1ST SYMPOSIUM ON SPACE EDUCATIONAL ACTIVITIES

UNIVERSITÀ DEGLI STUDI DI PADOVA

DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

CISAS G. COLOMBO

Development of a Ground Based Cooperating Spacecraft Testbed for Research and Education

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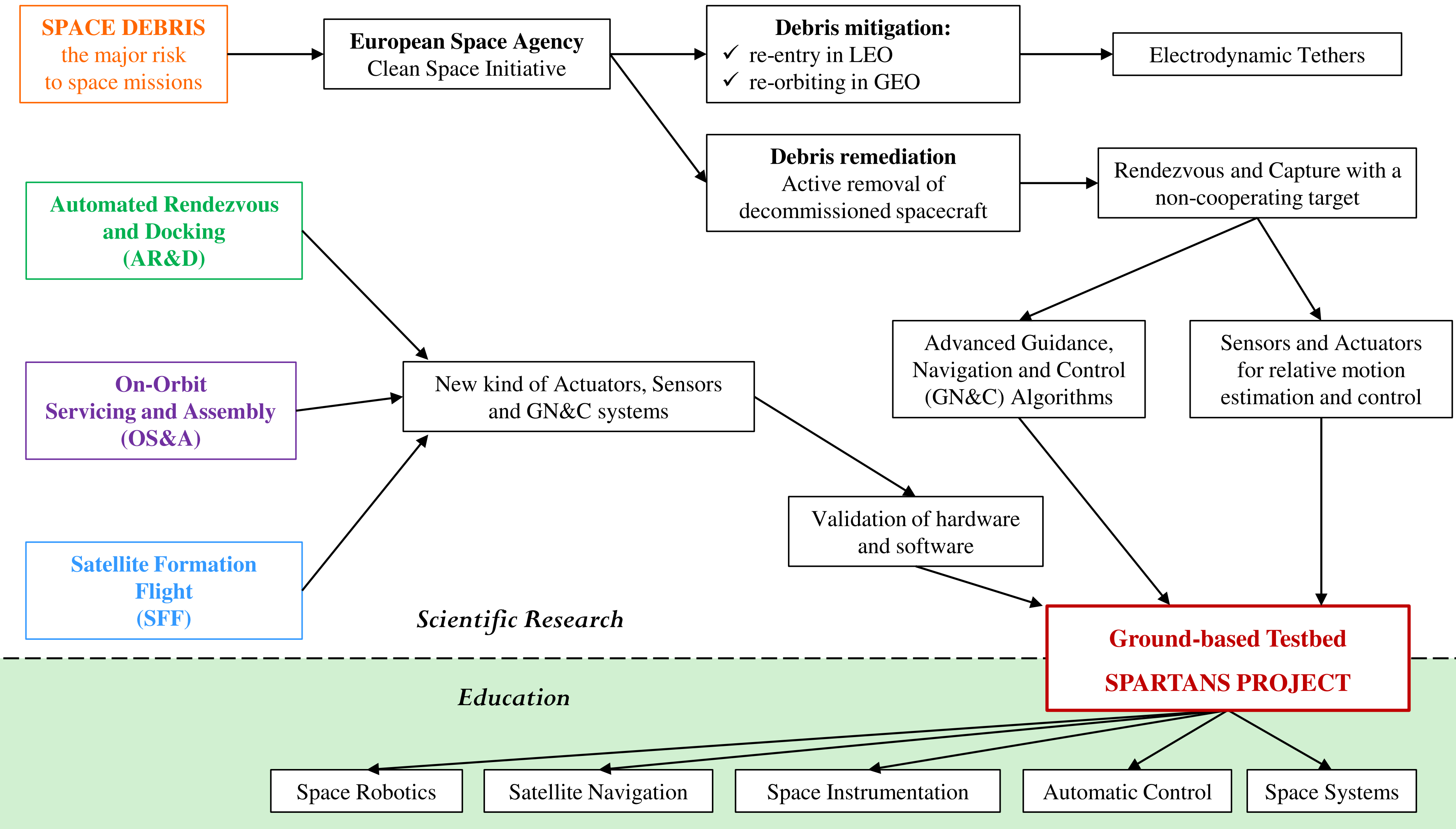
Presentation Outline

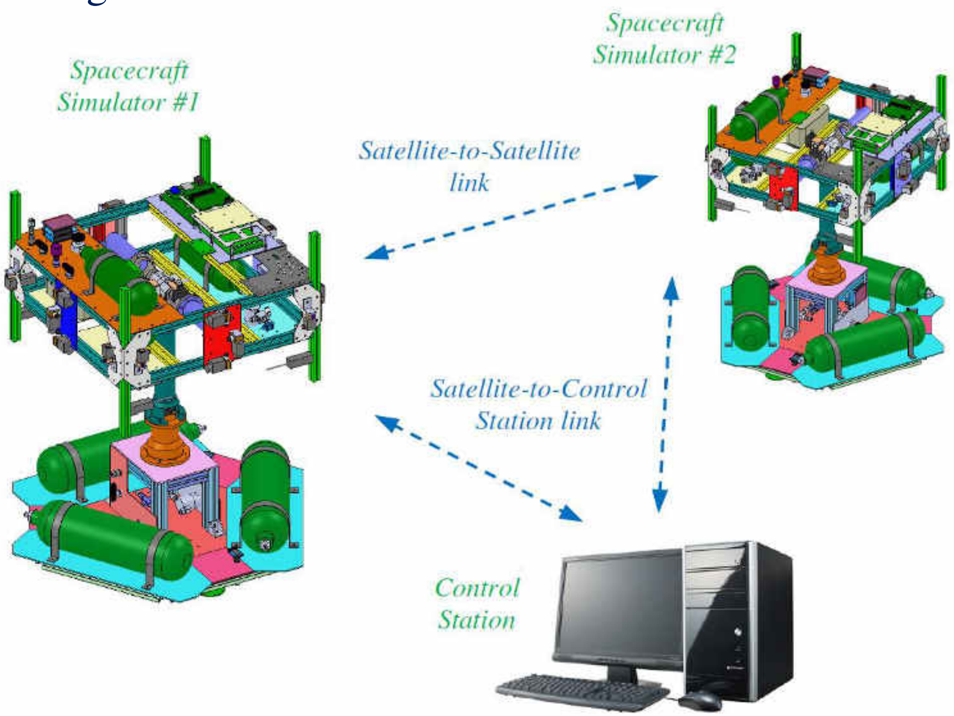
- Motivation
  - Space debris active removal
  - Automated Rendezvous and Docking (AR&D)
  - Satellite Formation Flying (SFF)
- SPARTANS Project Overview
- The Attitude Module
- Preparatory Experimental Activities
  - Mass balancing, thrusters characterization, inertia tensor determination
- Attitude Navigation System
  - Noise characterization, calibration, development and validation of the navigation algorithm
- Control Manuevers

SPARTANS Project Motivation



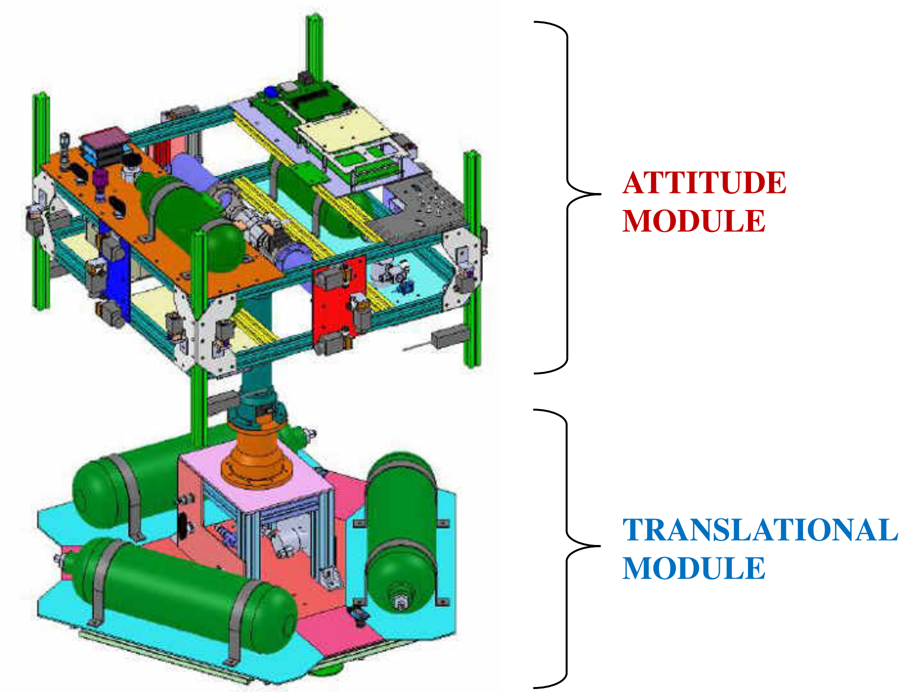
SPARTANS Project Overview

- SPARTANS: cooperating SPAcecRaft Testbed for Autonomous proximity operatioNs experimentS
  - Developed by Master's Degree students, PhD students and Post-docs
- Representative dynamic environment for the development and verification on the ground of:
  - sensors and algorithms for relative navigation;
  - coupled position and attitude proximity control algorithms.
- Some flexibility in changing the onboard configuration
  - Research and educational purposes
- SPARTANS final configuration:
  - Two ore more Spacecraft Simulators
  - External Control Station

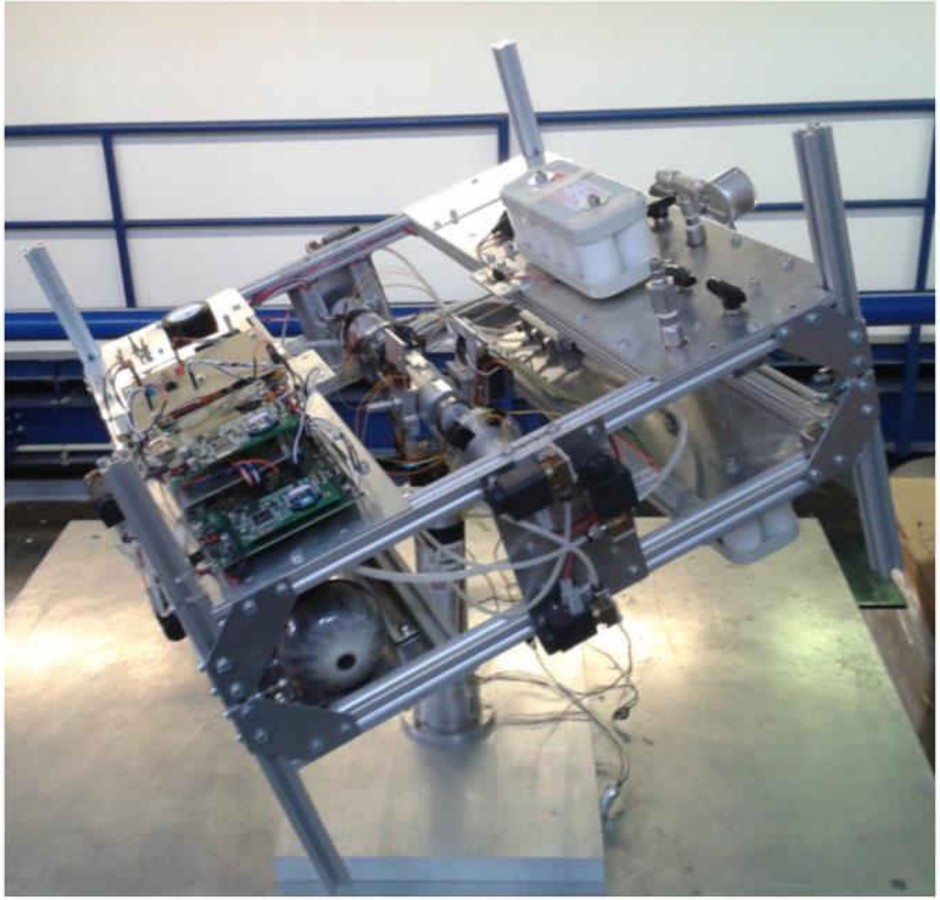


SPARTANS Project Main Features

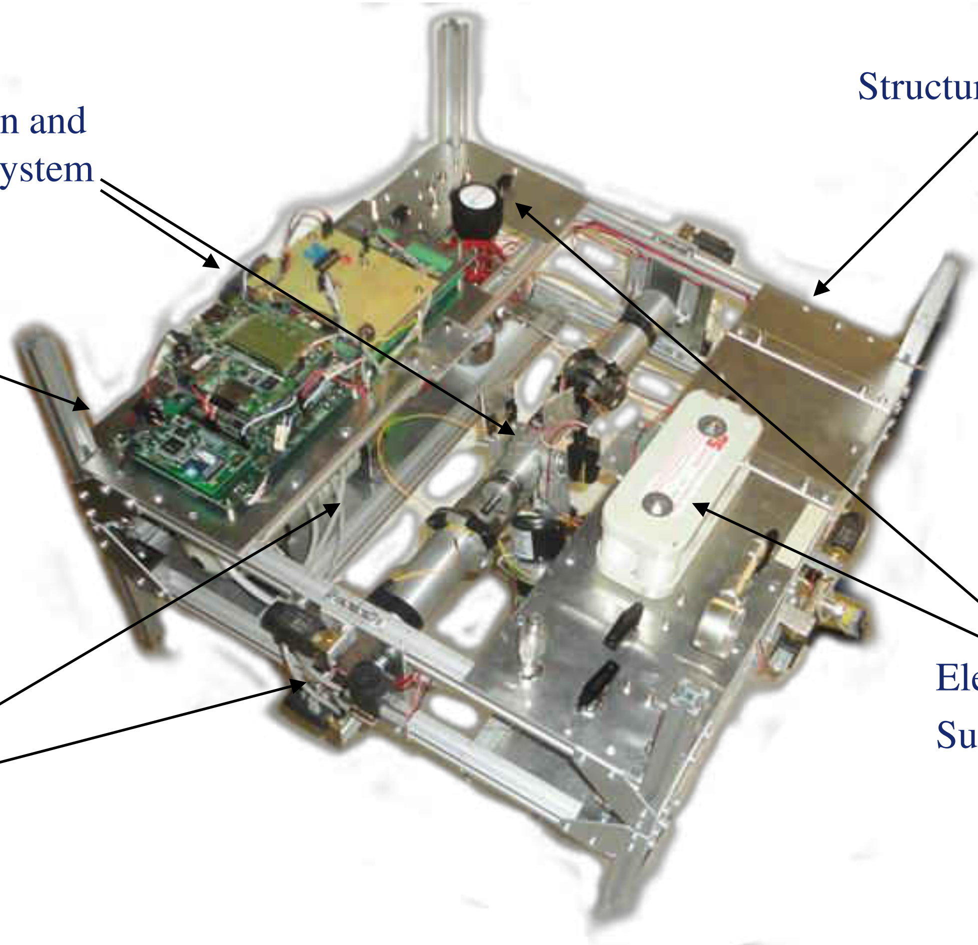
- Each simulator made of:
  - Attitude Module (AM)
    - ✓ three rotational degrees of freedom provided by mechanical gimbals
  - Translational Module (TM)
    - ✓ two position degrees of freedom
    - ✓ translating on a glass-covered table using a low friction air cushion system
- Three separate dynamic configurations:
  - 3 attitude DOF
    - ✓ only AM used;
  - combined 3 DOF (2 transl. + 1 att.)
    - ✓ relative motion between the two modules mechanically blocked
  - combined 5 DOF (2 transl. + 3 att.)
  - The only function of the TM is to allow a translational low friction motion of AM



Attitude Module first prototype

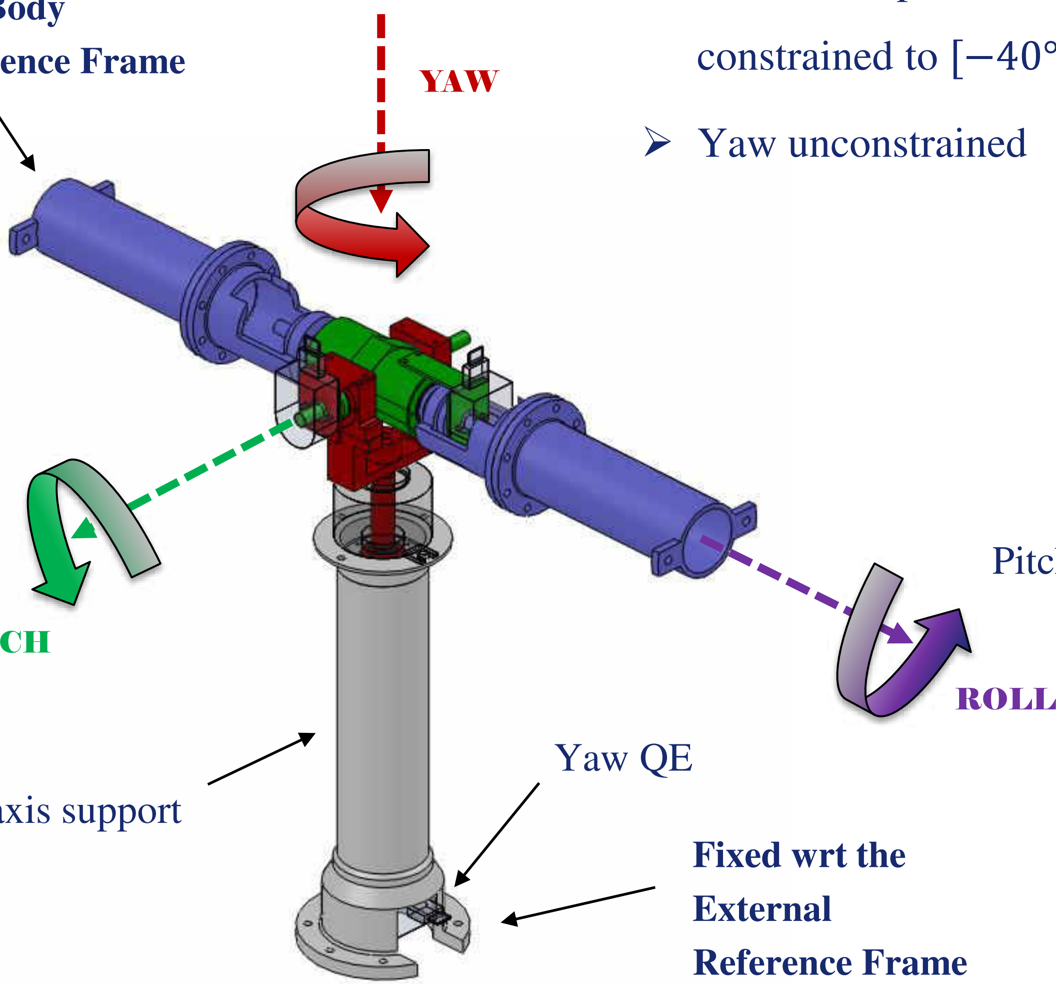


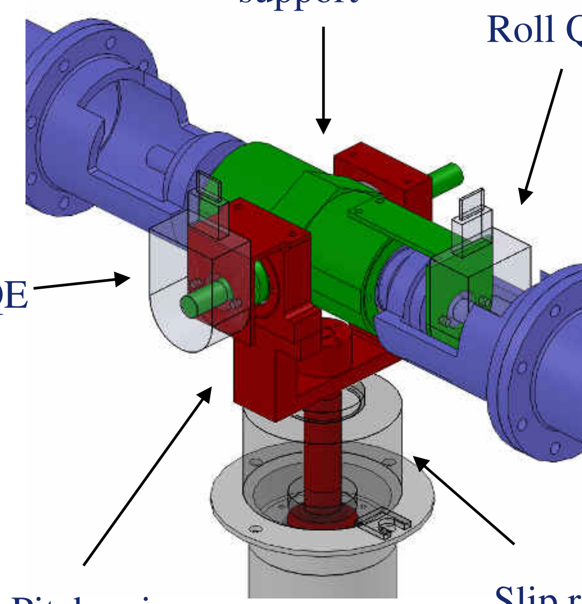
Attitude Module Subsystems



The Cardanic Joints System

- Roll and pitch mechanically constrained to $[-40°, +40°]$;
- Yaw unconstrained



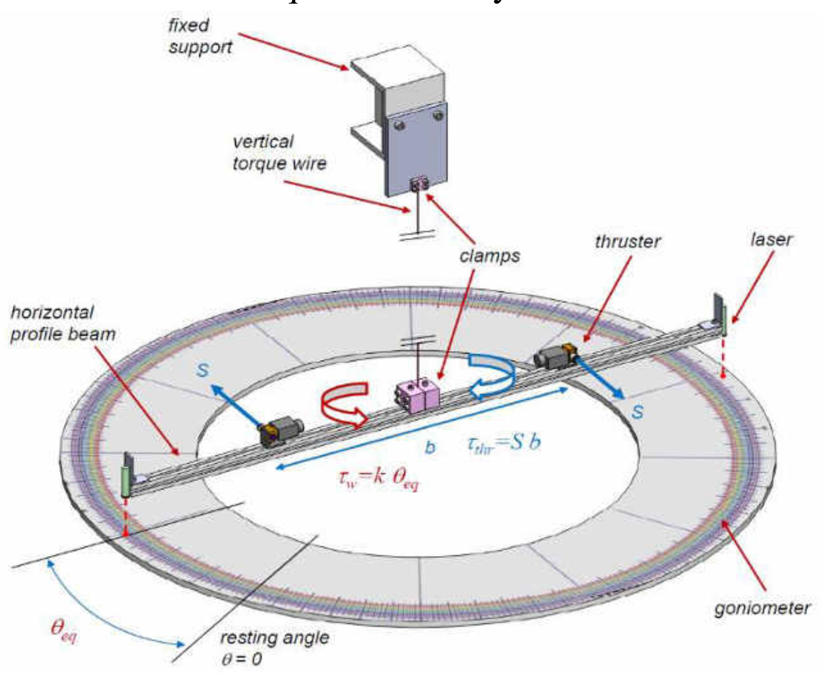


Preparatory Experimental Activities (1)

AM mass balancing → AM mass coincident with rotation center → reduced disturbance due to gravity torques

- AM components with similar masses placed at symmetric locations
- Trimming masses placed with trial and error procedure

Thrusters force estimation → Torque Balance System

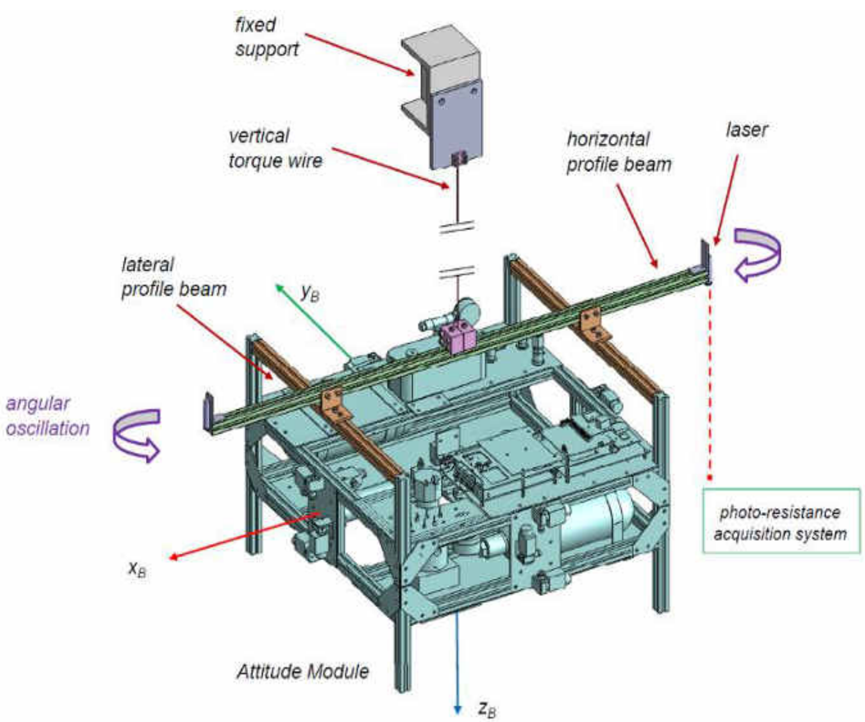


→ Estimated nominal force (equilibrium condition during thrusters activation)

$$S = \frac{k\,\theta_{eq}}{b} = (0.389\ \pm 0.007)N$$

Inertia tensor estimation

Torque Pendulum System



AM moment of inertia $I_{m,i}$ in the required direction estimated from measurements of overall system moment of inertia

$$I_{m,i,tot} = I_{m,i} + I_{m,i,frame} = \frac{k\,T^2}{4\,\pi^2}$$

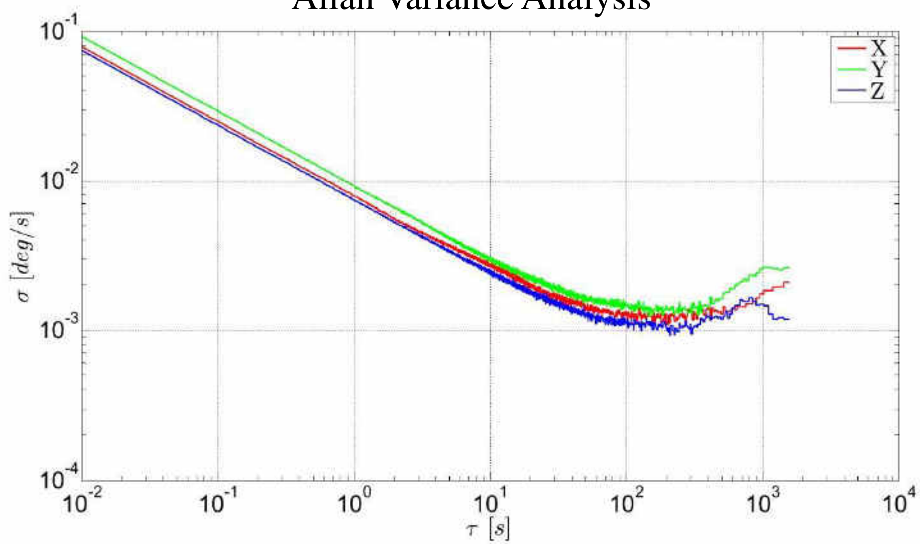
The Attitude Navigation System

Random Noise Characterization

- Attitude Navigation system: Determination of AM Body frame orientation wrt to external Global reference frame
  - ✓ 3 axis MEMS inertial sensor gyroscope;
  - ✓ Quadrature Encoders (QE) simulating star sensors
  - ✓ Sensor fusion through Extendend Indirect Kalman Filter
- Gyroscopic measurement: $\omega_m = \omega + b + n_\omega$
  - ✓ b bias, n_ω zero mean Gaussian noise
  - ✓ Bias model $\dot{b} = n_b$
- Star Tracker simulated by QE: $q_m = q + n_q$
- Allan Variance analysis
  - ✓ Gyroscope Angular Random Walk (ARW) coefficient N for high frequency noise n_ω
  - ✓ Rate Random Walk (RRW) coefficient K for low frequency bias noise n_b

Axis	N	B	K
	$\left(\frac{deg}{sec}\right)/\sqrt{Hz}$	$\frac{deg}{sec}$	$\left(\frac{deg}{sec}\right)\sqrt{Hz}$
X	7.867 E-3	1.241 E-3	1.111 E-4
Y	9.281 E-3	1.418 E-3	1.389 E-4
Z	7.389 E-3	1.117 E-3	1.111 E-4

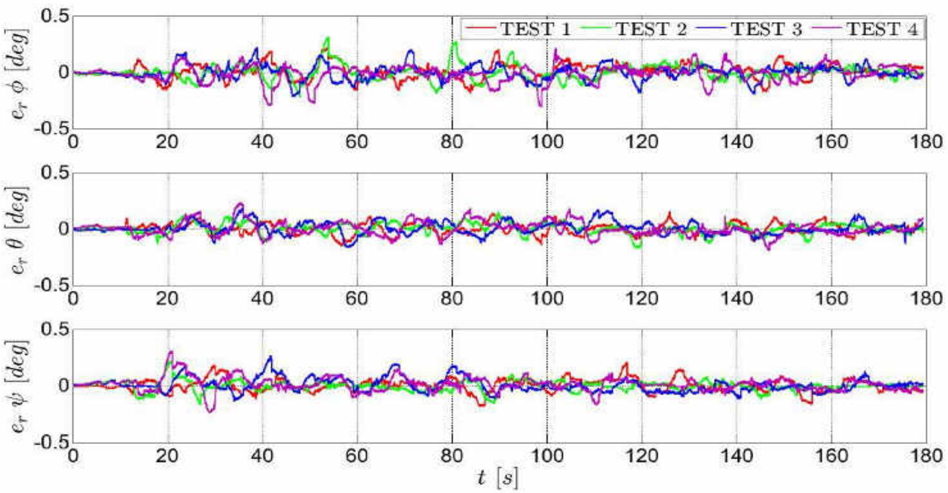
Allan Variance Analysis



The Attitude Navigation System
Navigation Algorithm Development and Validation

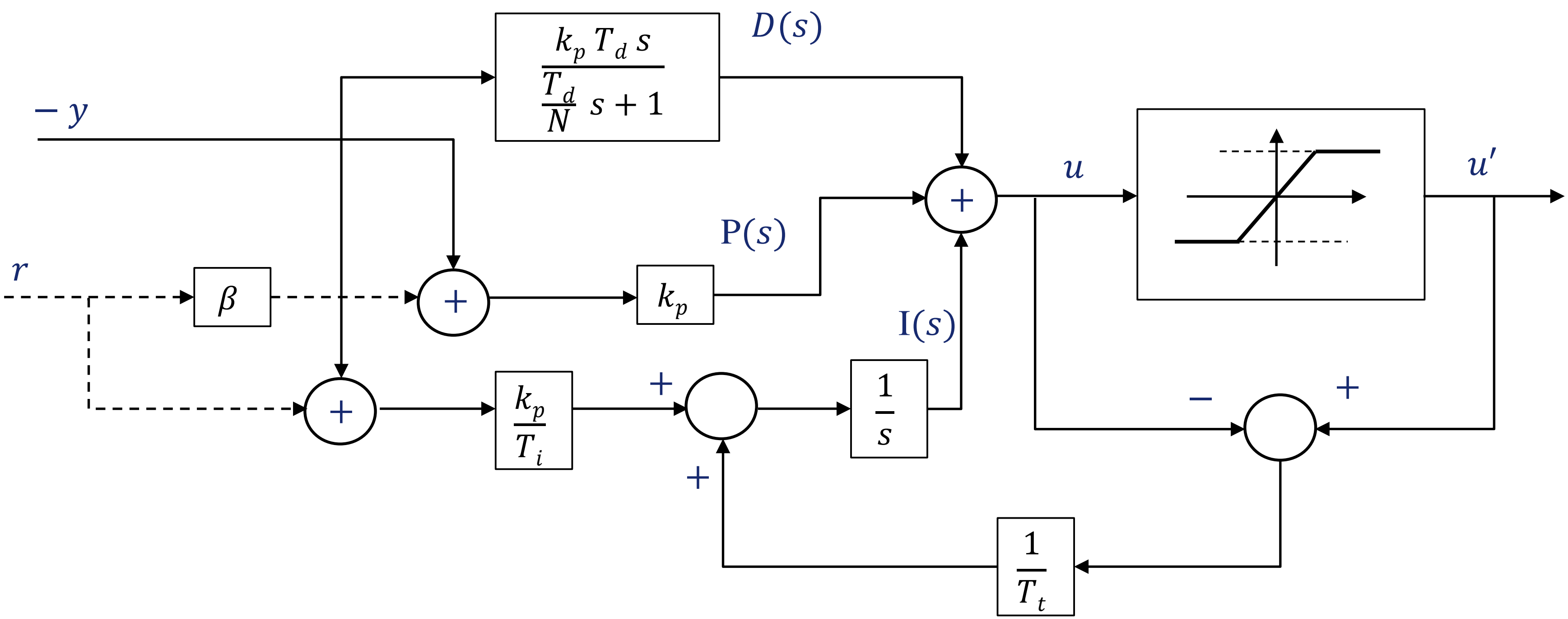
- Calibration procedure
  - ✓ Compensation of deterministic errors due to misalignments, scale factors and zero rate bias
  - ✓ Spline interpolation applied to QEs measurements as AM orientation fiducial reference
- Extended Indirect Kalman Filter (IKF)
  - ✓ Star sensors measurements used to compensate white noise integration in gyros measurements
  - ✓ Attitude dynamics linearization
- Experimental tests
  - ✓ IKF implemented in Arduino DUE microcontroller
  - ✓ Angular velocity estimation accuracy within ± 0.3 deg/s with 3σ confidence level

Test number	RMS errors on Euler Angles		
	ε_φ	ε_θ	ε_ψ
Test 1	0.062 °	0.049 °	0.058 °
Test 2	0.063 °	0.048 °	0.039 °
Test 3	0.059 °	0.052 °	0.057 °
Test 4	0.068 °	0.058 °	0.047 °



Control Maneuvers

- Quaternion-based PID regulator with discretized formulation
  - ✓ Proportional and derivative kick avoidance
  - ✓ Anti-reset windup feedback scheme
  - ✓ First order low pass filter for minimization of derivative component noise
  - ✓ Tuning of the regulator through trial and error procedure



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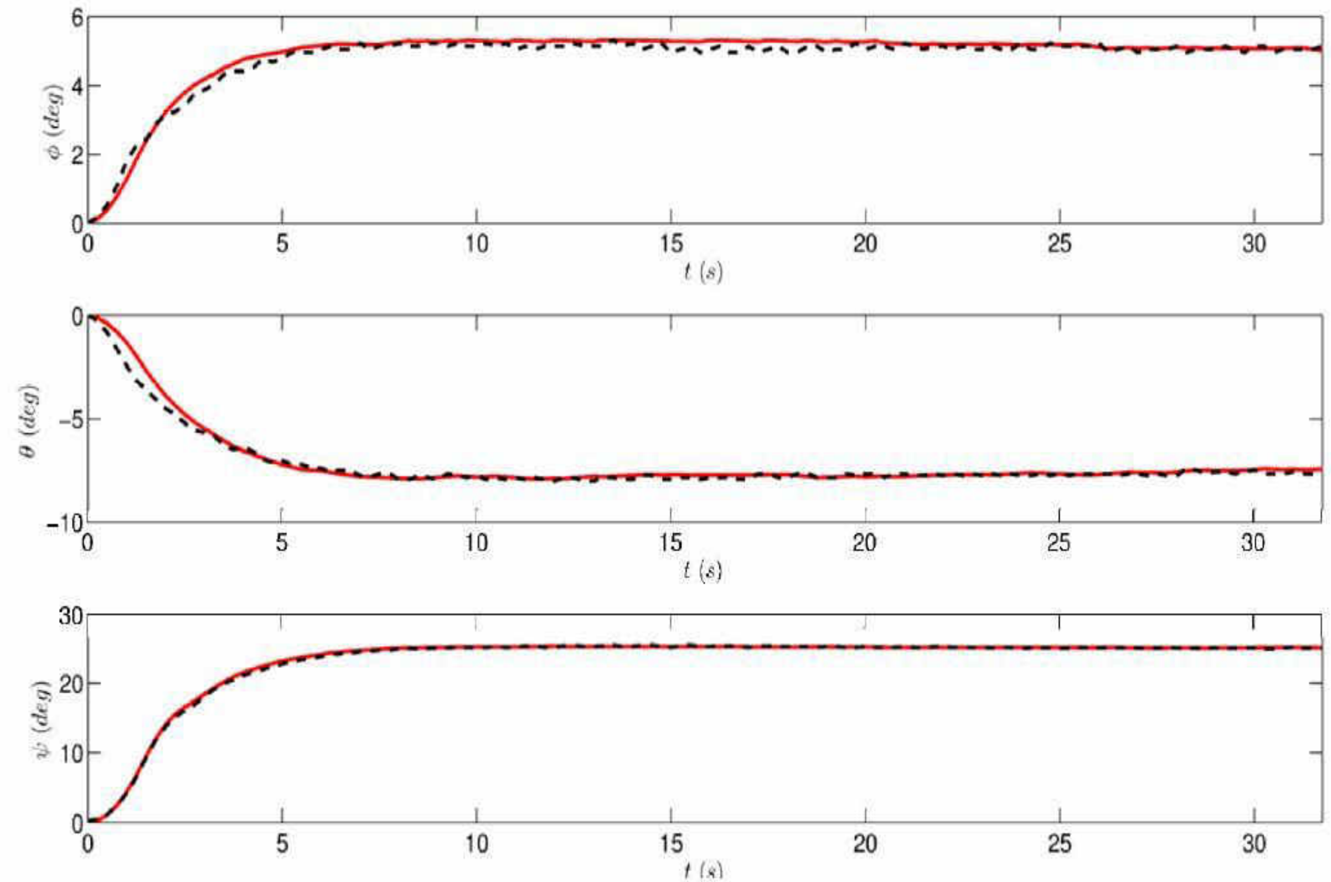
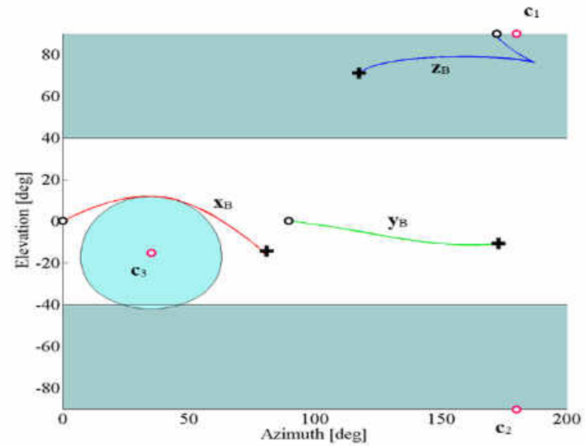
Control Maneuvers
Set Point Reaching Maneuver

- Set point reaching maneuver
  - ✓ Reference attitude: $\Theta_d = [\varphi_d,\ \theta_d,\ \psi_d] = [5,\ 7.5,\ 25]\ deg$
  - ✓ Concordance between software simulation results (continuous red line) and experimental results (dashed black line)
  - ✓ Tracking error lower than 0.5 deg in both steady state and dynamic conditions



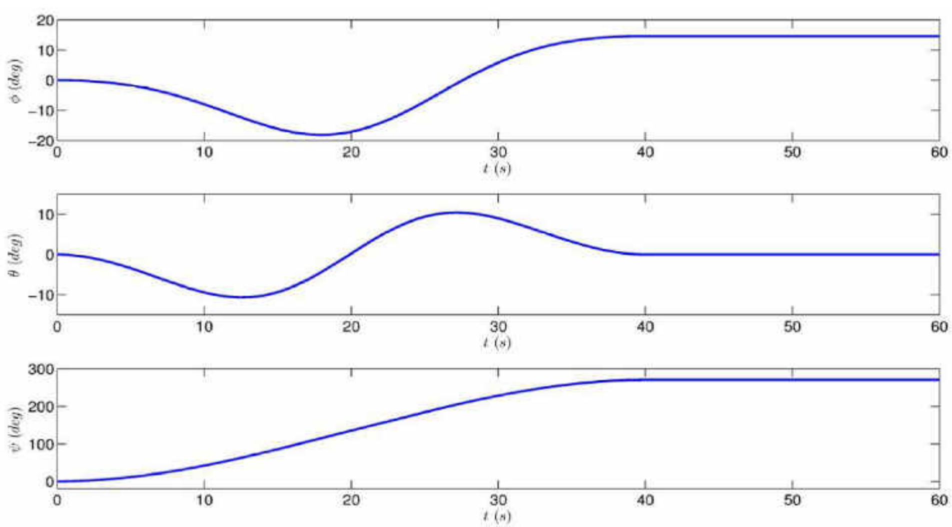
Control Maneuvers
Reference Trajectory Tracking

- Repointing maneuver with active constraints on the attitude state trajectory
  - ✓ Reference trajectory with keep – out cones obtained through pseudospectral optimization methods
  - ✓ Tracking errors always lower than 0.5 deg

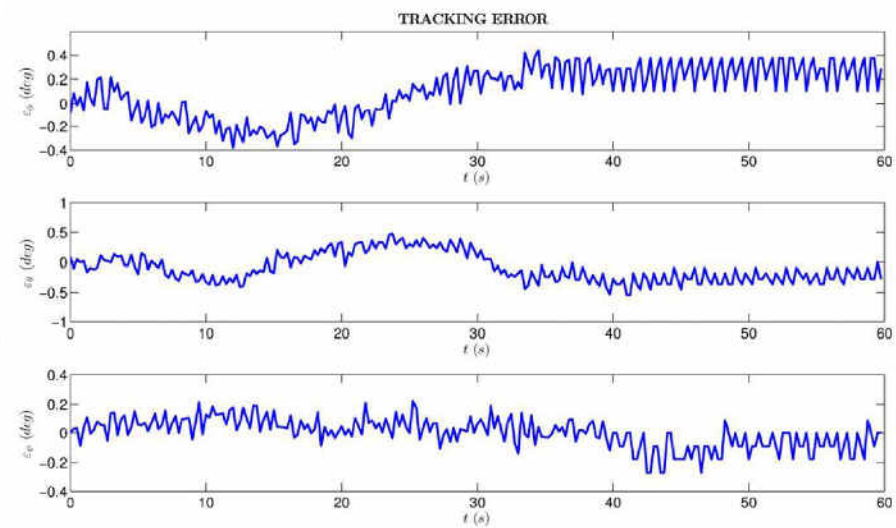


Polar Diagram with Body axes reference trajectories and keep-out cones (cyan areas)

Roll, Pitch, Yaw reference trajectories

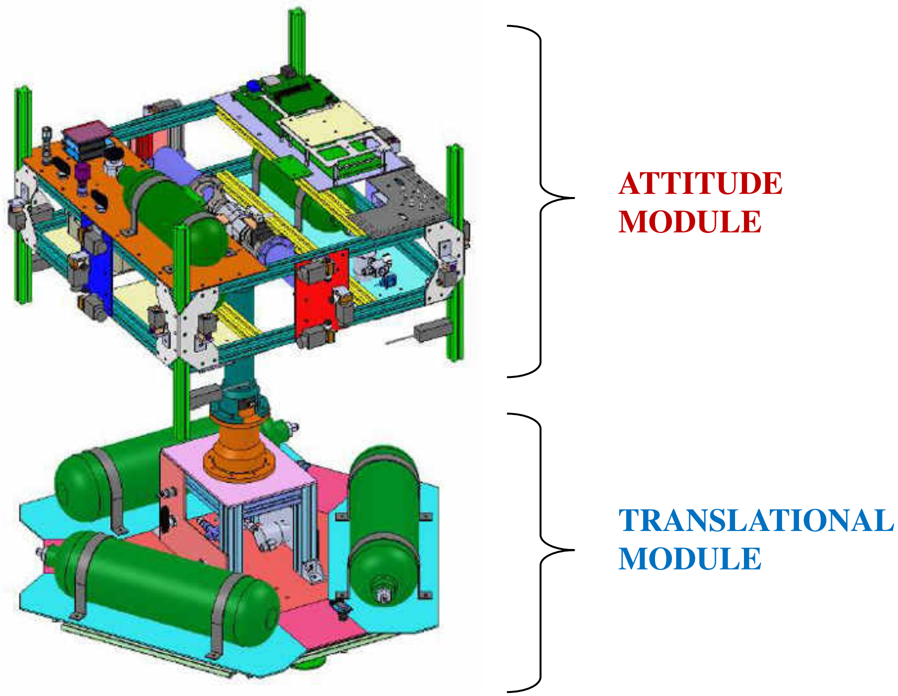


Roll, Pitch, Yaw tracking errors



Conclusions and Future Perspectives

- Attitude Module (AM) of the SPARTANS cooperating spacecraft testbed
  - ✓ Preparatory Experimental Activities
  - ✓ Attitude Navigation System
  - ✓ Control Maneuvers
- Translation Module (TM) of the SPARTANS cooperating spacecraft testbed
  - ✓ Low friction air skids suspension system for translation on glass table
  - ✓ Position and azimuth determination system
  - ✓ Attitude and position control maneuvers with 5 DOF



THANK YOU FOR YOUR KIND ATTENTION