Clean Space Industrial Days

END-TO-END ON GROUND SYSTEM DEMONSTRATION OF COMBINED TECHNOLOGIES FOR DEBRIS REMOVAL APPLICATIONS

INNOVATING SOLUTIONS

END-TO-END ON GROUND SYSTEM DEMONSTRATION OF COMBINED TECHNOLOGIES FOR DEBRIS REMOVAL APPLICATIONS

INTRODUCTION & SCENARIO DEFINITION

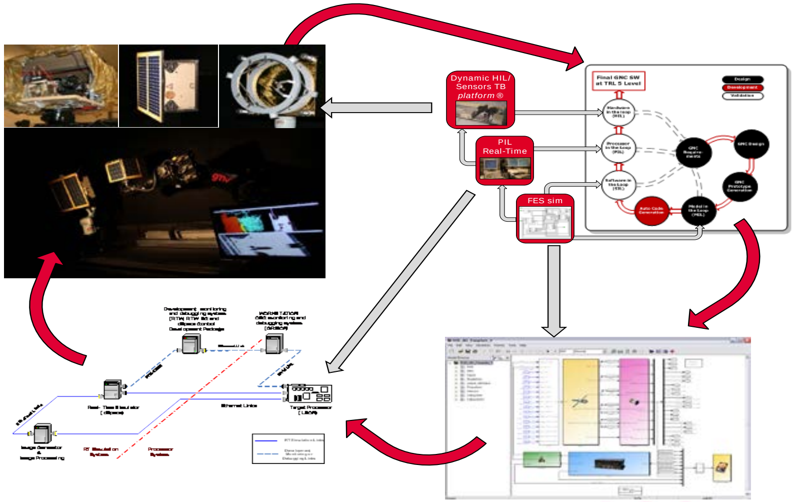
INTRODUCTION & BACKGROUND

This paper is based on the results of ORCO project, part of the **ESA StarTiger Permanent Initiative AO 2014-Step2**, whose objective has been to advance some of the key technologies required to perform complex robotic scenarios needing a rigid capture mechanism such as a robotic arm (applicable to **On-Orbit Servicing**, e.g. life extension and reparation, and **Active Debris Removal**), including:

- **Image processing chain** for relative navigation and robotic arm operation.
- **Chaser vehicle GNC** for approach and for close proximity operations.
- **Robotics control**. Robotic arm and the required grasping end effector.
- **Simultaneous operation of two control system** i.e. GNC and robotic arm during capture manoeuvres.
- **Combo system overall modelling** and dynamic characterization, requiring multi-body models.

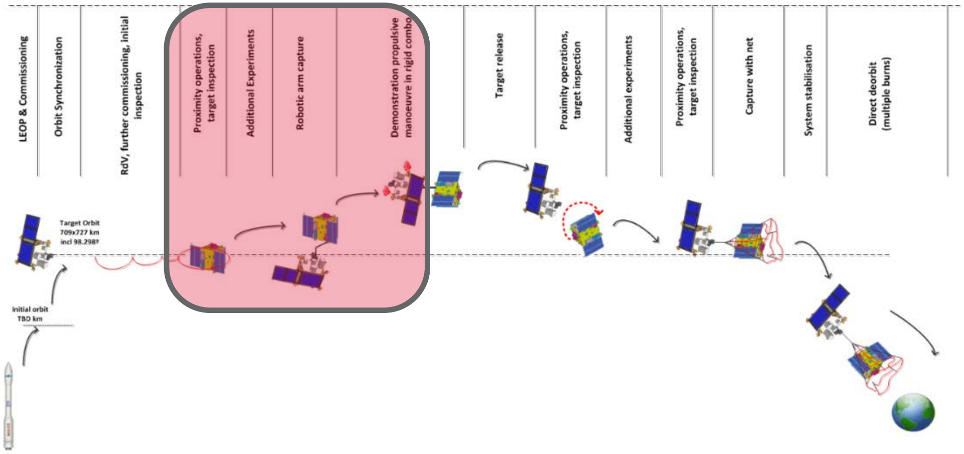
ORCO project has targeted an on-ground comprehensive end-to-end validation of all the above-listed major system elements within the full operations sequence (never done before), including:

- **Model-based** (MIL) simulation validation (Matlab/Simulink)
- **SW-based (SIL/PIL)** validation (autocoding + LEON processors in real-time environment)
- **HIL-based** validation with real air-to-air stimulation through space-realistic robotics-base dynamic laboratory

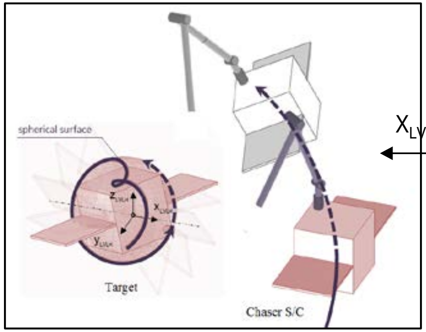


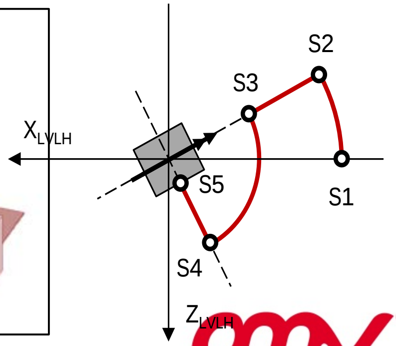
SCENARIO DESCRIPTION

- ORCO application scenario is based on ESA AnDROiD (Active Debris Removal for a small satellite –PROBA2-) mission, developed till a “preliminary definition” level by GMV, Qinetiq and CBK.
  - ORCO system target is limited to close-proximity phases
  - Both **cooperative** (e.g. target S/C controlled in attitude, representative of in-orbit servicing missions) **and non-cooperative scenarios** (e.g. target S/C not controlled in attitude or even spinning at high rates, representative of active debris removal missions) are considered in ORCO.



  - For the non-cooperative scenario (0.3°/s & 3.5 °/s):
    - Final approach/angular synchronization along any generic direction
    - Start of ORCO scenario is the final forced motion of the rendezvous
    - Contact phase: both free-floating and controlled (position and attitude) chaser options are analysed





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SYSTEM ARCHITECTURE & DESCRIPTION

ORCO SYSTEM ARCHITECTURE

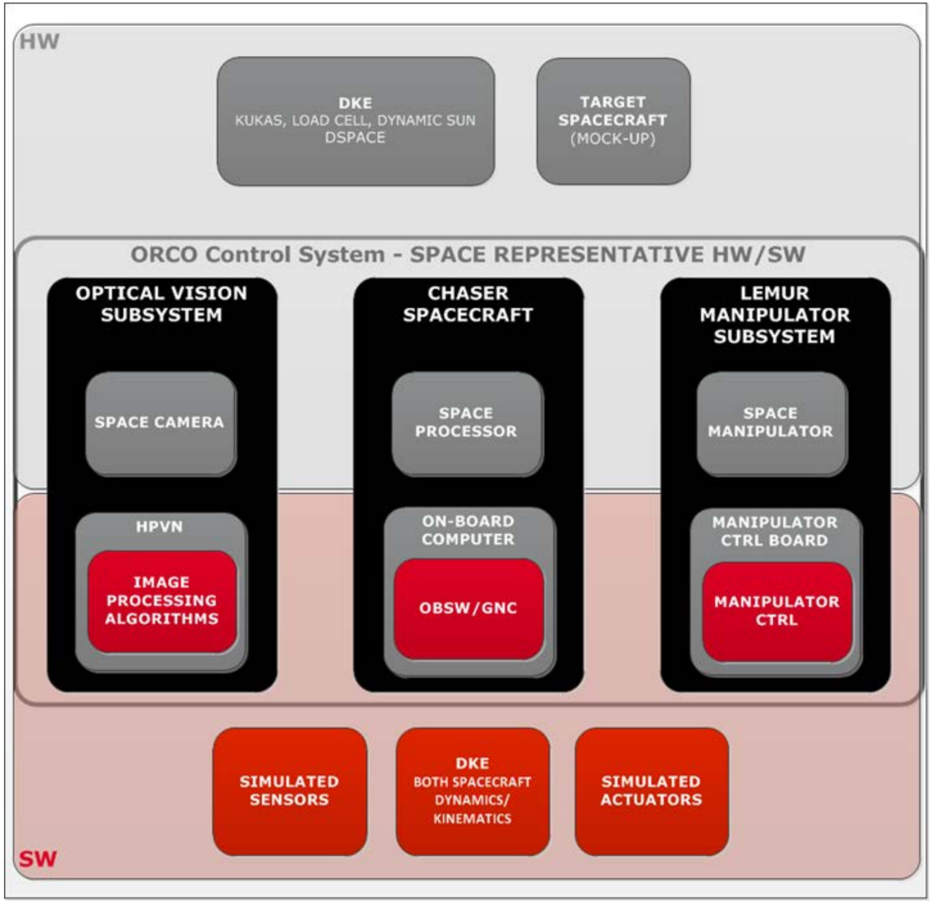
Three main HW elements/subsystems:

- Chaser spacecraft
- LEMUR robotic space manipulator
- Navigation camera system

Each subsystem relies on a specific SW brick (red), but also each one has interfaces and relations with the other elements and other HW elements (grey), thus allowing the System to work as a whole.

The three SW bricks are hosted and executed in separated processors:

- The Chaser OBSW/GNC on the spacecraft Main Computer (OBC)
- The LEMUR controller on a dedicated control board (LEMUR Control Board)
- The optical navigation algorithms on a dedicated FPGA system (HPVN)



HW

DKE
KUKAS, LOAD CELL, DYNAMIC SUN
DSPACE

TARGET
SPACECRAFT
(MOCK-UP)

ORCO Control System - SPACE REPRESENTATIVE HW/SW

OPTICAL VISION SUBSYSTEM

SPACE CAMERA

HPVN

IMAGE PROCESSING ALGORITHMS

CHASER SPACECRAFT

SPACE PROCESSOR

ON-BOARD COMPUTER

OBSW/GNC

LEMUR MANIPULATOR SUBSYSTEM

SPACE MANIPULATOR

MANIPULATOR CTRL BOARD

MANIPULATOR CTRL

SIMULATED SENSORS

DKE
BOTH SPACECRAFT
DYNAMICS/
KINEMATICS

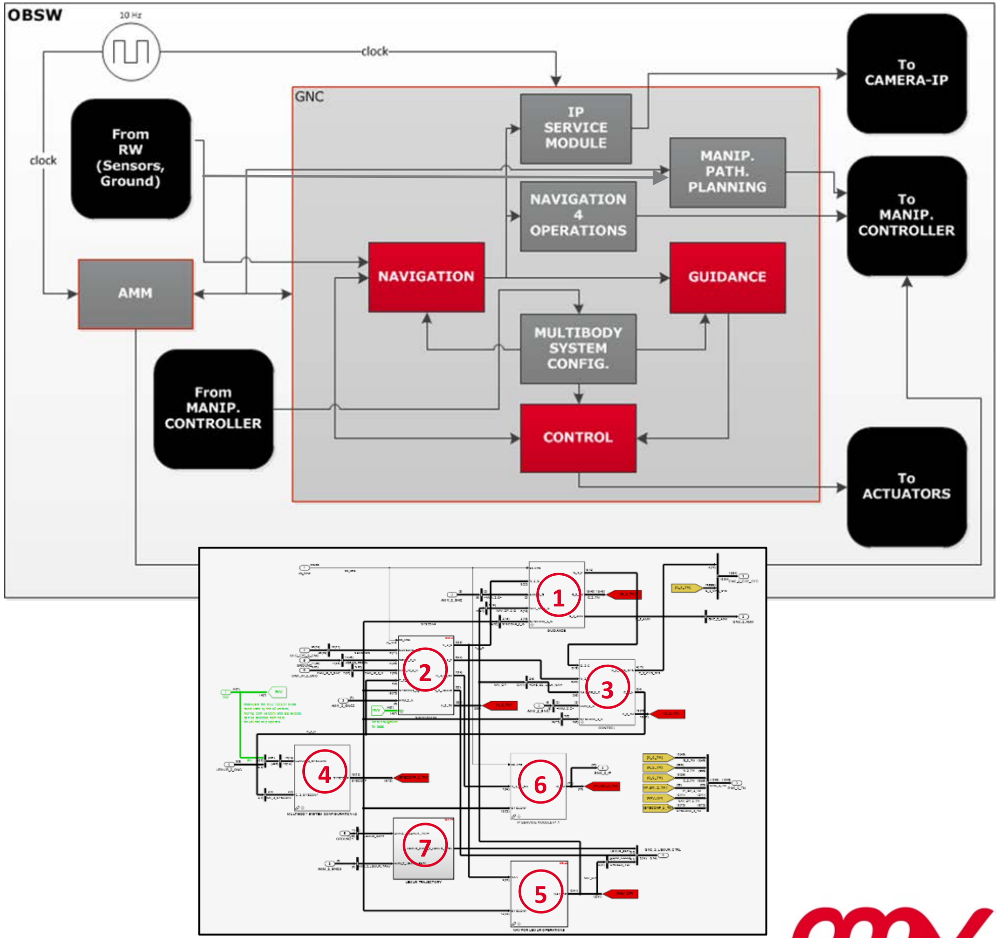
SIMULATED ACTUATORS

SW

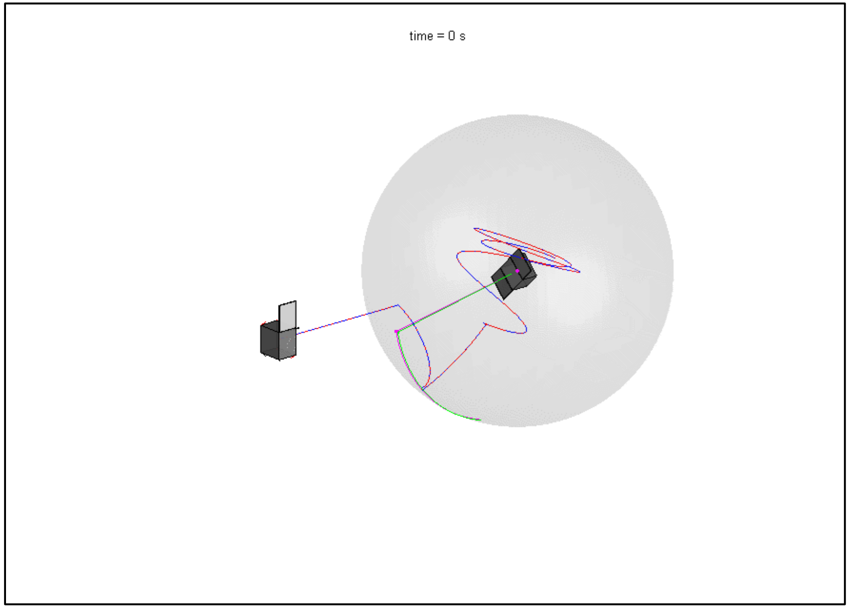
CHASER S/C GNC SYSTEM: ARCHITECTURE

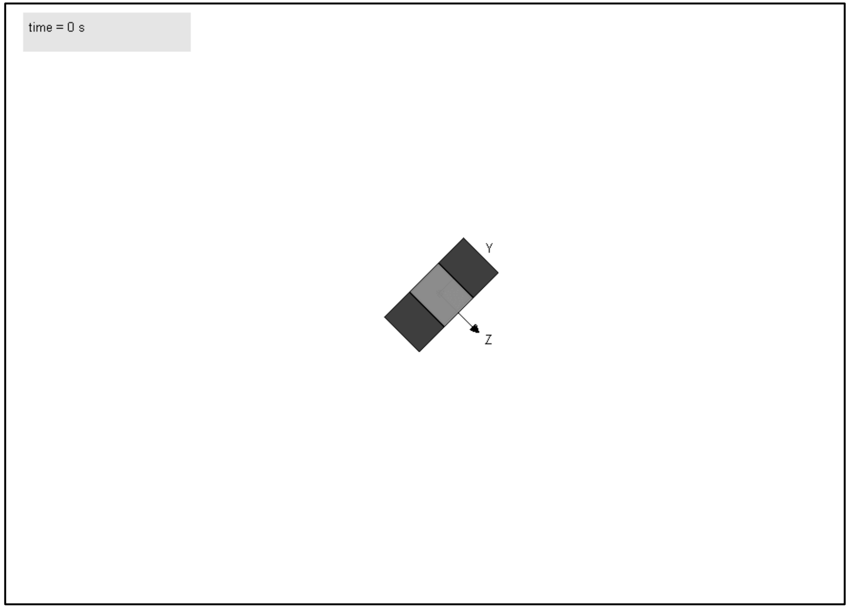
GNC is made up of 7 functions:

1. **Navigation** (chaser absolute, chaser relative wrt target, and target attitude state estimation)
2. **Guidance** (reference trajectory (attitude, angular rate, position and velocity) and the reference feed-forward forces and torques
3. **Control** (chaser robust control)
4. **Multibody System Configuration** (MCI properties and End-Effector kinematic state)
5. **Navigation for LEMUR operations** (chaser relative state and LEMUR end-effector kinematic state wrt Target Body Frame)
6. **IP Service Module** (Sun direction estimation and a-priori estimation of the target relative pose)
7. **LEMUR Trajectory** (pre-computed LEMUR trajectory as Look-up-table to be used as initial reference/path planning)



SYNCHRONIZATION ANIMATION

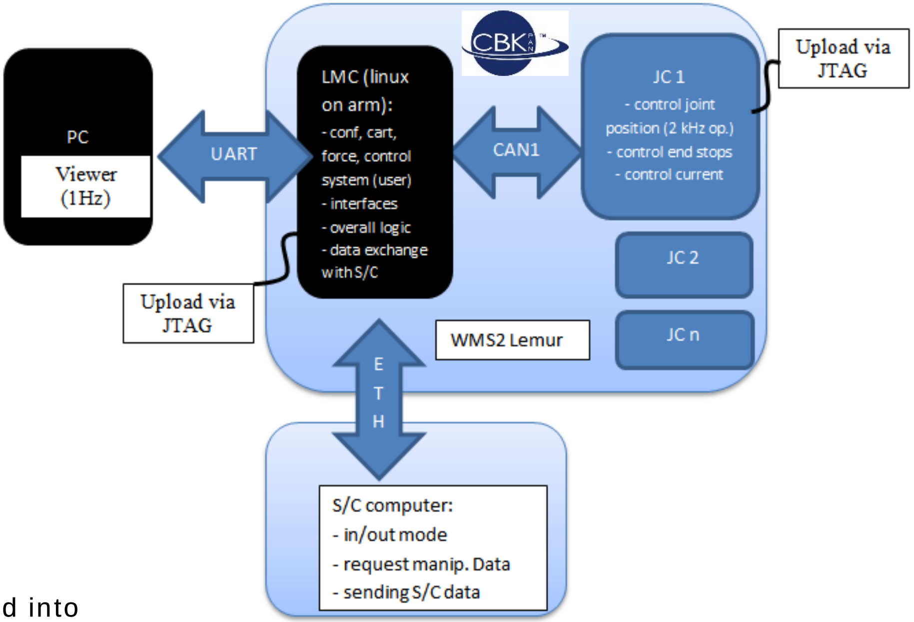




LEMUR SYSTEM ARCHITECTURE

Two electronic circuits:

- Lemur Main Computer (LMC)
  - Atmel ARM Cortex A5 ATSAMA5D36 processor
  - Performs trajectory control in configurational & cartesian space as well as force control and mode management
  - Computes and send the control signals (reference joint angles) to joint-controller boards.
- Joint controllers (JC)
  - 32bits ARM Cortex M3 microcontroller
  - Linear power converter
  - Set of input/output buffers
  - Interface to communicate with the encoders
- Robotic arm:
  - Original space WMS1 LEMUR design (3m span) has been evolved into lab WMS2 LEMUR prototype (1m span because of gravity limitations)
  - A dummy gripper (representative at force/torque level) has been added as end-effector



PC

Viewer (1Hz)

UART

LMC (linux on arm):
- conf, cart, force, control system (user)
- interfaces
- overall logic
- data exchange with S/C

Upload via JTAG

CAN1

JC 1
- control joint position (2 kHz op.)
- control end stops
- control current

Upload via JTAG

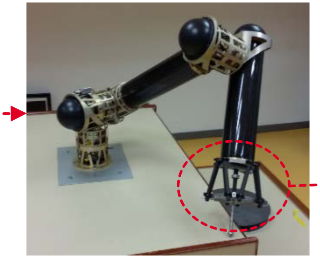
JC 2

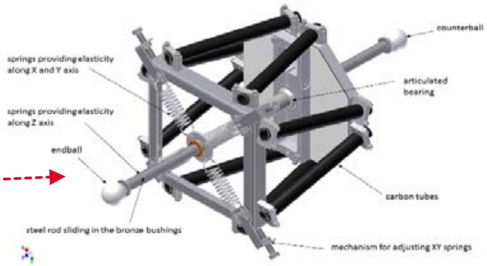
JC n

WMS2 Lemur

ETH

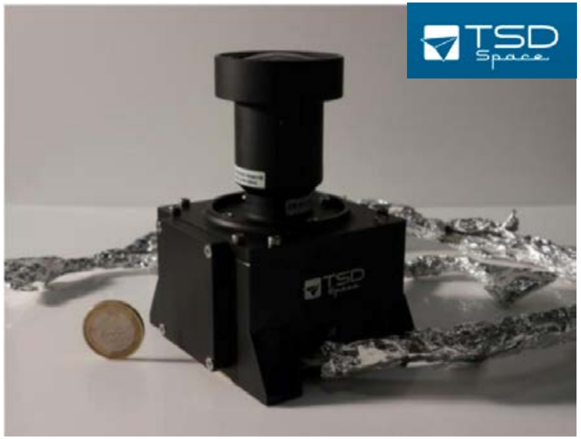
S/C computer:
- in/out mode
- request manip. Data
- sending S/C data

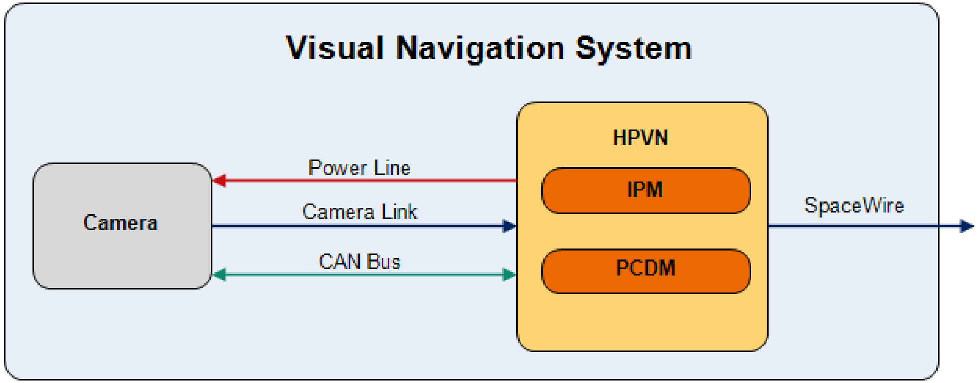




VISION-BASED SYSTEM: ARCHITECTURE

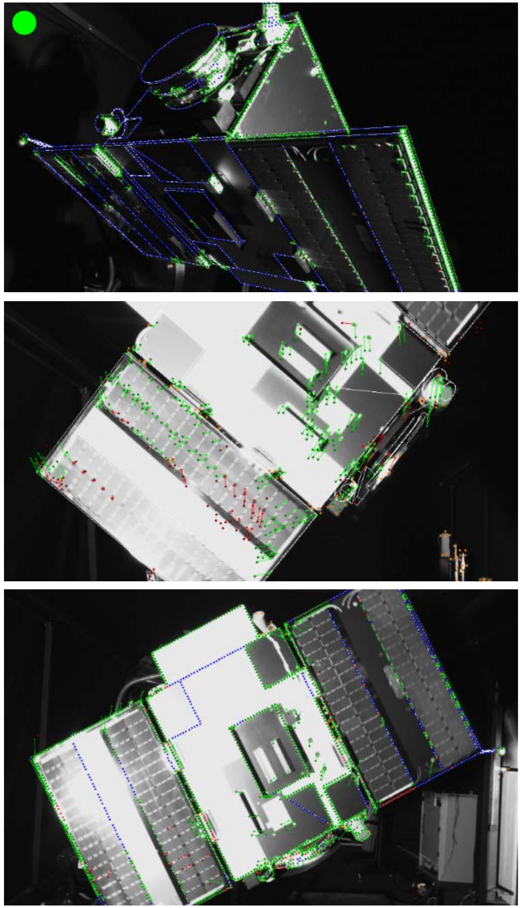
- Compact high-performance CMOS camera (1280x720 pixels) developed for space applications
- Based on Actel FPGA and high-reliability components available with different qualification levels
- The High-performance Processing unit for Visual-based Navigation (HPVN) is able to perform several hardware accelerated image processing algorithms.
- HPVN comprises two modules:
  - Image Processing Module (IPM)
  - Power Conditioning & Distribution Module (PCDM)

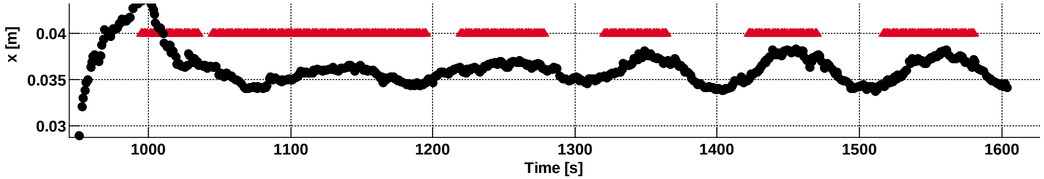




VISION-BASED SYSTEM: ALGORITHMS

- Model Based Tracking (MBT)
  - Edge tracking: absolute method, recovers from small errors, robust to light changes
  - If light direction is available, shadowed edges can be removed and not tracked in RT
  - Robust to Earth albedo and Earth on background
  - It can suffer if it is bad initialized (or with big leaps between frames)
- Landmark tracking (KLT)
  - Relative method, suffers from drift, but can be useful on final phase in stationary mode
  - Robust to big leaps between frames as long as enough landmarks are still seen
- Hybrid MBT + KLT
  - The best of both: landmark tracking provides a really good estimation of the relative movement from n^{th} to $(n+1)^{th}$ frame, then MBT prevents and corrects the drift.
  - Higher robustness to leaps between frames (due to high speed maneuvers, lost frames, etc.) and also to lightning variations as our tests showed.
  - Very suitable for middle-textured targets as Proba2 (not a fully textured target that could be tracked reliably only based on landmarks, but also textured enough that a model-based (edge) tracking could be tricked in some circumstances).
  - **Hybrid KLT + MBT has been implemented in VHDL**
  - **Tested with real images at 1.5 Hz (easily improvable to 2 Hz)**
  - **Performance (experimental tests): ±0,5cm, ±0,5° (at 2-5 meters distance in SK)**





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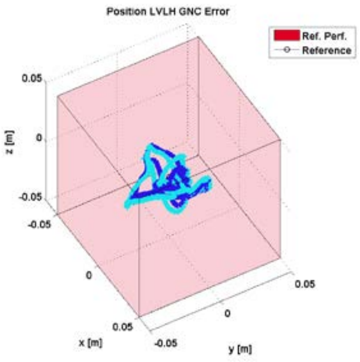
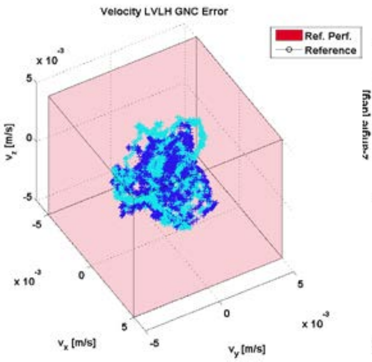
SYSTEM VALIDATION TESTS

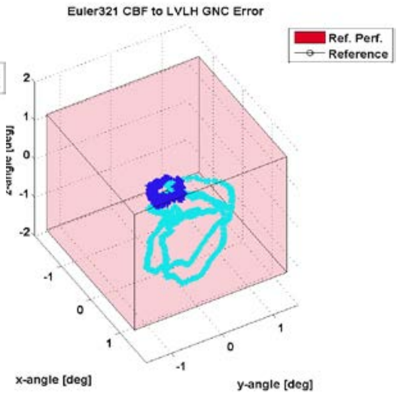
ORCO SIMULATOR TEST RESULTS

Scenario #3 (most demanding scenario, capture of non-cooperative object, 3.5°/s, ENVISAT-like). Chaser S/C GNC/control error (position, velocity, attitude and attitude rate) at Station Keeping position:

- With robotic arm being deployed (light blue)
- With robotic arm braked/folded (dark blue)

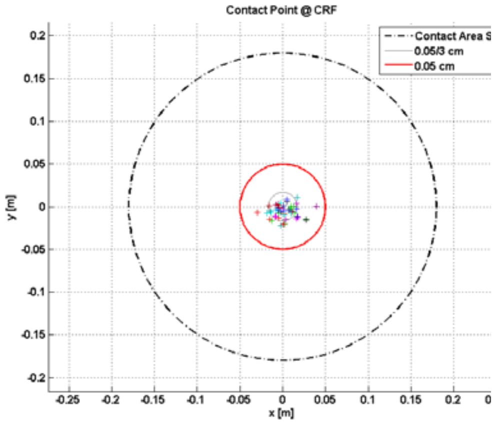


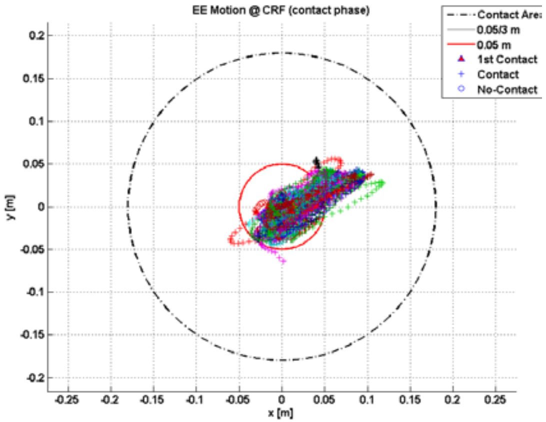




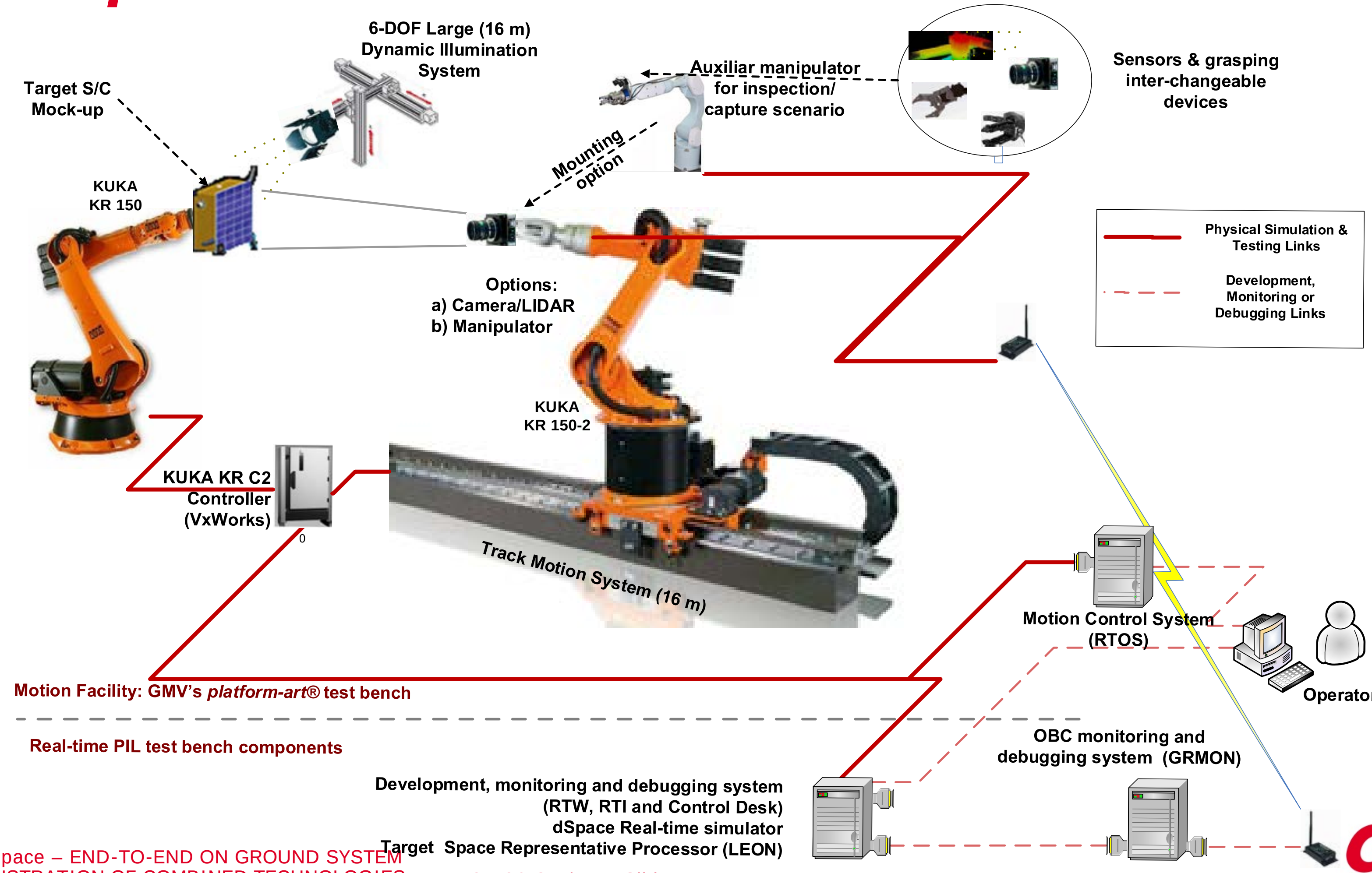
MonteCarlo, Scenario #1 (capture along V-bar of a cooperative object inertially stabilized, both chaser S/C GNC and robotic arm controller in the loop). Contact performance assessment:

- End-Effector first contact point (left)
- End-Effector contact point trajectory evolution over sliding target surface (right). Target is to keep it at the center.





HIL: *platform-art®* T/F SET-UP & ELEMENTS



6-DOF Large (16 m) Dynamic Illumination System

Target S/C Mock-up

KUKA KR 150

Auxiliar manipulator for inspection/ capture scenario

Mounting option

Sensors & grasping inter-changeable devices

Options:
a) Camera/LIDAR
b) Manipulator

🟥	**Physical Simulation & Testing Links**
- - -	**Development, Monitoring or Debugging Links**

KUKA KR 150-2

KUKA KR C2 Controller (VxWorks)

0

Track Motion System (16 m)

Motion Control System (RTOS)

Operator

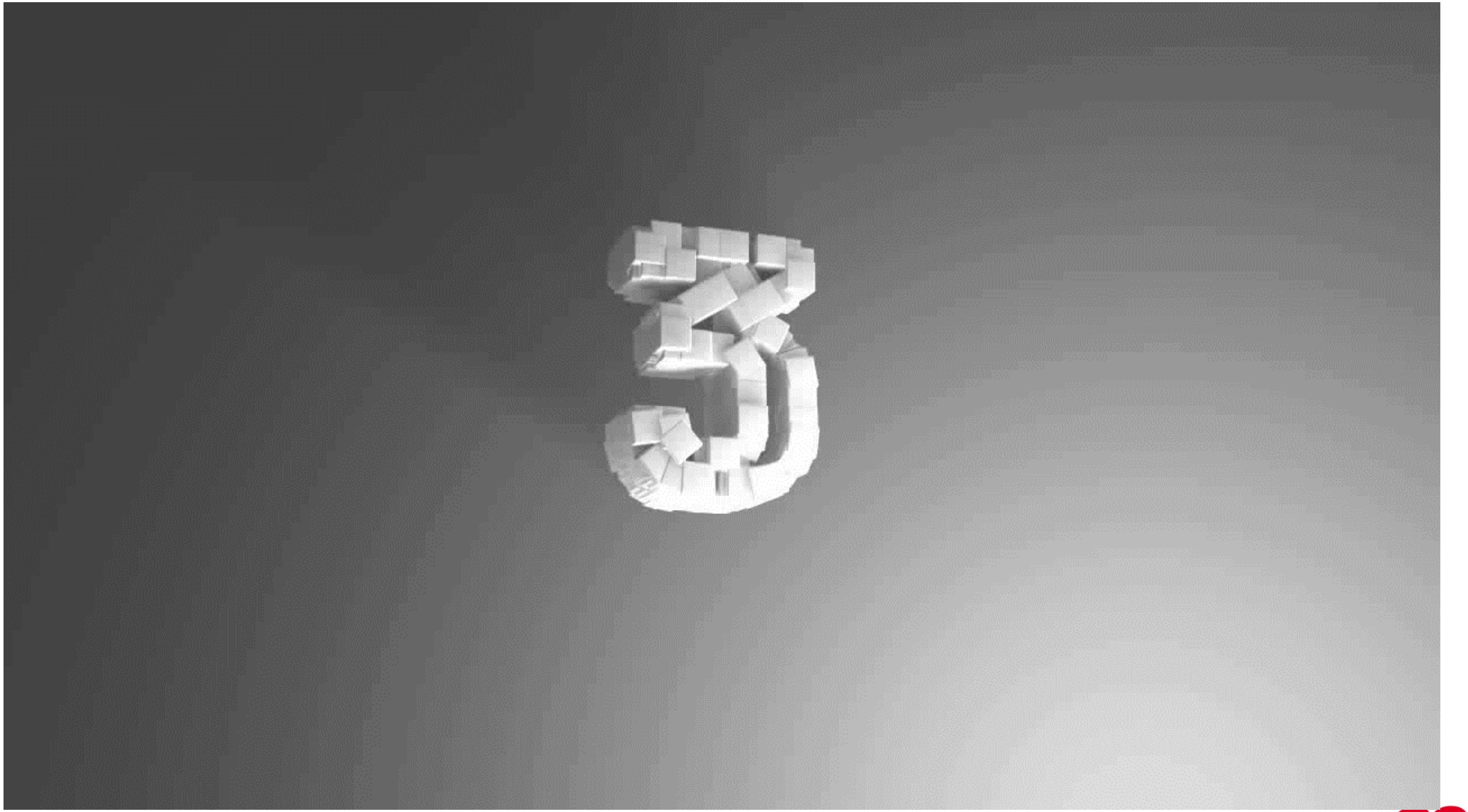
Motion Facility: GMV's *platform-art®* test bench

Real-time PIL test bench components

OBC monitoring and debugging system (GRMON)

Development, monitoring and debugging system (RTW, RTI and Control Desk)
dSpace Real-time simulator
Target Space Representative Processor (LEON)

HIL TESTS: Videos



MAIN CONCLUSIONS

Major conclusions:

- The full set of identified critical technologies for In-Orbit Servicing/Active Debris Removal (IOS/ADR) have been significantly worked out/matured during ORCO activity
- Rendezvous and close-proximity operations have been successfully demonstrated with only a vision-based camera as relative navigation sensor assumed that:
  - The navigation filter and the IP have information about the illumination quality (in terms of goodness/badness for IP purposes) ➔ blackouts are solved by propagating previous state (stable target rotation)
  - There is an on-board illumination source that can be used for the very last meters of operations (to avoid blackouts/propagation periods in very high collision risk operations)
- Successful independent operation of chaser SC GNC and robotic manipulator controller has been demonstrated assumed that:
  - There is a-priori knowledge of the intended dynamic (guidance/path planning crossed-knowledge)
  - Force/torque load cell is in the loop for feedback during the contact
- Achieved TRL can be set in:
  - TLR 4/5 for the full system (TRL5 at functional level, TRL4 at interfacing level)
  - TRL 5/6 for the vision-based system (both functional and interfaces) ➔ candidate to be flown as experiment

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THANK YOU

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