Vision-Based Navigation (VBN) Sensors for Debris Removal (and On-Orbit Servicing): Technology Developments and Supporting Activities for GNC

Manuel Sanchez Gestido
ESA/TEC-SAG

ESA CleanSpace Industry Days (CSID) 2021
Session: "Debris removal and servicing: Technologies for Servicer Vehicles: GNC"
22/09/2021

Vision-Based Navigation (VBN) Sensors for Debris Removal (and On-Orbit Servicing): TEC-SAG section

- Multispectral cameras (breadboard and GNC Navigation solution for position and attitude estimation):
    - IRPN ("Image Recognition and Processing for Navigation")
    - Multispectral Sensing for Relative Navigation (MSRN)
    - Breadboard MultiSpectral Camera (for Relative Navigation in Lagrangian Orbits in the Earth-Moon System, MSRN2)
    - Supporting activities:
        - TIRVOA ("Assessment and comparing conditions in vacuum with open air experiments in thermal infra-red")
        - PANGU version_v6 for synthetic image generation in the thermal Infrared (planets/moons/asteroids and spacecrafts)
- Other technologies:
    - Plenoptics
    - Event-based cameras

Vision-Based Navigation (VBN) Sensors for Debris Removal (and On-Orbit Servicing): Multispectral cameras

esa

- Cameras in visible and thermal Infrared bands provide complementary information for a robust Navigation solution (position and attitude estimation)
- Multispectral camera as passive sensor (saving mass/power), potentially primary or complementary sensor with others depending on the distance to the target
- Thermal signature information in eclipse from contrast between contiguous surfaces with different thermal properties (thermal evolution and/or emissivity)
- Different rendering tools used for generating synthetic images (PANGU, SurRender, SpiCam, ASTOS CamSim): Need for a benchmarking set of reference scenarios with common metrics for comparison
- Testing/Validation:

images	representativeness	+	–
in-orbit (real cam)	best	full representative	limited availability of data & ground truth
on-ground (real cam)	varying	easier to obtain, real camera hardware	simulator always limited (trajectories, illumination, …), IR not straightforward
synthetic (rendered)	worst (at limited effort)	any trajectory feasible, low effort for different scenarios	not all effects/details can be simulated (glares, imperfections, …)

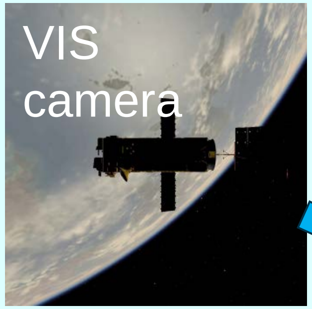
From "Lessons-learned from on-ground testing of image-based non-cooperative rendezvous navigation with visible-spectrum and thermal infrared cameras", ESA GNC 2017, F. Schnitzer et al.

Vision-Based Navigation (VBN) Sensors for Debris Removal (and On-Orbit Servicing): IRPN

- IRPN (“Image Recognition and Processing for Navigation”): Usage of different complementary sensors (VNIR, Infrared camera, LIDAR) with performance and robustness assessment of separate and combined solutions
- Relative trajectory from 100 m to 2 m

Structure IRPN system

sensors



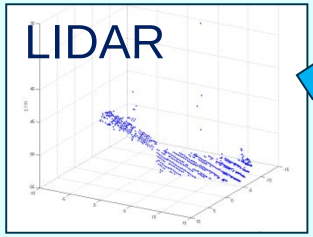


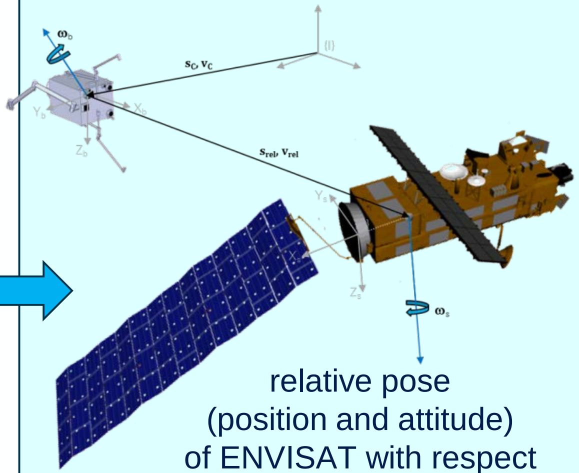
image recognition and processing (IRP) algorithms to be developed

- IRP algorithms for visible spectrum (VIS) camera
- IRP algorithms for infrared spectrum (IR) camera
- IRP algorithms for LIDAR

navigation function to be developed

- Navigation Function

objective

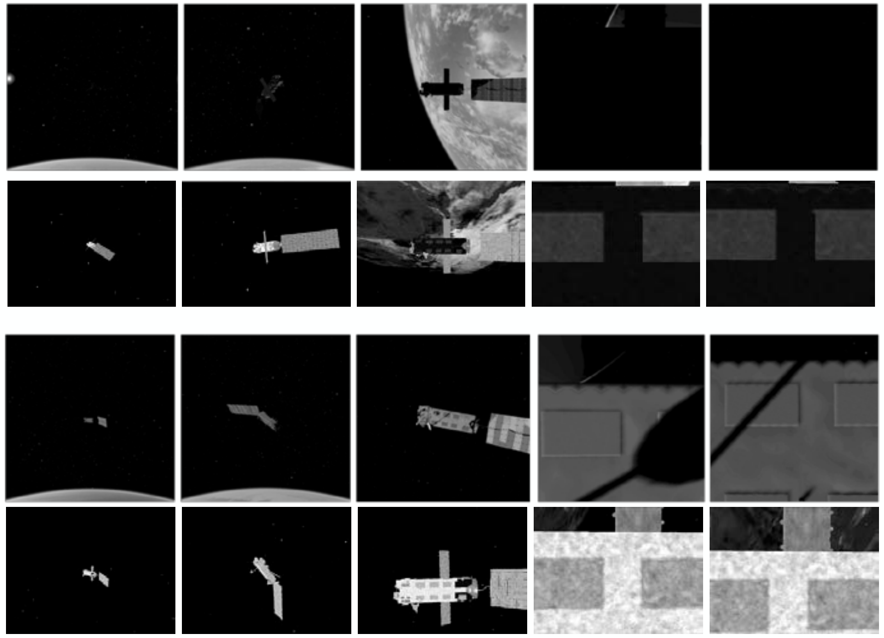


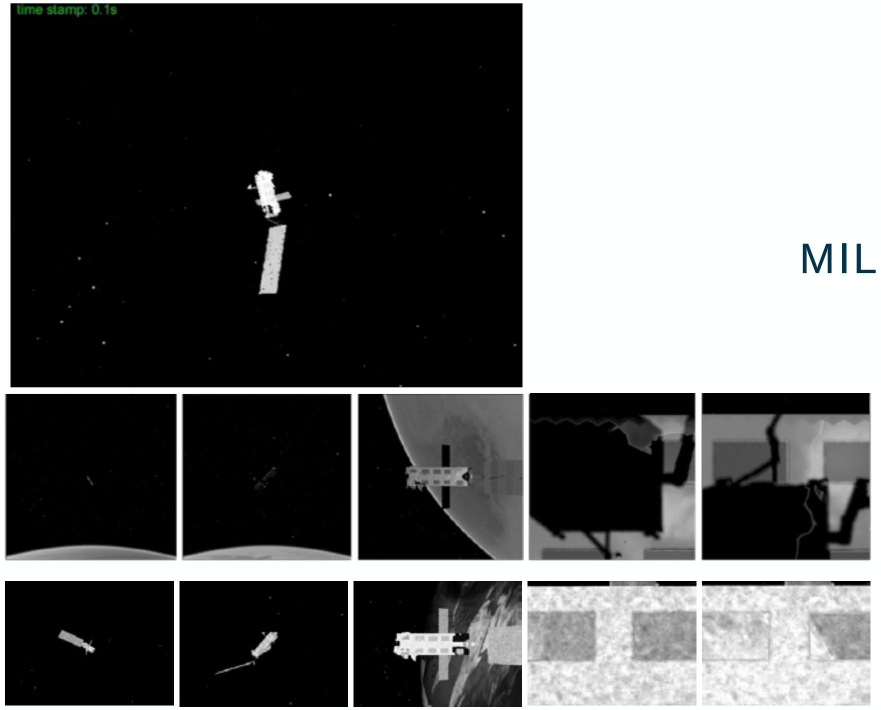
relative pose (position and attitude) of ENVISAT with respect to the chaser

→ **define requirements to run algorithms on dedicated hardware**

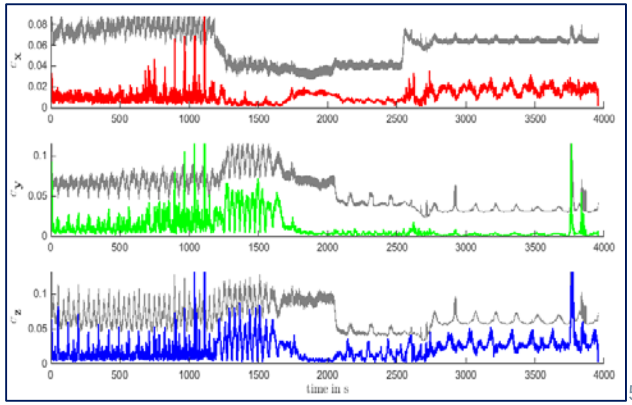
Vision-Based Navigation (VBN) Sensors for Debris Removal (and On-Orbit Servicing): IRPN

- Tests on different platforms:
  - Model-in-the-Loop (MIL): Synthetic Images, MATLAB Simulink, fast algorithm evaluation (faster than real time)
  - SW-in-the-Loop (SIL) model for automatic code generation for target hardware
  - Processor-in-the-Loop (PIL)
  - HW-in-the-Loop (HIL) in the MiPOS facility at Technische Universiteit Dresden (TUD)



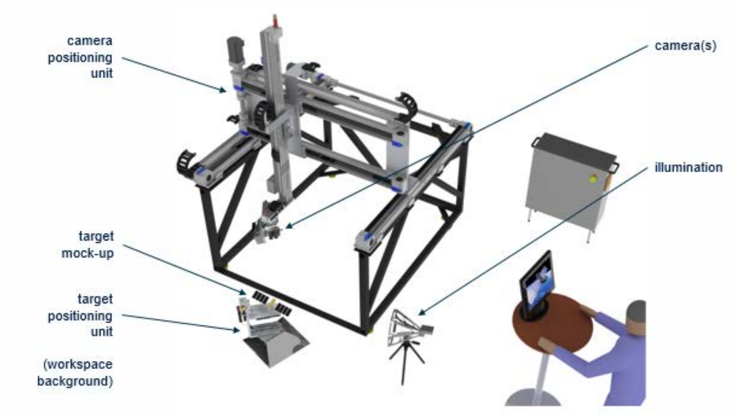


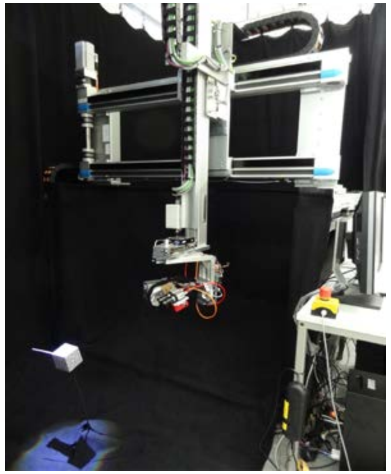
MIL testing with synthetic images

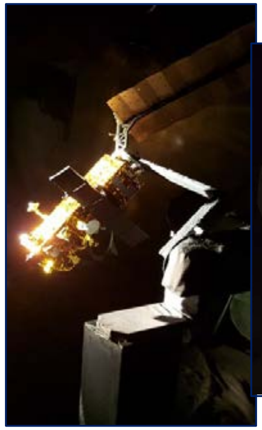


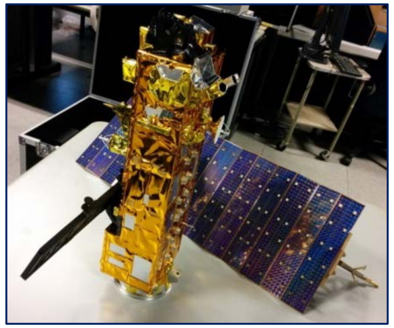
Vision-Based Navigation (VBN) Sensors for Debris Removal (and On-Orbit Servicing): IRPN

- Portal robot with spherical joints for camera system:
  - –3 translational DOF
  - –3 rotational DOF
  - –workspace:1.5 m x 0.8 m x 0.8 m (L × W × H)
- Target unit with spherical joint for target mock-up
  - –3 rotational DOF
- Black curtains for dark background
- COTS cameras (in stereo configuration):
  - –Visual spectrum: 2x AV Manta G-419B
  - –Thermal infrared spectrum: 2x Xenics Gobi-640
- Illumination (+ heating):
  - –Halogen floodlight (500 W)
  - –Dual head high performance halogen spotlight (2x150 W, UV filter)
- Two ENVISAT mock-ups (scale 1:25 and 1:5)





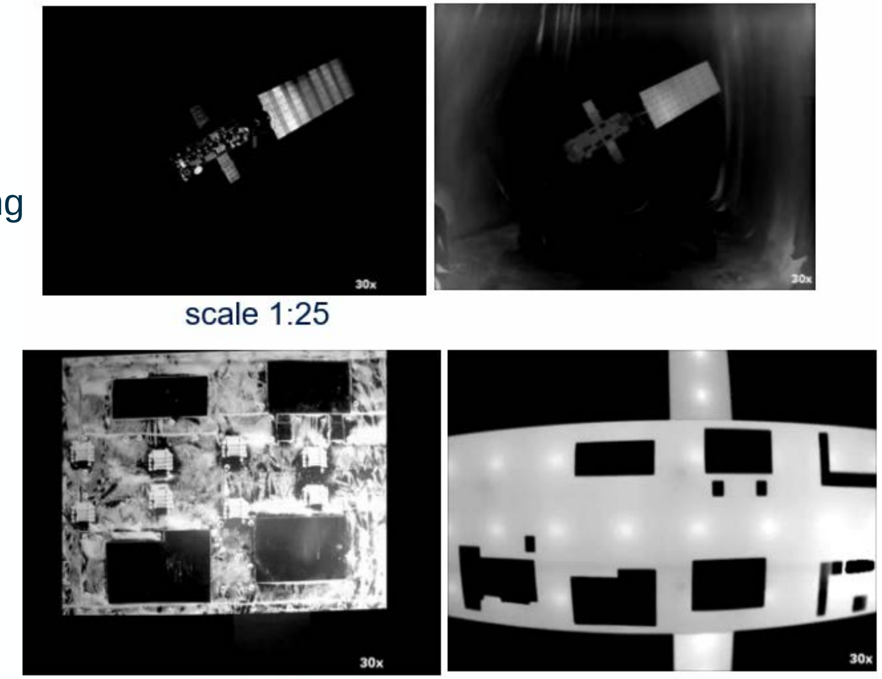




Vision-Based Navigation (VBN) Sensors for Debris Removal (and On-Orbit Servicing): IRPN (Lesson learnt on-ground GNC_Lab testing)

- Laboratory & simulator need to be big enough (and capable) to simulate relative motion of all elements (incl. illumination by sun and earth!)
- Downscaling causes undesired effects:
    - High detailed small-scale mock-up needed
    - Depth of field / defocus with distance not scaled easily: for representative image blurring time-consuming refocusing or scale change necessary
- Seamless assembling of trajectory patches (variable focus/scale) is complicated
- Background in the laboratory should be invisible for cameras: Visible spectrum -> Very low reflectance
- Thermal infrared spectrum:
    - Open-air testing for GNC_lab robotic test facility cannot emulate space conditions but work-arounds are possible and correlation factors can be qualitative and quantitatively assessed
    - Space background is cold (3K) when compared to GNC_lab robotic lab (difficulty in "darkening" in the thermal Infrared):
        - Boundary condition for radiation effect
        - Thermal emission from the surroundings
    - Cooling lab background or heating mock-up to create enough representative contrast for Vision-Based Navigation (VBN) compared with simulations in thermal SW tools
    - Convection effects (on-ground testing) are limited and can be quantified

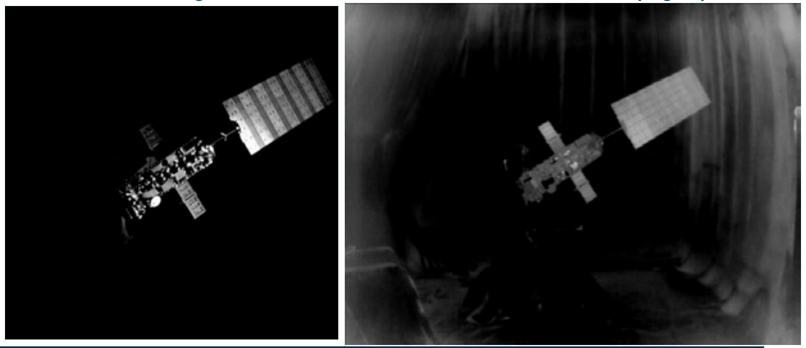
On-ground testing (thermal IR images before distortion correction)



scale 1:25

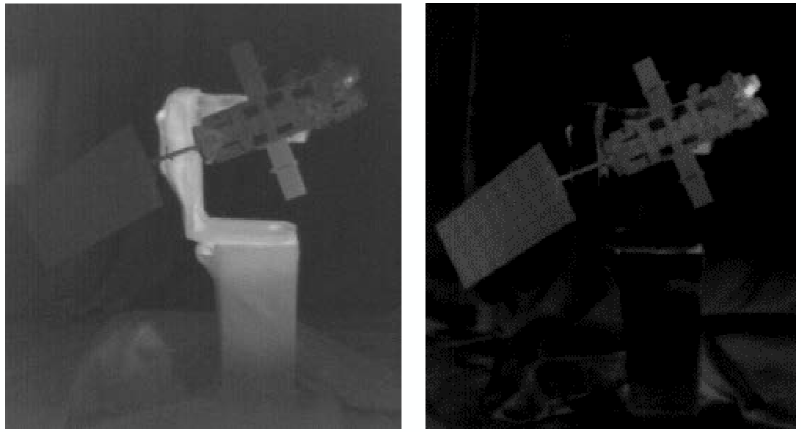
scale 1:5

Background visible and thermal Infrared (right)



Vision-Based Navigation (VBN) Sensors for Debris Removal (and On-Orbit Servicing): IRPN (Lesson learnt)

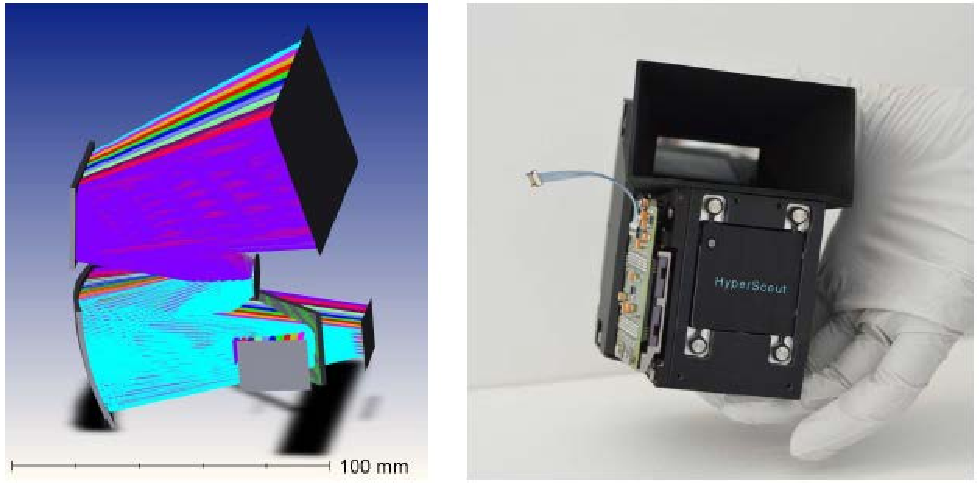
- Mounting/wrist joint should be invisible for cameras: Heating of target unit can heat up also mounting during the experiments
- Realism: Image Processing (IP) algorithms' behaviour with real camera image data should not be drastically different to the behaviour with synthetic image data:
    - Dedicated efforts are needed to improve representativeness in a variety of conditions and scenarios, using techniques like Machine Learning for image generation and enhancement)
    - Test algorithms with real camera images as early as possible and compare with the equivalent synthetic image data set.
    - Testing with images from real cameras is essential (synthetic images only are not sufficient)



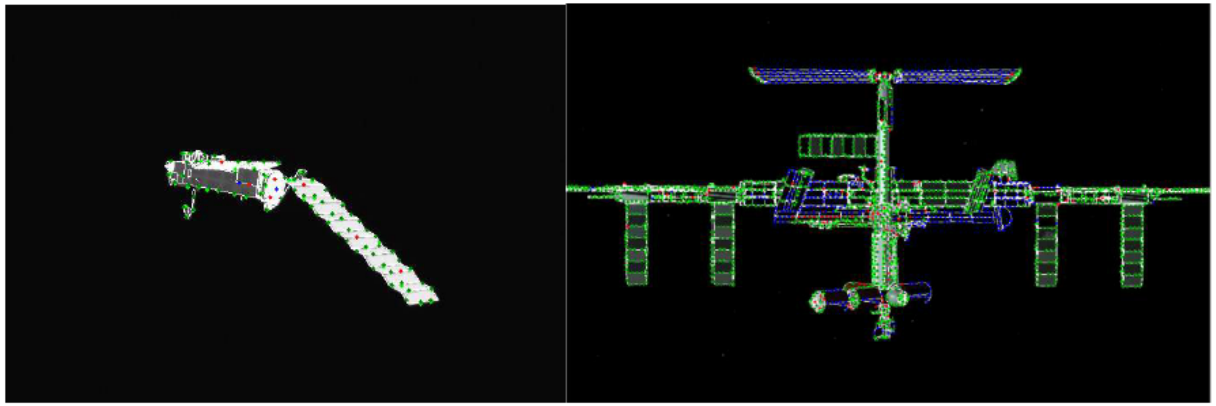
GNC_Lab testing (mounting in visible and thermal_IR)

Vision-Based Navigation (VBN) Sensors for Debris Removal (and On-Orbit Servicing): MSRN (NL)

- MSRN = Multispectral Sensing for Relative Navigation
- Assessment in a bottom-up approach, of the potential use of the combination of visible / NIR (Near-IR), thermal-IR and UV wavelengths for navigation sensing.
- Review existing space-qualified detectors technology which could be used for such purpose and their response in the identified spectral bands
- Architecture and a preliminary design of a Multispectral Camera



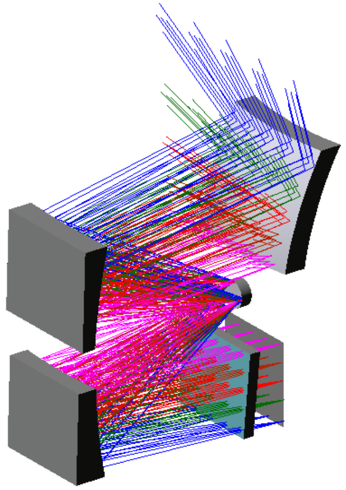
Overview of the optics (left) of the reflective design, and HyperScout (right) from Cosine_NL



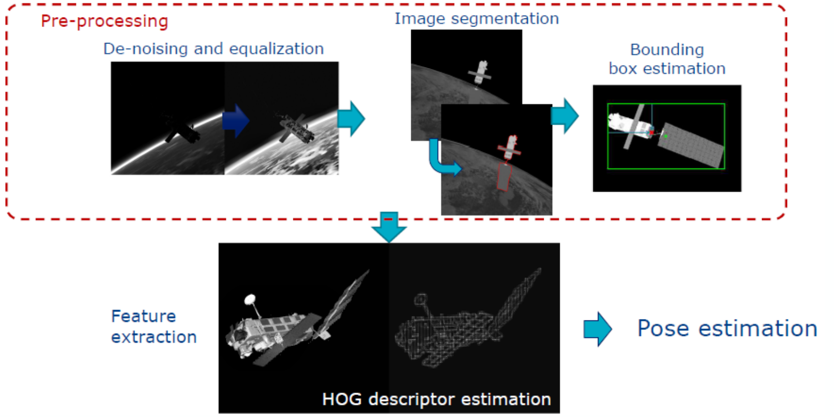
Example of model based edge tracking algorithm performing on Envisat thermal infrared sequence (at 100 m distance) and on ISS visible sequence (at 150 m)

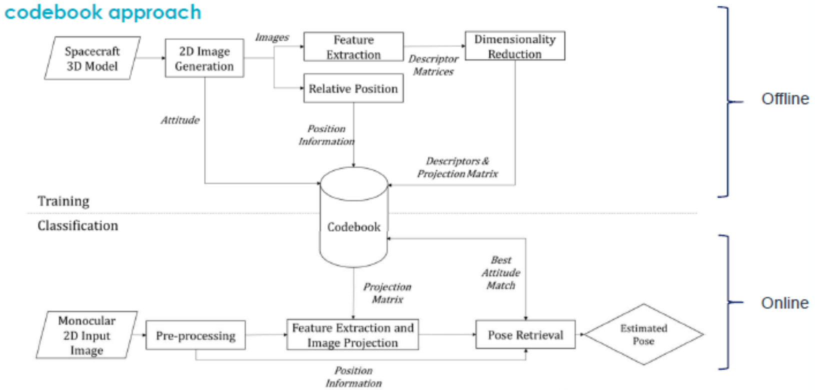
Vision-Based Navigation (VBN) Sensors for Debris Removal (and On-Orbit Servicing): MSRN (FR)

- MSRN_FR as parallel contract to MSRN_NL (same objectives)
- Thermal Infrared particularly useful:
  - Image segmentation
  - Scenarios with shadowing (self-casted or from chaser spacecraft)
- UV band helpful for separation when Earth in background

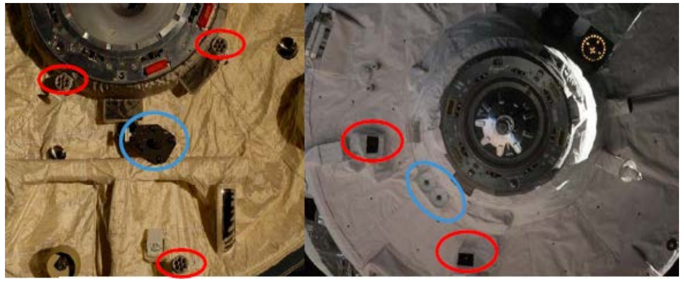


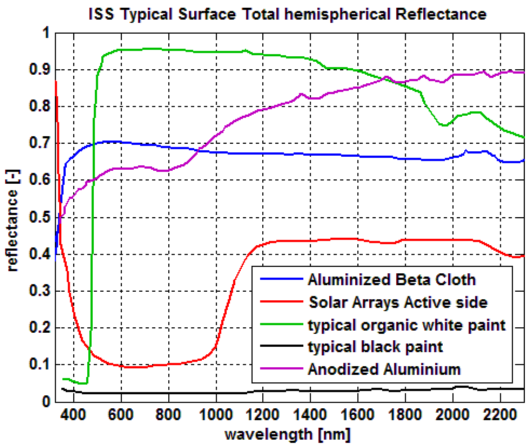
WALRUS Optical Design: Wide Angle Large Reflective Unobscured System (large distortions but calibrated)





ID	Colour	Wavelength (nm)
1	NUV	300-380
2	BLUE	380-450
3	VIS	500-850
4	NIR	1200-2250
5	TIR	5e3 – 30e3

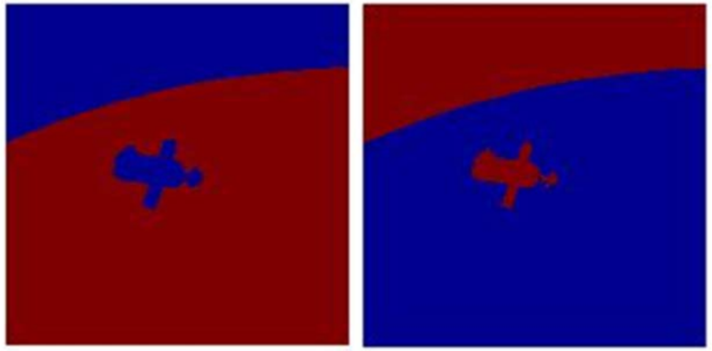




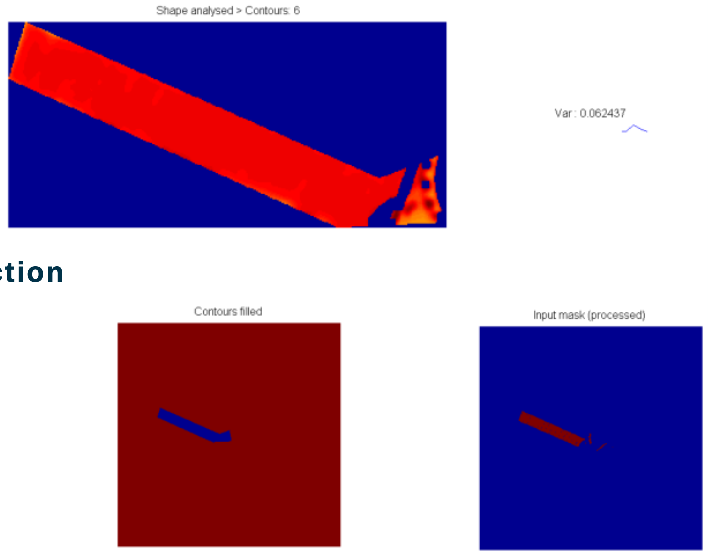
Material analysis for ISS

Vision-Based Navigation (VBN) Sensors for Debris Removal (and On-Orbit Servicing): MSRN (FR)

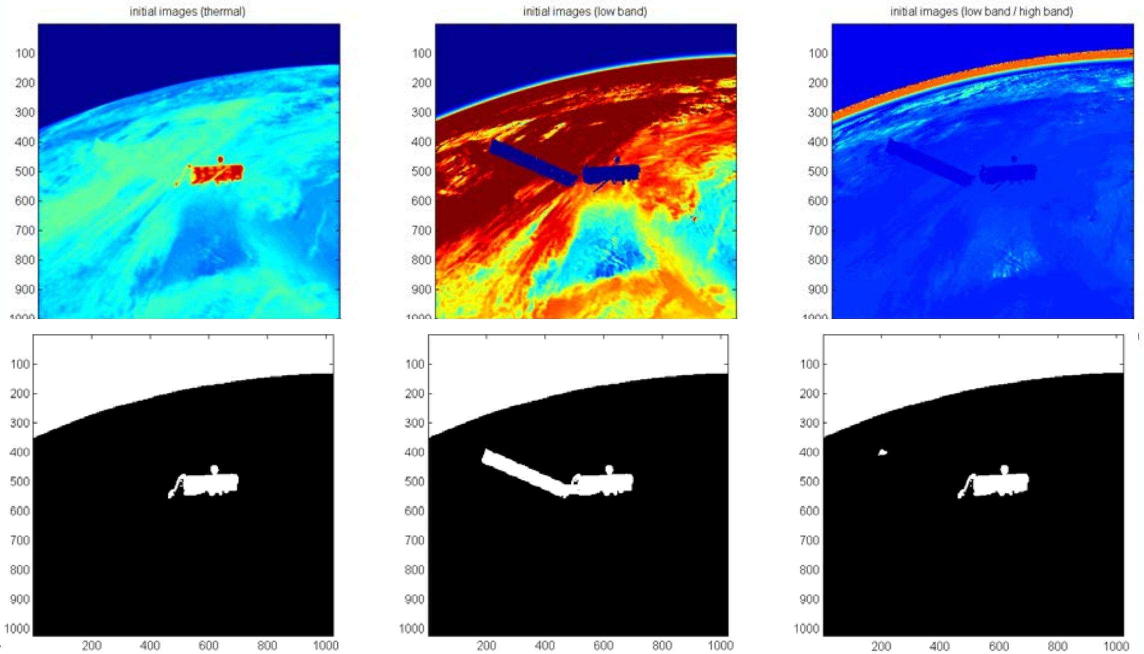
- Improved segmentation design
- Some adaptations were made to cope with the high thermal PSF resulting from the MSRN design. The following steps have been introduced :
    - Basic segmentation: quantization, filtering and threshold
    - Shape detection
    - Spectral bands data fusion



1. First mask



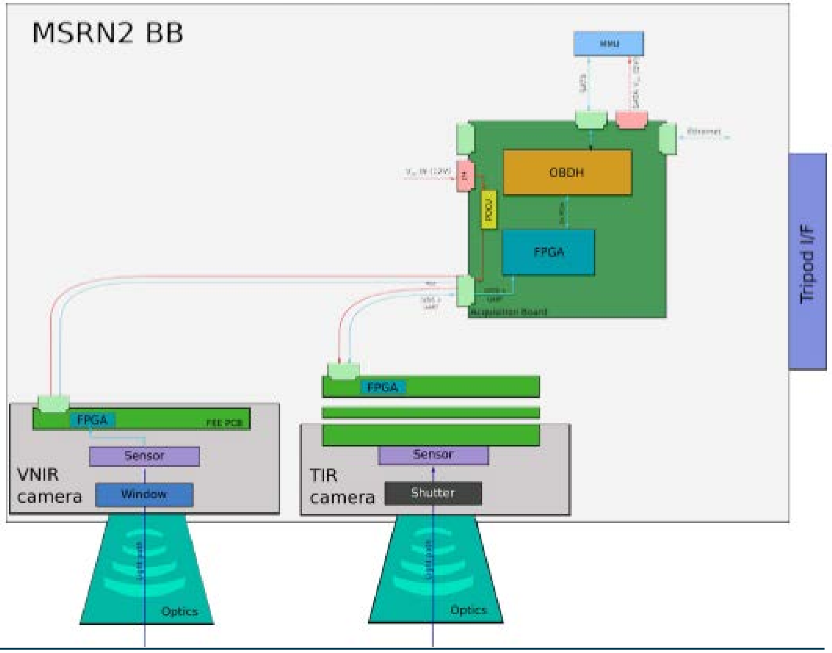
2. Shape detection



3. Band fusion

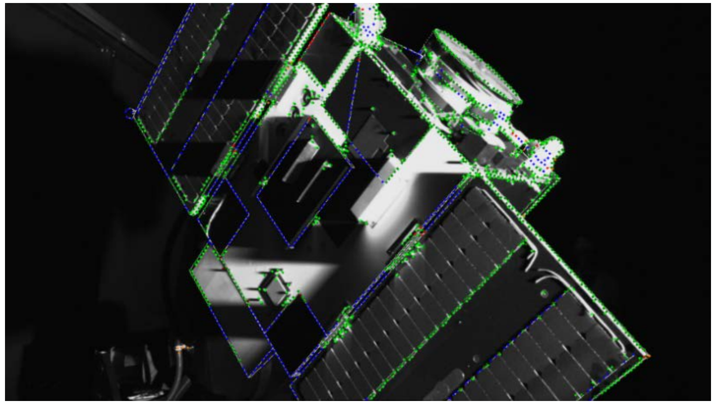
Vision-Based Navigation (VBN) Sensors for Debris Removal (and On-Orbit Servicing): Breadboard Multispectral Camera (MSRN2)

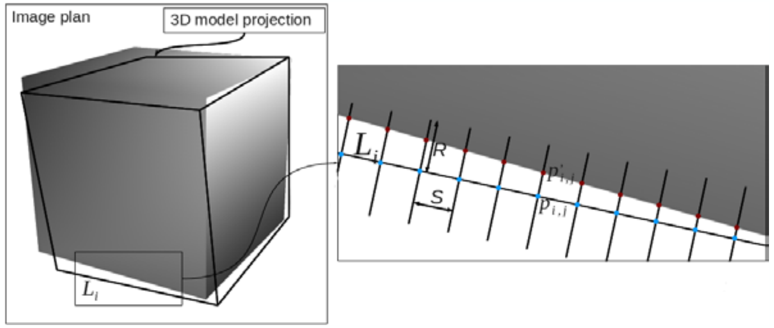
- Breadboard MultiSpectral Camera (for Relative Navigation in Lagrangian Orbits in the Earth-Moon System, MSRN2)
- Dual channel camera
  - Separate VNIR and TIR heads
  - Shared mechanical housing
  - Shared electronics and software
- Design drivers
  - Large field of view (30 x 30 deg)
  - Extended Depth of Field
  - Breadboard representativity of target instrument

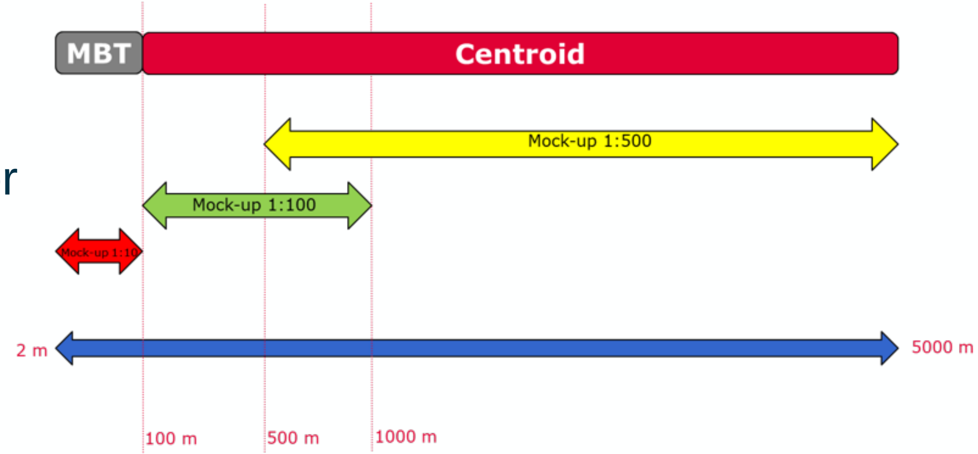


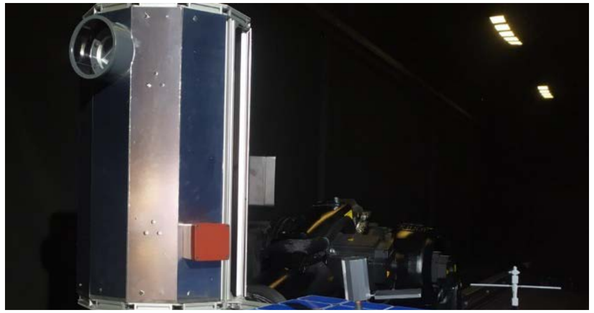
Vision-Based Navigation (VBN) Sensors for Debris Removal (and On-Orbit Servicing): Breadboard Multispectral Camera (MSRN2)

- Algorithms (different ranges):
    - Centroid
    - Model-Base Tracking: Tracking based on edge features, reliable under different illumination contexts, Robust to noise and poor textures
- Several mock-ups:
    - Mock-up 1:10, including 17 independent thermal surfaces for Close range
    - Mock-up 1:100, with Thermal capabilities for Mid-range
    - Mock-up 1:500: 3D printed model for far range









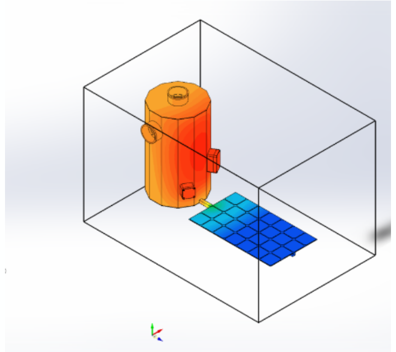
Vision-Based Navigation (VBN) Sensors for Debris Removal (and On-Orbit Servicing): Breadboard Multispectral Camera (MSRN2)

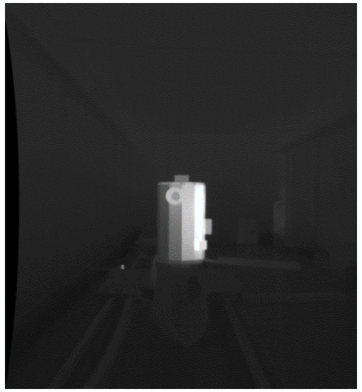
- Thermal signature simulation with Mentor FloTHERM XT, taking into account Sun incidence vector, Solar radiance, Materials, Environment temperature
- Test executed at Platform-art facility with 1 trajectory and 4 illumination & thermal setup conditions, using 3 mock-ups and VNIR + TIR cameras
- Cartesian spotlight
- Trajectory composed of three sub-phases:

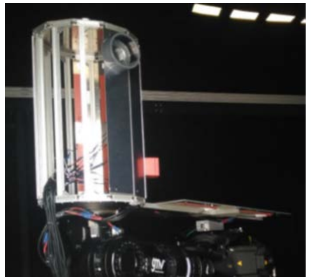
- Initial approach (100 m – 35 m)

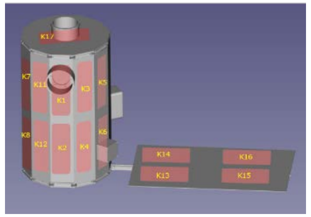
- Fly-around (35 m)

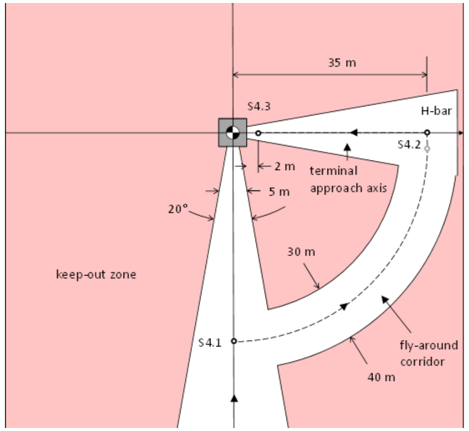
- Final approach (35m – 2m)

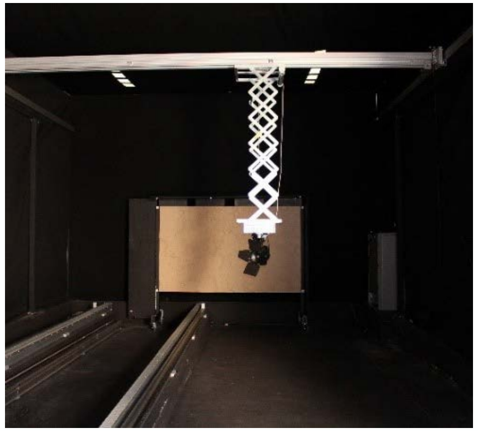


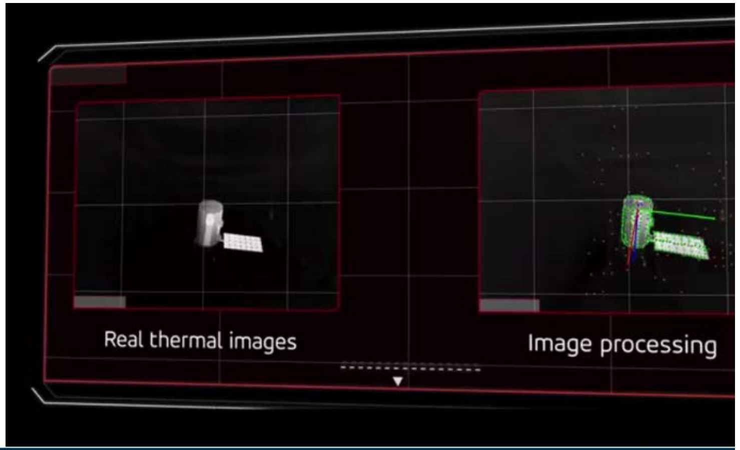








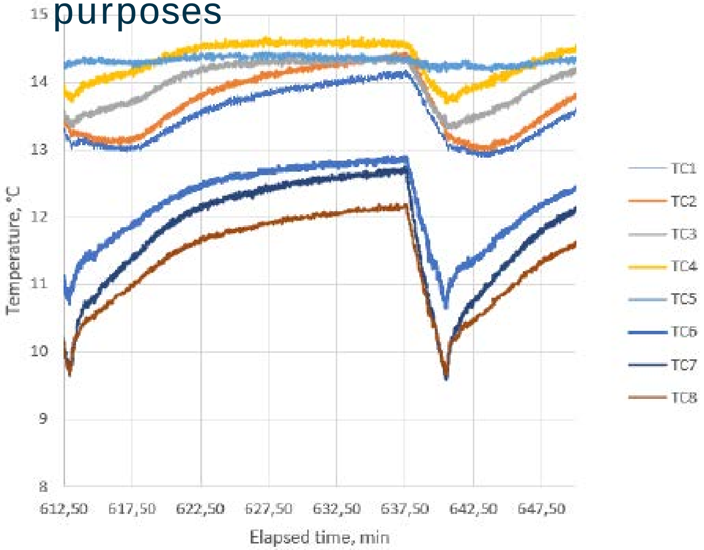


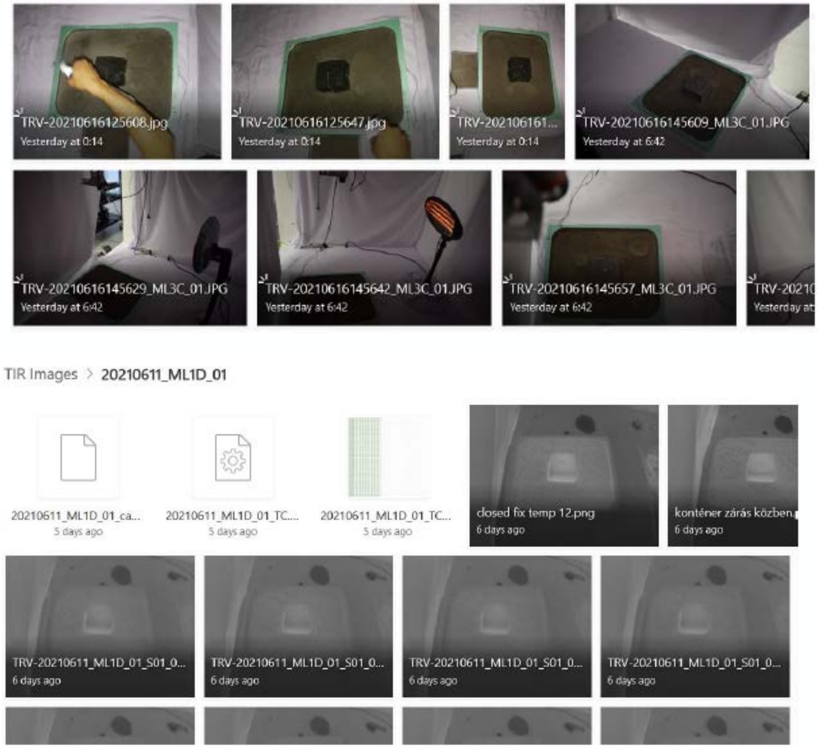


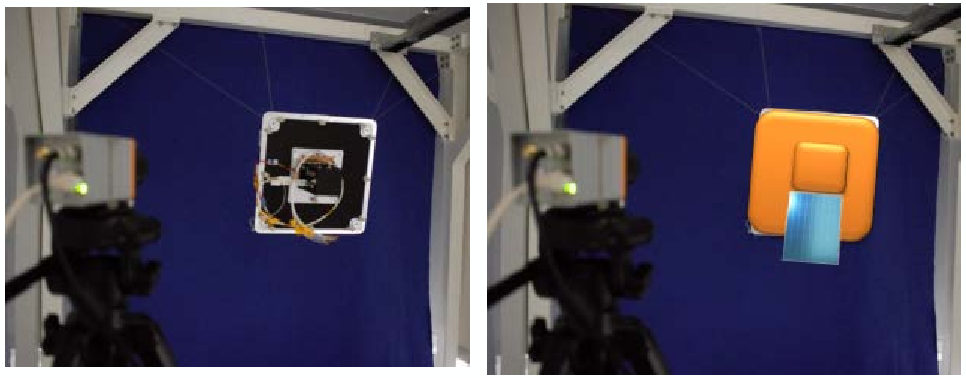
Vision-Based Navigation (VBN) Sensors for Debris Removal (and On-Orbit Servicing) / Supporting activities: TIRVOA

- TIRVOA: Assessment and comparing conditions in vacuum with open air experiments in thermal infra-red
- Test chamber with controlled conditions to calibrate open-air tests in GNC_Lab with GNC robotic facilities and models with conditions in space (evaluated with thermal SW simulations and results from thermal vacuum chamber tests)

Temperature profiles to replicate contrast (different materials) for vision-Based Navigation (VBN) purposes



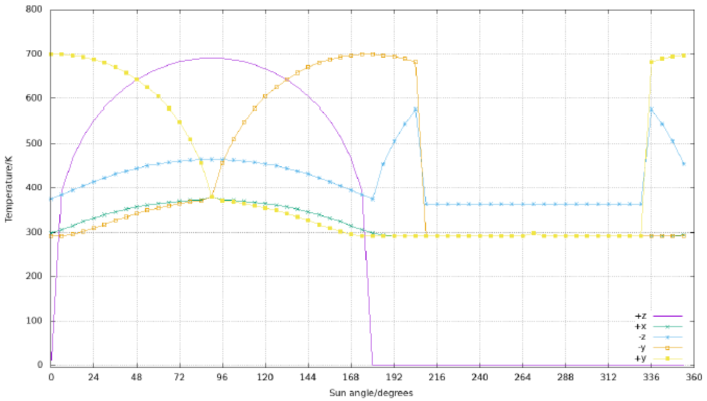




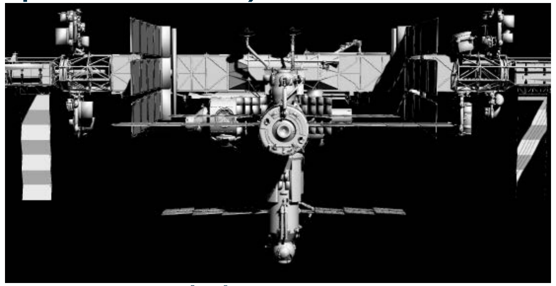
RAMP Breadboard with Kapton MLI and extension as solar panel (right)

Vision-Based Navigation (VBN) Sensors for Debris Removal (and On-Orbit Servicing) / Supporting activities: PANGU v6/v7

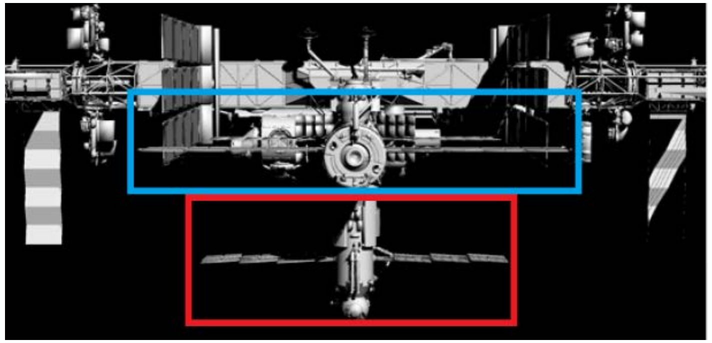
- Intended for real-time simulations (simplifications in the models valid for the purpose of Vision-Based Navigation)
- Comparison with real images by:
  - Temperature profiles
  - Results after Image Processing (Feature detected, etc)
- Difficulty in getting same CAD model for the real images in ISS, Envisat, etc (appendage position, etc)

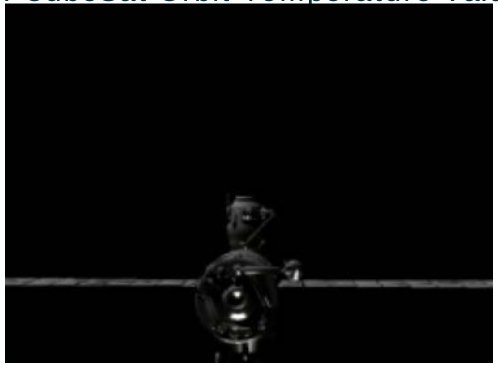


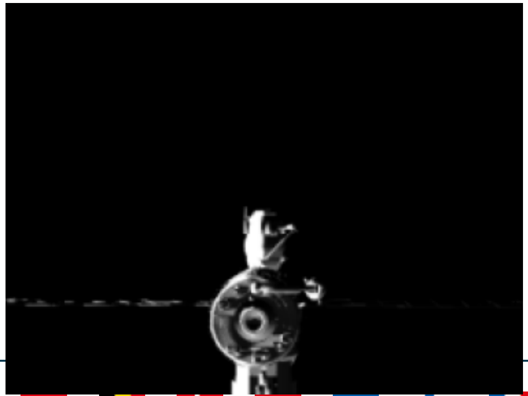
PANGU: CubeSat Orbit Temperature Values

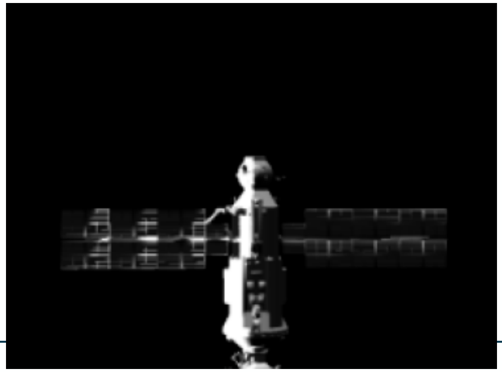

ISS model PANGU VIS

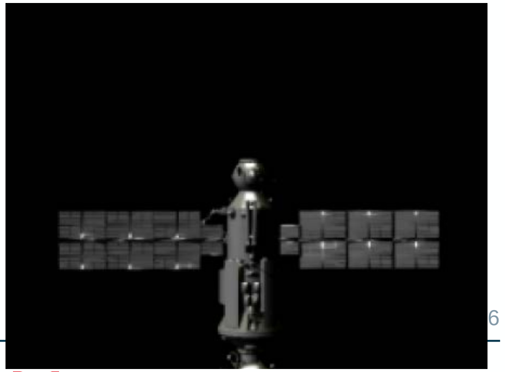

LIRIS TIR image of ISS from 17 m range


Extracted sections of the ISS model




PANGU ISS docking port


PANGU simulation of the extended module

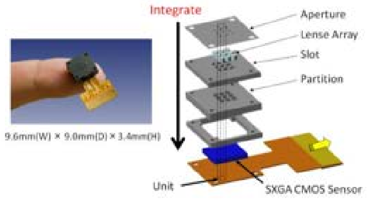

PANGU TIR simulation of docking section (top) and Soyuz/Progress

Vision-Based Navigation (VBN) Sensors for Debris Removal (and On-Orbit Servicing): Plenoptics (Light-Field)

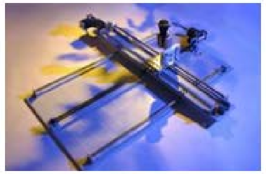
- Assessment of Plenoptics Refocusing Methods for 3D Visions-Based Relative Navigation
- Any light field capture device could be used, although for testing COTS camera more practical
- Plenoptics sensor for rendezvous (collaborative and non-collaborative) can be used as a conventional 2D in the far-mid range and provide a 3D depth map in the close-range where this 3D information matters the most.


Wilburn et. al. 2005

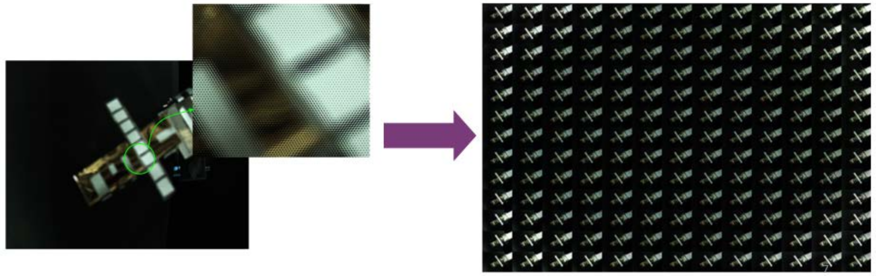

Geogiev & Intwala, 2006



Tanida, 2007

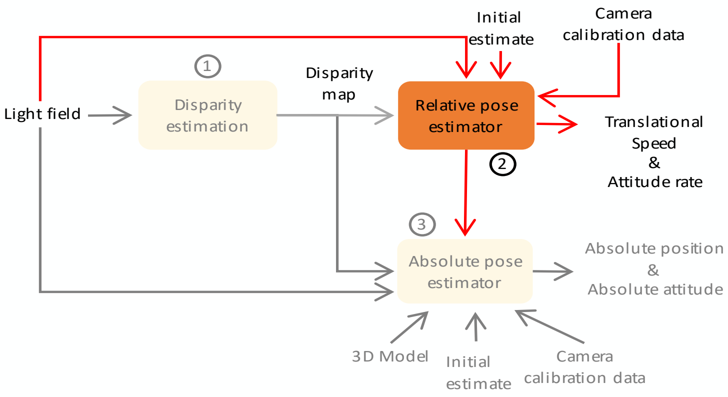

Unger et al., 2003

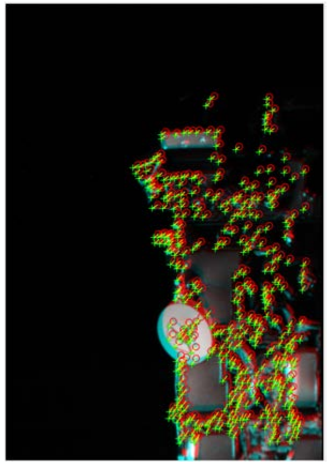

Lytro, Inc.

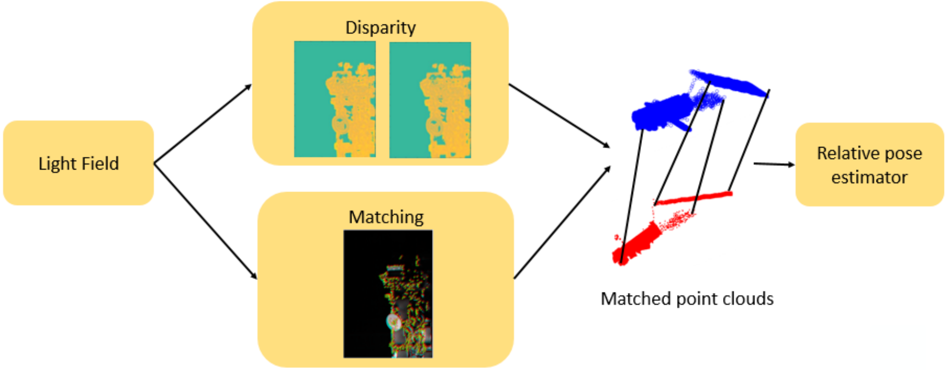


Decoding & Rectification


Disparity estimation







Disparity assisted by Light-Field

Vision-Based Navigation (VBN) Sensors for Debris Removal (and On-Orbit Servicing): Conclusions

- Several sensors (active/passive) can be combined to obtain a more accurate and robust Navigation solution (relative position and attitude estimation)
- Main sensor and Functional back-up at several ranges from the target spacecraft.
- Assessment of testing set-up in open-air GNC_Lab testing with robotics facility for correlation with space conditions
- Synthetic image rendering in visible and thermal Infrared for Vision-Based Navigation
- Different rendering tools used for generating synthetic images (PANGU, SurRender, SpiCam, ASTOS CamSim): Need for a benchmarking set of reference scenarios with common metrics for comparison
- Breadboarding MultiSpectral camera activities reaching TRL 5 for further development in EQM and FM
- Other technologies being evaluated (plenoptics, event-based cameras, etc)

Thank you for your attention!
Questions: manuel.sanchez.gestido@esa.int