Università degli Studi di Padova

CISAS "G. Colombo"
Centro di Ateneo di Studi e Attività Spaziali

Scuola di Dottorato in

Scienze Tecnologie Misure Spaziali

PRESENTATION OF PHD ACTIVITIES

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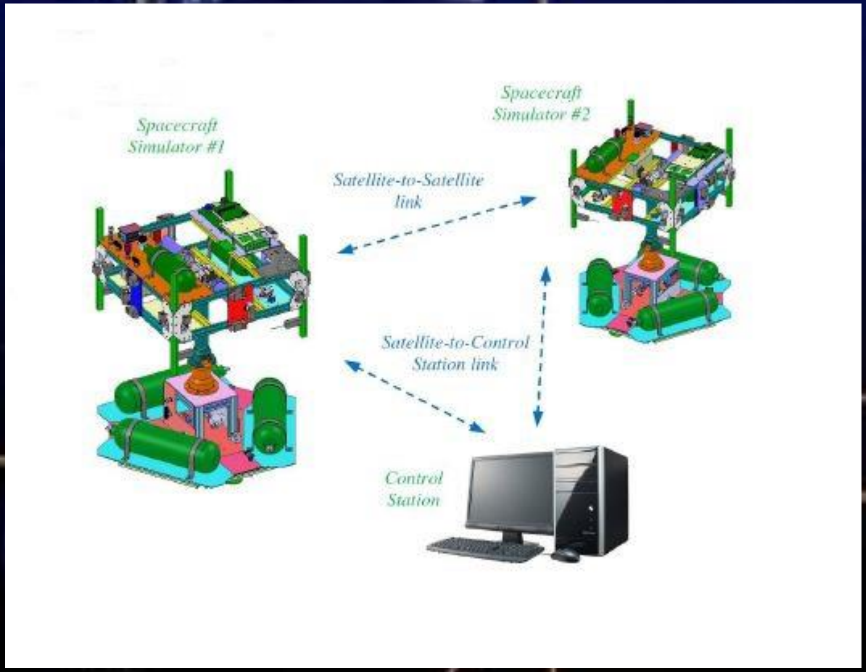
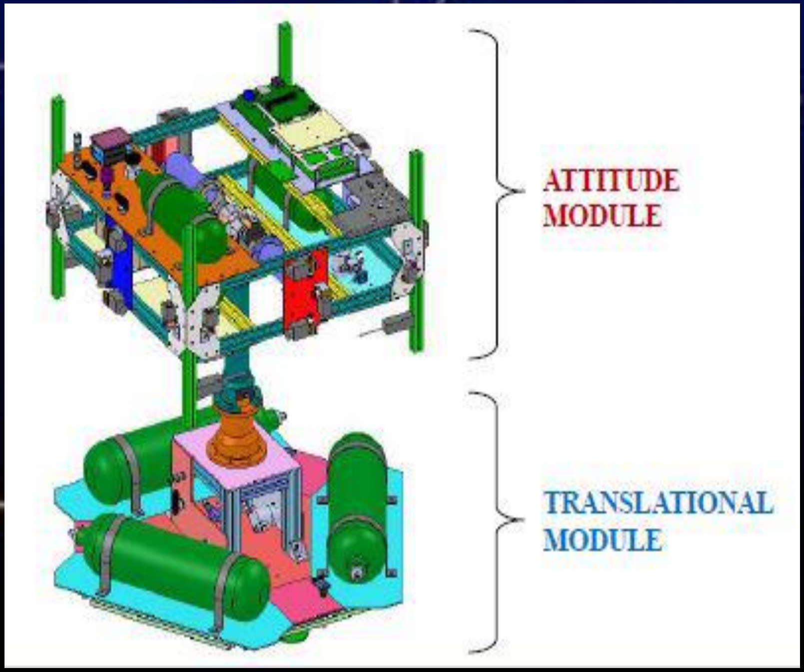
Presentation Outline

- Phd Activities during the three years mainly concentrated on the development and testing of the SPARTANS cooperating spacecraft hardware testbed
  - Development of the Translation Module (TM) of the Units Air suspension system, structural design
  - Development of the Optical Flow Sensor (OFS) navigation system → calibration and testing
  - Development of the test table for the Units
  - Development of software simulator for planning of position and attitude control maneuvers
- Analysis of inspection scenario for non cooperative spacecraft

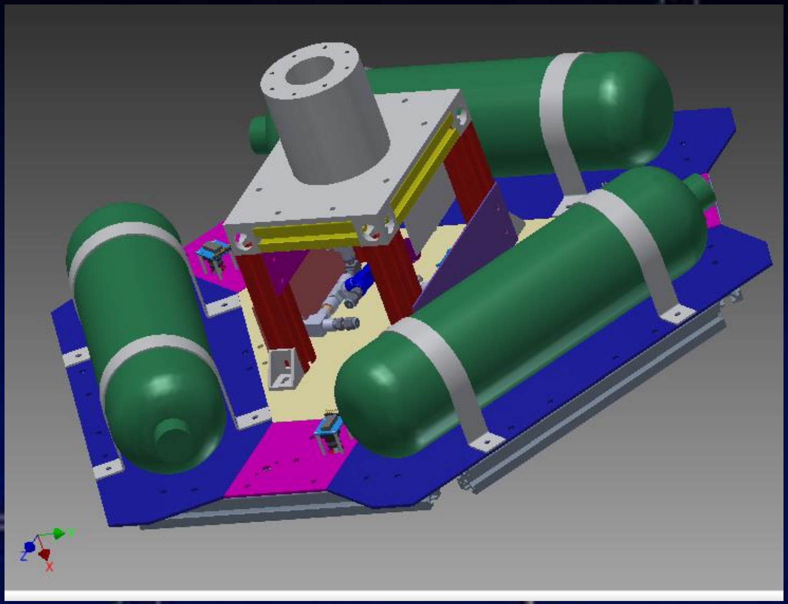
The SPARTANS cooperating spacecraft testbed

- SPARTANS (cooperating SPAcecRaft Testbed for Autonomous proximity operatioNs experiments) → simulator with two or more hardware Units representative of a spacecraft
- Employment of the Simulator → study of spacecraft proximity operations, formation flying, collision avoidance maneuvers etc. through maneuvers tests with hardware in the loop
- Each hardware Unit is made up of two main sections, the Attitude Module (AM), with 3 DOF enabled by a gimbal structure, and the Translation Module (TM) with 2 planar DOF enabled by Air skids Suspension System





Development of the Translation Module (TM)

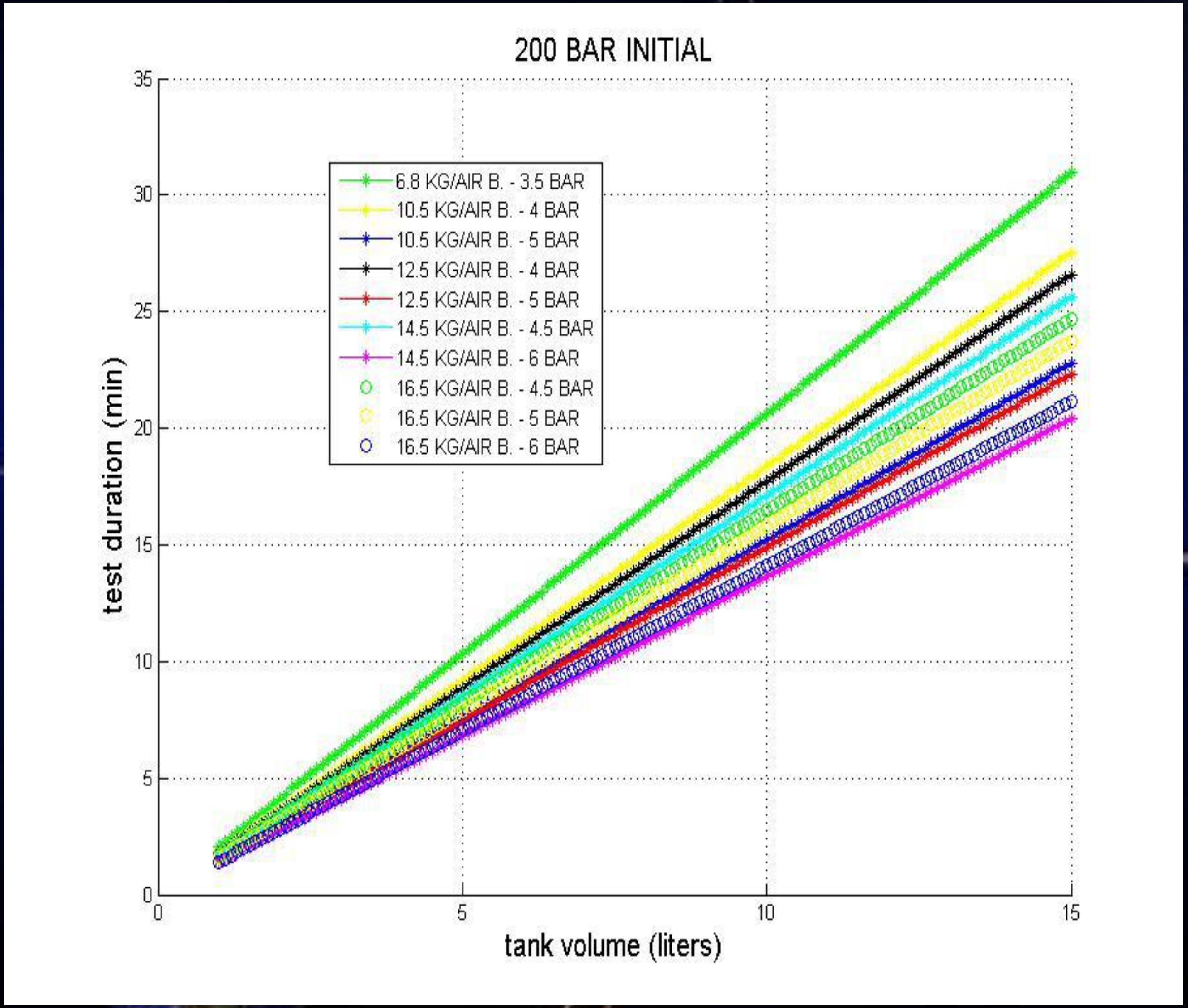


- Characterization of laboratory skids for the air suspension system
- Design of the structural components of the TM
- Numerical simulations on the TM Finite Element Analysis, vibration analysis
- Design of interface between AM and TM

Air Skids Characterization

- Determination of autonomy levels for the air suspension system
- Determination of pressure levels downstream the pressure regulator for motion smoothness
- Air skids and platform available in the Measurements Laboratory
- Two test types with varying platform load: air skids operative pressure levels, autonomy levels
- Test durations in the order of few minutes
- Selection of operative pressure levels based on motion smoothness perceived by the test performer

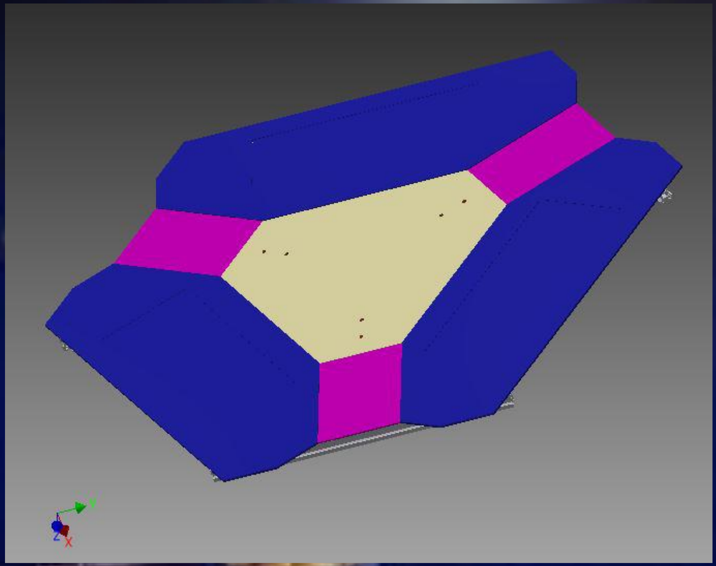
Air Skids Characterization



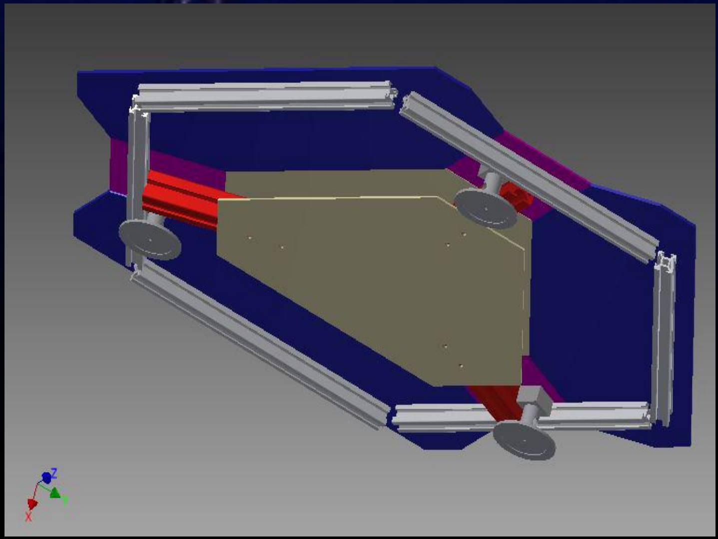
- Data elaboration for 200 and 100 bar initial pressure in external air tanks
- Curves parametric in operative pressure level and load per skid → estimation of platform autonomy level and initial air mass
- Estimated initial air mass of 2.3 kg (solution with 3 air tanks for a total of 9 Lt. capacity)

Design of TM structural components

- Aluminium and plexiglas structural components
- Modular design
  - Function partition → air tanks support, air skids support, AM support, navigation sensors support, hydraulic circuit, batteries, boards and cables support
  - Components replacement → repair, docking hardware
- Design drivers air suspension system autonomy, total Unit mass, TM dimensions

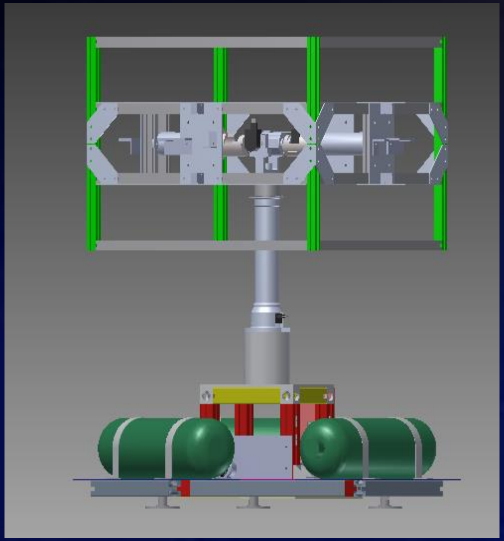


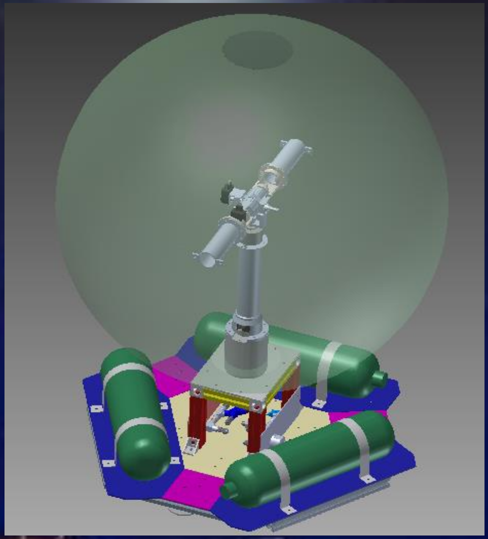
	Air tanks	Estimated total Unit mass	Characteristic TM dimension	Estimated TM autonomy (200 bar initial)	Estimated min. time for position control actuation
Solution 1	3 Luxfer 4.7lt.	42.1 – 42.6 kg	760 mm	25 min.	20 sec
Solution 2	3 Luxfer 3 lt.	36.8 – 37.3 kg	650 mm	17 min.	20 sec

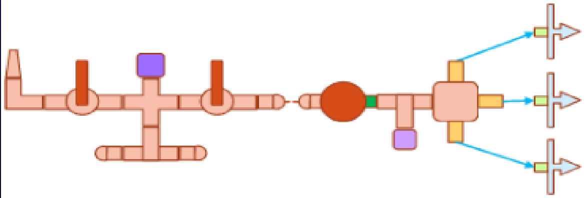


Design of TM structural components and AM interfaces

- Final TM design with central aluminium sandwich structure, stiffening aluminium profile beams, 3 Luxfer air tanks with 3 lt. Capacity disposed on the outer sections of the TM at 120° wrt to each other
- Central aluminium structure for AM support and TM hydraulic circuit housing
- Remaining free areas allocated to sensors, batteries, electronic boards, cables support, additional hardware (docking)







Tubo 3 mm x 5 mm
Attacco rapido con ugello da 4 mm.

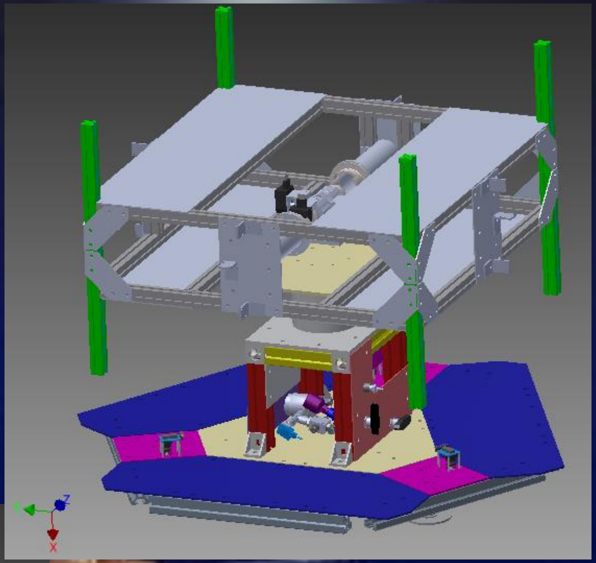
- CKD press. transd => 97 Euro @ Airsoft
- Ashcroft press. trasd. => 210 Euro @ Indra

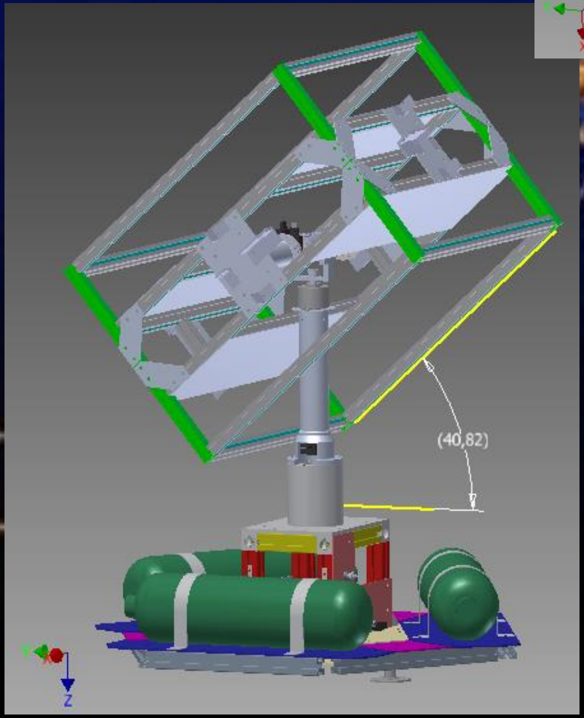
CIRCUITO PNEUMATICO ALTA PRESSIONE			
Description	**Q.tà**	**Prod.**	**ID**
Quick-connect	1	Swagelok	SS-QM2-S-2PM
Elbow	1	Swagelok	SS-2-E
Hex niple	3	Swagelok	SS-2-HN
Ball valve	2	Swagelok	SS-42GF-2
Cross	1	Swagelok	SS-2-CS
Tee	1	Swagelok	SS-2-BT
Tube fitting	4	Swagelok	SS-200-1-2
Pressure transducer	1	Ashcroft	KM15
Pressure Regulator	1	Swagelok	KCP1GRA2A2P10000

CIRCUITO PNEUMATICO BASSA PRESSIONE			
Description	**Q.tà**	**Prod.**	**ID**
Hex niple (NPT to G 1/8)	1	Swagelok	B-2-HN-2RS
Tee	1	Camozzi	2003 1/8
Pressure transducer	1	CKD	PPE-P10A-H6-B
Tube fitting	1	Camozzi	S6510 6-1/8
Hex niple	1	Camozzi	2501 1/8
Manifold	1	Camozzi	3033 1/8
Tube fitting	3	Camozzi	S6510 5-1/8

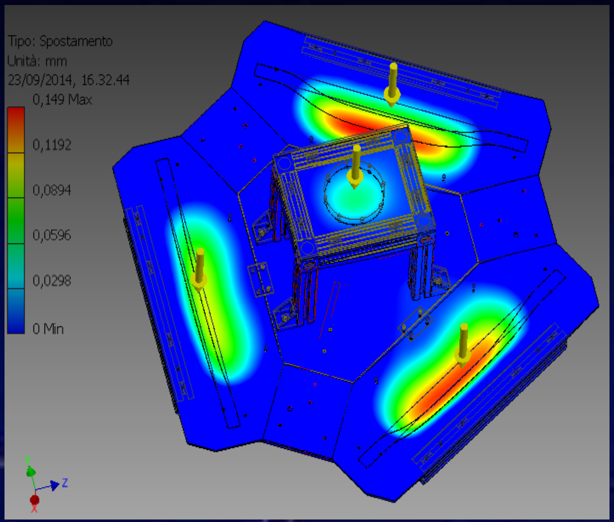
Design of TM structural components and AM interfaces

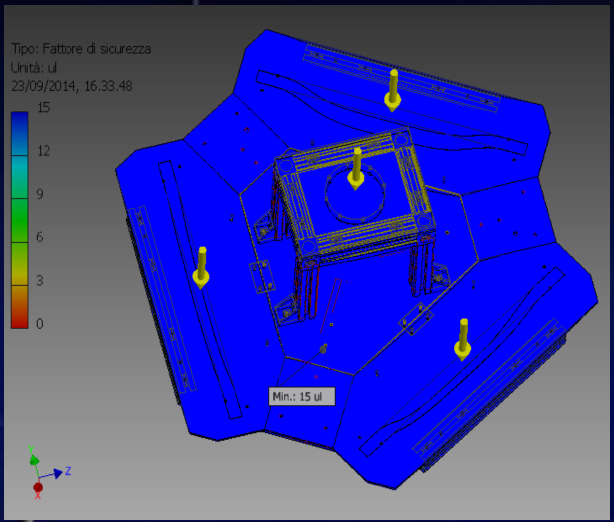
- Additional interfaces designed for AM DOF extension / modification
  - Aluminium cylinder on TM upper section in order to allow full range of AM pitch and roll (± 40°)
  - Aluminium plate in order to block AM pitch and roll with Yaw axis support removed



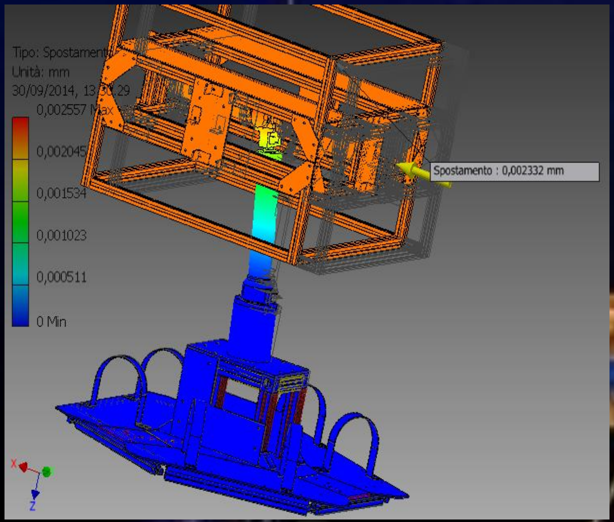


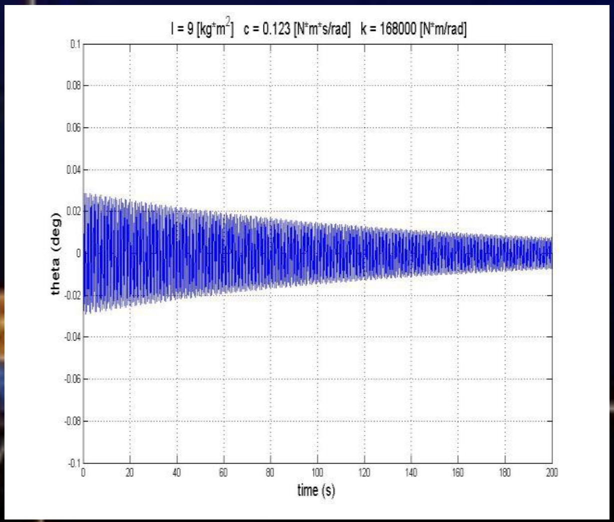
Structural and vibrations numerical analyses





- Finite Element Analyses (FEA) with over than maximum foreseen loads due to AM and air tanks
- Max estimated elastic displacements at the ~ 0.1 mm level

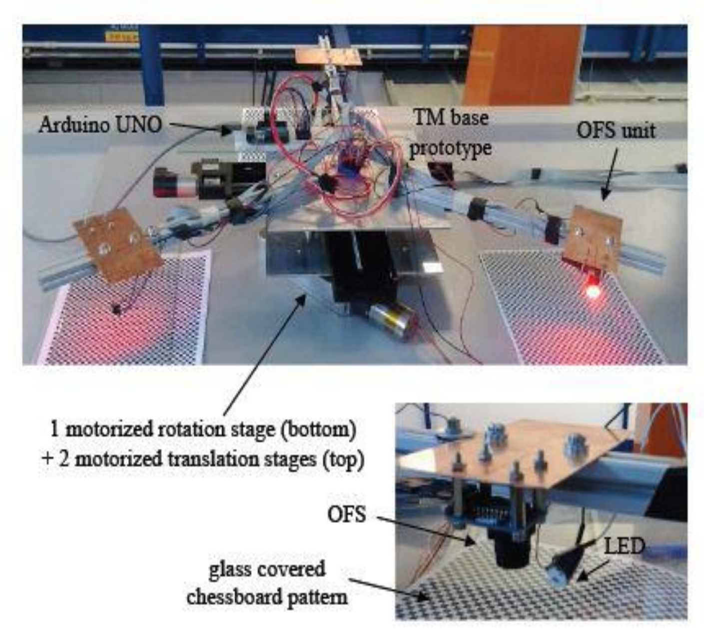


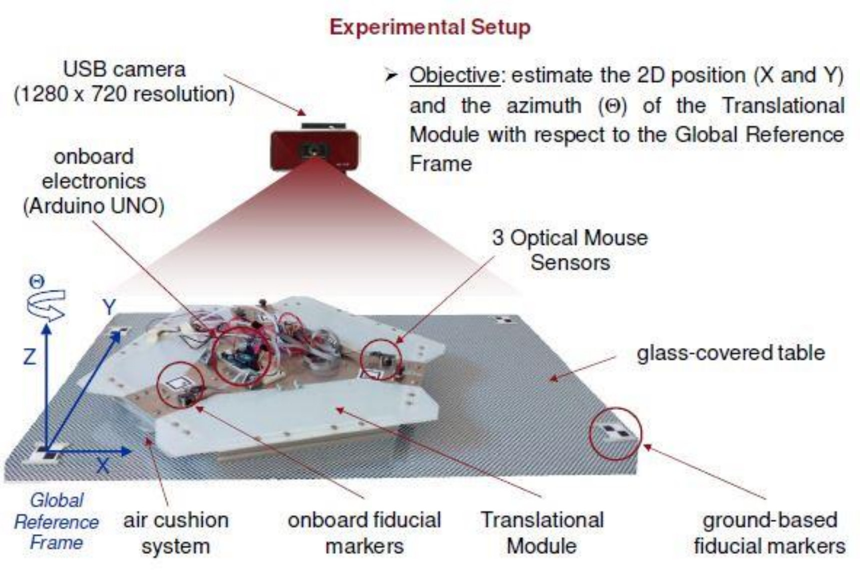


- Vibration analyses for estimation of Unit elastic oscillations due to position control induced torque
- 1 DOF analysis
- Estimation of complete Unit flexular stiffness through FEA
- Oscillation levels estimates within ± 0.1 °

Development and testing of the Optical Flow Sensor (OFS) based navigation system

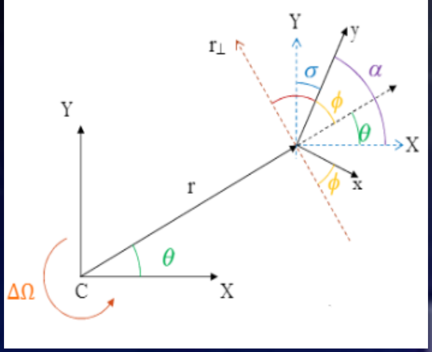
- Incremental navigation system based on mouse-like Optical Flow Sensors (OFS) to be installed on the TM
- OFS system to be integrated with external vision based navigatio system providing fiducial reference
- Test setup → TM base prototype with three OFS installed 120° wrt to each other
- Motorized stages mounted on each other for motion imposition → lower stage rotational, upper stage translational along 2 planar axes
- Selection of pattern through OFS output parameter (SQUAL) providing information about surface quality → chessboard pattern provides SQUAL > 80 %
- Pattern illumination through LEDs mounted on the TM base prototype
- Calibration → OFS intrinsic parameters
- Motion reconstruction tests





OFS calibration with TM base prototype

- Calibration based on Bonarini, Matteucci, Restelli 2004
- Estimations of OFS scale factors (metric distance/counts), position/orientation wrt TM base Body Frame
- Automatization of calibration procedure with modified equations
- Rotational and translation maneuvers imposed with the motorized stages
- Parameters refinement → minimization of mean square error between acquired and predicted OFS measurements, with the initial estimates of the intrinsic parameters
  - Minimization problem solved in MATLAB → *fmincon* function, interior point algorithm

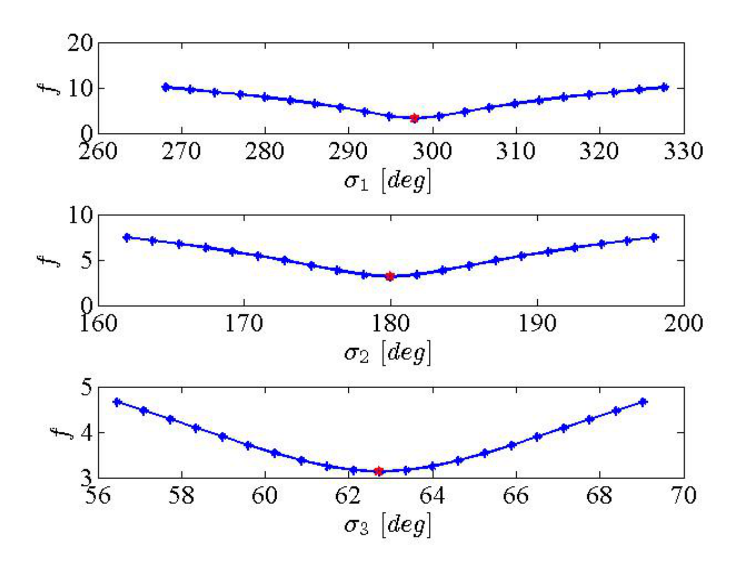


$$k_i = \frac{\sqrt{\Delta X^2 + \Delta Y^2}}{\sqrt{\delta\tilde{x}_i^2 + \delta\tilde{y}_i^2}}$$

$$\sigma_i = arctan\left(\frac{\Delta X}{\Delta Y}\right) - arctan\left(\frac{\delta\tilde{x}_i}{\delta\tilde{y}_i}\right)$$

$$r_i = \bar{k}_i \frac{\sum_j \delta l_{ij}}{\Delta\Theta} = \bar{k}_i \frac{\sum_j \sqrt{\delta\tilde{x}_{ij}^2 + \delta\tilde{y}_{ij}^2}}{\Delta\Theta}$$

$$\tau_i = arctan\left(\frac{\delta\tilde{x}_{ij}}{\delta\tilde{y}_{ij}}\right)$$



OPTIMIZED CALIBRATION PARAMETERS – MODIFIED CALIBRATION PROCEDURE							
	k [m/count]	σ [deg]	r [m]	τ [deg]	θ [deg]	φ [deg]	α [deg]
OFS 1	5.99e-4	297.9	0.3836	262.3	-35.6	187.7	152
OFS 2	6.66e-4	180	0.3831	263.2	83.2	186.8	270
OFS 3	6.66e-4	62.7	0.3865	264.5	201.8	185.5	27.25

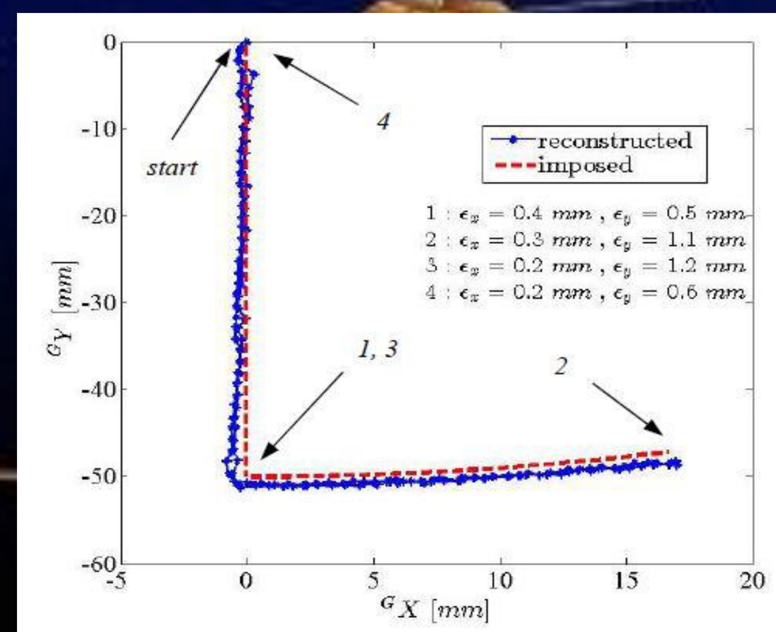
OFS system motion reconstruction tests with TM base prototype

- Imposition of known translational, rotational and combined maneuvers with the motorized stages
- Rotation stage → 0.02 ° accuracy, Translation stage → 0.5 μm accuracy
- Employment of optimized calibration parameters results in accuracy improvement in all types of maneuvers
- Maximum deviations: ~ 0.1° over 40° total angular displacement, ~ 1 mm over 100 mm total translational displacement

$$\Delta S = [\Delta X, \Delta Y, \Delta \Theta]^T$$
$$\Delta z = [\delta x_1, \delta y_1, \delta x_2, \delta y_2, \delta x_3, \delta y_3]^T$$

$$A = \begin{bmatrix} c\sigma_1 & -s\sigma_1 & -r_1\, s\tau_1 \\ s\sigma_1 & c\sigma_1 & r_1\, c\tau_1 \\ c\sigma_2 & -s\sigma_2 & -r_2\, s\tau_2 \\ s\sigma_2 & c\sigma_2 & r_2\, c\tau_2 \\ c\sigma_3 & -s\sigma_3 & -r_3\, s\tau_3 \\ s\sigma_3 & c\sigma_3 & r_3\, c\tau_3 \end{bmatrix} \qquad \Delta S = A^+ \Delta z$$

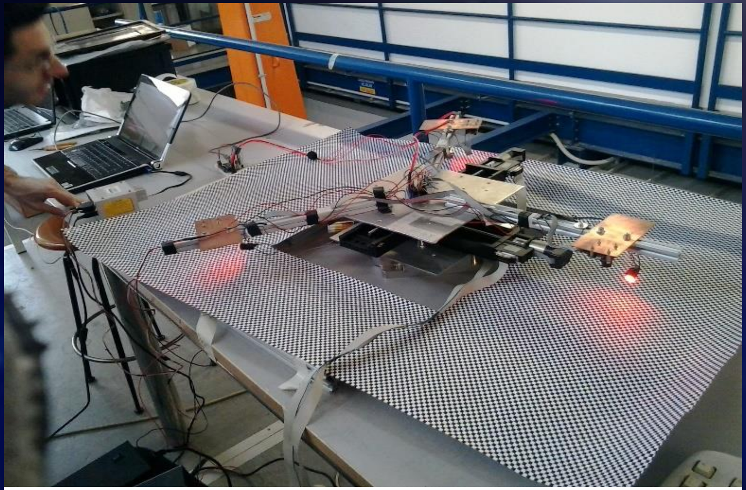
$${}^G X_k = {}^G X_{k-1} + \Delta X_k \cos(\Theta_{k-1}) - \Delta Y_k \sin(\Theta_{k-1})$$
$${}^G Y_k = {}^G Y_{k-1} + \Delta X_k \sin(\Theta_{k-1}) + \Delta Y_k \cos(\Theta_{k-1})$$
$${}^G \Theta_k = {}^G \Theta_{k-1} + \Delta \Theta_k$$

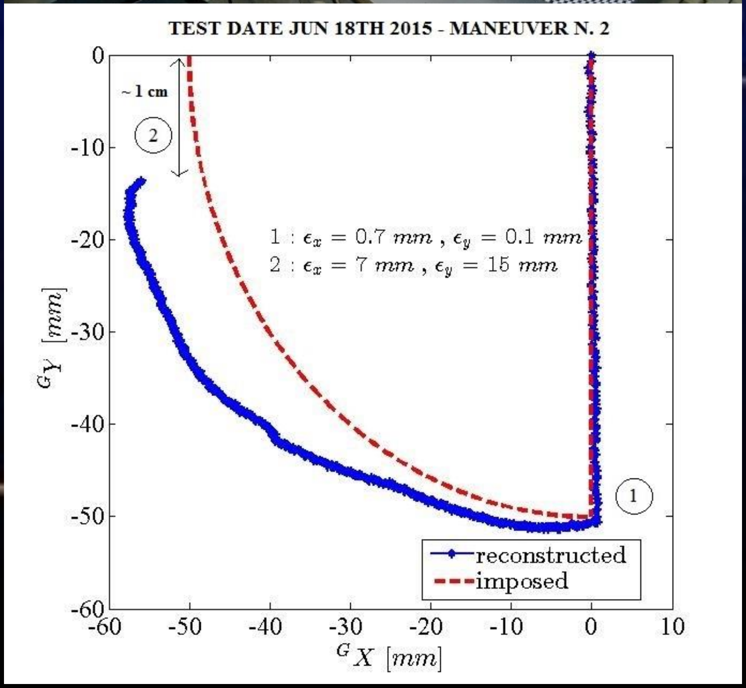


OFS system motion reconstruction tests with TM base prototype

- Further motion reconstruction tests with extended rotational range in combined maneuvers

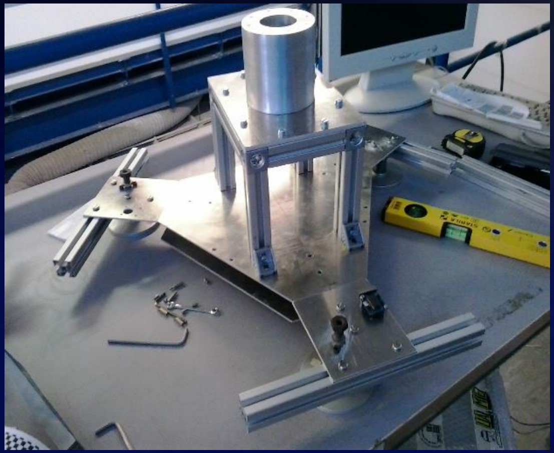
- Extended curvilinear trajectories → visible drift reaching ~ 1 cm for a 90° rotation with 5 cm radius
- Drift most likely caused by periodic counts losses along sensors axes with lower displacement
- Drift compensation through external absolute navigation system

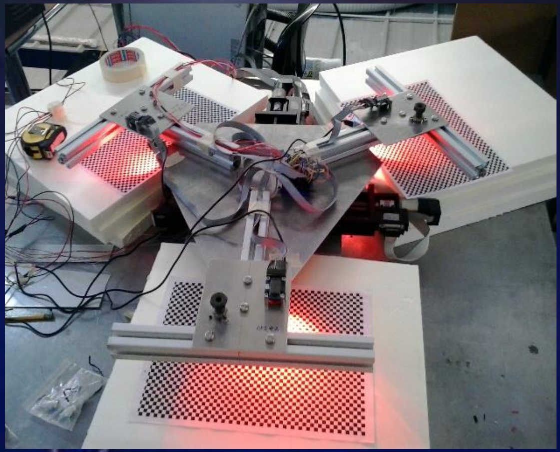




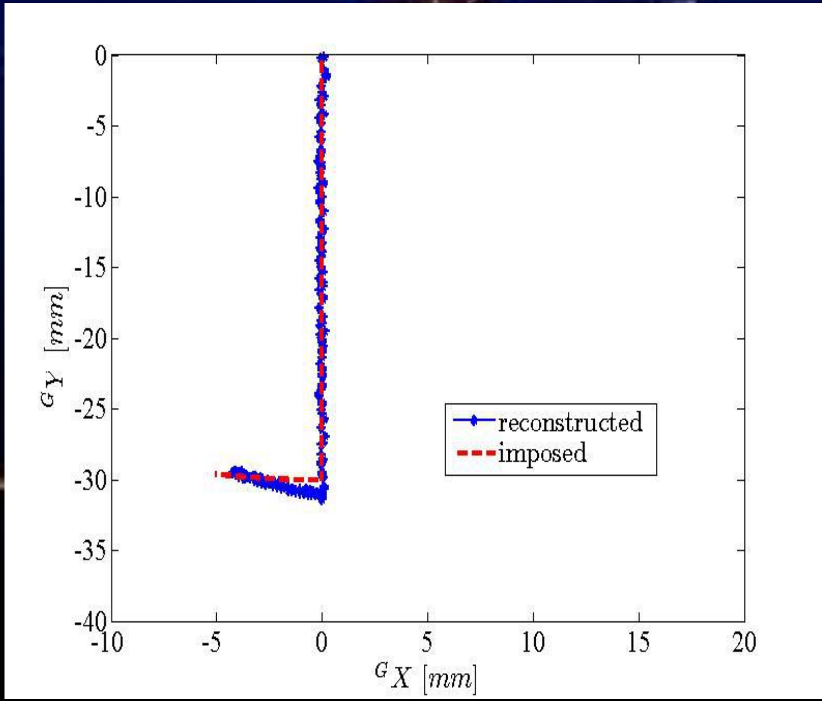
Preliminary assembly of TM, calibration and testing of the OFS system in nominal configuration

- Assembly of TM with air skids
- Installation in the TM of the OFS system
- OFS system calibration in the nominal configuration
- Motion reconstruction tests in nominal configuration
    - Accuracy estimates at the levels obtained with the TM base prototype tests



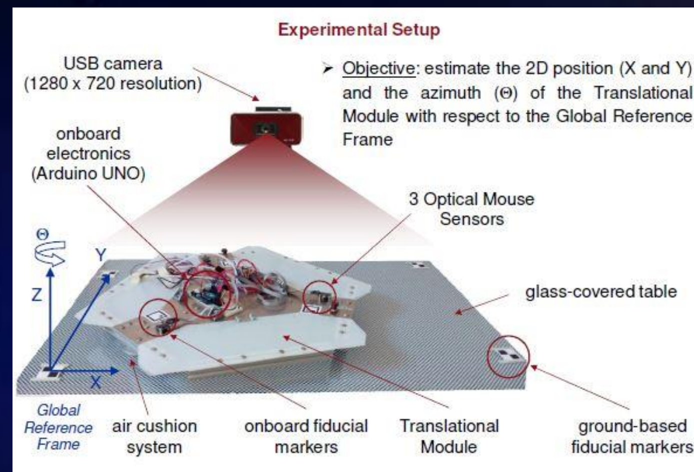


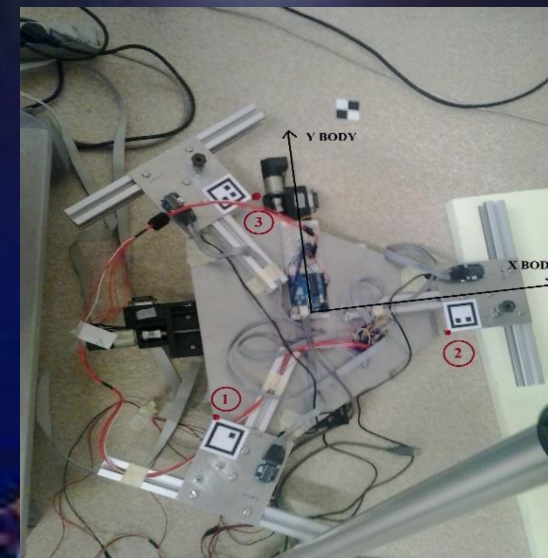
OFS CALIBRATION PARAMETERS IN NOMINAL TM CONFIGURATION							
	k [m/count]	σ [deg]	r [m]	τ [deg]	θ [deg]	φ [deg]	α [deg]
OFS 1	5.77e-4	28	0.2499	260.8	251.1	170.7	61.9
OFS 2	5.47e-4	269.5	0.2569	263.5	7	173.4	180.4
OFS 3	5.64e-4	150.7	0.2514	263.4	125.6	173.6	299.2

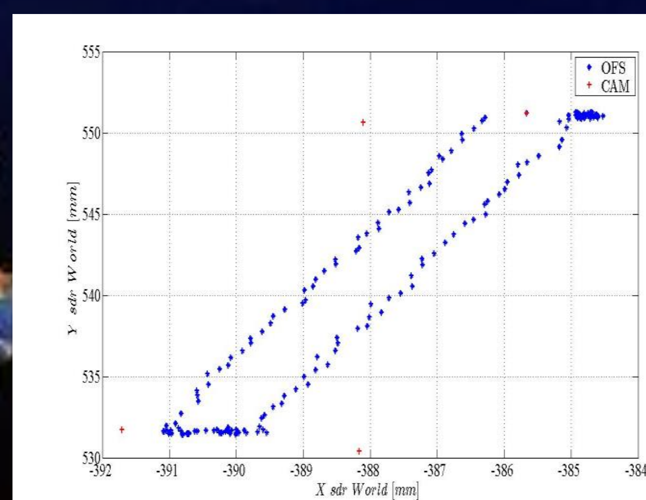


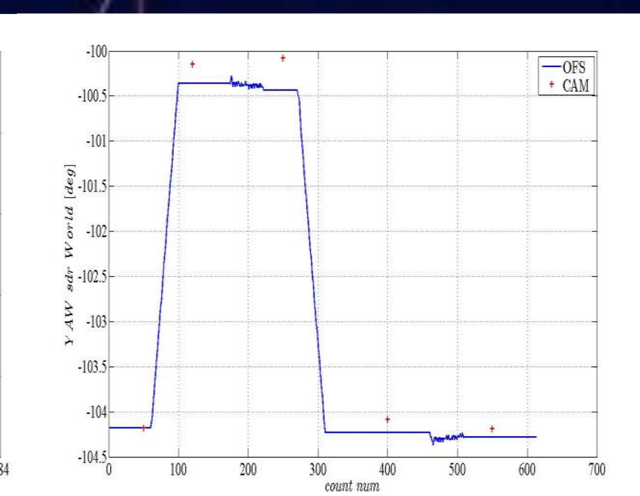
Integration of the OFS system with the vision based external navigation system

- Vision based pose estimation system based on recognition of fiducial markers applied on the test platform
  - Perspective from 3 Points (P3P) with RANSAC scheme and non-linear optimization
  - Low frequency measurements
- Rotational, translational and combined maneuvers tests
  - Concordance between the two navigation systems in the order of few mm for position, comprised between ± 1° for platform Azimuth



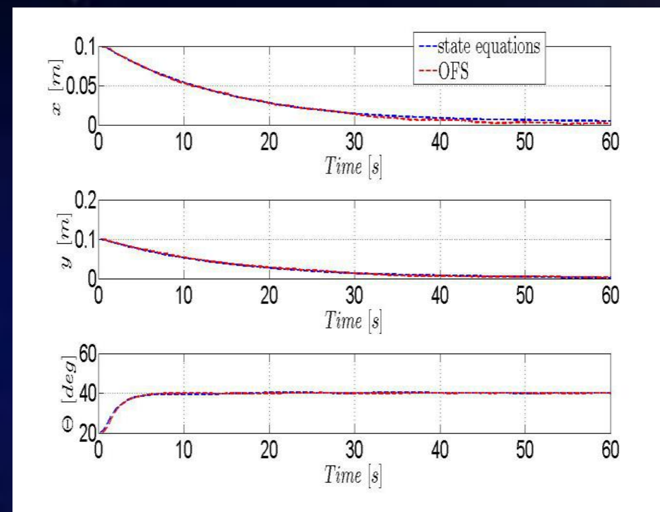






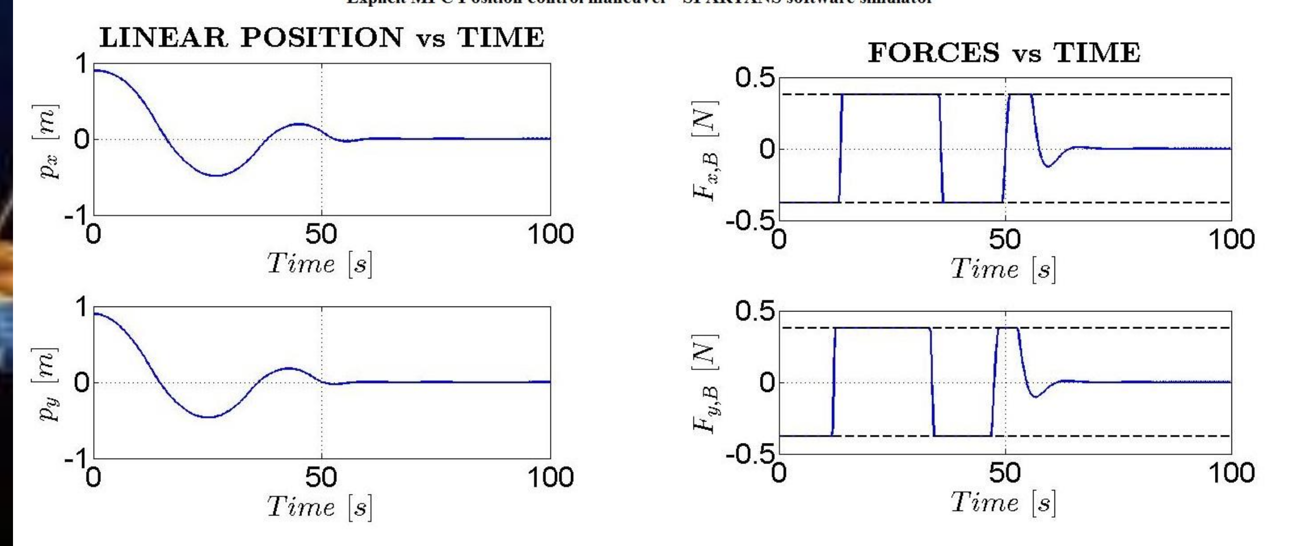
Development of MATLAB simulator for 2D position and Azimuth/3DOF Attitude control maneuvers

- Software simulator for planning and verification of position and attitude control maneuvers with offline control synthesis
    - PID control maneuvers
    - Explicit MPC control maneuvers
    - LQR control maneuvers
- Fixed set point reaching and trajectory tracking
- Implementation of OFS measurement model with counts loss



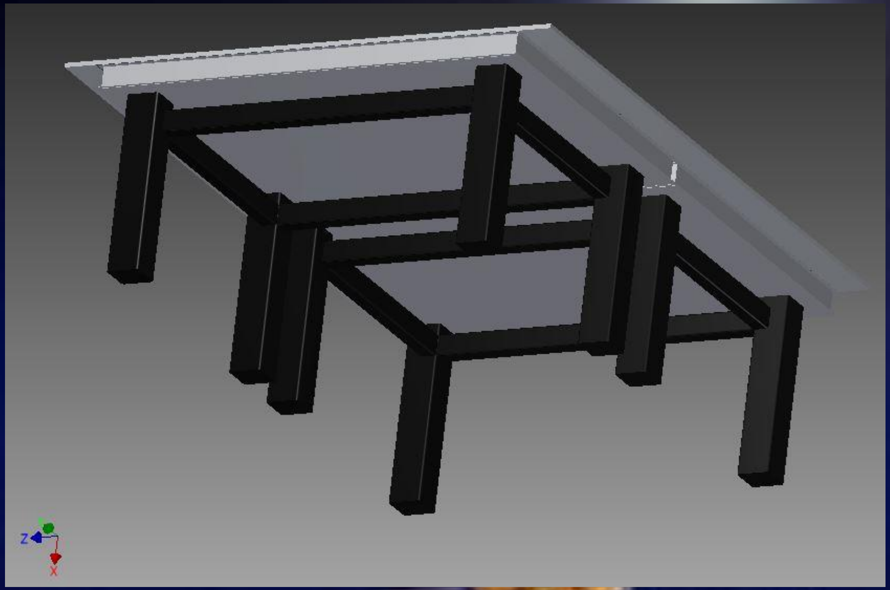
3 DOF SATELLITE FORMATION FLYING UNIT MATLAB SIMULATOR – v07.02	
Initial Conditions	Px_0 = 0.1 m Vx_0 = 0 m/s Py_0 = 0.1 m Vy_0 = 0 m/s Θ_0 = 20° ω_0 = 0.1 °/s
Reference	Px_r = 0 m Vx_f = 0 m/s Py_r = 0 m Vy_f = 0 m/s Θ_r = 40° ω_f = 0 °/s
Translation Control Type	PID
Azimuth Control Type	PID
Thrusters Activation Scheme	PWM
OFS Measurement Model included	Included w/h error model (white noise and counts loss)
Disturbances included	No
Simulation Runtime	60 s
Translation Control Settling Time (10%)	~ 35 s
Final differences bewteen State (ODE 45) and OFS	$\delta x_{f,OFS}$ = 0.9 mm $\delta y_{f,OFS}$ = - 6.5 mm $\delta\Theta_{f,OFS}$ = - 0.13 °
Final differences bewteen State (ODE 45) and Reference	δx_f = 3.6 mm δVx_f = - 0.1 mm/s δy_f = - 2 mm δVy_f = - 0.3 mm/s $\delta\Theta_f$ = - 0.13 ° $\delta\omega_f$ = - 0.03 °/s

Explicit MPC Position control maneuver - SPARTANS software simulator

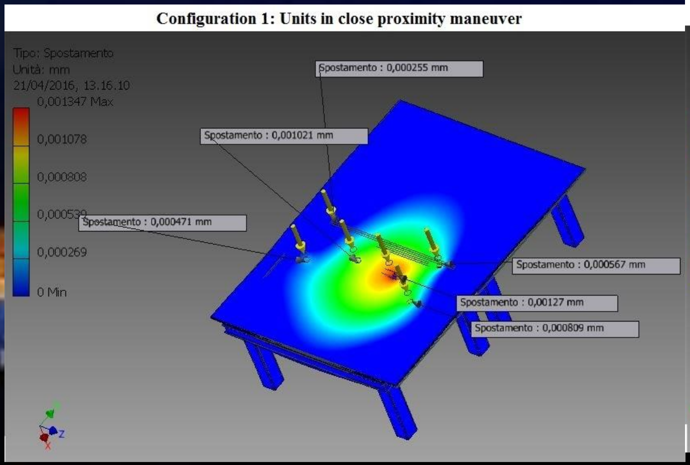


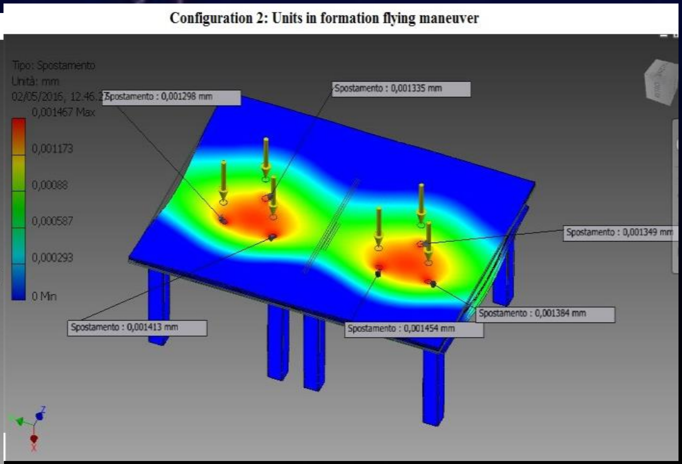
Design and development of Units test table

- Different configurations evaluated → granite tables – separate lower support structure with upper aluminium, rubber and glass layers
- Final design based on levable steel legs available in the market and upper layers of honeycomb, rubber and glass



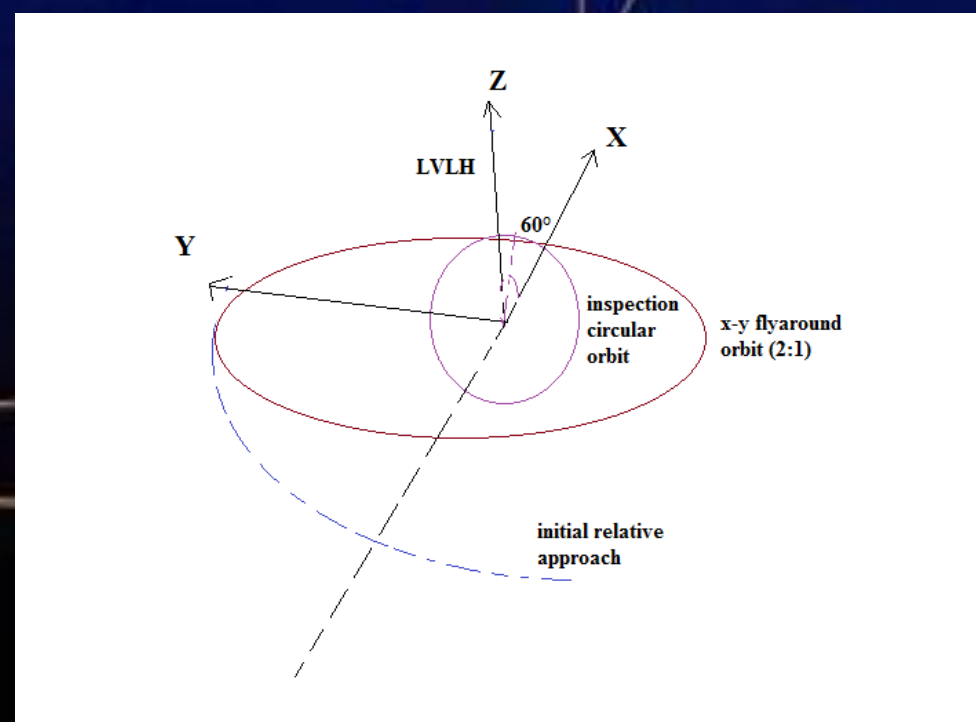
- FEA for estimation of upper surface deformation due to Units weight
- Max estimated deformation results compatible with requested planarity level for the maintainance of the air film of the TM suspension system





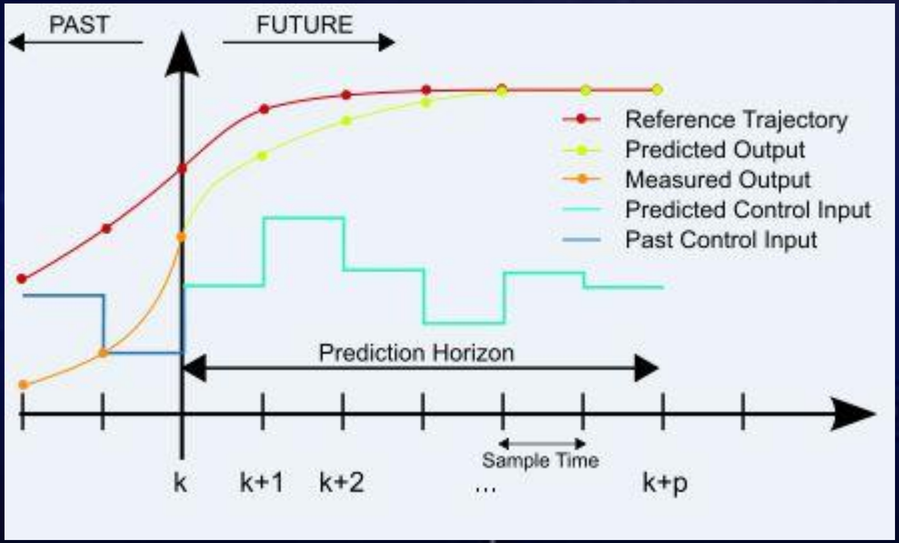
Analysis of non cooperative spacecraft inspection scenario

- Passive Relative Orbits for inspection purposes → non cooperative tumbling satellites inspection
- circular relative orbit at ± 60° wrt to the x-y LVLH plane in order maintain fixed distance from the target
- Envisat inspection scenario
- 98° inclination, 780 km altitude, almost circular orbit
- phases: relative approach → fly-around x-y relative orbit (~ 120 x 60 m ellipse) → circular inspection relative orbit (~ 40 m radius)



Analysis of non cooperative spacecraft inspection scenario

- Evaluation of optimal controllers performances → LQR and implicit MPC for inspection orbit acquisition from the flyaround orbit and automatic inspection orbit maintainance
- Relative translational state assumed available with good accuracy from vision based measurements, order of few mm for position and 0.5 mm/s level for velocity (Yu et al. 2014)
- Differential disturbances → J2, drag
- J3 neglected for low orbit eccentricity
- Reproduction of maneuvers relative dynamics in scale with the SPARTANS simulator with explicit MPC and LQR



Analysis of non cooperative spacecraft inspection scenario

- Envisat dimensions in full deployment: 25 x 20 x 7 m → relative orbit with radius not lower than 40 m (~ 1.5 h relative orbit period)
- Initial flyaround orbit ~ 120 x 60 m ellipse

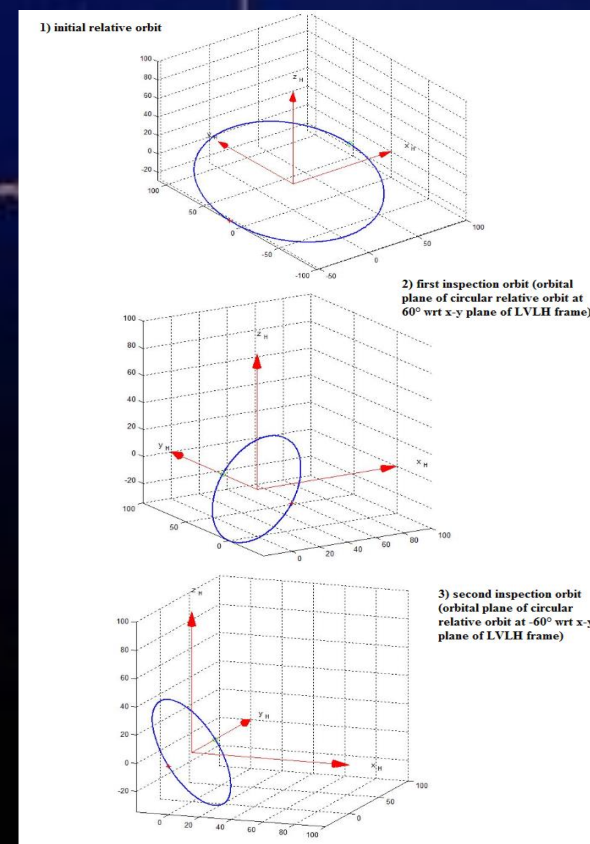
- Control synthesis → discretized Hill-Clohessy Wiltshire equations at Ts = 1 s sampling time
- Preliminary manual tuning of LQR and MPC controllers
- Automatic orbit correction scheme through LQR and MPC → rephasing with automatic position reference obtained with fixed y coordinate and reference circular orbit radius, triggered by circular orbit radius margin (± 2 m)

- Acquisition maneuver through precomputed 2 impulses maneuver → evaluation reference for automatic acquisition through MPC, LQR

$$\dot{x}(t)=Ax(t)+Bu(t) \qquad K(t)=R^{-1}(t)B^T P(t)$$

$$y(t)=Cx(t) \qquad P(t)A+A^T P(t)-P(t)BR^{-1}(t)B^T P(t)+Q(t)=0$$

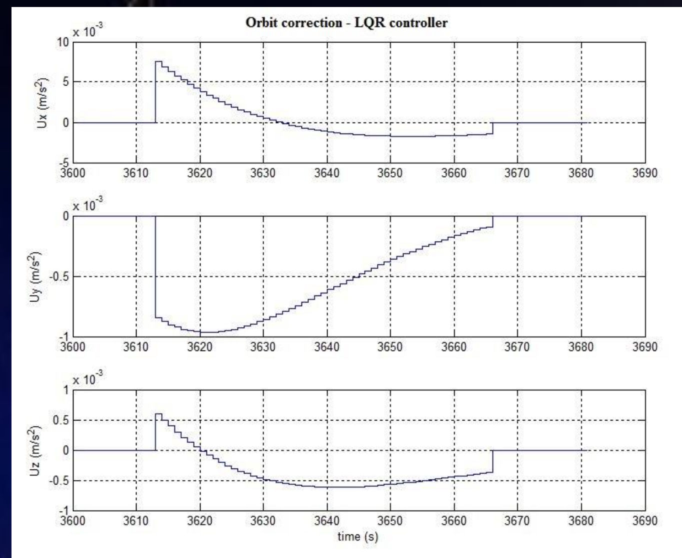
$$K_{LQR}=\begin{bmatrix} 7.8921e\text{-}4 & -1.1608e\text{-}5 & 0 & 0.0401 & 1.214e\text{-}5 & 0 \\ 1.1608e\text{-}5 & 7.8894e\text{-}4 & 0 & -1.2045e\text{-}5 & 0.0401 & 0 \\ 0 & 0 & 7.8894e\text{-}4 & 0 & 0 & 0.0401 \end{bmatrix}$$

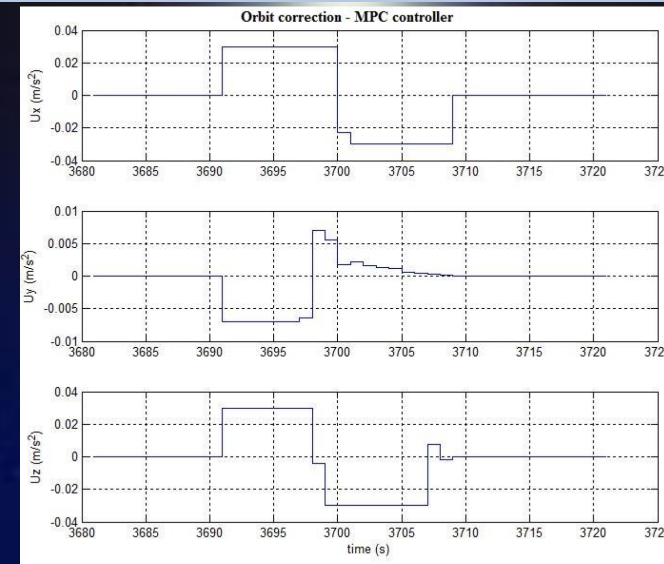


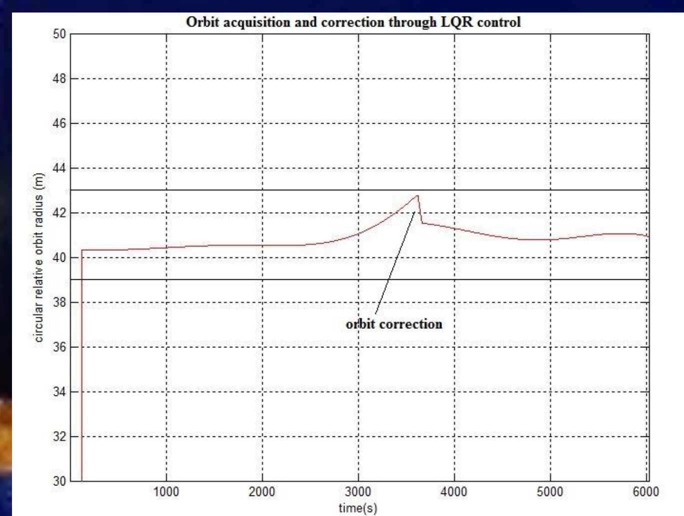
Analysis of non cooperative spacecraft inspection scenario

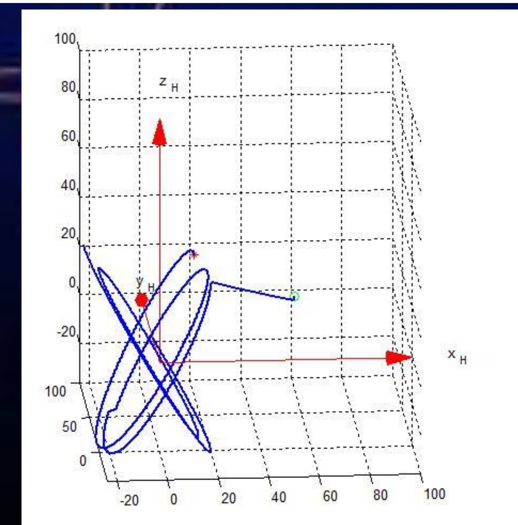
- Delta-v for inspection orbit acquisition and correction higher for MPC wrt LQR
- Lower tracking error for MPC (< 10 cm) wrt to LQR (< 1 m)
- In LQR manuvers simulations the circular orbit radius remains slightly longer (~ 100 s over ~ 2.5 h) within established margin (± 2 m)

- Both LQR and MPC controllers present higher total delta-v wrt to 2 impulses maneuver







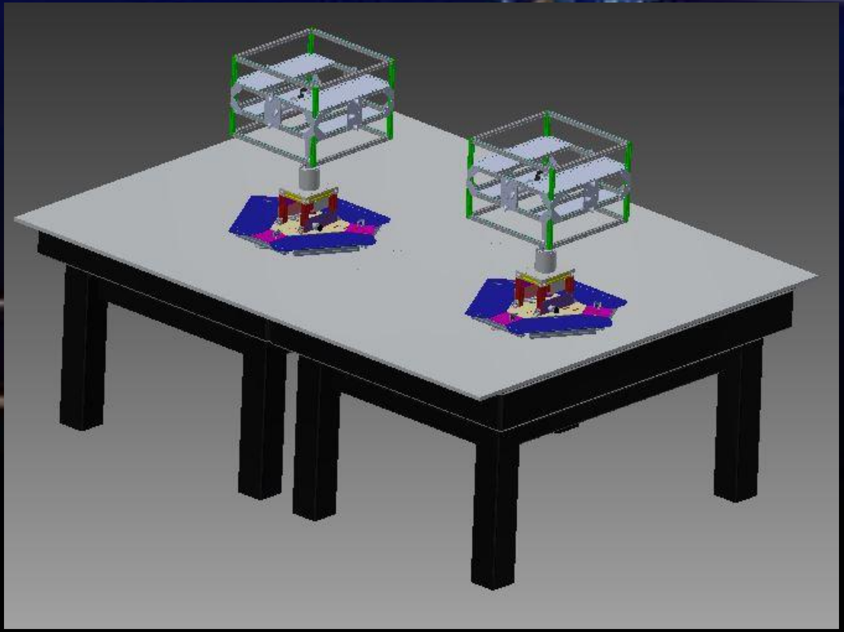


Total delta-v requirement for inspection orbit acquisition through LQR control	Total delta-v requirement for inspection orbit correction through LQR control
$\Delta v_x = 1.38\,m/s$	$\Delta v_x = 0.1\,m/s$
$\Delta v_y = 0.35\,m/s$	$\Delta v_y = 0.03\,m/s$
$\Delta v_z = 0.27\,m/s$	$\Delta v_z = 0.02\,m/s$

Total delta-v requirement for inspection orbit acquisition through MPC control	Total delta-v requirement for inspection orbit correction through MPC control
$\Delta v_x = 1.42\,m/s$	$\Delta v_x = 0.53\,m/s$
$\Delta v_y = 0.39\,m/s$	$\Delta v_y = 0.06\,m/s$
$\Delta v_z = 1.3\,m/s$	$\Delta v_z = 0.4\,m/s$

Future Activities and Perspectives

- TM assembled and subsystems designed with components selected
- Assembly of updated version of AM with position control air actuators
- Assembly of modular test table
- Planning and execution of 3DOF (Position and Azimuth) and 5 DOF maneuvers (Position and Yaw, Pitch, Roll) with hardware in the loop
- Assembly of second Unit
- Installation and testing of docking interfaces for Automatic Rendez-Vous and Docking/Capture maneuvers



List of Publications

- A. Valmorbida, F. Scarpa, M. Mazzucato, S. Tronco, S. Debei and E. C. Lorenzini, *Attitude Module Characterization of the Satellite Formation Flight Testbed*, IEEE Metrology for Aerospace 2014, May 29-30 2014, Benevento, Italy
- A. Valmorbida, M. Mazzucato, A. Aboudan and S. Tronco, *Test of Attitude Control Maneuvers with a Satellite Formation Flight Testbed*, IEEE Metrology for Aerospace 2014, May 29-30 2014, Benevento, Italy
- Valmorbida A., Mazzucato M., Tronco S., Debei S., Lorenzini E C., *SPARTANS – a cooperating spacecraft testbed for autonomous proximity operations experiments*, Instrumentation and Measurement Technology Conference (I2MTC), 2015 IEEE International, Pisa, Italy
- Valmorbida A., Tronco S., Mazzucato M., Debei S., Lorenzini E. C., *Optical flow sensor based localization system for a cooperating spacecraft testbed*, IEEE Metrology for Aerospace 2015, June 4-5 2015, Benevento, Italy
- Mazzucato M., Tronco S., Valmorbida A., Scibona F., Lorenzini E. C., *Development of a ground based cooperating spacecraft testbed for research and education*, 1° Symposium on Space Educational Activities, December 9-11 2015, Padova, Italy
- Mazzucato M., Valmorbida A., Tronco S., Costantini M., Debei S., Lorenzini E. C., *Development of a camera-aided optical mouse sensors based localization system for a free floating planar robot*, IEEE Metrology for Aerospace 2016, Firenze, Italy

THANK YOU FOR YOUR KIND ATTENTION