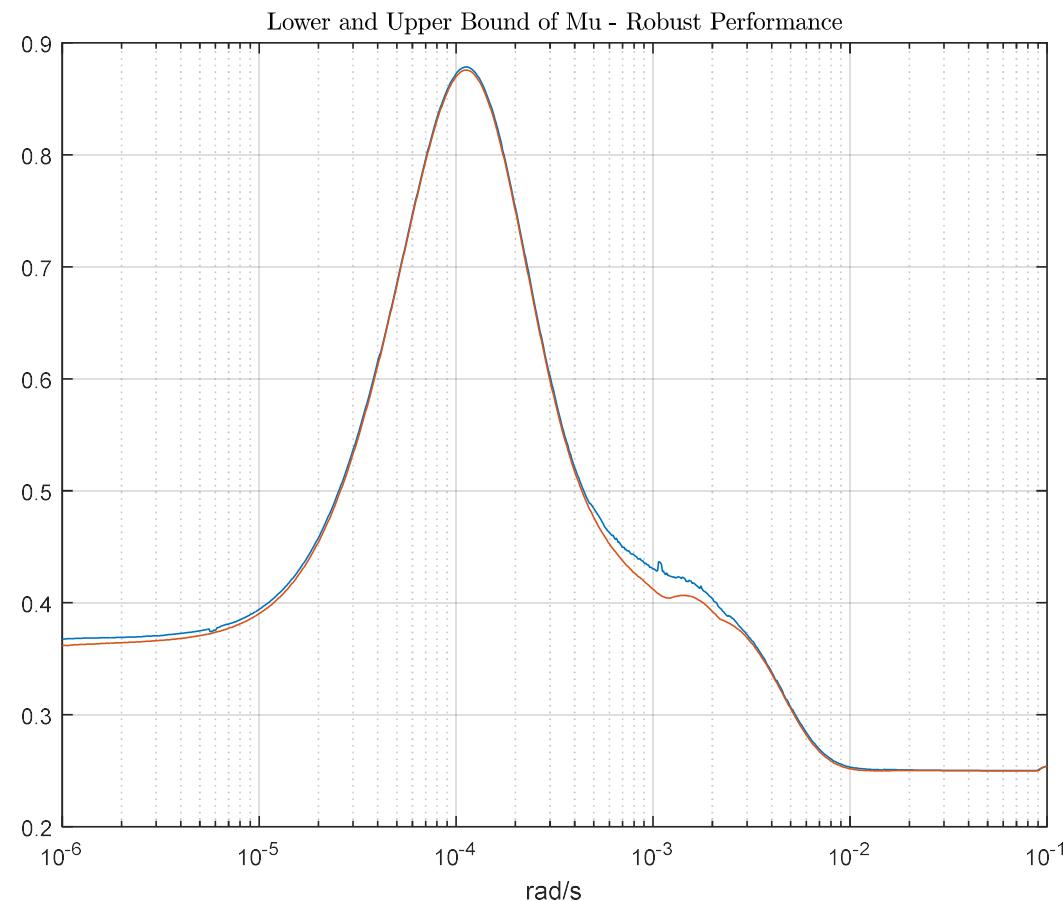
Wide frequency region (1000 points)

FMC– SIGMA PLOTS

Sigma plots of the closed-loop transfer functions from reference to: e, y and u
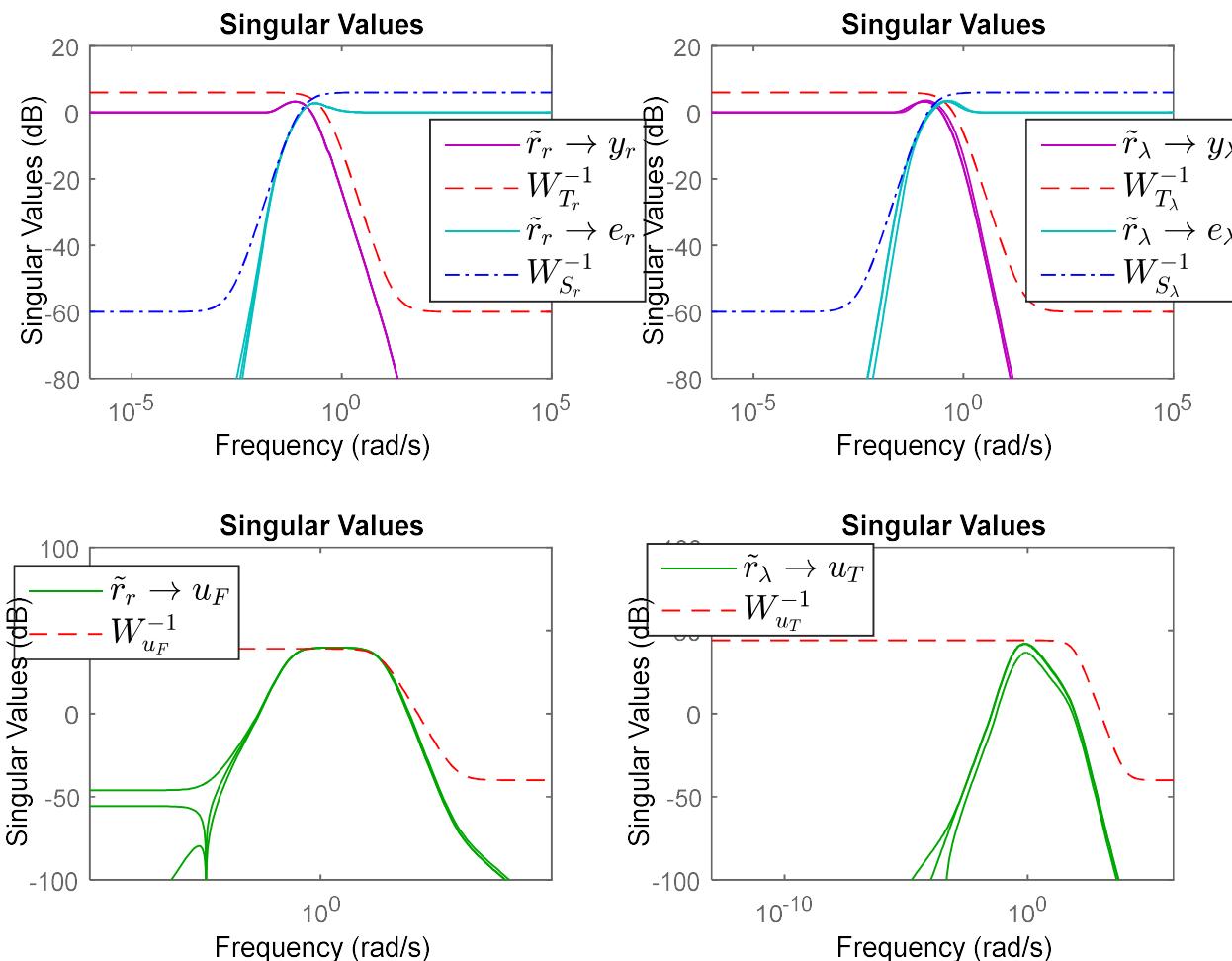
FMC– SIGMA PLOTS

Sigma plots of the closed-loop transfer functions from disturbance to: y and u
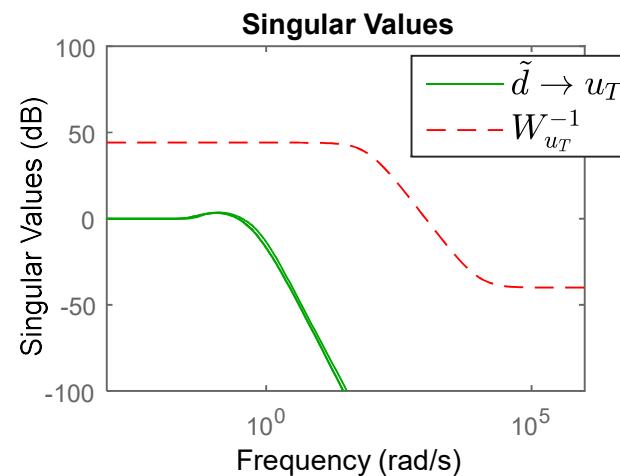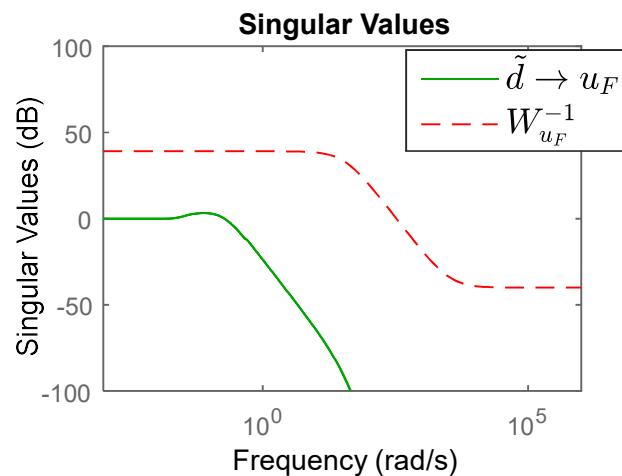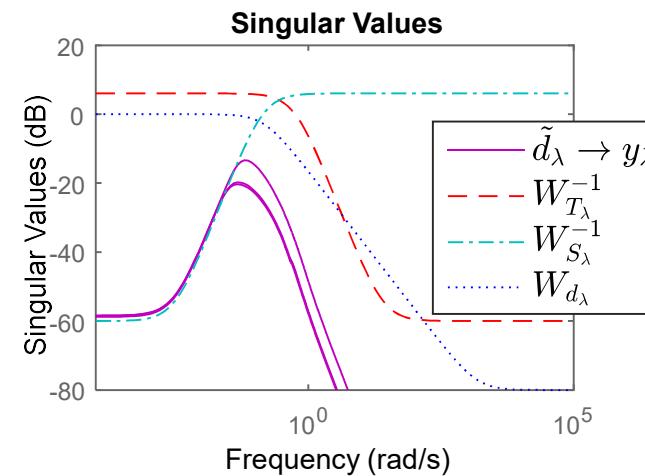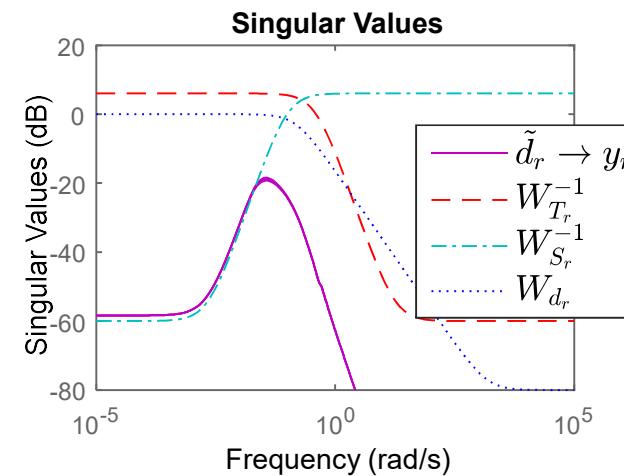
FMC– SIGMA PLOTS

Sigma plots of the closed-loop transfer functions from sensor noise to: y and u
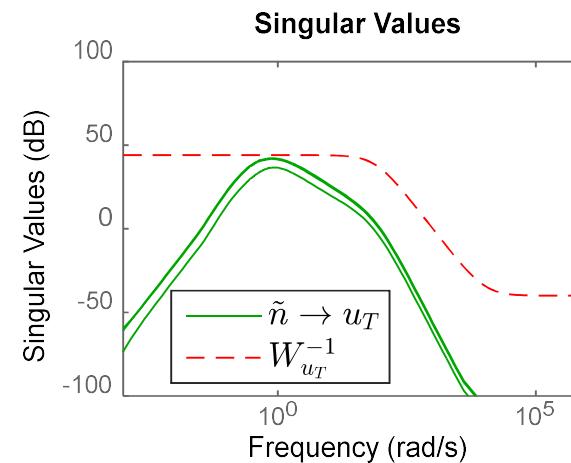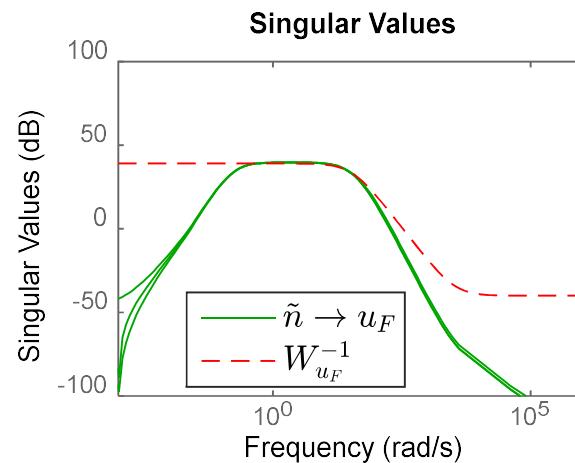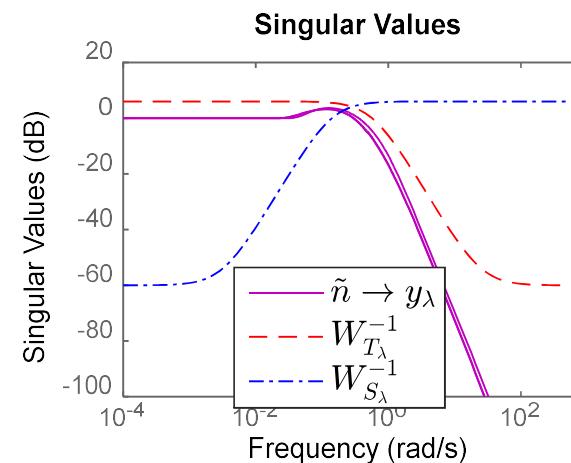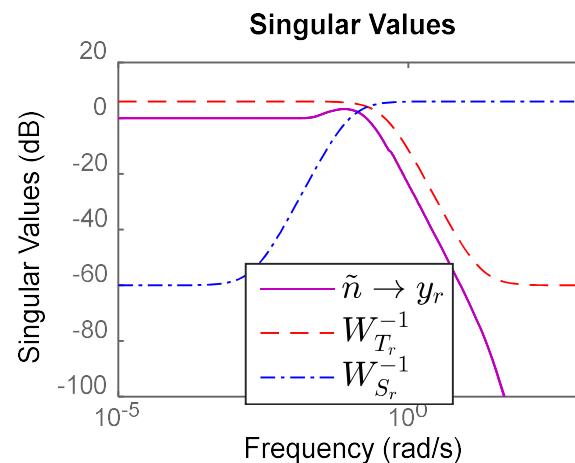
FMC– CLOSED LOOP STEP RESPONSES

Step response outputs
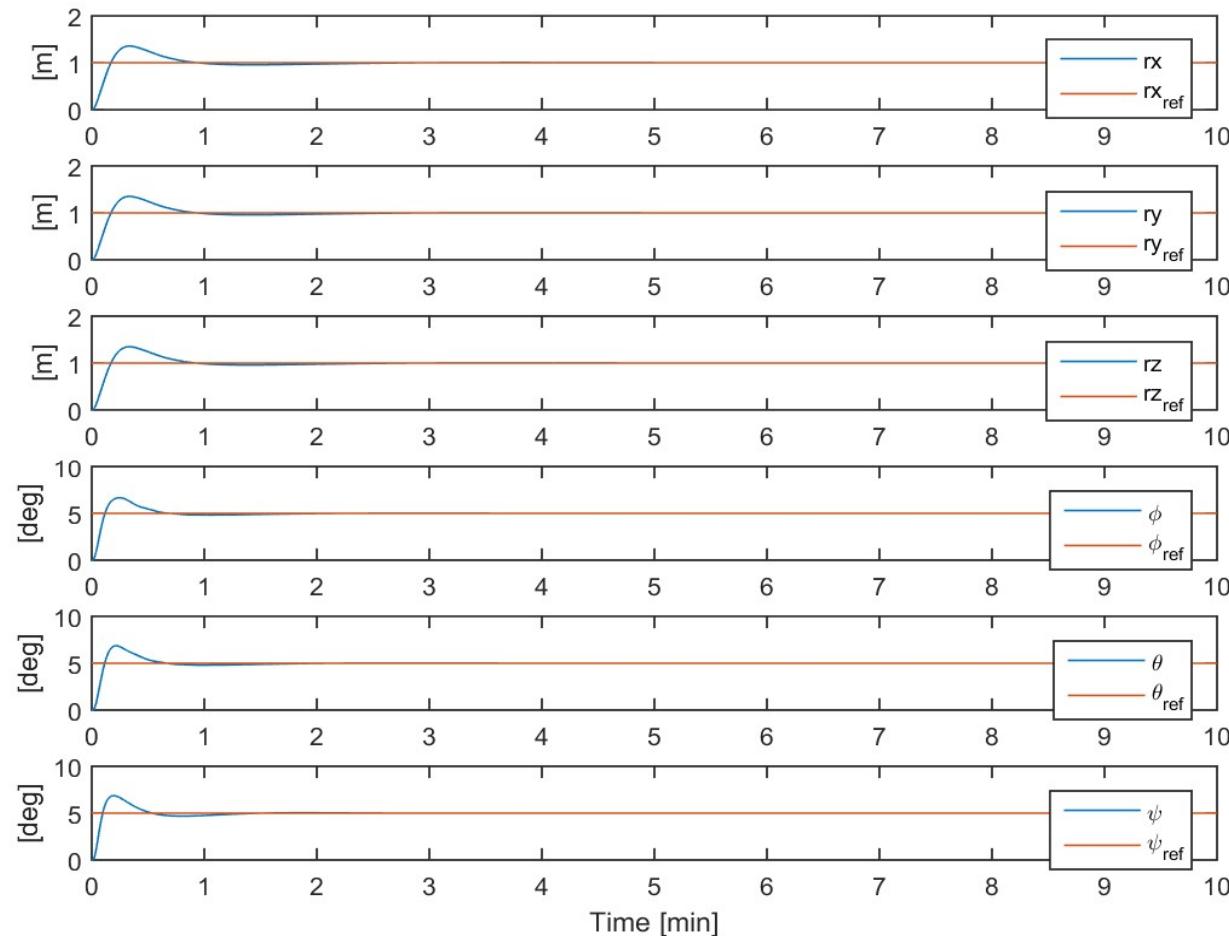
FMC– CLOSED LOOP STEP RESPONSES

Step response outputs
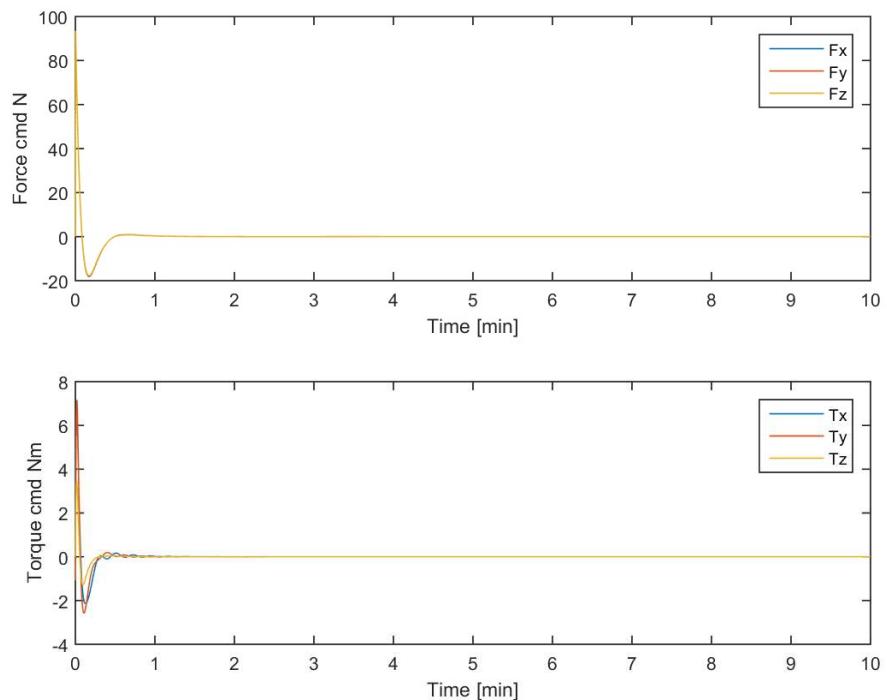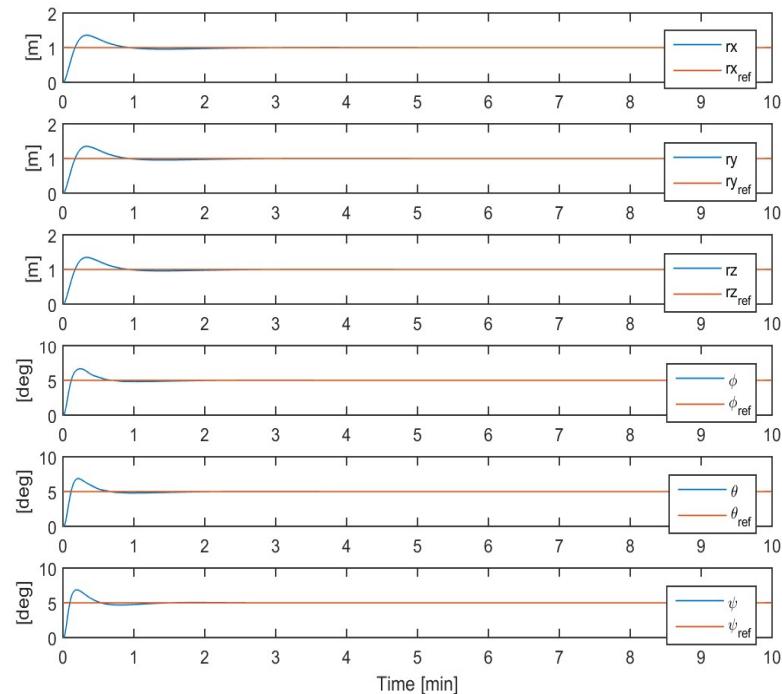
FMC– ANALYSIS

Robust stability
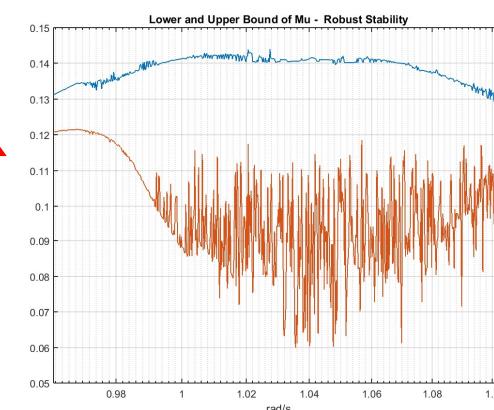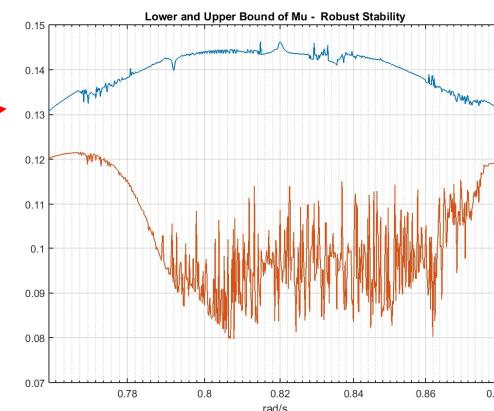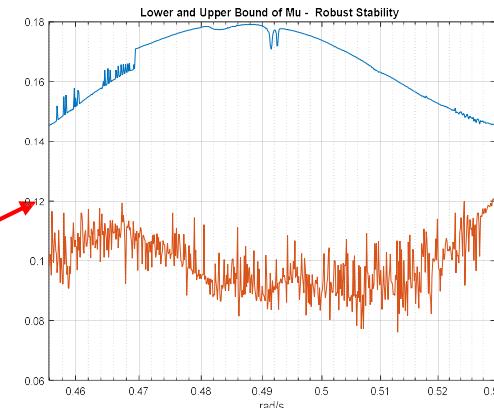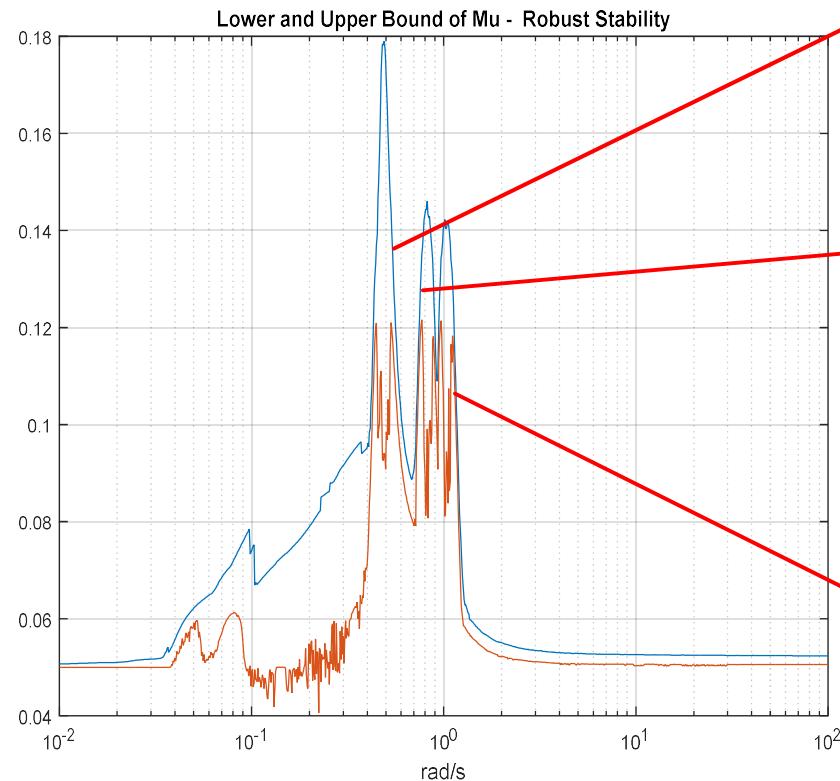
FMC– ANALYSIS
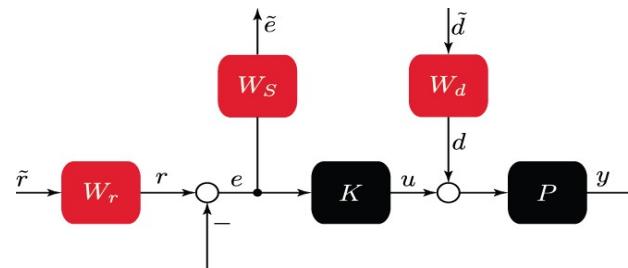
Robust performance
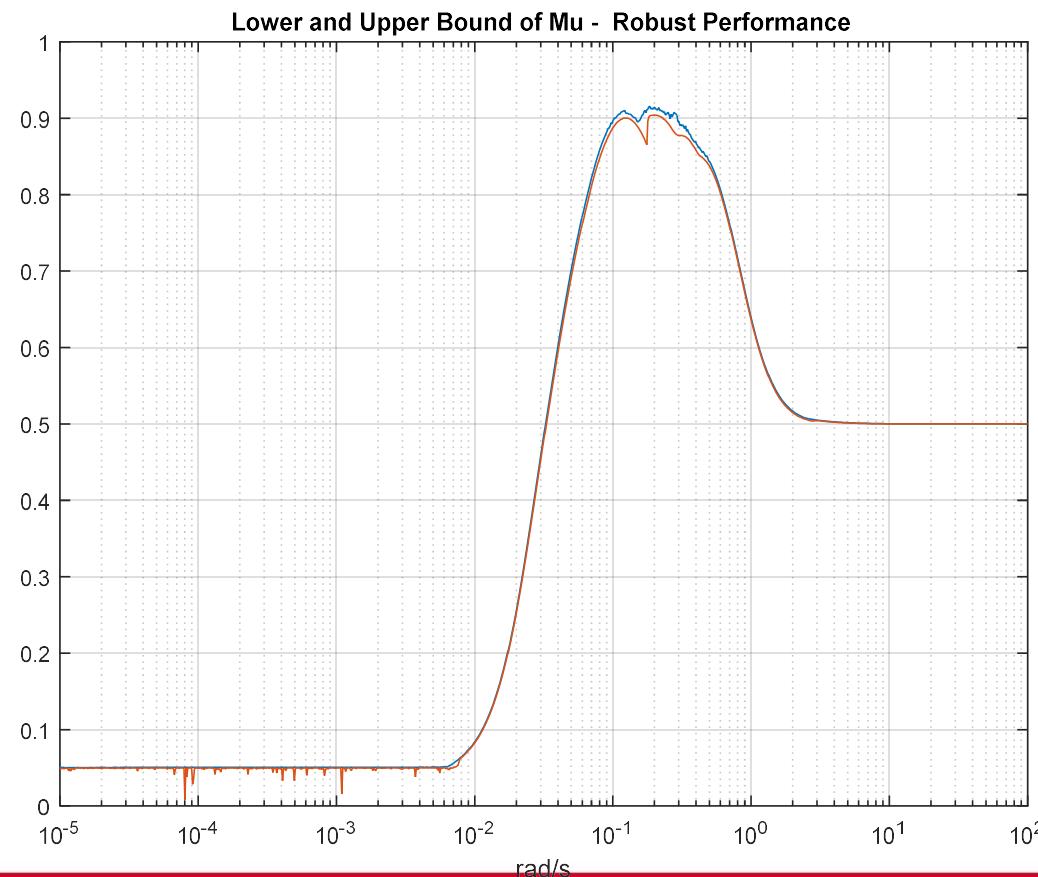
FMC2–SYNTHESIS PLANT
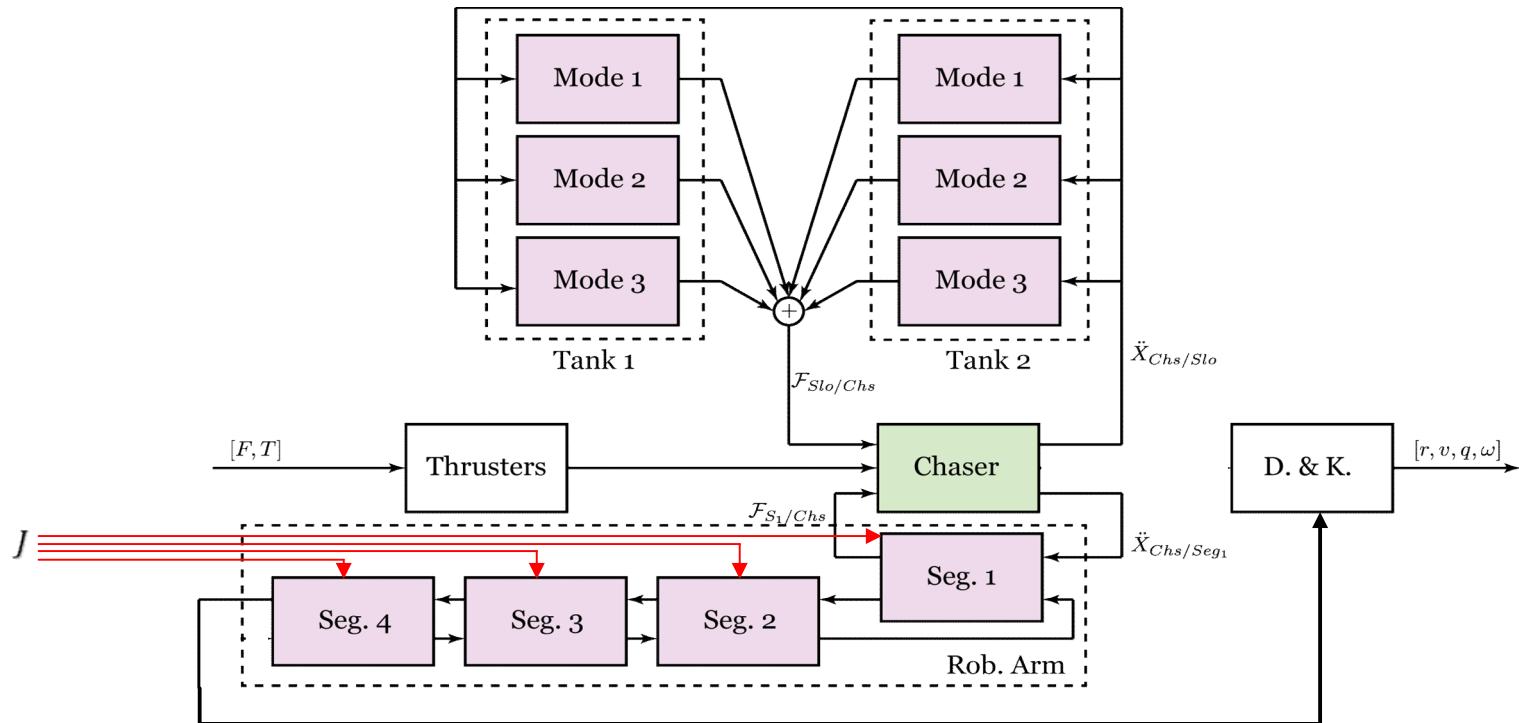
FMC2– SIGMA PLOTS

Sigma plots of the closed-loop transfer functions from reference to: e, y
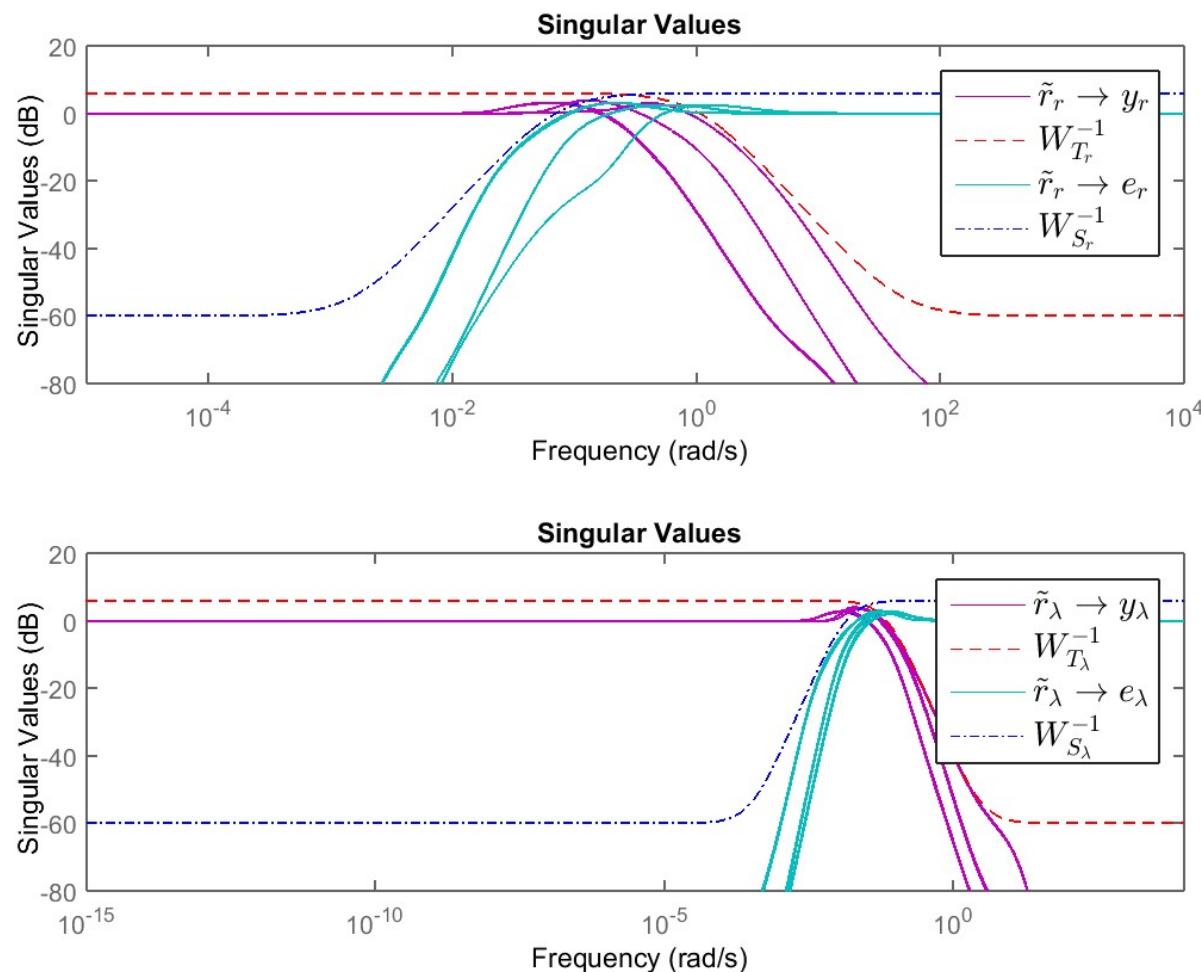
FMC2– SIGMA PLOTS

Sigma plots of the closed-loop transfer functions from reference to: u
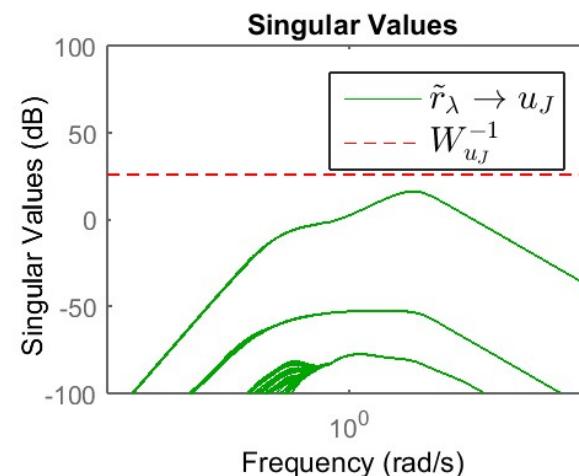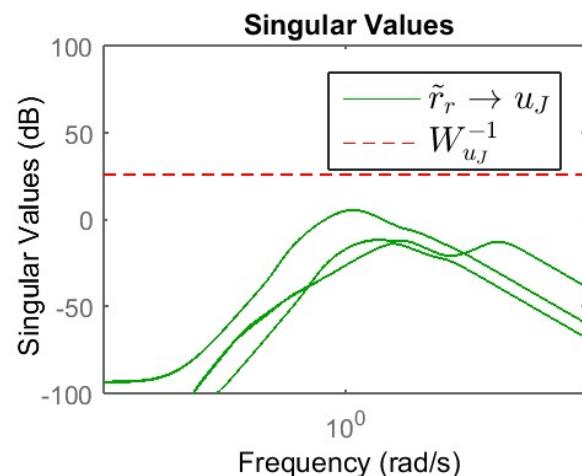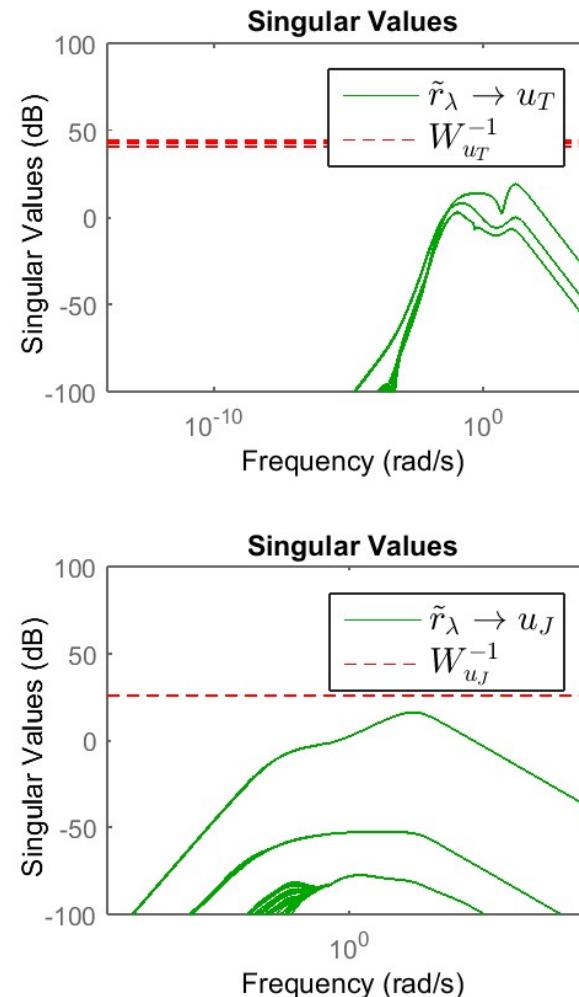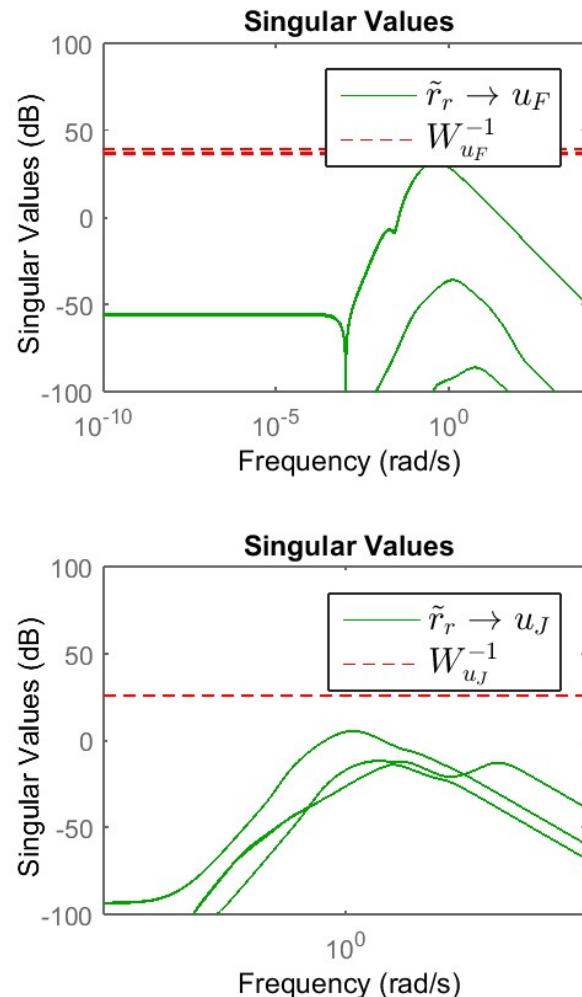
FMC2– CLOSED LOOP STEP RESPONSES

Step response outputs
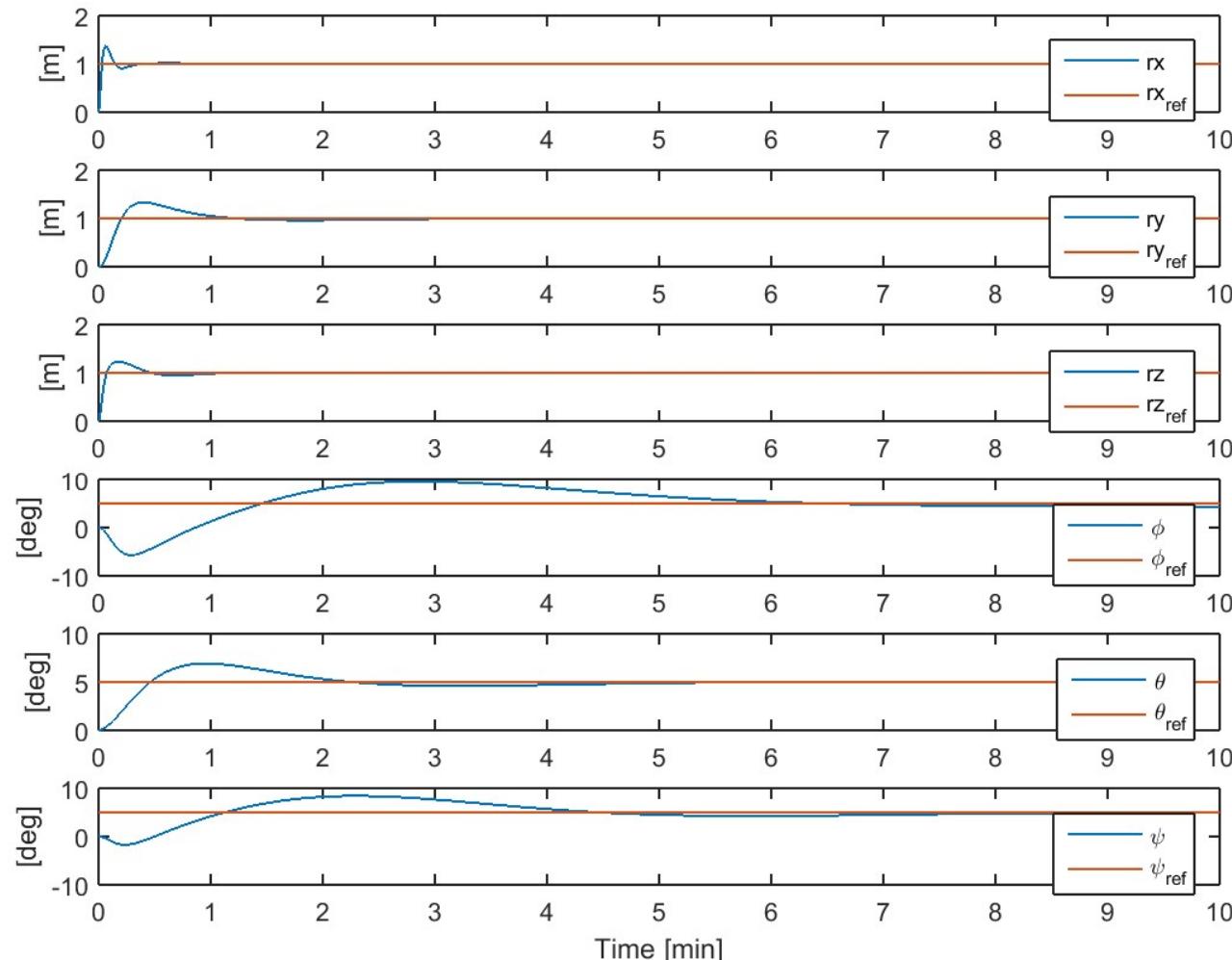
FMC2– CLOSED LOOP STEP RESPONSES

Step response outputs
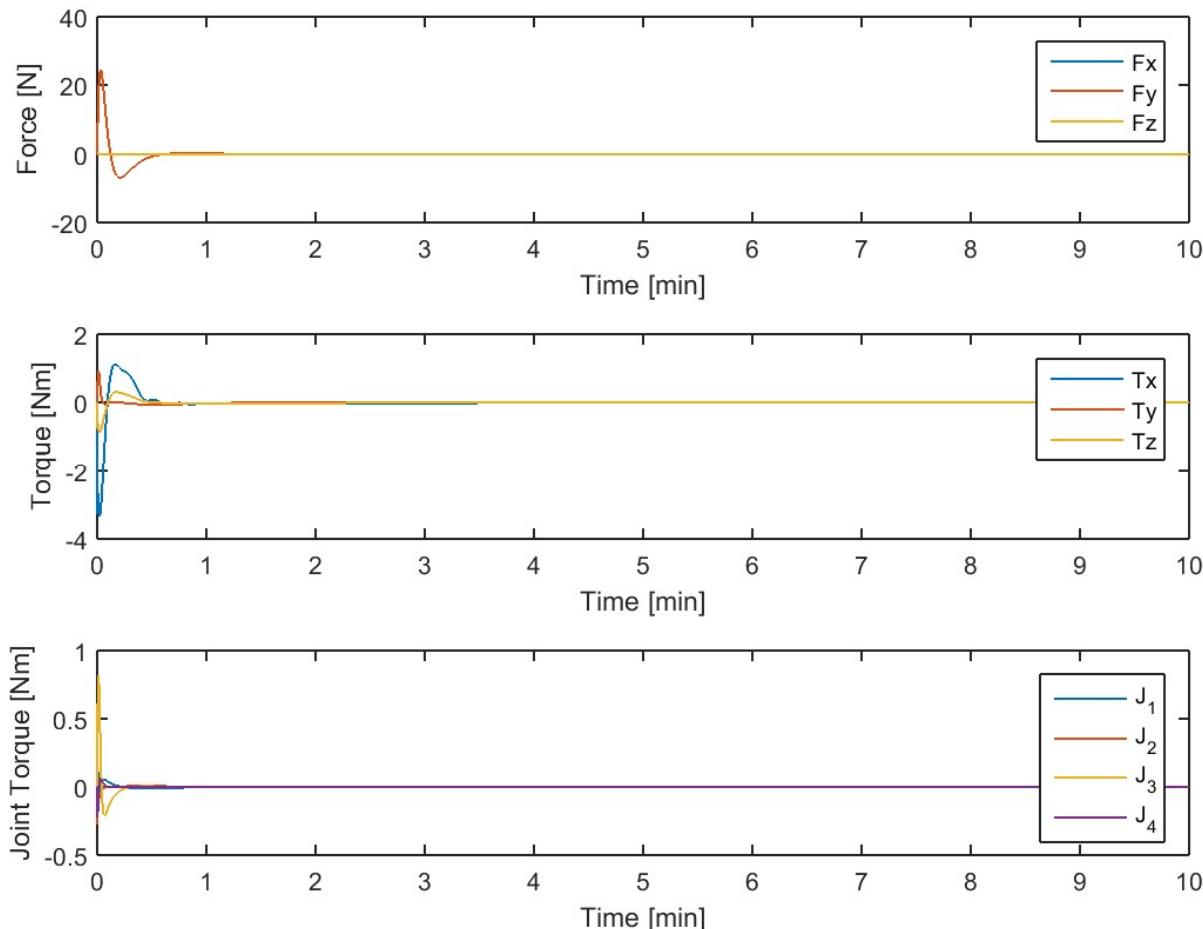
FMC2– ANALYSIS

Robust stability
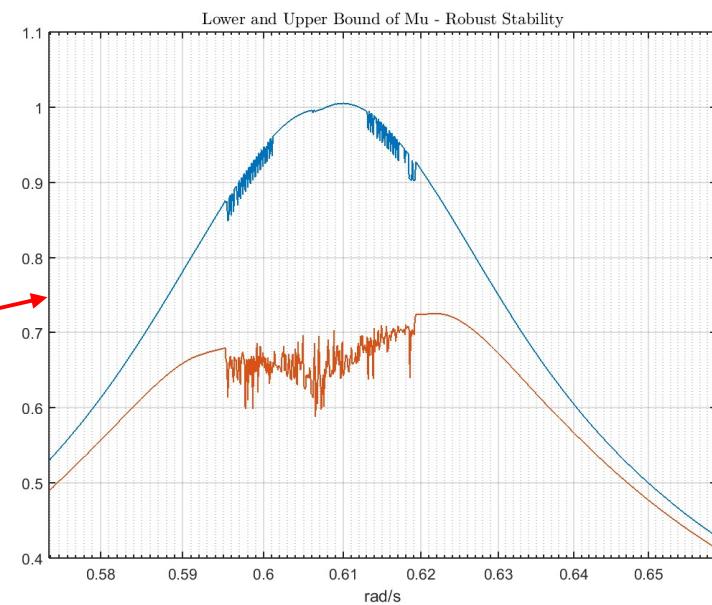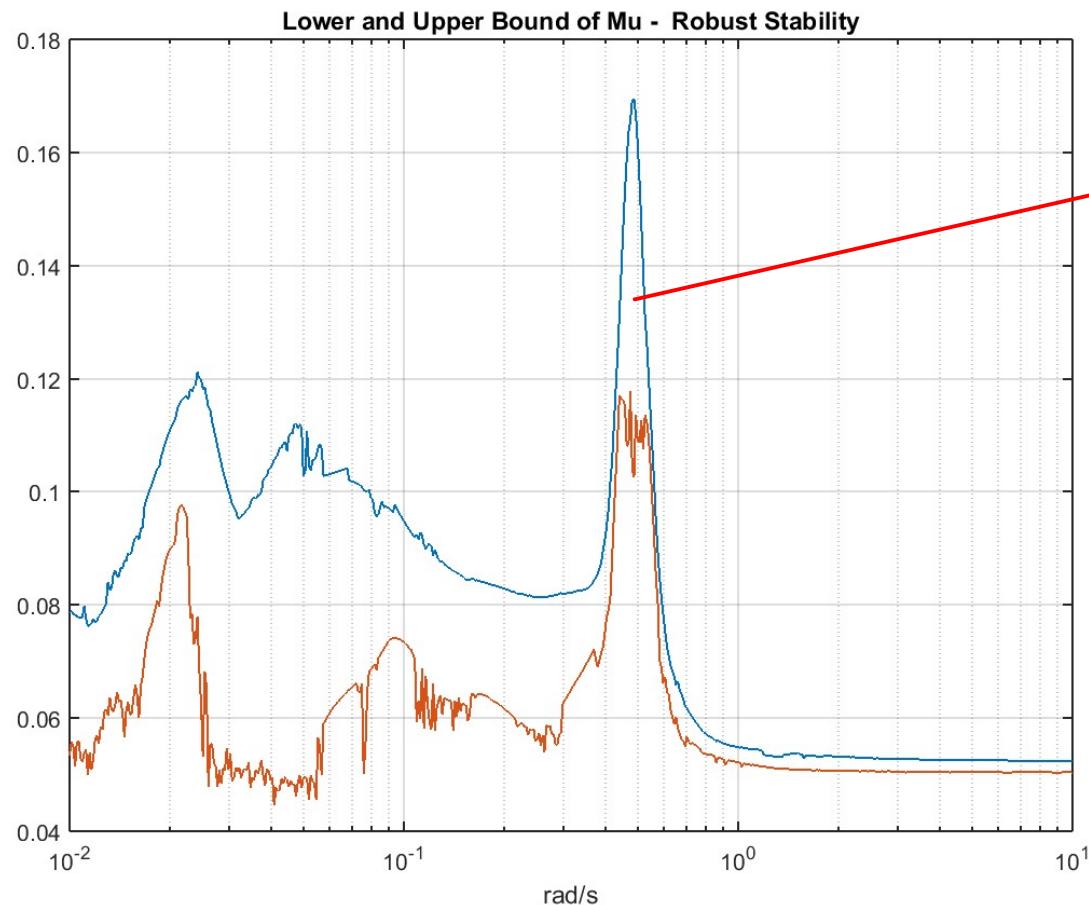
FMC2– ANALYSIS
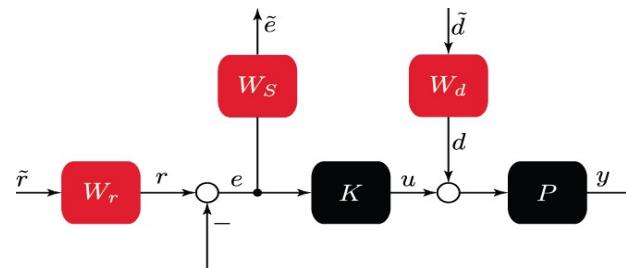
Robust performance
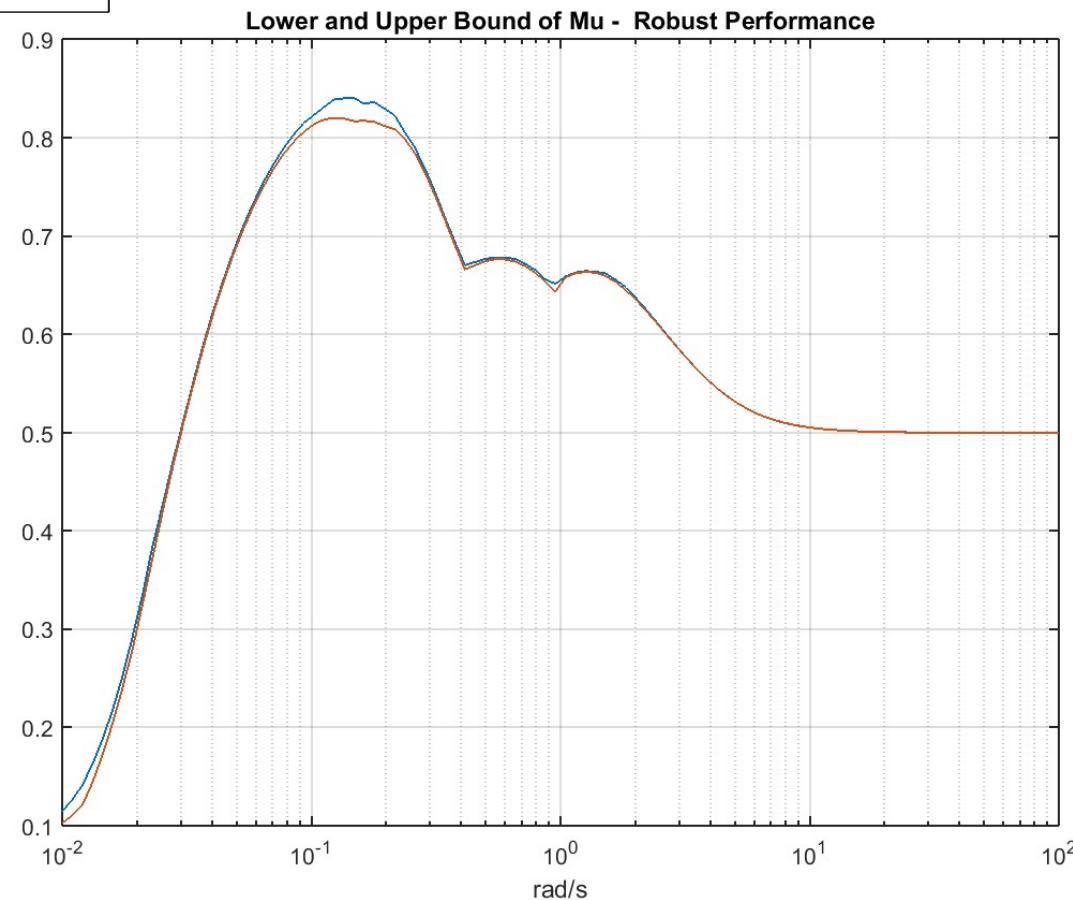
DETUMBLING
Validation campain

FUNCTIONAL ENGINEERING SIMULATOR AND VALIDATION CAMPAIGN

- FES accounts for **effects that could not be captured in the linear** analyses:
  - **M.B. dynamics/kinematics** non-linear effects (e.g. second order terms in accelerations, full attitude kinematics…)
  - **Measurements** non-linearities (rate limits, discretization, Sun blinding etc …) and more complex error models (e.g. Gauss-Markov processes for representing time evolution of the bias terms).
  - **Actuation** system non-linearities:
    - Thrusters Management Function (simplex optimisation of the thruster firings)
    - Thrusters MIB, saturation and other effects in their error modelling
    - Much more approximate evaluation of the propellant consumption (by accounting for real geometry and thrust limitations of the different thrusters sets).

FUNCTIONAL ENGINEERING SIMULATOR

- Implementation:
  - As **GNCDE Templates**: GNCDE v3.8.1 (Running on Matlab R2015a 64 bits)
  - Independent implementation for several phases was considered cleaner and more efficient:
    - **DETUMBLING_M_COMPOSITE**. Detumbling phase (composite configuration). Multi-body dynamics: Chaser/Arm/Target with joints in locked configuration (modelled as flexible elements).
    - **DETUMBLING_M_COMPOSITE10DOF.** Variant for simultaneous braking and relocation of target by arm movements. Multi-body dynamics: Chaser/Arm/Target with torque inputs to joints and readable angle encoders.
    - **DETUMBLING_M_CH_ARM**. Arm deployment phase. Multi-body dynamics: Chaser/Arm with torque inputs to joints and readable angle encoders.
    - **DETUMBLING_M_CH**. Sub-phases of the close Rendezvous and Synchronisation phase where the Arm is not moving. Chaser+Arm treated as a single rigid body for computational efficiency
    - **DETUMBLING_M_CAPTURE.** Capture sub-phase (up to contact) with 10DOF controller. Chaser/Arm with torque inputs to joints and readable angle encoders.

MULTI-BODY DYNAMICS

■ **M.B. dynamics/kinematics models**:

– multi-body attitude and position dynamics and kinematics of a chain composed of several elements**: base + arm segments + target + SA** connected by means of **revolute joints.**

– several versions of the model implemented:

- **MB_arm_locked**
- **MB_arm_free**
- **MB_arm_free_target**

– Simscape multibody implementation validated against the formulation proposed in *Queen S. (NASA Goddard) "Momentum-Based Dynamics for Spacecraft with Chained Revolute Appendages"*

MULTI-BODY DYNAMICS

Fundamentals of the *Queen S. (NASA Goddard) "Momentum-Based Dynamics for Spacecraft with Chained Revolute Appendages"* formulation
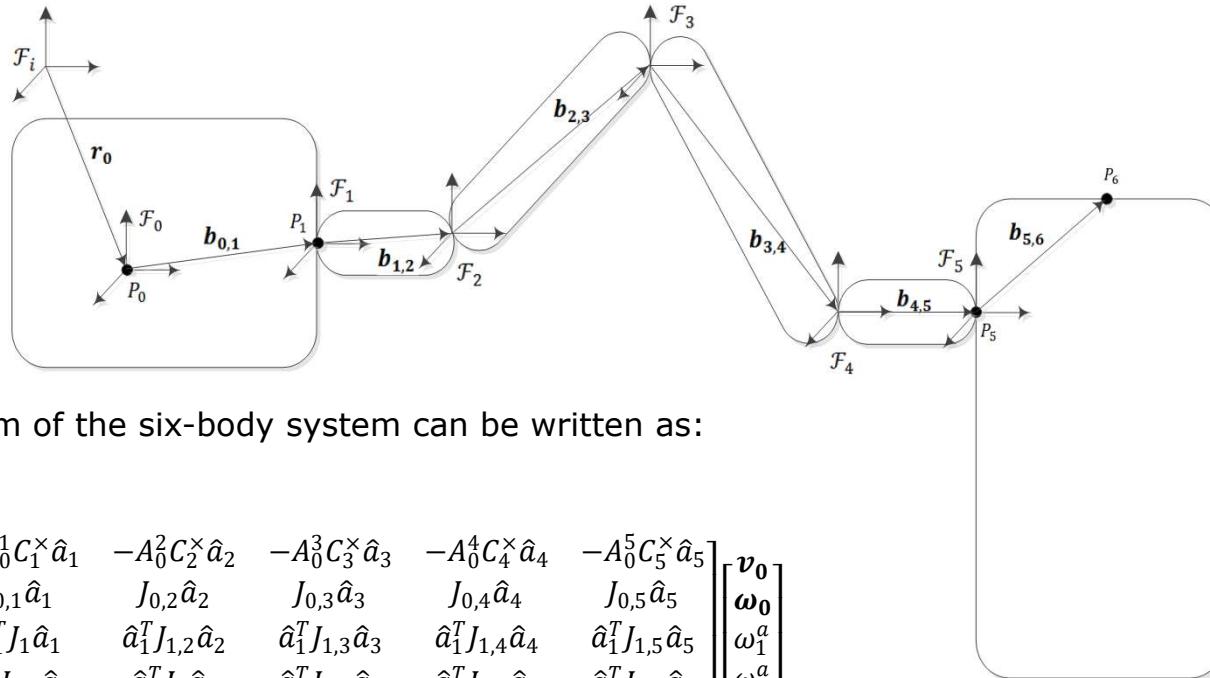
The generalized momentum of the six-body system can be written as:

$$\mathcal{P} = \mathcal{M}\mathcal{V}$$

$$
\begin{bmatrix} \boldsymbol{P_0} \\ \boldsymbol{H_0} \\ H_1^a \\ H_2^a \\ H_3^a \\ H_4^a \\ H_5^a \end{bmatrix} =
\begin{bmatrix}
M_0 \cdot \mathbb{I} & -C_0^\times & -A_0^1 C_1^\times \hat{a}_1 & -A_0^2 C_2^\times \hat{a}_2 & -A_0^3 C_3^\times \hat{a}_3 & -A_0^4 C_4^\times \hat{a}_4 & -A_0^5 C_5^\times \hat{a}_5 \\
C_0^\times & J_0 & J_{0,1}\hat{a}_1 & J_{0,2}\hat{a}_2 & J_{0,3}\hat{a}_3 & J_{0,4}\hat{a}_4 & J_{0,5}\hat{a}_5 \\
\hat{a}_1^T C_1^\times \mathcal{A}_1^0 & \hat{a}_1^T J_{1,0} & \hat{a}_1^T J_1 \hat{a}_1 & \hat{a}_1^T J_{1,2}\hat{a}_2 & \hat{a}_1^T J_{1,3}\hat{a}_3 & \hat{a}_1^T J_{1,4}\hat{a}_4 & \hat{a}_1^T J_{1,5}\hat{a}_5 \\
\hat{a}_2^T C_2^\times \mathcal{A}_2^0 & \hat{a}_2^T J_{2,0} & \hat{a}_2^T J_{2,1}\hat{a}_1 & \hat{a}_2^T J_2 \hat{a}_2 & \hat{a}_2^T J_{2,3}\hat{a}_3 & \hat{a}_2^T J_{2,4}\hat{a}_4 & \hat{a}_2^T J_{2,5}\hat{a}_5 \\
\hat{a}_3^T C_3^\times \mathcal{A}_3^0 & \hat{a}_3^T J_{3,0} & \hat{a}_3^T J_{3,1}\hat{a}_1 & \hat{a}_3^T J_{3,2}\hat{a}_2 & \hat{a}_3^T J_3 \hat{a}_3 & \hat{a}_3^T J_{3,4}\hat{a}_4 & \hat{a}_3^T J_{3,5}\hat{a}_5 \\
\hat{a}_4^T C_4^\times \mathcal{A}_4^0 & \hat{a}_4^T J_{4,0} & \hat{a}_4^T J_{4,1}\hat{a}_1 & \hat{a}_4^T J_{4,2}\hat{a}_2 & \hat{a}_4^T J_{4,3}\hat{a}_3 & \hat{a}_4^T J_4 \hat{a}_4 & \hat{a}_4^T J_{4,5}\hat{a}_5 \\
\hat{a}_5^T C_5^\times \mathcal{A}_5^0 & \hat{a}_5^T J_{5,0} & \hat{a}_5^T J_{5,1}\hat{a}_1 & \hat{a}_5^T J_{5,2}\hat{a}_2 & \hat{a}_5^T J_{5,3}\hat{a}_3 & \hat{a}_5^T J_{5,4}\hat{a}_4 & \hat{a}_5^T J_5 \hat{a}_5
\end{bmatrix}
\begin{bmatrix} \boldsymbol{v_0} \\ \boldsymbol{\omega_0} \\ \omega_1^a \\ \omega_2^a \\ \omega_3^a \\ \omega_4^a \\ \omega_5^a \end{bmatrix}
$$

And the associated first order differential equations of motion for the momentum states are:

$$\dot{\boldsymbol{P}}_0 = -\boldsymbol{\omega}_0^\times \boldsymbol{P}_0 + \boldsymbol{F}_0^{ext}$$

$$\dot{\boldsymbol{H}}_0 = -\boldsymbol{\omega}_0^\times \boldsymbol{H}_0 - \boldsymbol{v}_0^\times \boldsymbol{P}_0 + \boldsymbol{G}_0^{ext}$$

$$\dot{H}_n^a = \boldsymbol{\omega}_n^T a_n^\times \boldsymbol{H}_n + \boldsymbol{v}_n^T a_n^\times \boldsymbol{P}_n + \hat{\boldsymbol{a}}_n^T \boldsymbol{g}_n + \hat{\boldsymbol{a}}_n^T \boldsymbol{G}_n^{ext}$$

MULTI-BODY DYNAMICS

- **M.B. dynamics/kinematics**
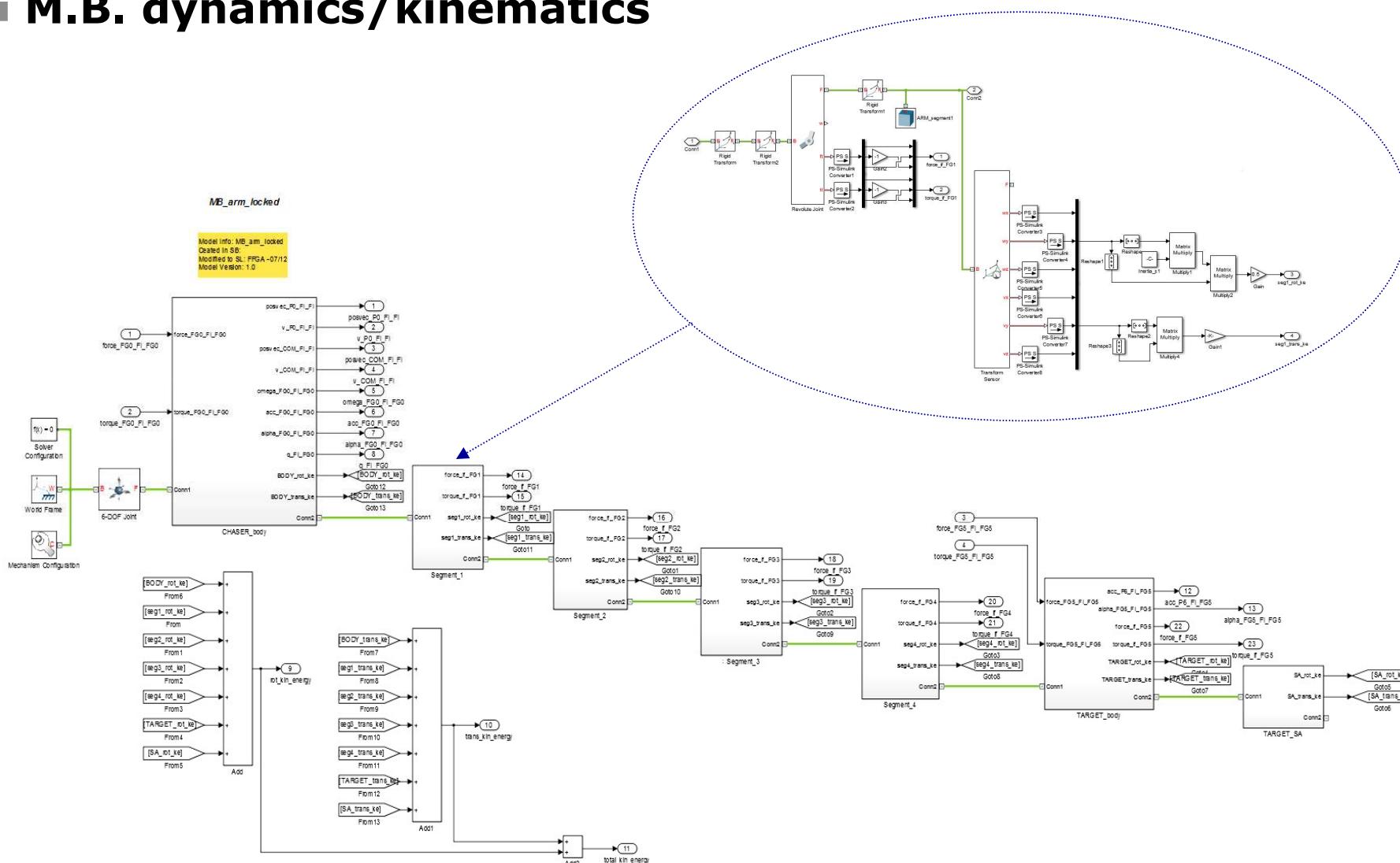
NON-LINEAR VALIDATION (MC CAMPAIGN)

- Monte Carlo campaign in Fast Accelerator mode.
  - Target rotation: 3º/s to 5º/s
  - Propulsion system baseline: 6x4 22N thrusters (Isp = 290s). Simplex thrust optimisation method.
  - Multi-body dynamics for sub-phases: Arm-deployment, Capture, Detumbling and Detumbling with simultaneous Chaser relocation.
  - Arm not sensored (only joint encoders)
  - Absolute attitude/attitude rate sensors simulated
  - Relative navigation behavioural models
- Parameters variation according to defined boundaries (same as LFTs > 60 parameters varied in FMCC mode) + noise model seeds and others
  - High sensitivity to chaser physical properties (mass,inertia, COM position) and sloshing parameters (freq. and damping)

NON-LINEAR VALIDATION (MC CAMPAIGN)

- ## Arm unfolding

Joint	Start time [s]	Start angle [deg]	End time [s]	End angle [deg]
1	0	0	0	0
2	100	90	200	-50
3	120	180	220	80
4	120	-180	220	-40
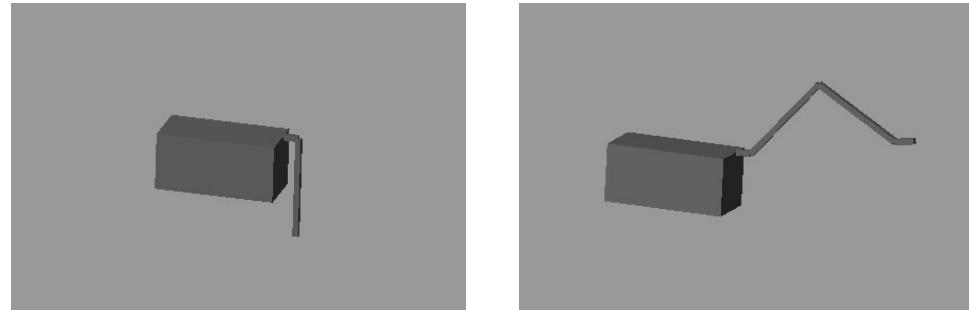
Joints 2,3 and 4 angles profile
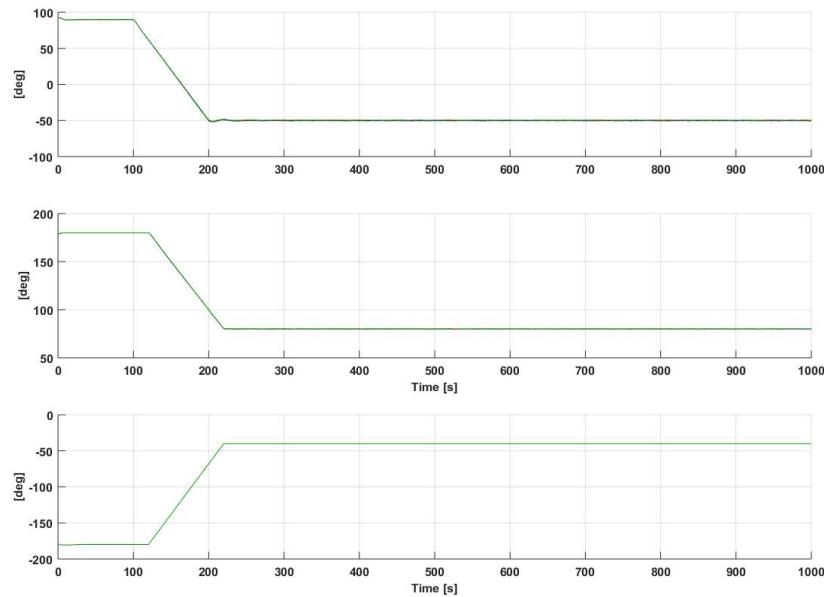
Joints 2,3 and 4 torque profiles
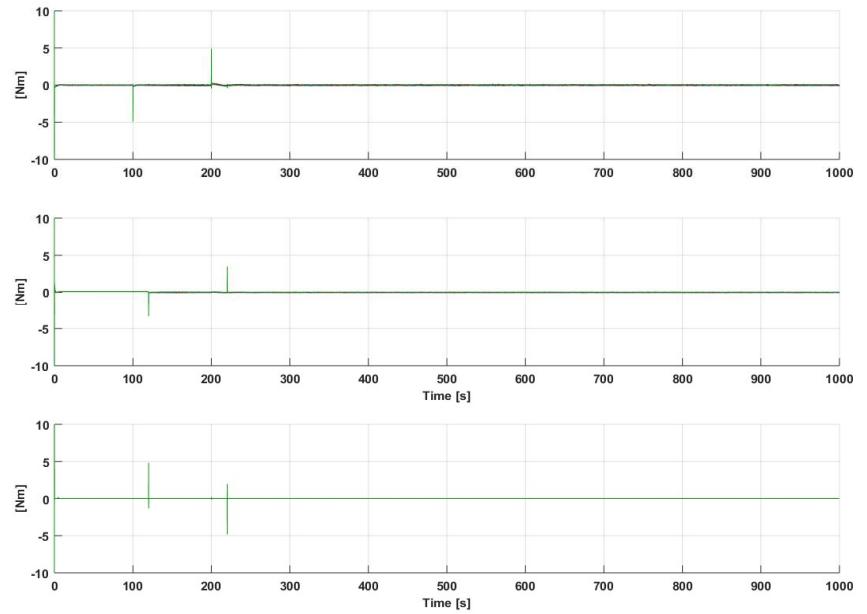
NON-LINEAR VALIDATION (MC CAMPAIGN)

■ **Arm unfolding**

Pointing error (321Euler angles [deg]) – 100 cases
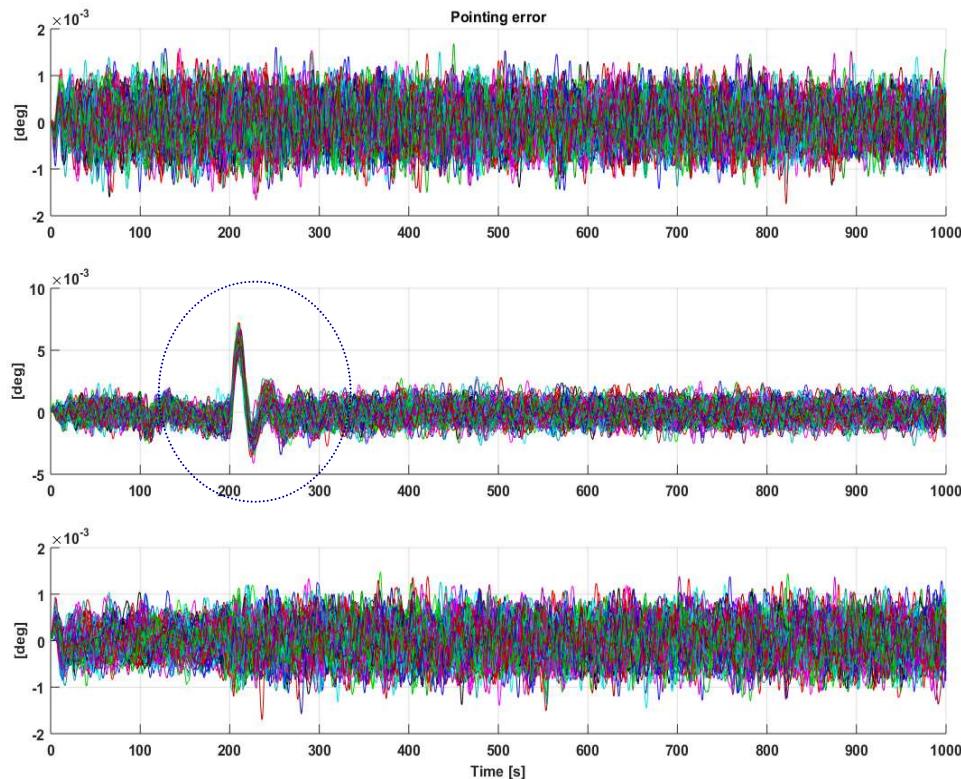
Pointing error (error angle [deg]) – 100 cases
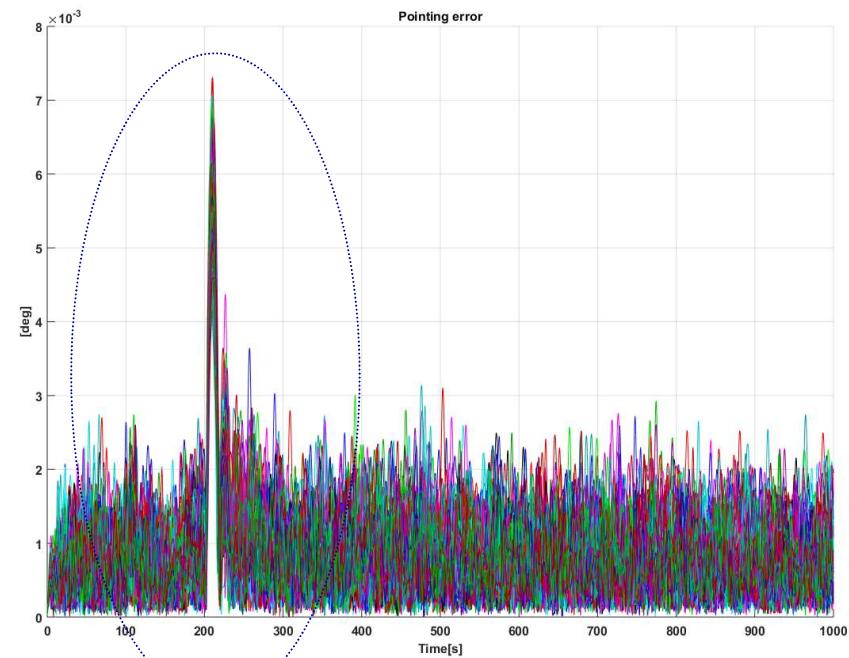
NON-LINEAR VALIDATION (MC CAMPAIGN)

■ **Arm unfolding**

Commanded and actuation torques (100 cases)
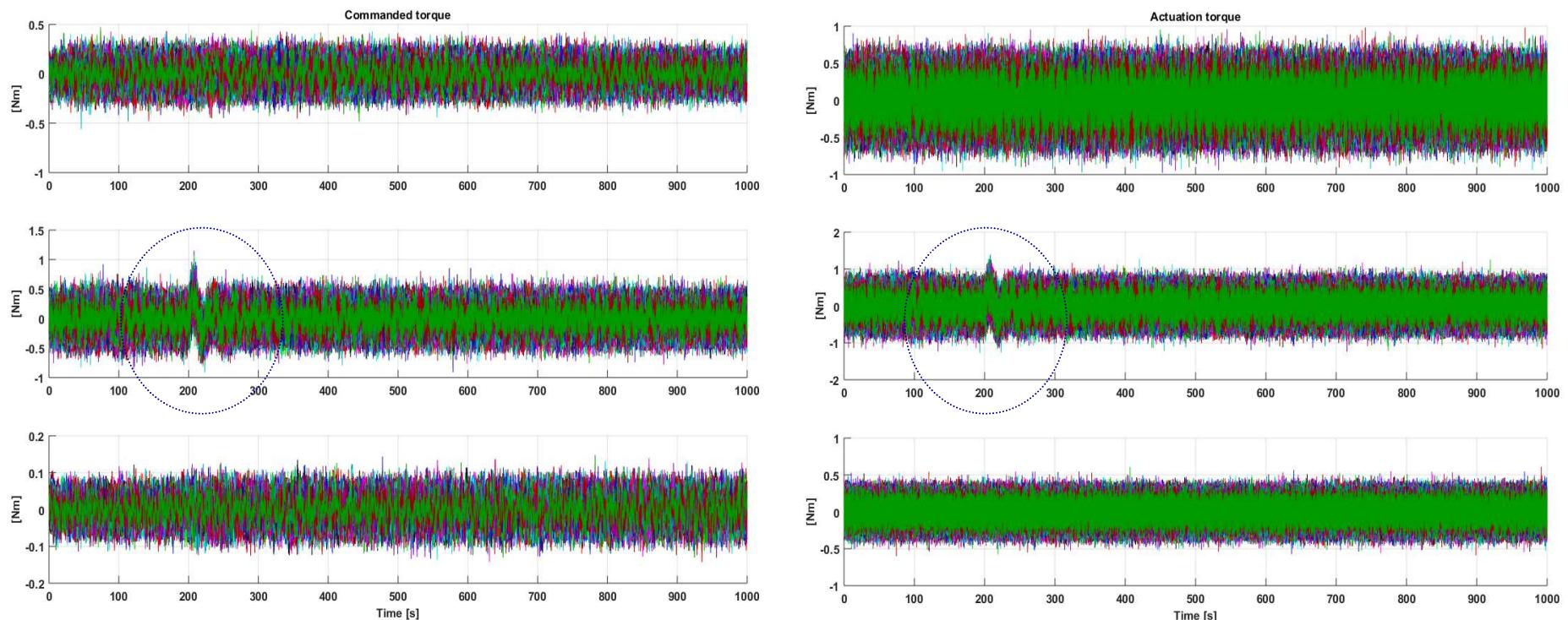
NON-LINEAR VALIDATION (MC CAMPAIGN)

- **Chaser close-in and synchronization with target**

Sub-phase id.	Description	Duration [s]	Start distance	End distance
1	V-bar forced approach	180	100	30
2	Fly around to H (angular momentum) vector	300	30	30
3	Chaser closing along H vector direction	180	30	7
4	Chaser transfer to target frame	10	7	7
5	Fly-around the target	180	7	7
6	Chaser close in target frame	180	7	0

Guidance profiles (100 cases)
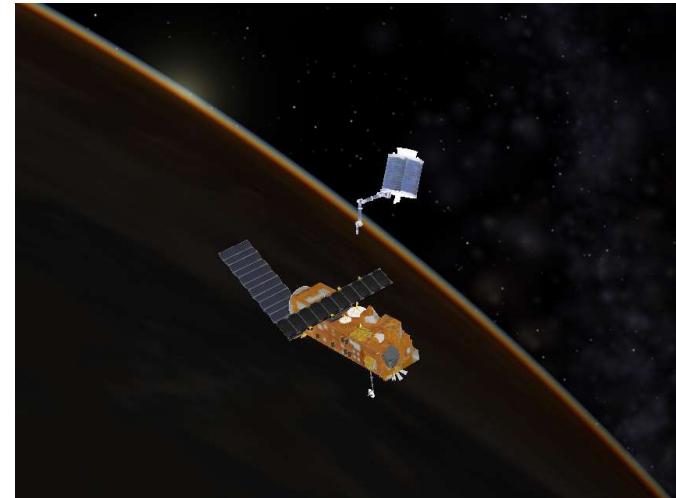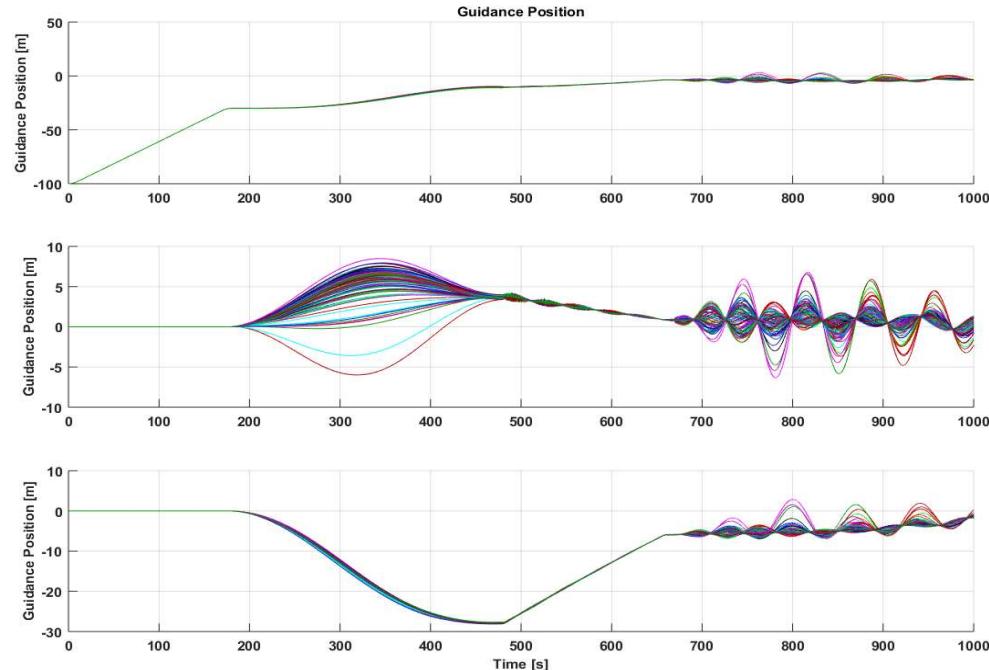
NON-LINEAR VALIDATION (MC CAMPAIGN)

- **Chaser close-in and synchronization with target**

Angular rate error (100 cases)
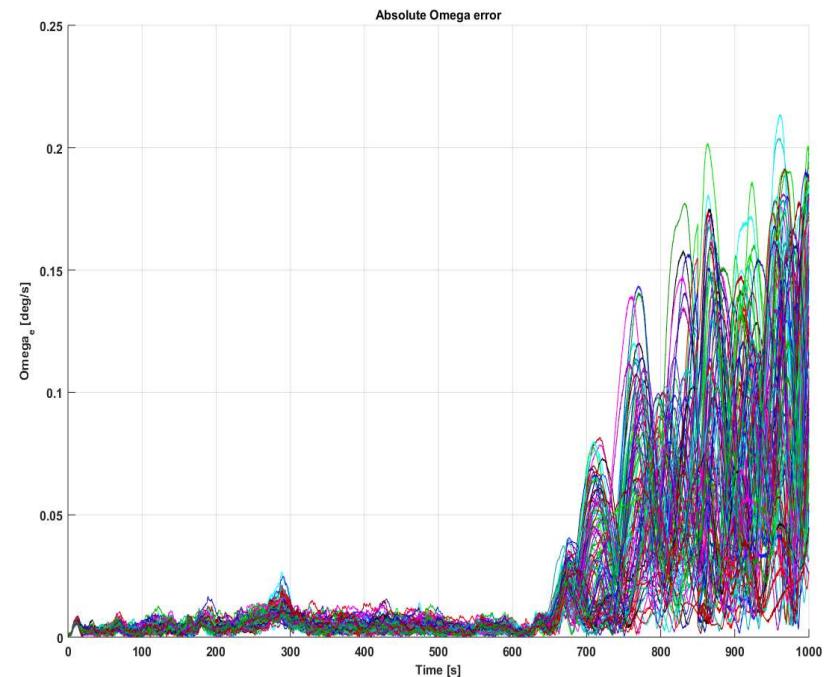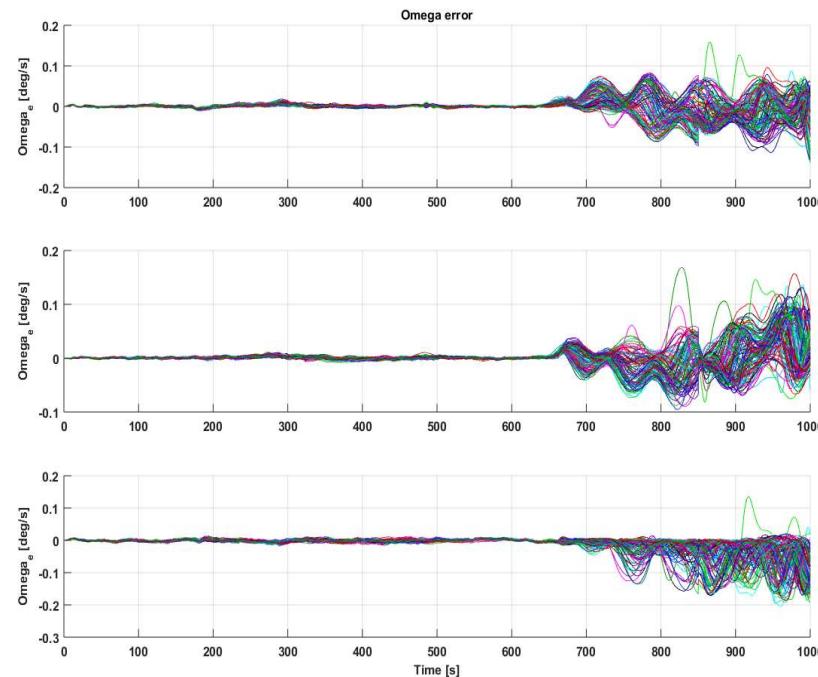
NON-LINEAR VALIDATION (MC CAMPAIGN)

■ **Chaser close-in and synchronization with target**

Pointing error (100 cases) along all sub-phases
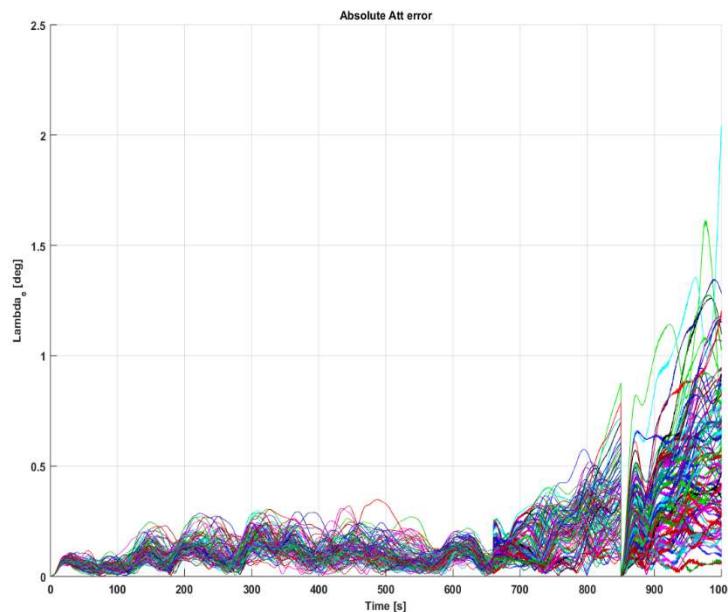
Position error (100 cases) along all sub-phases
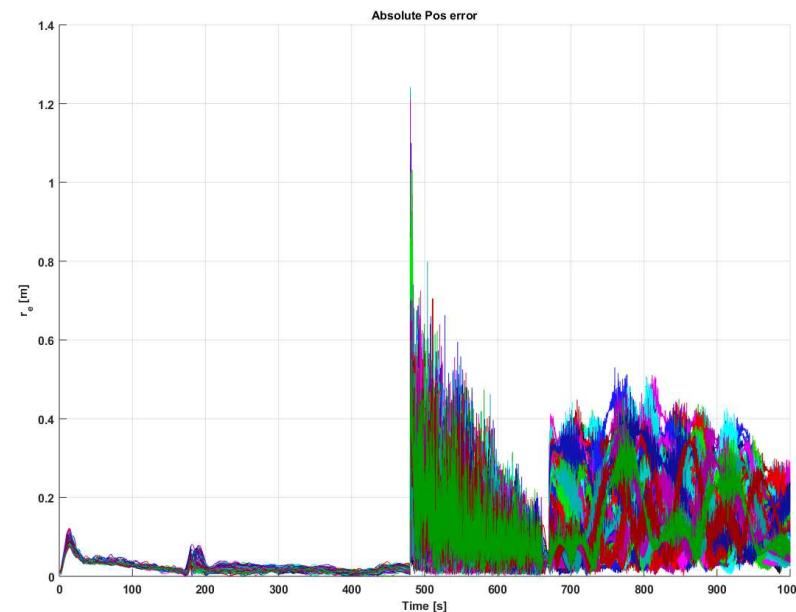
NON-LINEAR VALIDATION (MC CAMPAIGN)

- **Detumbling phase**
  - Chaser initially synchronised to target rotational state
  - Arm joints in locked in fixed configuration (rigidised)

Evolution of COMPOSITE angular velocity (100 cases)
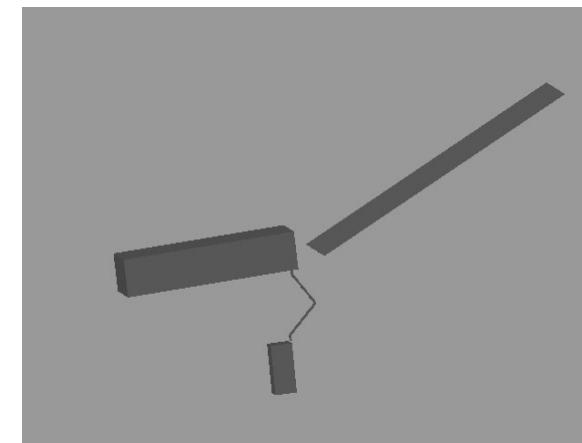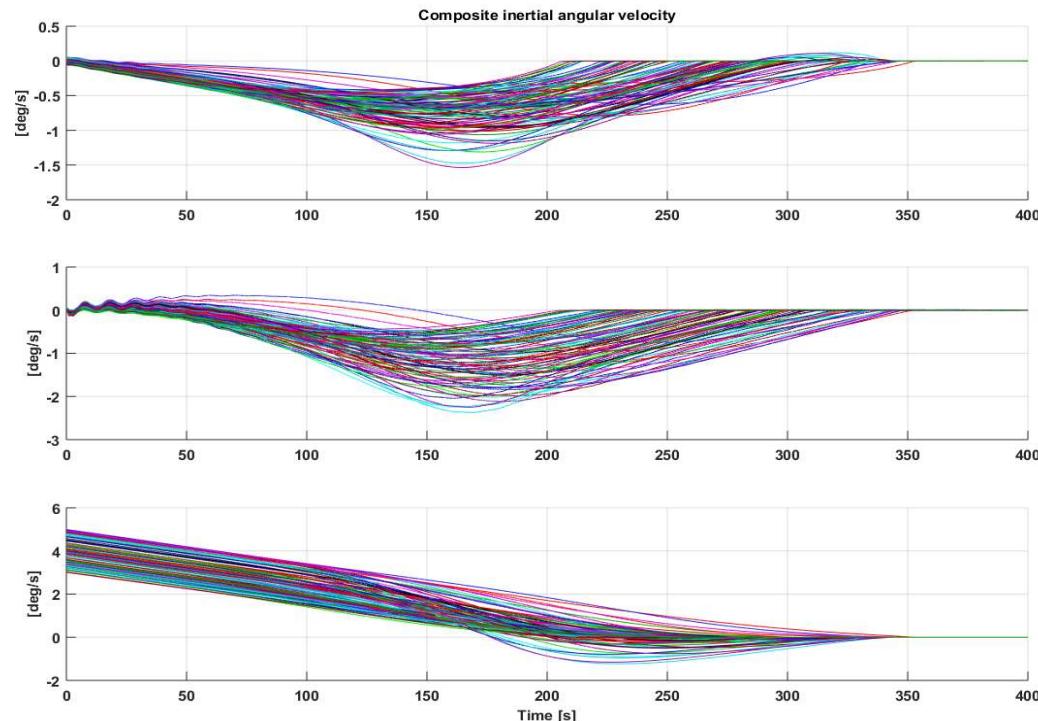
NON-LINEAR VALIDATION (MC CAMPAIGN)

– Control effort (main variation due to initial COMPOSITE rotational kinetic energy)

Evolution of COMPOSITE rotational kinetic energy (100 cases)
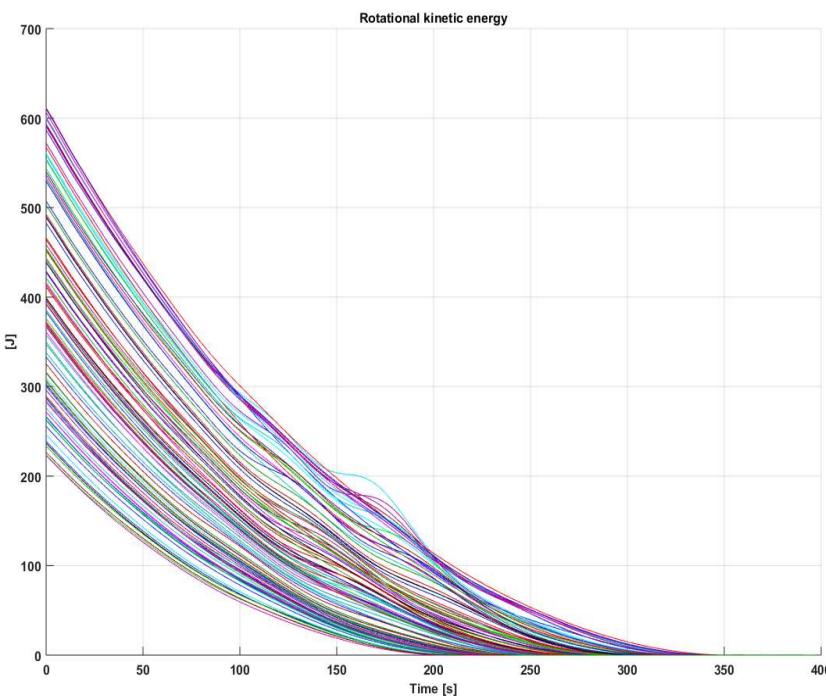
Propellant consumption (100 cases)
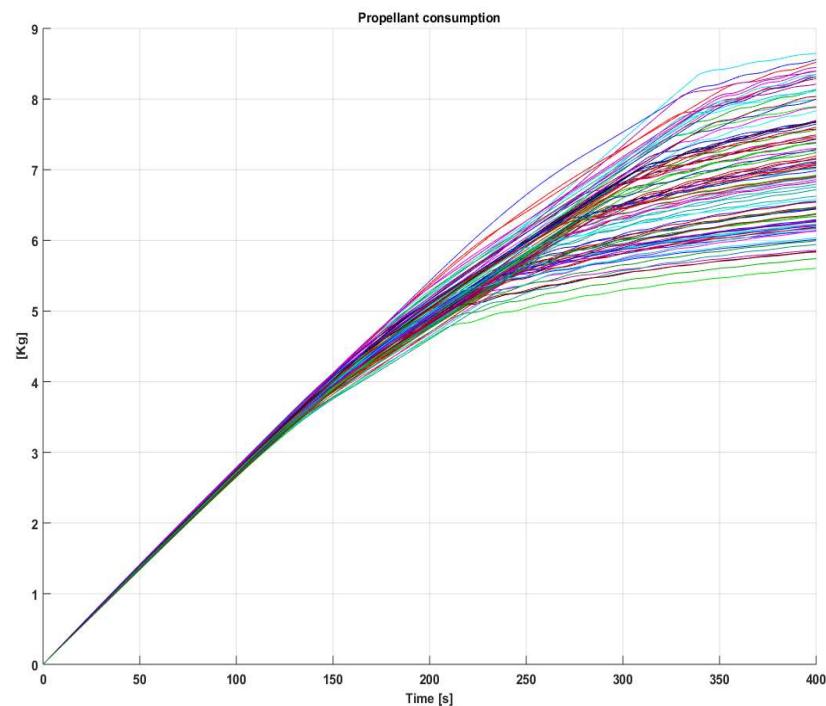
NON-LINEAR VALIDATION (MC CAMPAIGN)

– Important control forces are required to keep chaser synchronisation and avoid overloading joints
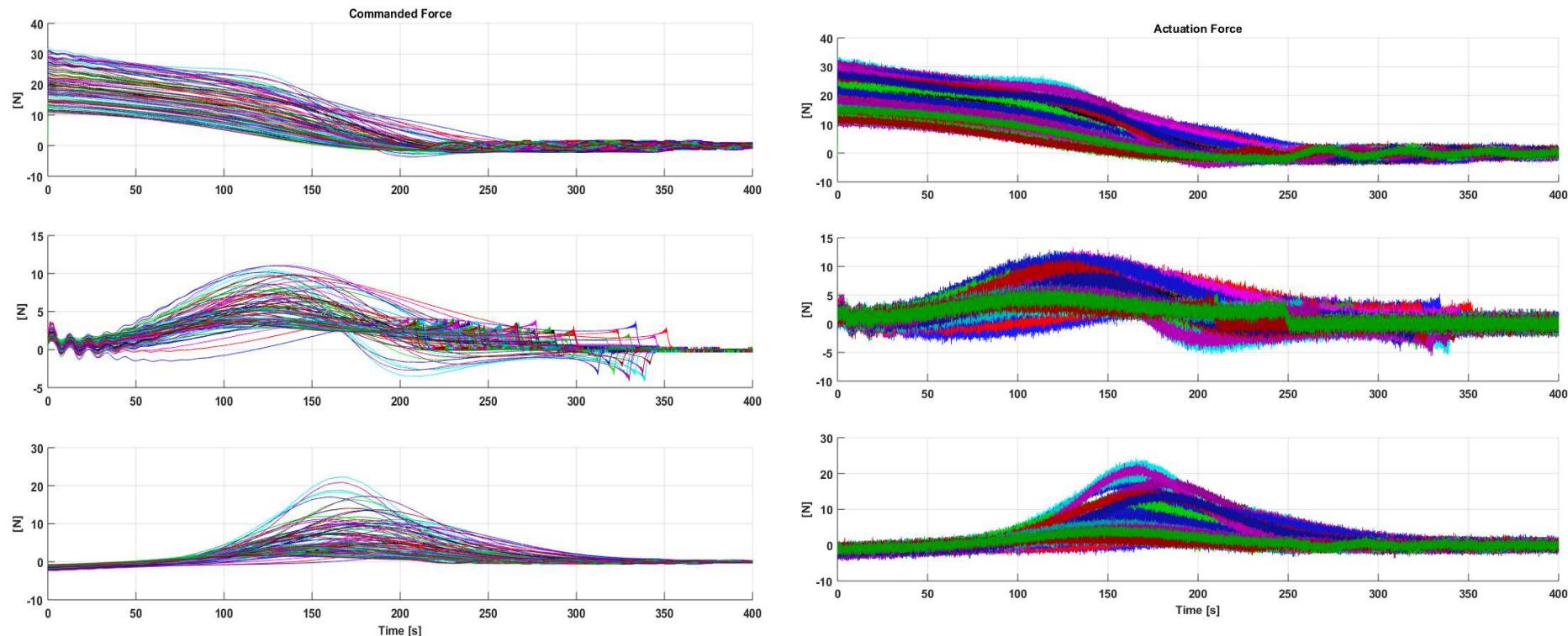
NON-LINEAR VALIDATION (MC CAMPAIGN)

– Also attitude agility (important torque levels) and precission are required to keep synchronised
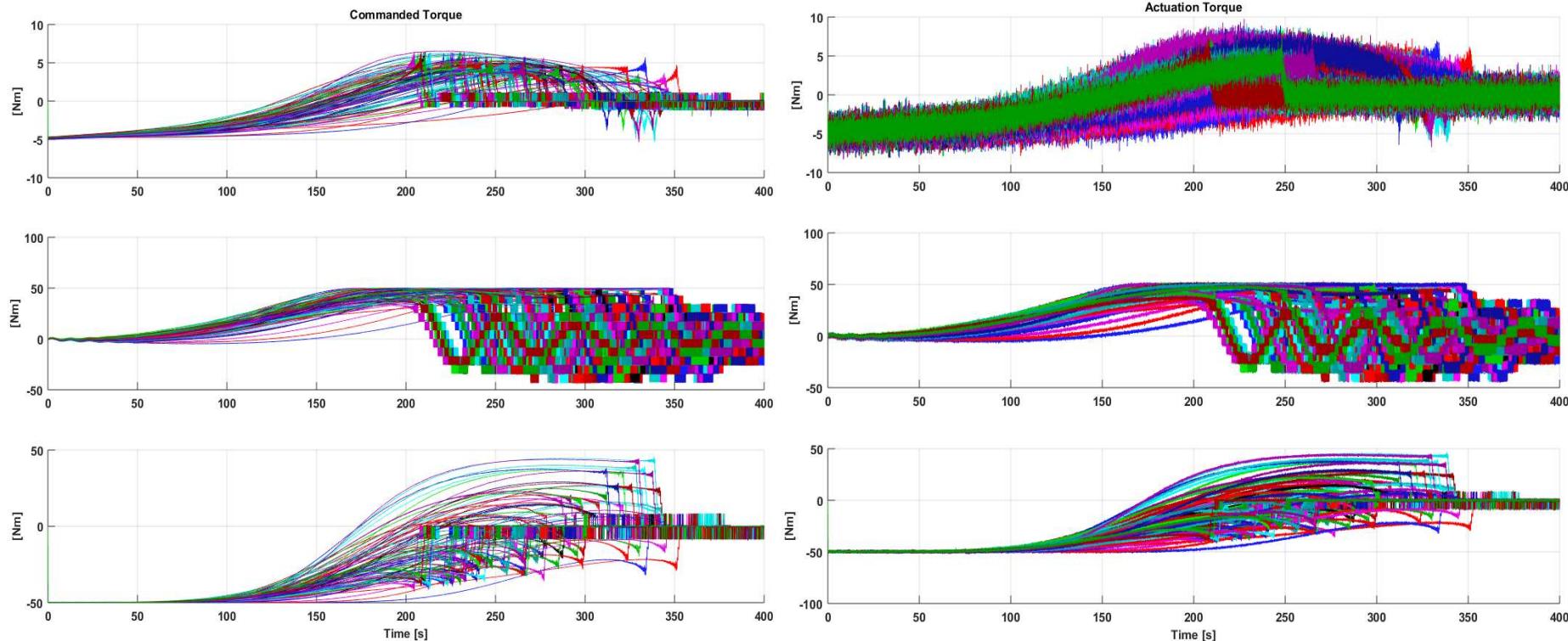
NON-LINEAR VALIDATION (MC CAMPAIGN)

– Joint loads (joint 1)
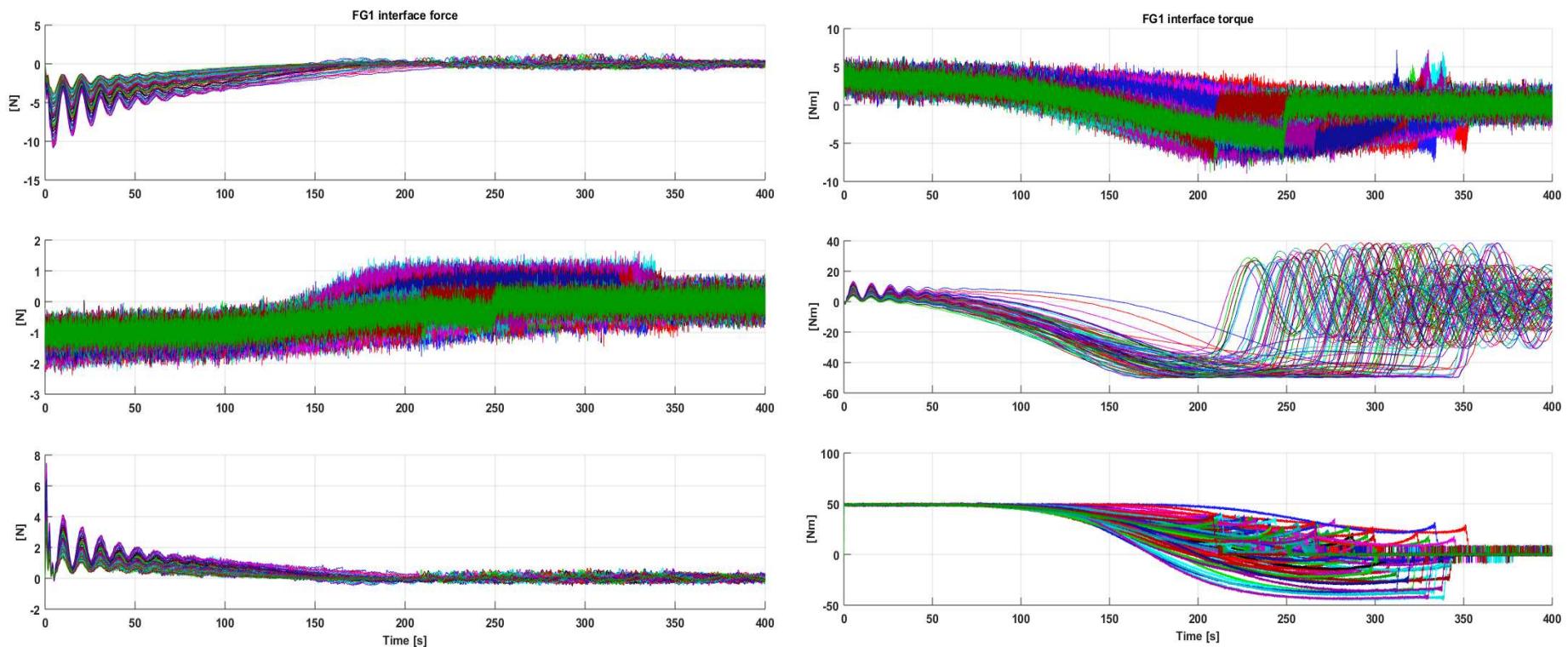
NON-LINEAR VALIDATION (MC CAMPAIGN)

– Joint loads (joint 4)
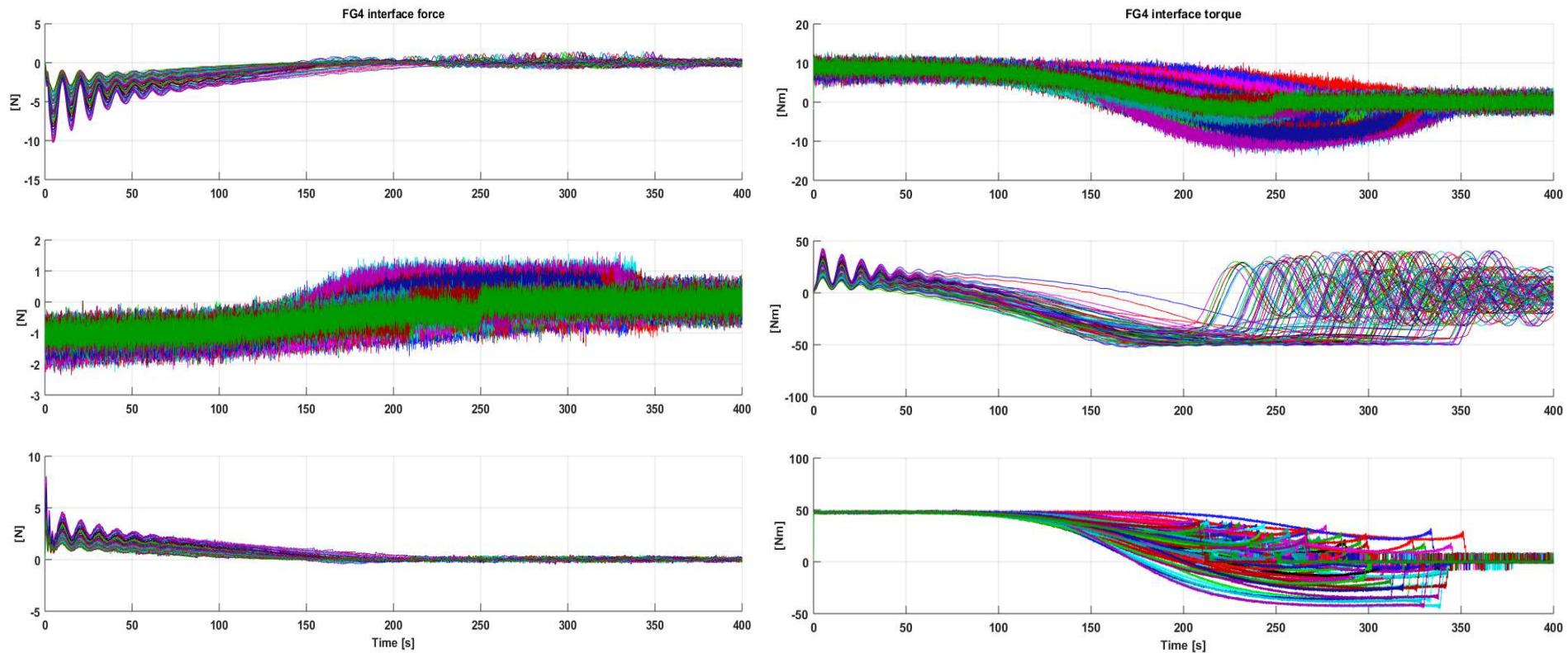
NON-LINEAR VALIDATION

- **Detumbling phase with simultaneous chaser relocation**
  - Chaser initially synchronised to target rotational state
  - Arm joints controlled to relocate the chaser while composite braking


Composite inertial angular velocity
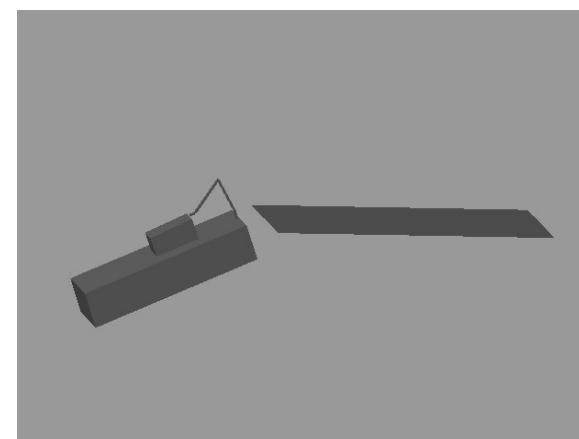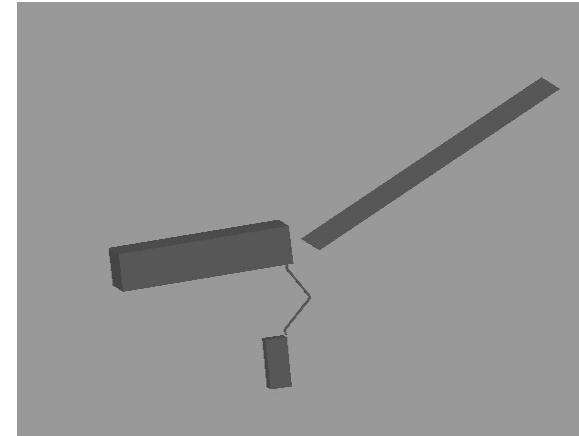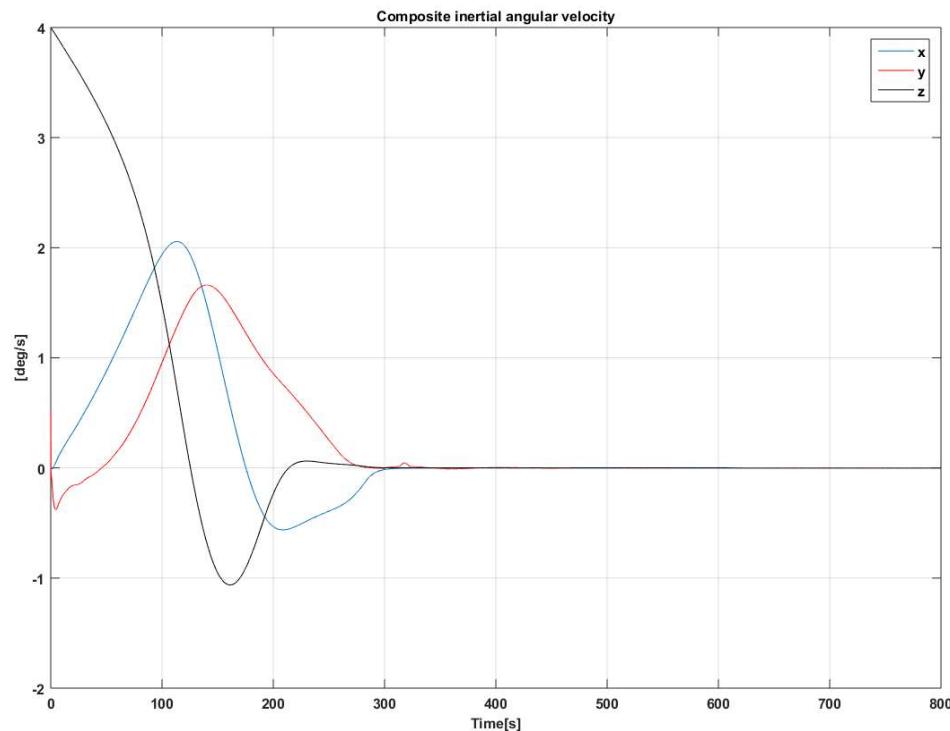
NON-LINEAR VALIDATION

– Control effort

- Propellant consumption does not show significant impact w.r.t the arm locked case.
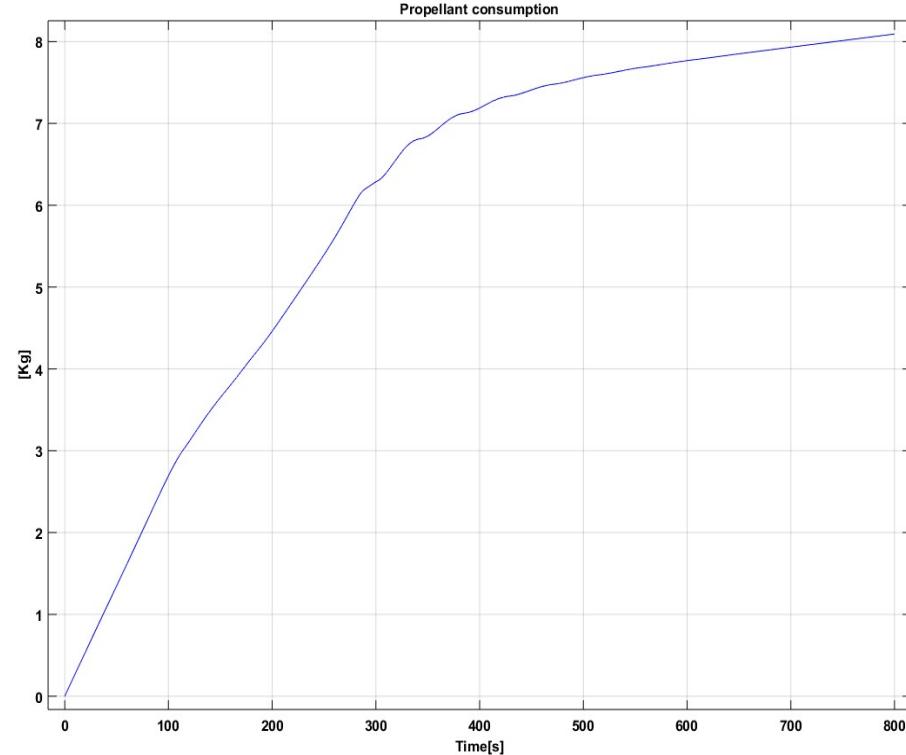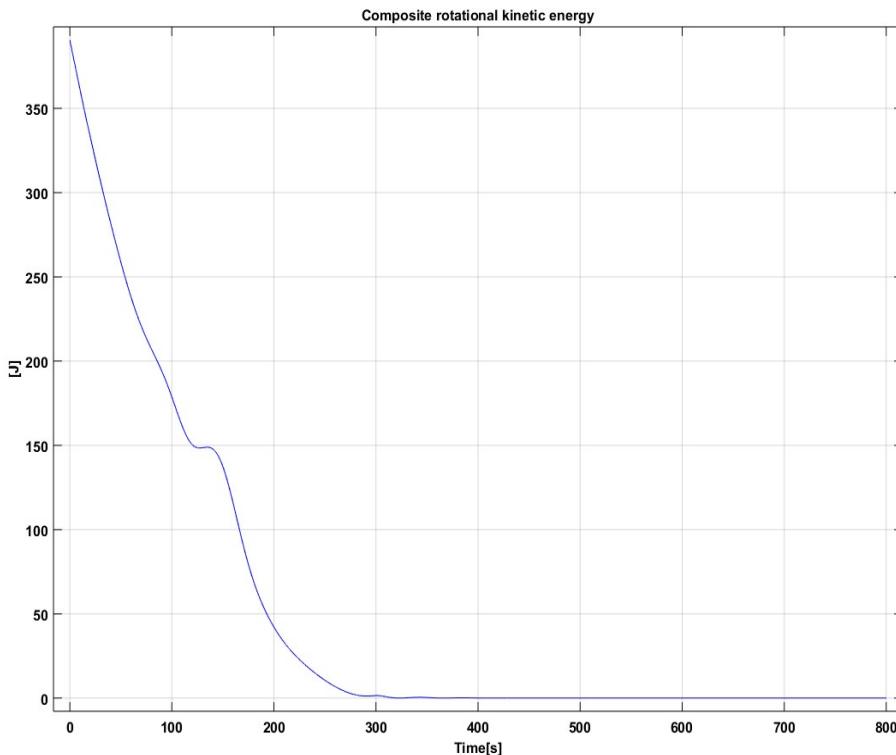
NON-LINEAR VALIDATION

– Arm joint interface loads and joint motor control torques
  - Motor torques required to compensate for centripetal loads are high for large targets rotating at high speed
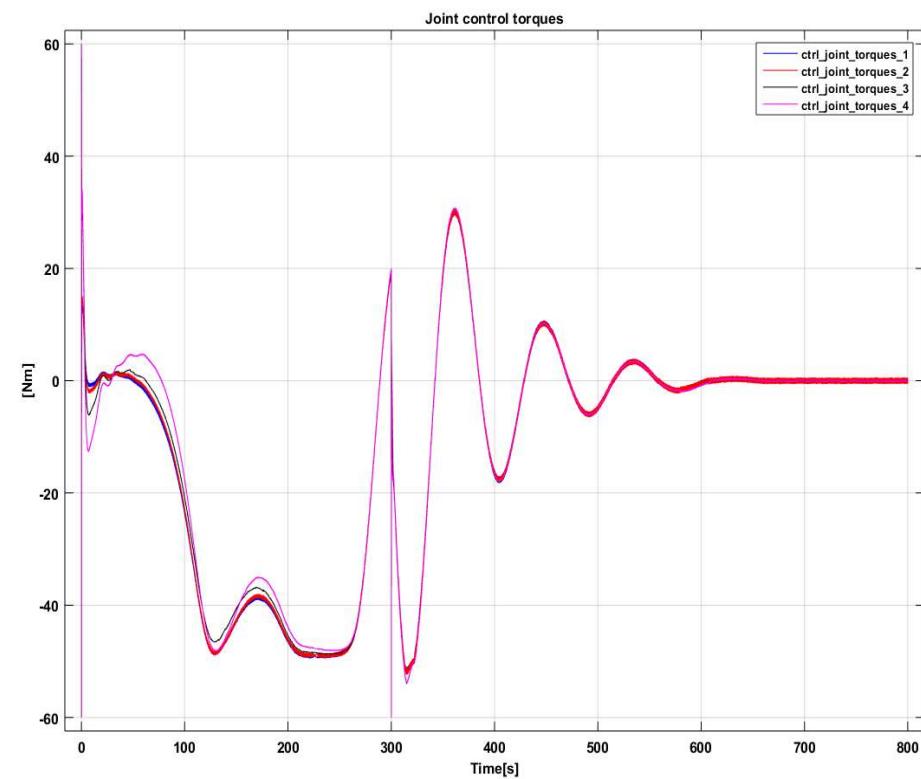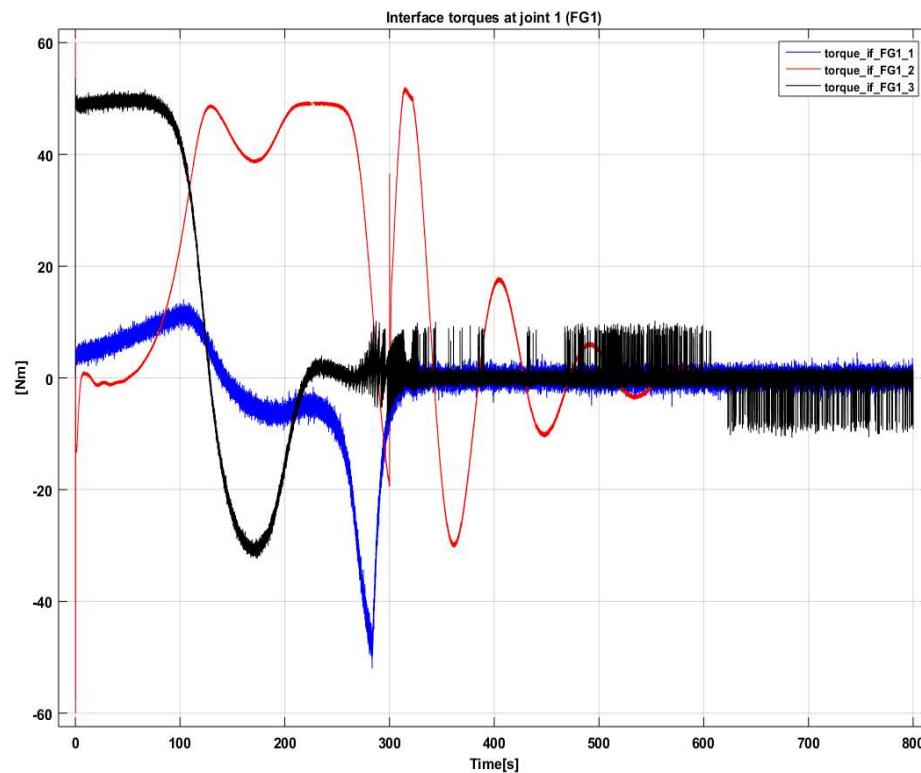
NON-LINEAR VALIDATION

- Control effort
  - Chaser control forces to keep synchronisation to target rotational state are similar to the pure braking case
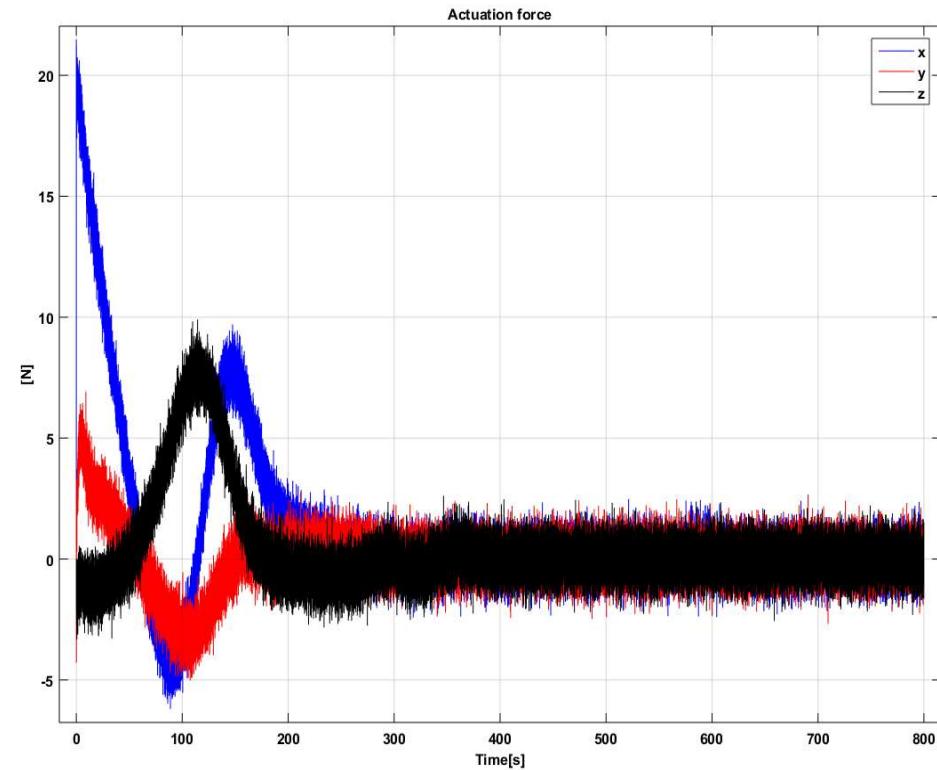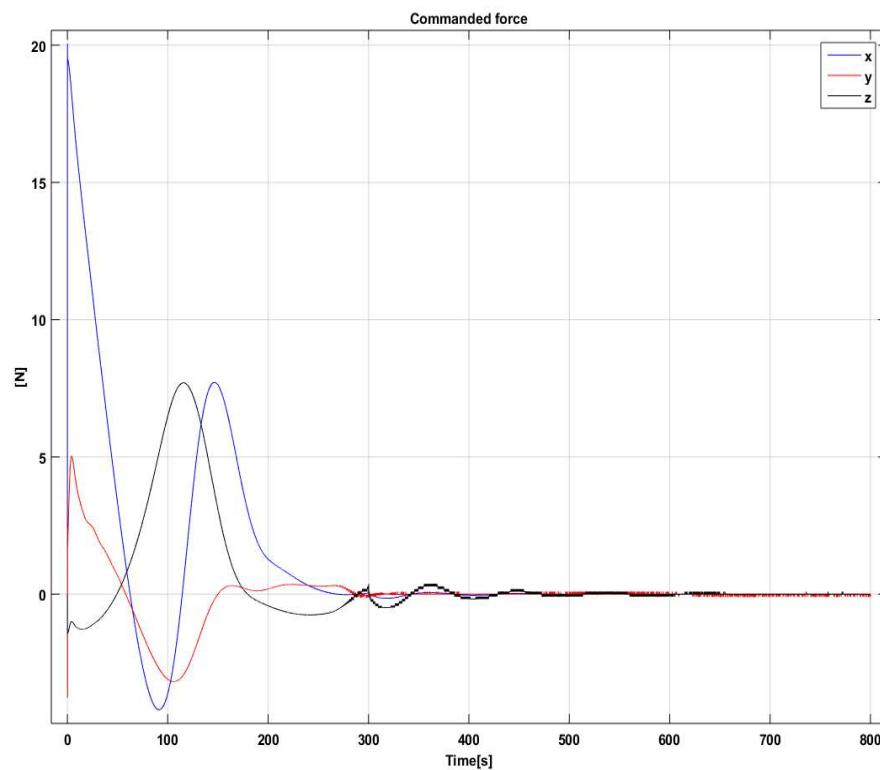
NON-LINEAR VALIDATION

– Chaser commanded and actuation torques
  • Similar to pure braking without relocation of the chaser
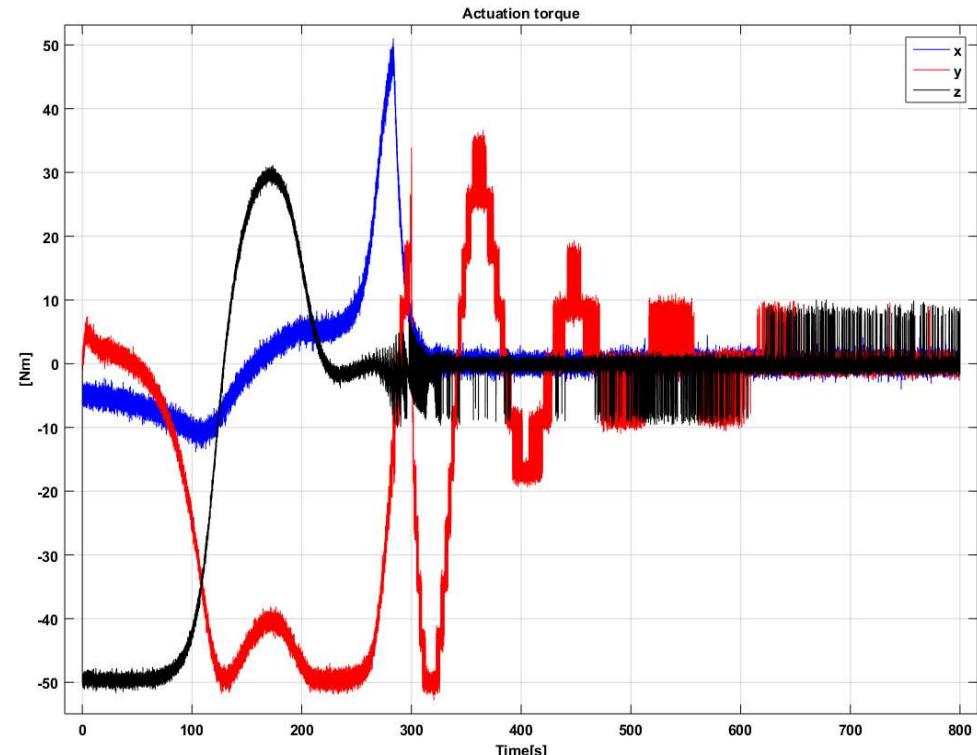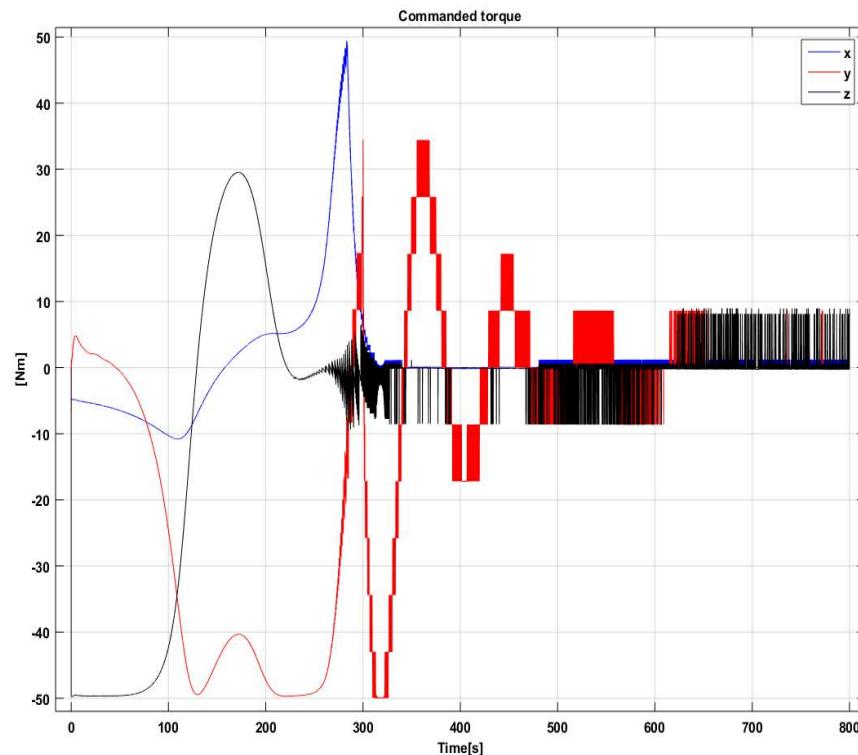
DETUMBLING
Conclusions

CONCLUSIONS - I

- MIMO **Robust synthesis/analysis** approach demonstrated to be valid for all sub-phases of a robotic arm detumbling mission (contact capture phases out of the scope of the study)
- MonteCarlo campaign **confirmed robust stability/performance** of the designed controllers for
  - arm unfolding
  - chaser close-in and synchronization
  - composite detumbling
  - composite detumbling with simultaneous chaser relocation
- **Arm unfolding phase**: no significant impact on the chaser attitude stabilisation while in target pointing (ts < 50s and control actions <1.5Nm for unfolding time = 100s)
- **Synchronisation phase:** very demanding for the GNC (high agility + low actuation and navigation errors) due to **target body rotation rate** (up to 5º/s).
  - FMC1 mean pointing error (<1deg) for the whole synchronisation phase.
  - Relative position errors in the limit of usability → Propulsion system for higher agility and lower noise levels seems required for dealing with targets rotating at such a high rate.

CONCLUSIONS - II

- **Detumbling phase:** impact of large target rotation rate and size of the target. Analyses show:
  - Just **centripetal loads** while in composite configuration could be able to cause mechanical problems. Keeping an almost perfect synchronisation of the chaser to the target tumbling state is required, but it cannot be achieved with current relative navigation technology.
  - **Arm loads measuring** (indirect way of measuring the synchronization) seems highly desirable for this phase.
  - If not relying on sensored joints (as is our study case), careful selection of the nominal **arm geometry** has demonstrated being able to contain the maximum loads on joints. Also efficient **feed-forward** laws that help reducing the composite kinetic energy quicker (before chaser desynchronization is large) have demonstrated to be very useful.
- **Simultaneous Composite braking and chaser relocation:**
  - Demonstrated to be feasible with MIMO robust control.
  - No significant impact on settling time, control effort and joint loads.
  - To properly perform the relocation manoeuvre, torques provided by the joint control inner loops (joint motors) are required to withstand centripetal loads (if no relocation, joint brakes withstand the loads appearing in the joint axes directions).

DETUMBLING
AoB

Thank you

Thomas Vincent Peters (GMV)

Pedro Arroz Correia (GMV)

Joris Naudet (QinetiQ)

Fernando Gandía(GMV)

DETUMBLING
Backup slides

DETUMBLING
ENVISAT and COSMOS rotational state

LTP SIMULATOR VERIFICATION APPROACH (3/4)

Envisat

- Rotation axis known
- Characteristic decay time ~4.5 years
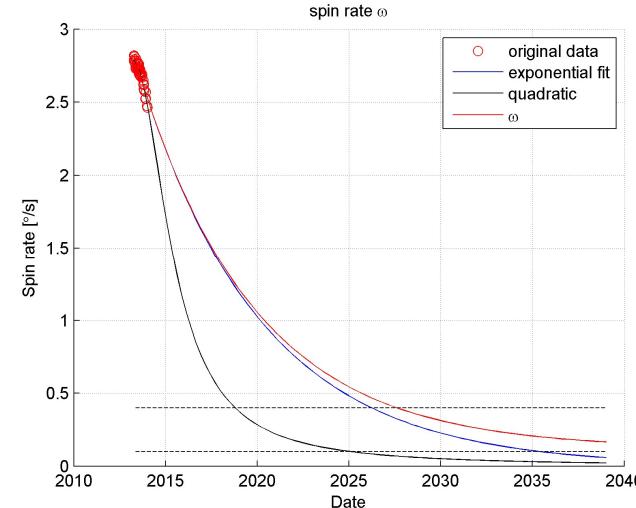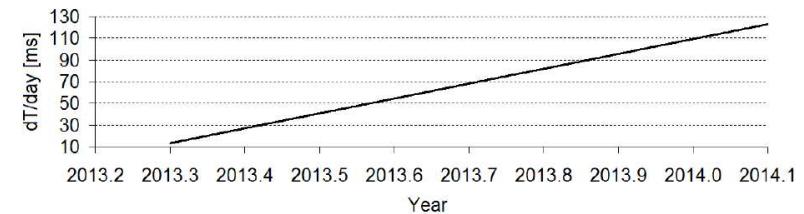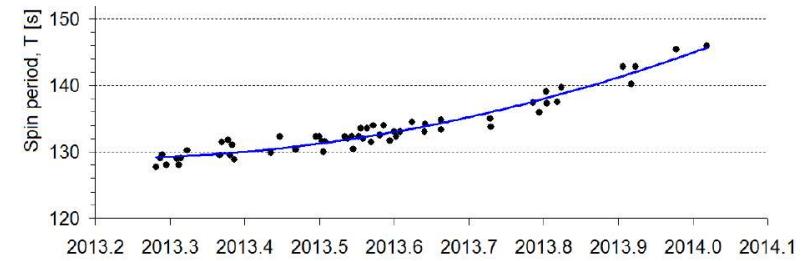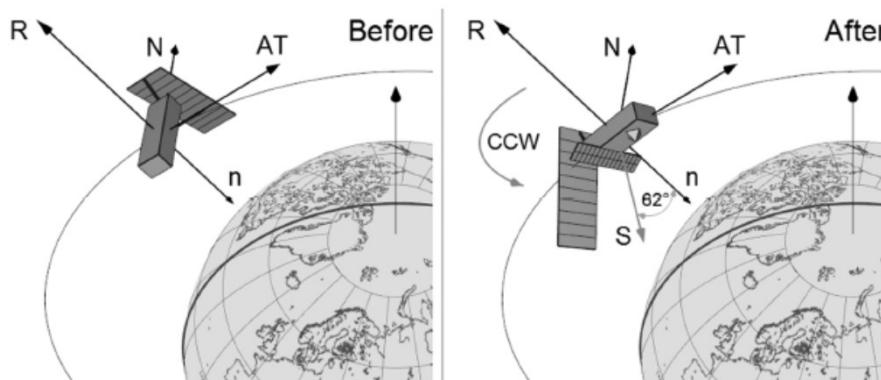
LTP SIMULATOR VERIFICATION APPROACH (4/4)

COSMOS

- Rotation around major axis
  - Observability constraint; axial spin not observable

- Characteristic decay time between 100 and 470 days, with a mean of 161 days and median of 129 days

ROCKET INTERCOSMOS 11   (1974-34-B)
DECELERATED PART

TUMBLING PERIOD (S)

TIME AFTER LAUNCH (DAYS)
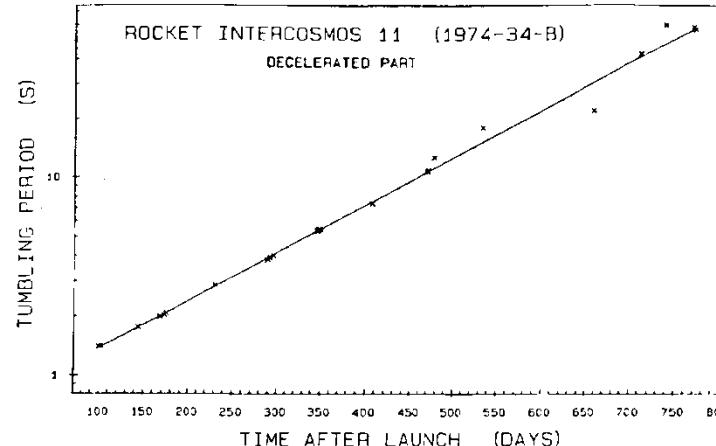
TABLE 1. SATELLITE FLASH PERIODS AND ORBITAL INFORMATION

| Satellite	Time for spin decay by factor of 10 (yrs)	Perigee altitude (km)	Apogee altitude (km)	Semi latus rectum (km)	Inclination of the orbit (degrees)
68–70B	1.2	575	631	6981	56.17
70–36J	2.7	1473	1590	7909	74.04
70–83B	1.1	743	755	7127	74.00
70–86B	0.95	776	806	7169	74.06
70–102B	1.35	967	1004	7363	74.03
70–108B	1.15	974	979	7354	74.02
71–13B	0.85	519	545	6910	74.03
71–20B	0.90	983	995	7367	65.82
71–86J	4.25	1501	1628	7942	74.03
72–9B	1.13	964	994	7357	74.08
72–19B	1.85	1171	1194	7560	82.97
72–35B	1.25	965	991	7356	74.02
72–43B	1.3	779	803	7169	74.06
72–57J	2.7	1500	1598	7927	74.03
72–62B	1.55	952	975	7341	82.97
72–74B	1.0	975	1002	7366	65.83
72–87J	1.15	1470	1594	7910	74.03
72–88B	0.78	508	543	6903	74.02
73–3B	0.9	501	545	6901	74.03
73–5B	1.32	566	614	6968	50.66
73–10B	0.87	504	542	6901	74.02
73–37J	2.0	1479	1606	7920	74.02

DETUMBLING
GNC requirements

WORK PERFORMED: TASK 2

■ System and **GNC Requirements** were specified for the baselined concept
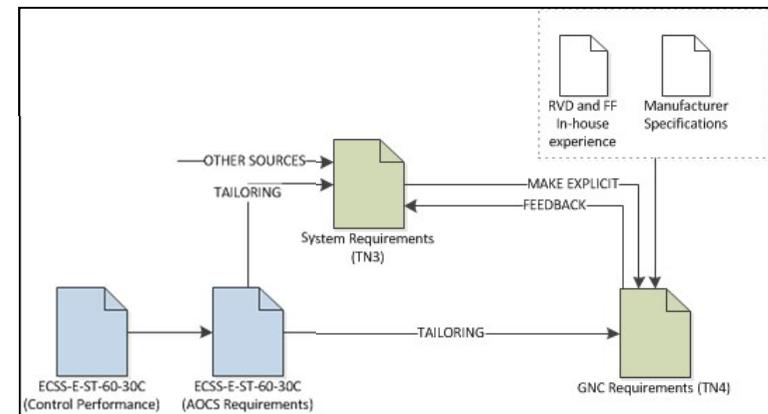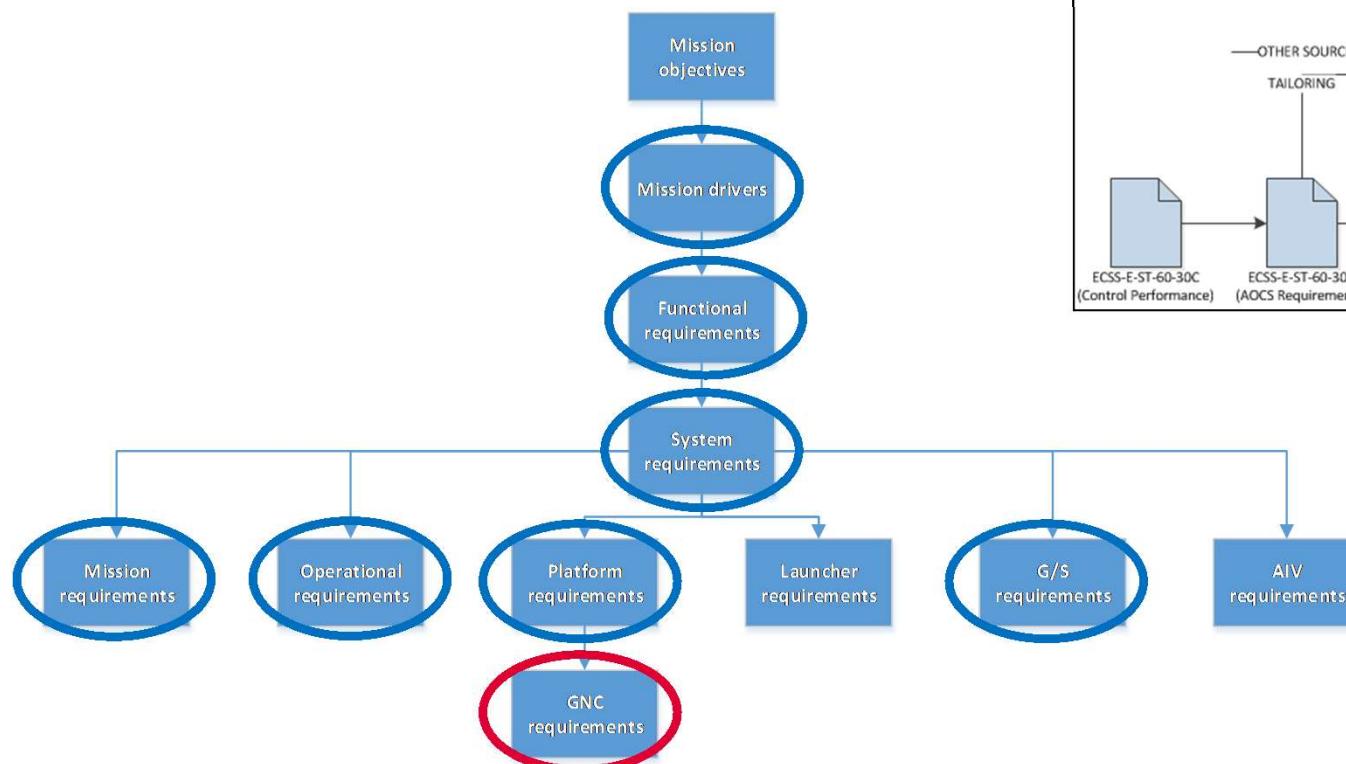
DETUMBLING

Error model assumptions

ERROR MODEL ASSUMPTIONS

- Propulsion system: 6x4 22N, Isp = 290s, 5% thrust error (3σ)
- Relative navigation behavioural model:
  - relative position estimates in the target LVLH reference frame with an error <0.25% of the range to target and <0.05 deg in LOS at distances <100m and >10m from the target (3σ).
  - relative position/velocity estimates in the target LVLH reference frame with an error <2.5cm and <0.25 cm/s respectively on any axis at distances <10m from the target (3σ).
  - target attitude and attitude rates estiation with an accuracy better than 1 deg on any axis and 0.1 deg/s respectively (3σ).

DETUMBLING
Other plots

ERROR MODEL ASSUMPTIONS

■ Synchronisation gudiance v.s. rel position in LVLH
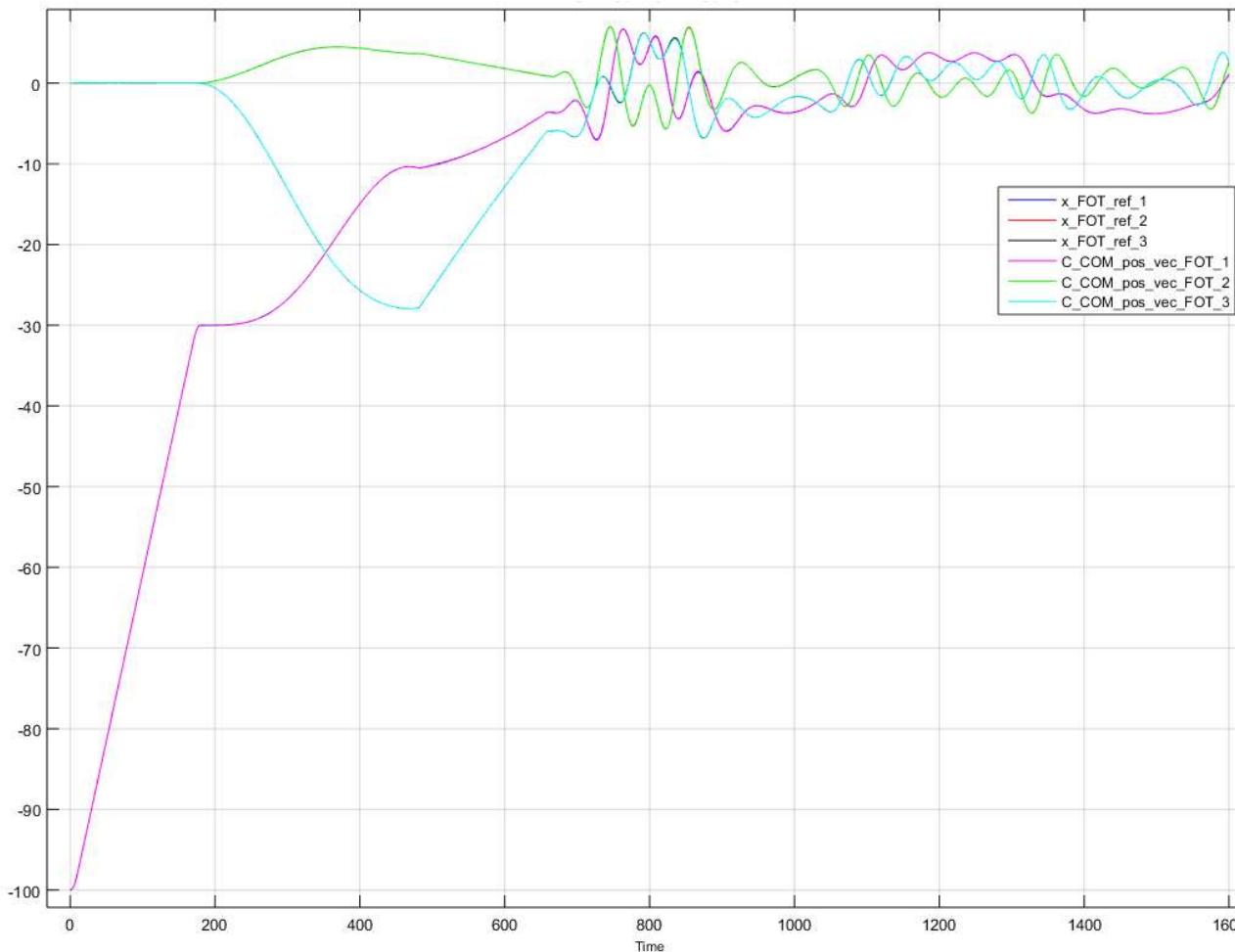
ERROR MODEL ASSUMPTIONS

■ Synchronisation position control error (extended time)
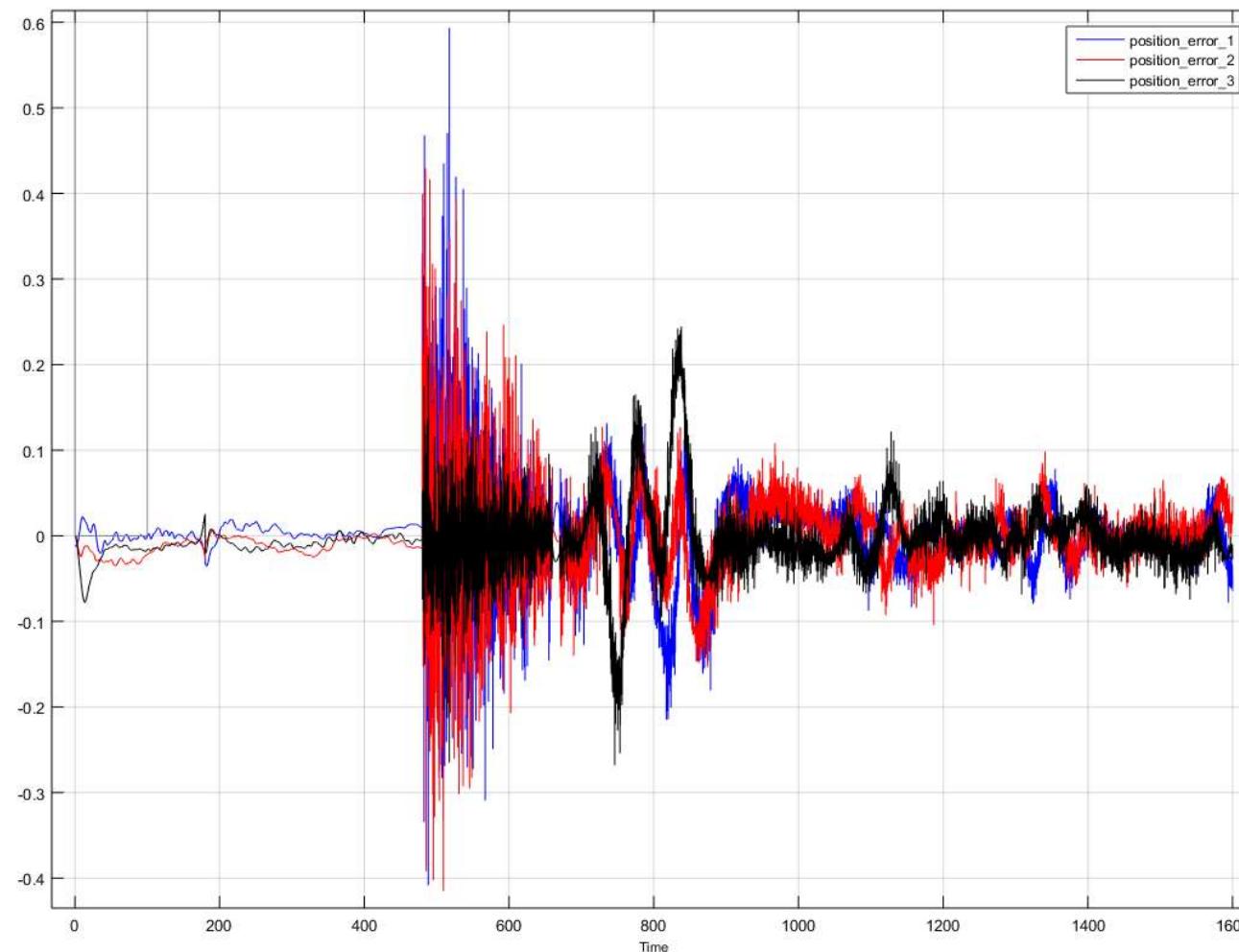
Computation of MC number of cases

MC NUMBER OF CASES

- The stochastic processes that determine the value of the variable assumed to be Gaussian.
- Desired width of the confidence interval for the estimated variance corresponding to the interest variable is specified (it is first estimated from an initial given number of run cases ~ 30)
- The values of M(n) and N(n) are computed from the estimation of the variance s^2 and the specification of the confidence interval width δ_a and δ_b

$$M(n) = \left(1 + \frac{\delta_b}{3s}\right)^2$$

$$N(n) = \left(1 + \frac{\delta_a}{3s}\right)^2$$

- Example application (FMCC in detumbling phase):
  - Applied on variable: end rotational kinetic energy
  - s estimated from 30 cases: s_est = 0.0168 J
  - Desired δ_a = δ_b = s_est/2 = 0.0084 J
  - M(n) = 1.3611
  - N(n) = 0.6944
  - → nb_cases ~ 80