Compact high-resolution 3D real-time imaging for robotic vision with sub-mm accuracy

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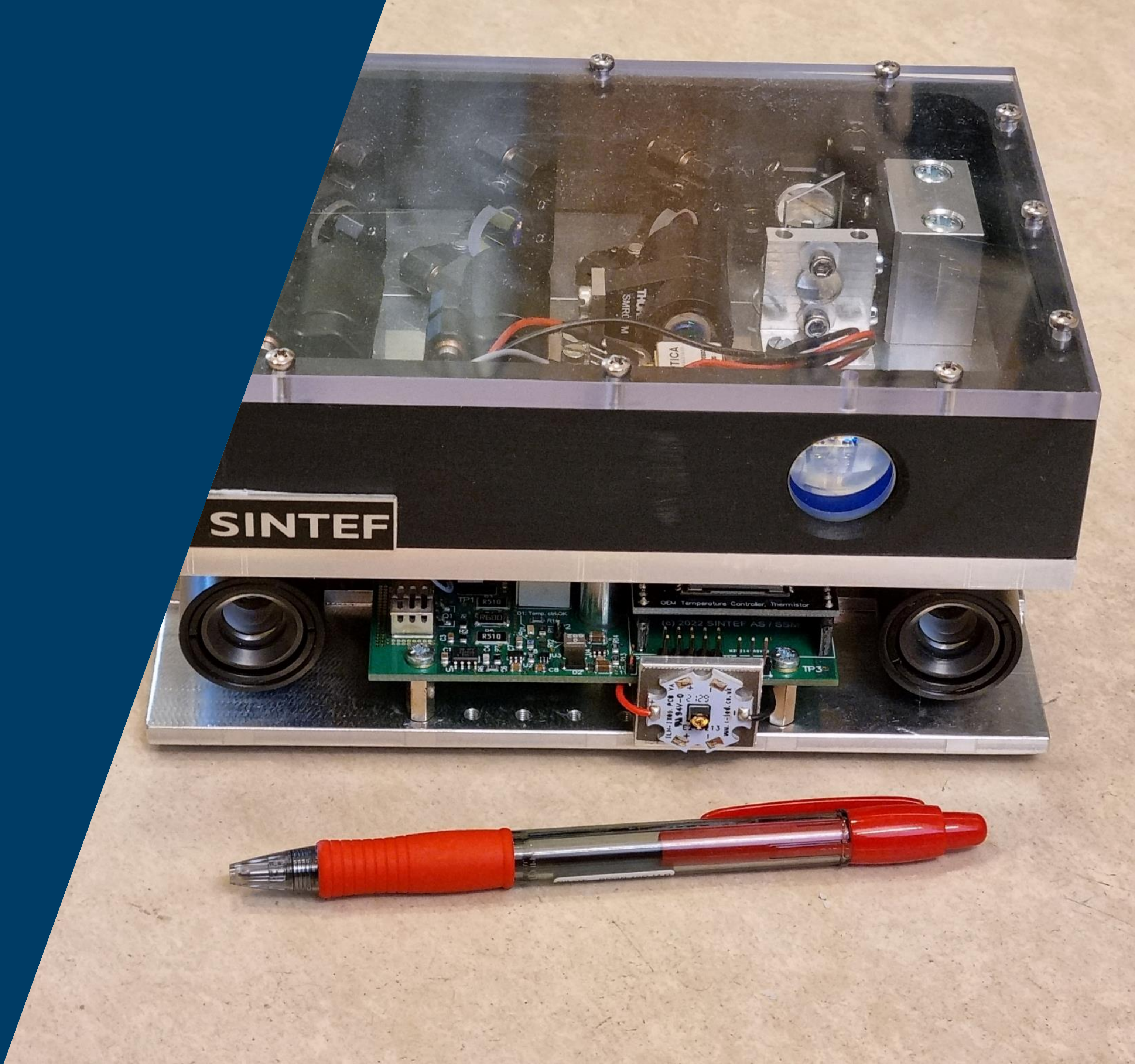
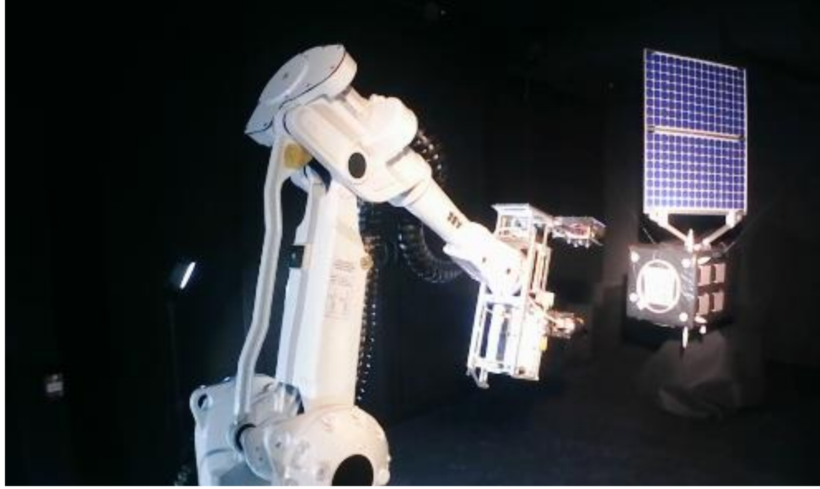
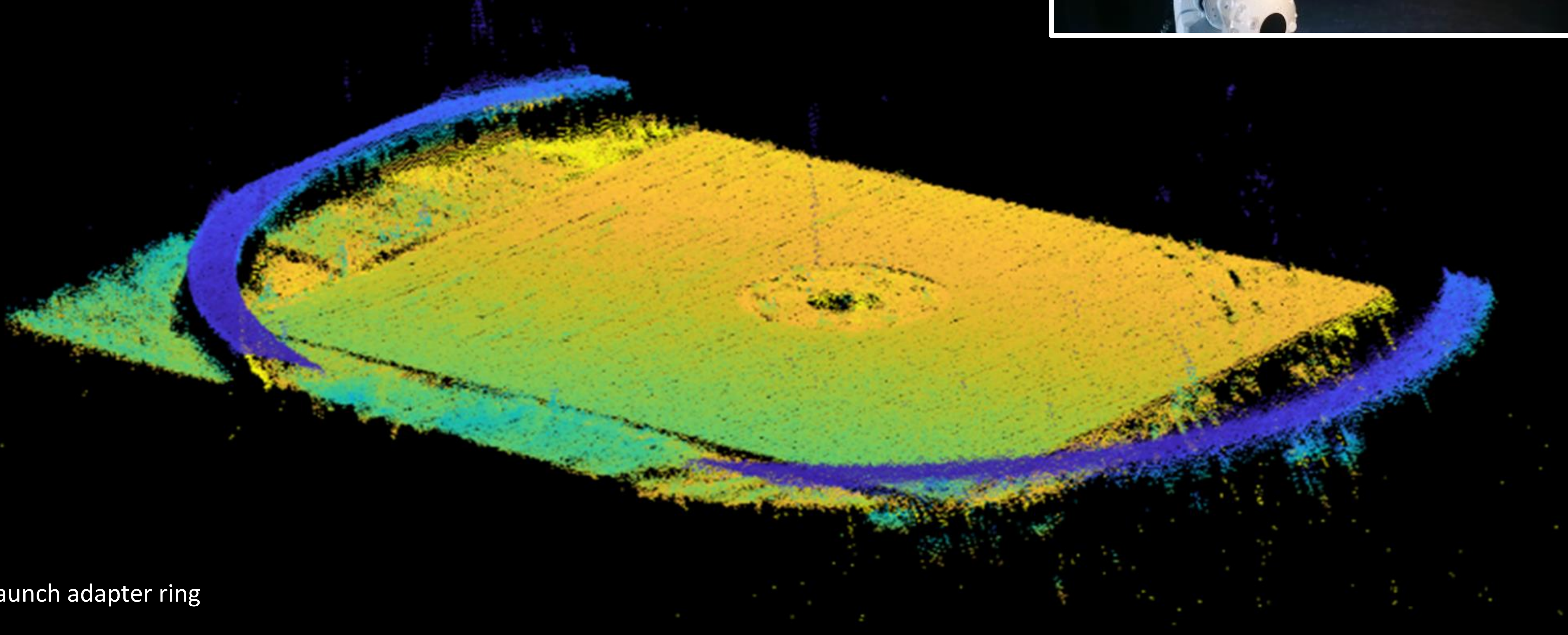
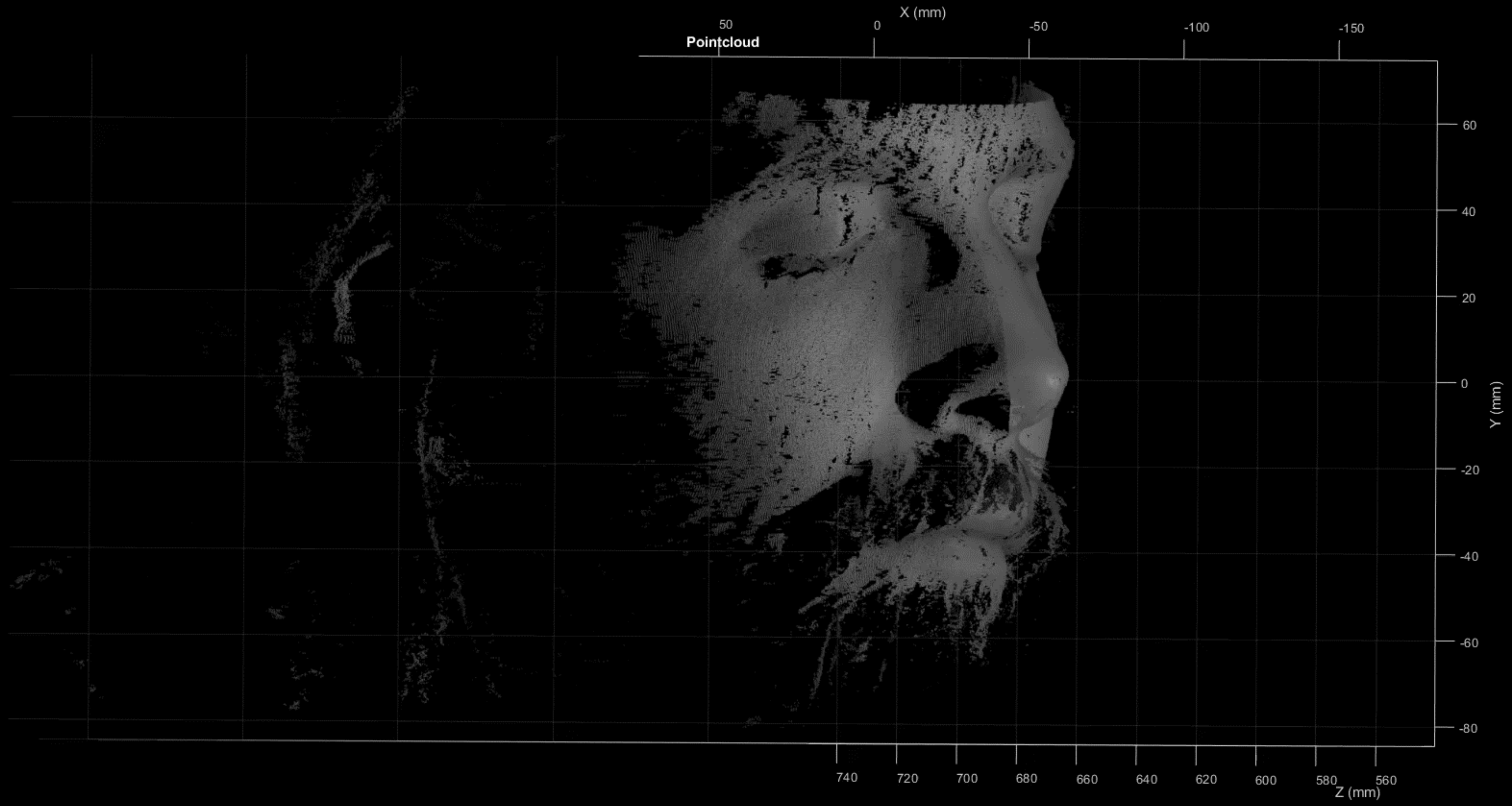


Realtime 3D images @ 10 Hz





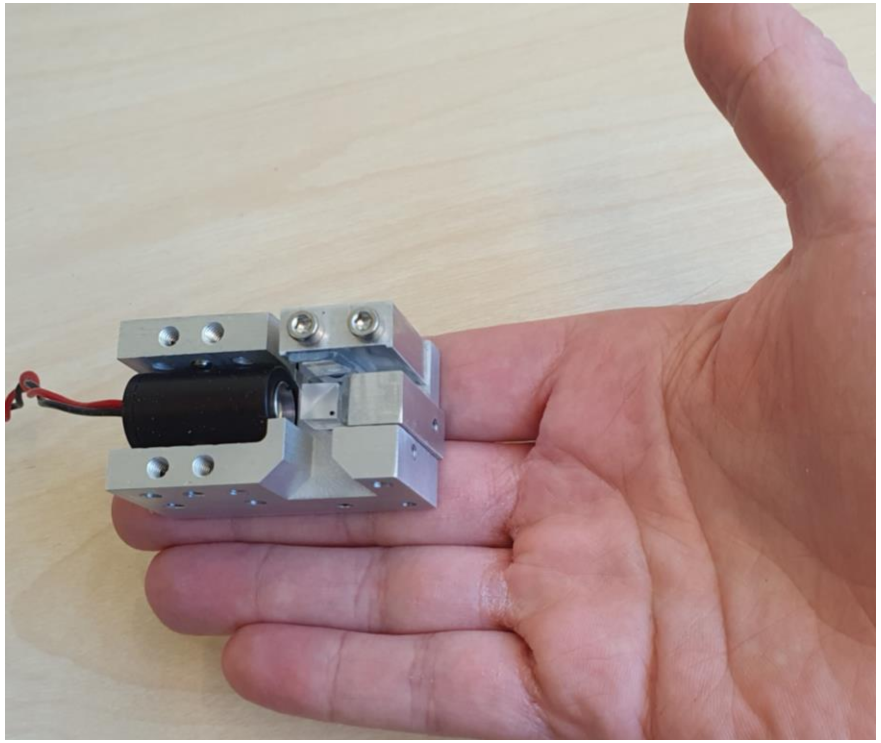
Launch adapter ring



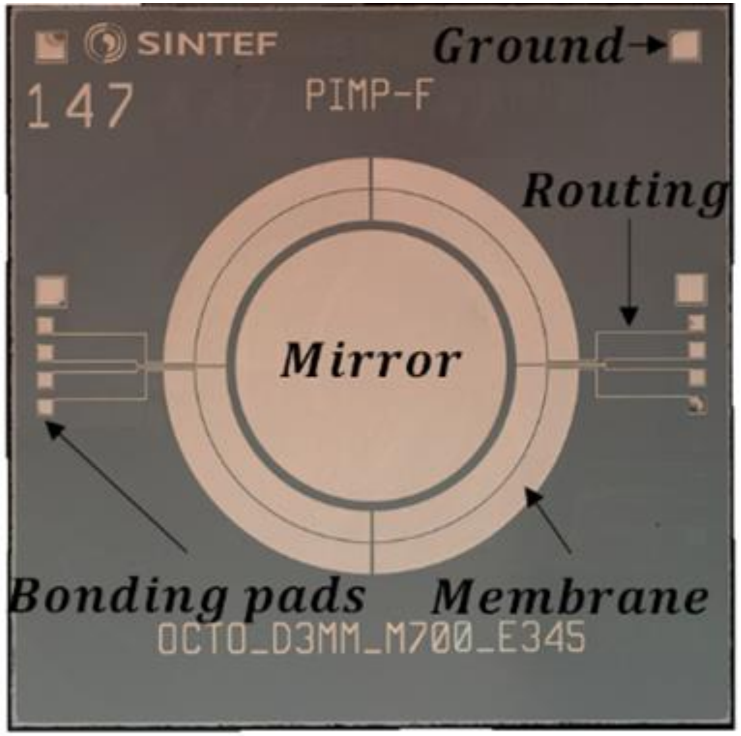
Pointcloud
X (mm)
50
0
-50
-100
-150
Y (mm)
60
40
20
0
-20
-40
-60
-80
Z (mm)
740
720
700
680
660
640
620
600
580
560

Power-efficient, compact projector

Miniaturizable pattern projector. 2.5 W.



Radiation-tolerant micro-mirror



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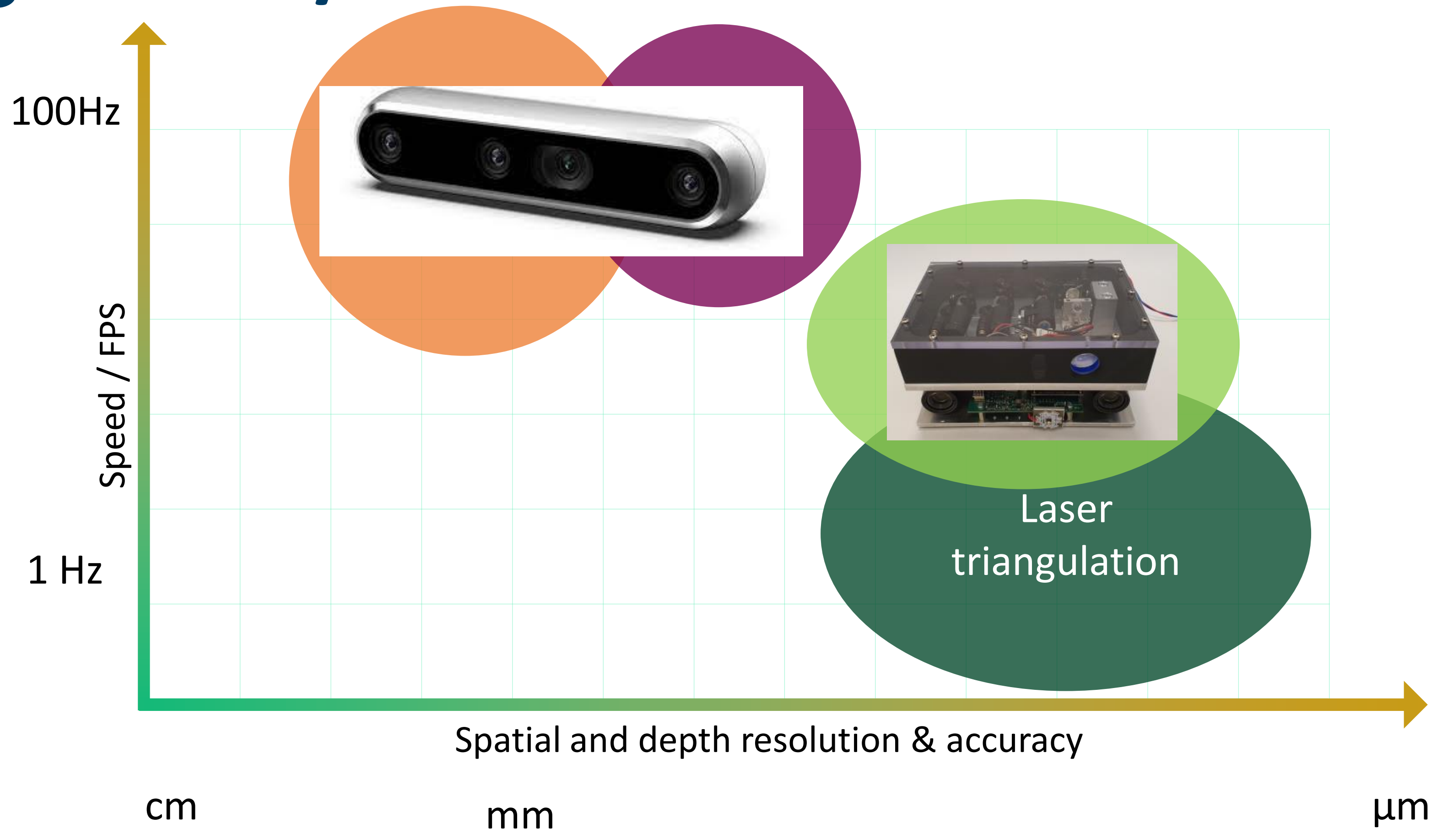
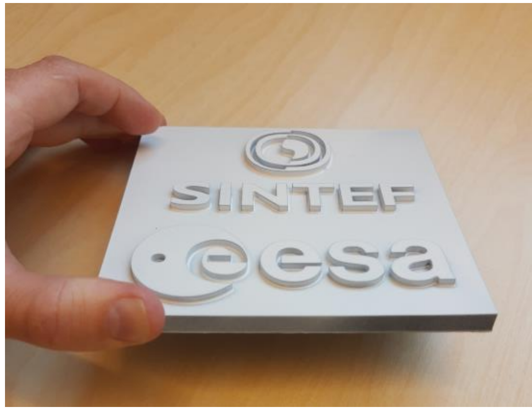
Agenda

- Brief introduction to 3D imaging
- Method: Active stereo with pattern projection
- Test setup and results
  - Internal lab tests
  - Tests in robotic test bench
- Summary and outlook

Triangulation / stereo – from coarse to fine

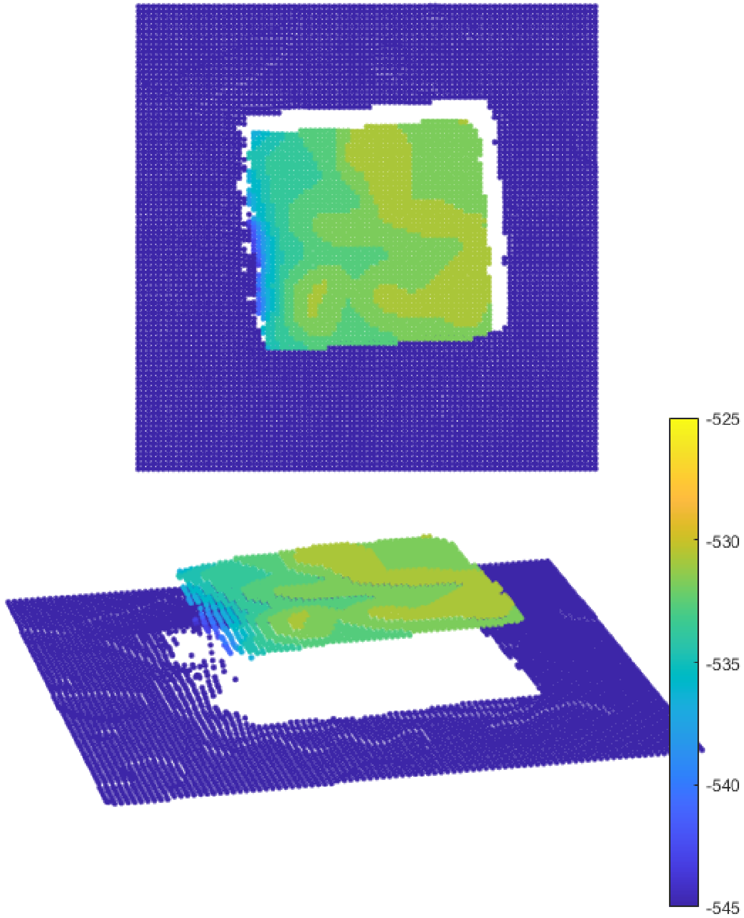


Dense, high-quality 3D data



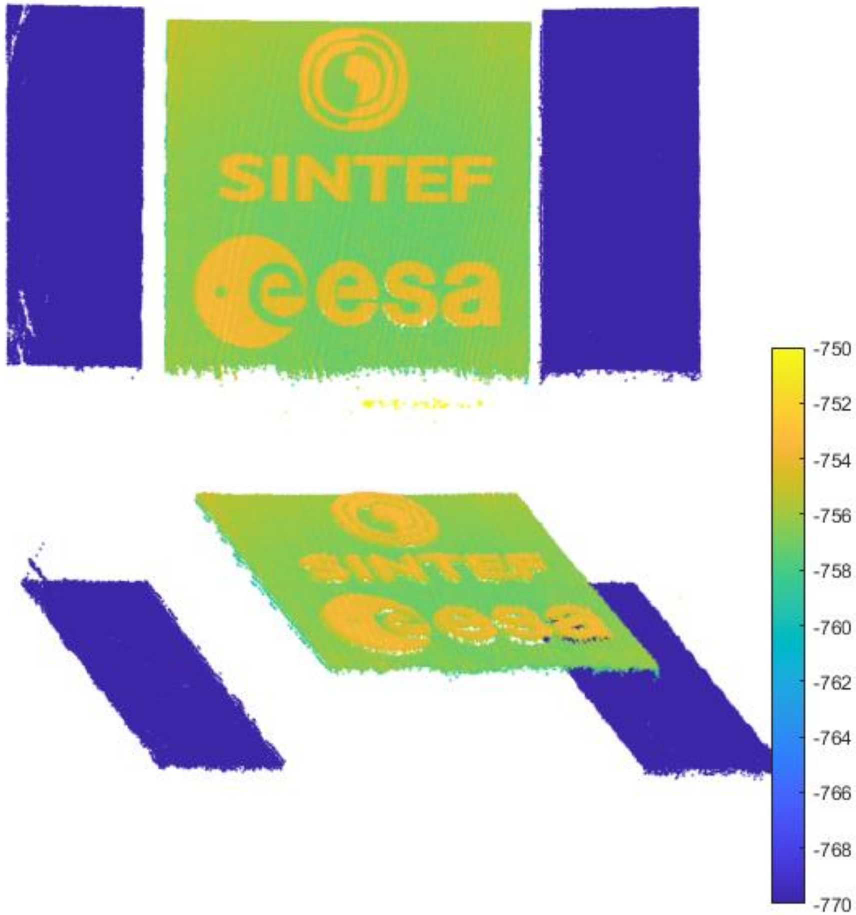
Intel Realsense

Sparse measurements + interpolation.



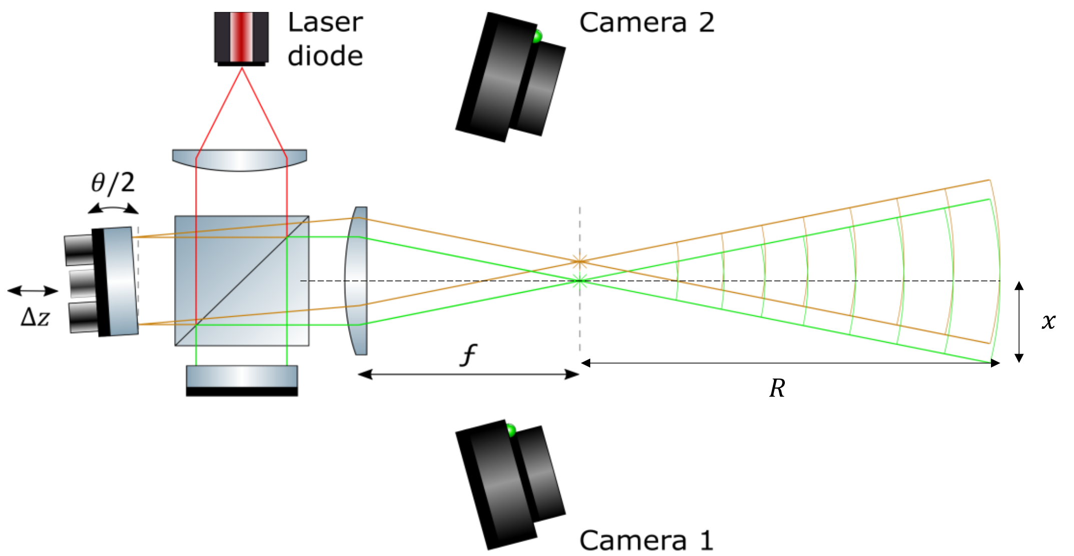
Our camera

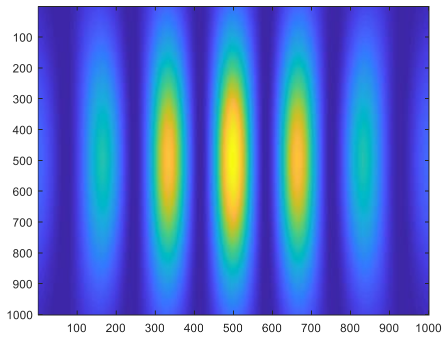
Each pixel measured independently. No interpolation/filtering

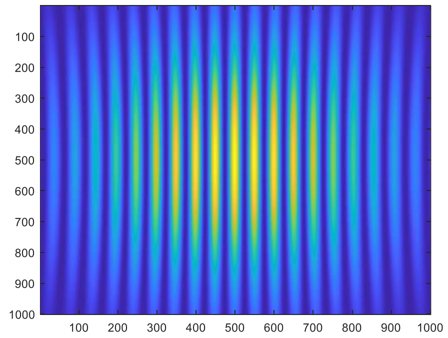


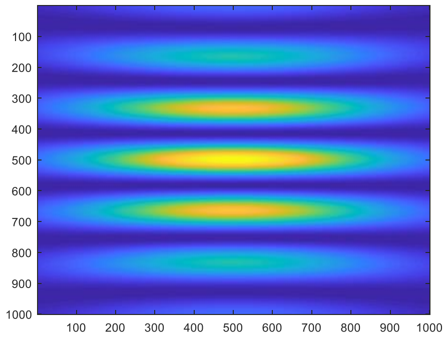
Active stereo with temporal patterns

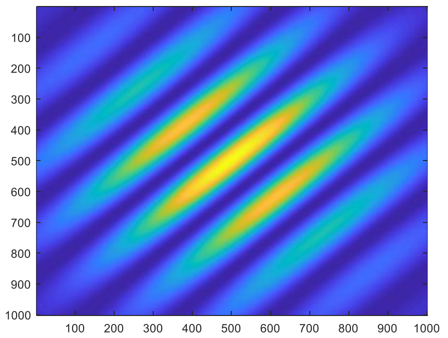
- Michelson interferometer used to project sine wave patterns with controllable phase and frequency
  - 3D data on texture-less surfaces.
- Projected patterns observed by two cameras placed in stereo configuration.
  - 15 "raw images" per 3D image
- Zero-normalized cross-correlation used for 3D reconstruction
  - ~100 ms computation per reconstruction











J. B. Thorstensen, J. T. Thielemann, P. Risholm, J. Gjessing, R. P. Dahl-Hansen, and J. Tschudi, "High-quality dense 3D point clouds with active stereo and a miniaturizable interferometric pattern projector," Opt. Express, vol. 29, no. 25, pp. 41081–41097, 2021. https://doi.org/10.1364/oe.444641

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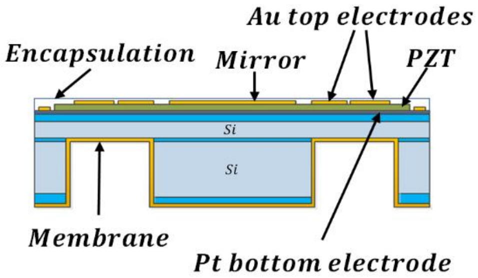
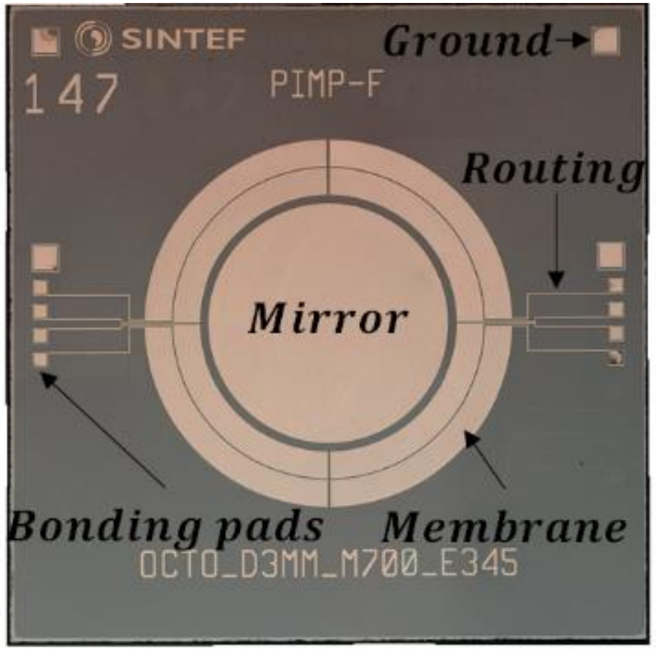
Space-tolerant mirror



- We use an in-house developed MEMS-mirror to control frequency and phase of this pattern, by tilt and piston movement of the mirror.
- Test conditions:
  - Thermal cycling (-40 to 70 °C)
  - Vibration up to 20 g
  - Radiation testing (100 krad (Si))
- No degradations were observed
- Lifetime was estimated to 1200 years at 30°C and 10 V electrode voltage, and 12 years at 70°C and 10 V electrode voltage.
- Promising results for space applications.



R. Dahl-Hansen, J. Gjessing, P. Mardilovich, C. Fragkiadakis, and J. Thorstensen, "Reliable Pb(Zr,Ti)O3-based thin film piezoelectric micromirrors for space-applications," Appl. Phys. Lett., vol. 121, no. 13, p. 132901, Sep. 2022, https://doi.org/10.1063/5.0106933.

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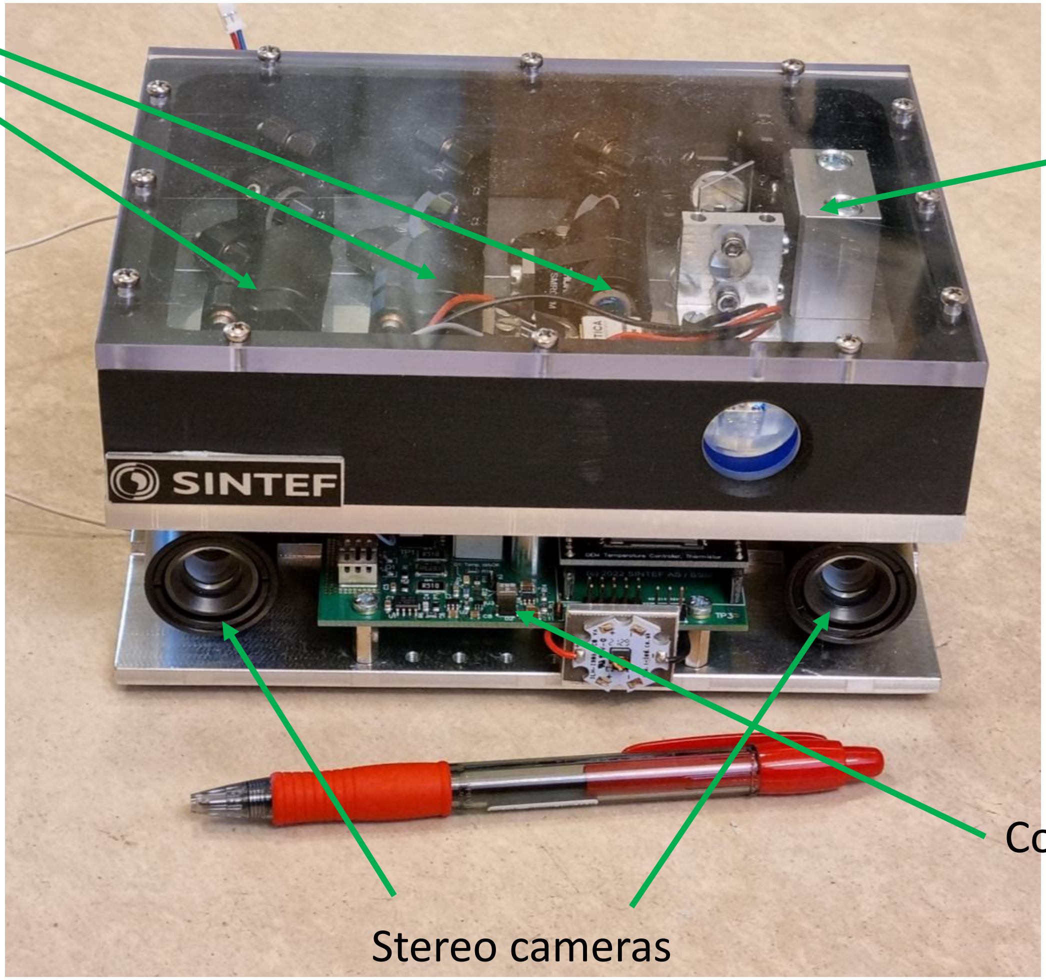
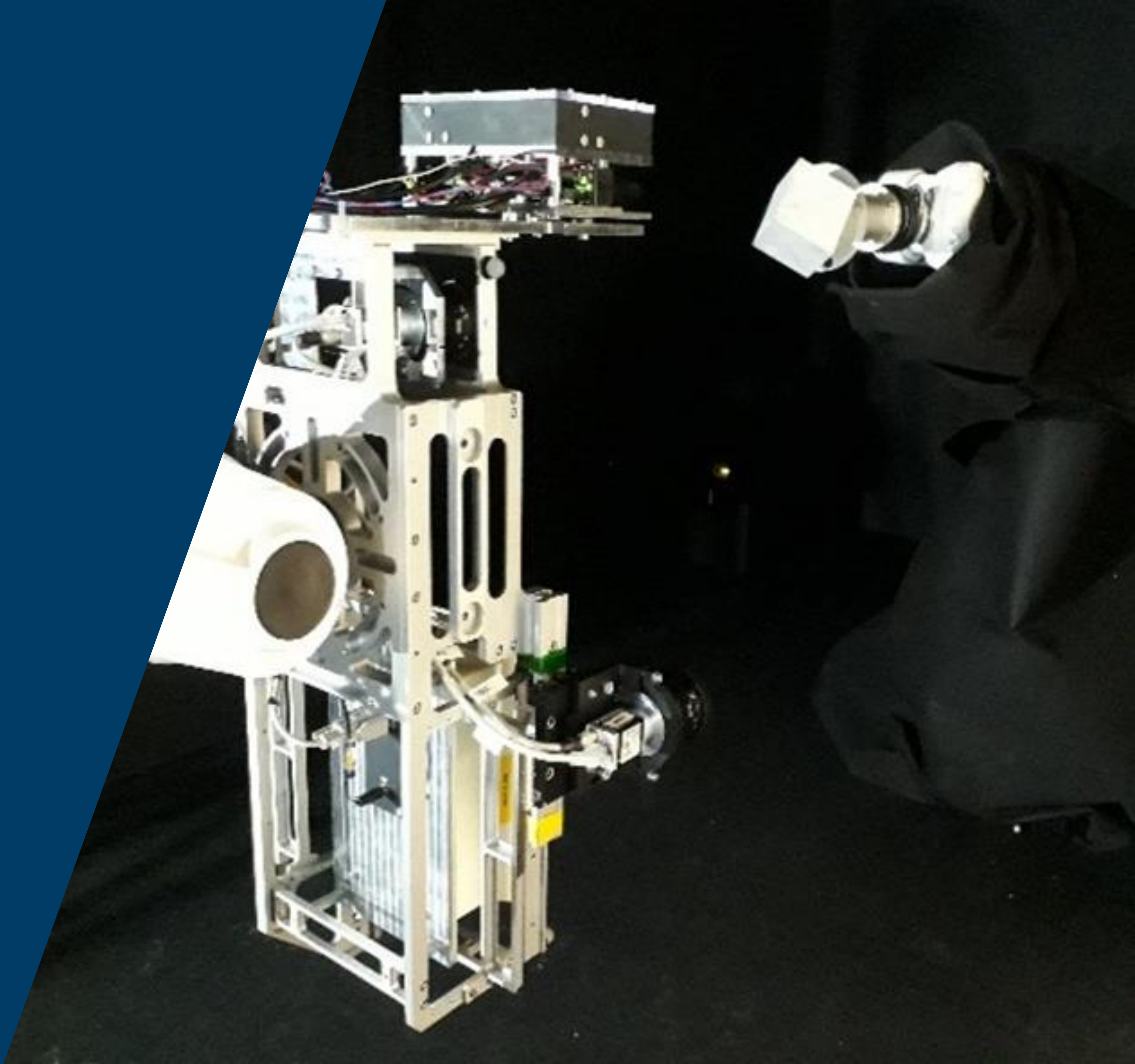
Prototype camera

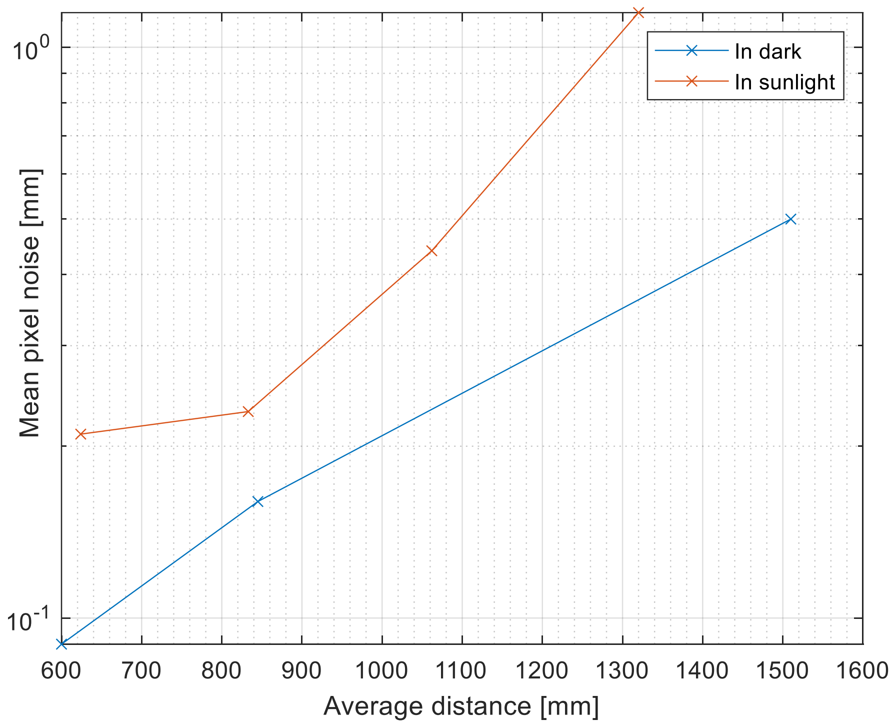


Results

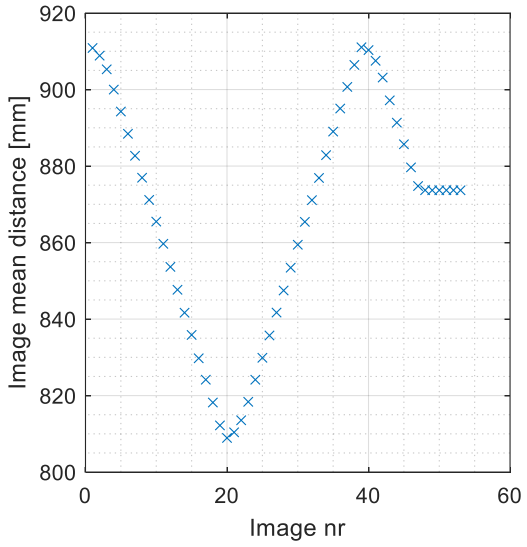


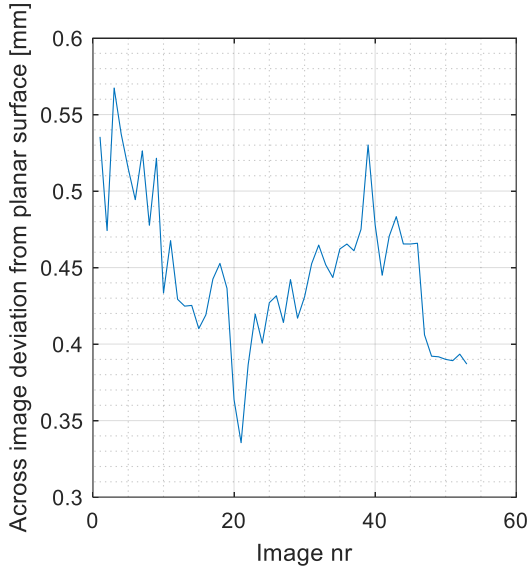
Noise characteristics

Sunlight tolerance



Motion tolerance.

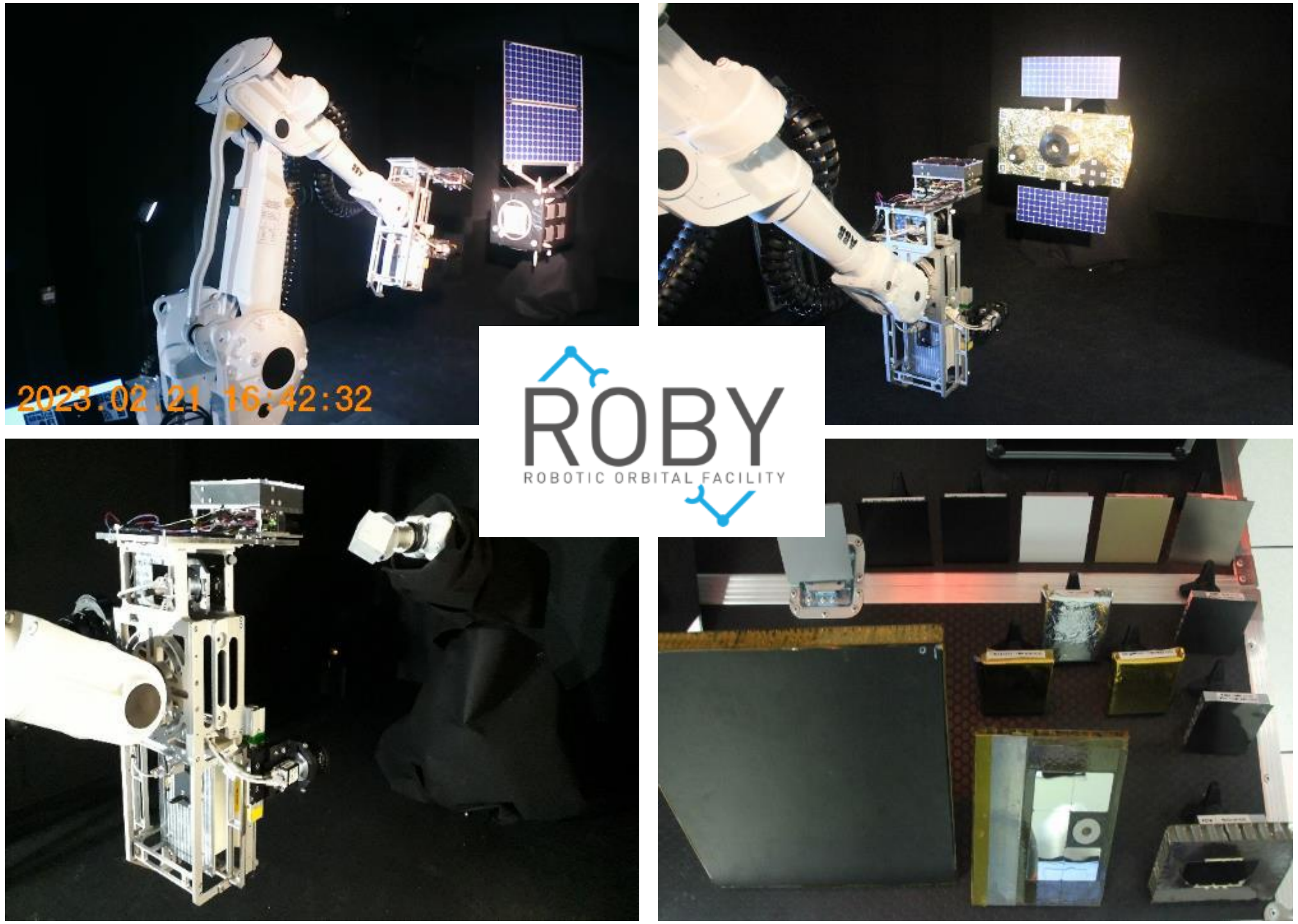




Test setup

- **Bench:** Robotic orbital facility (ROBY). Thales Alenia Space, Cannes.
  - 1x Robotic Arm on a rail : sensors
  - 1x Robotic Arm fixed on ground : samples

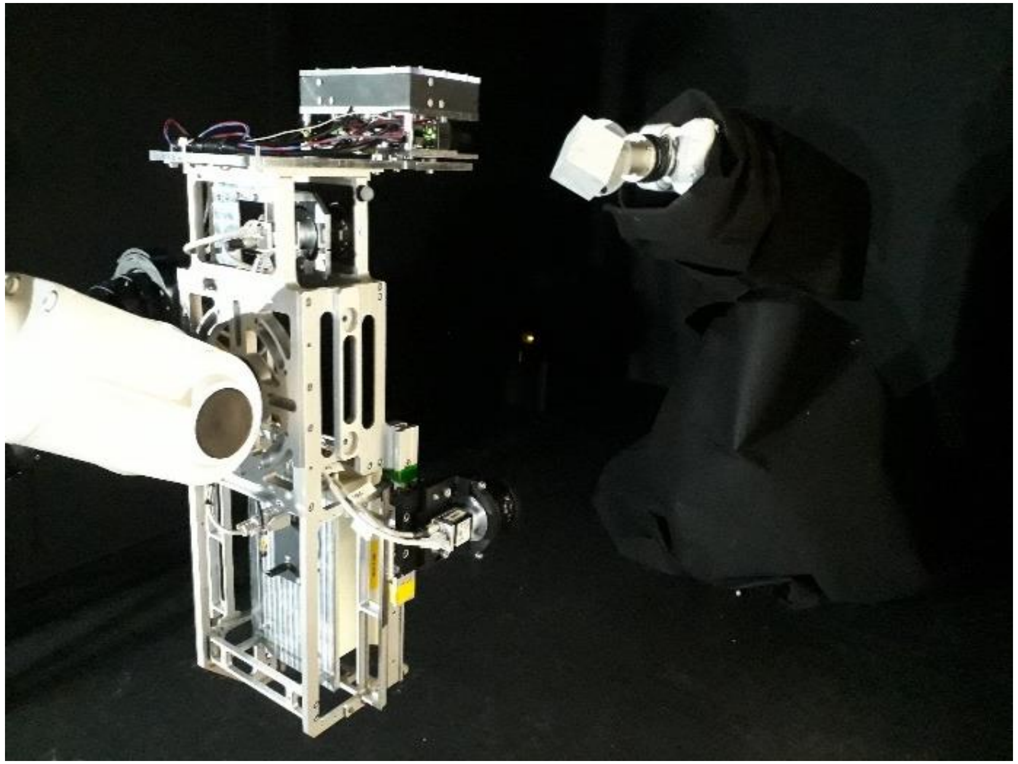
- **3D Camera Test Configuration**
  - Open-Loop test to characterize a sensor
  - No closed-loop with a rendezvous Guidance, Navigation and Control (GNC)
  - Different samples & mock-ups tested for future mission suitability



6DOF accuracy and precision tests

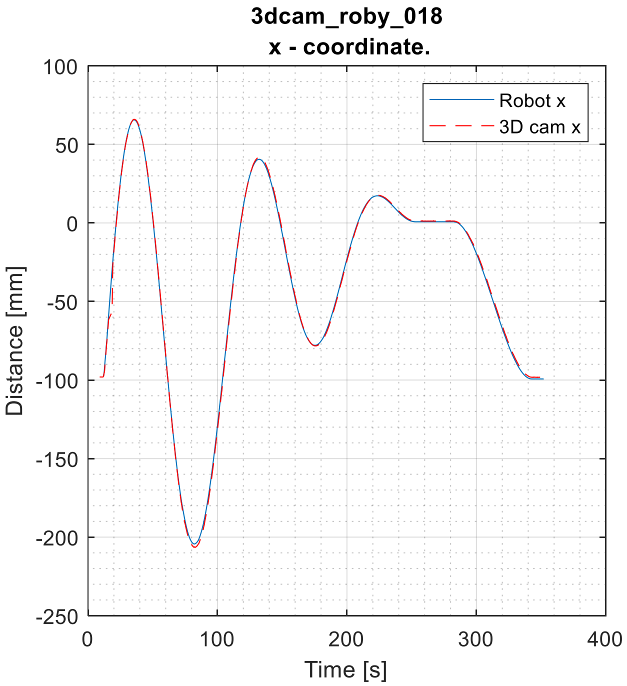
- Brushed aluminum cube mounted on MKP robot. 8x8x8 cm

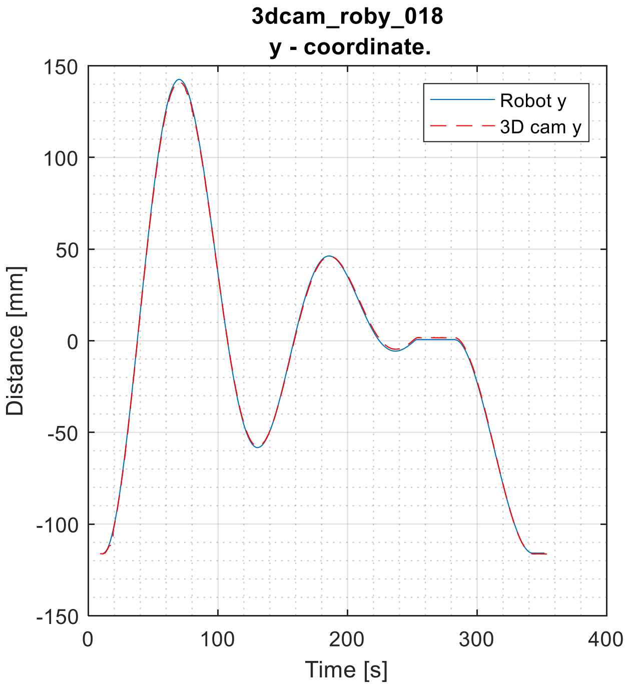
- 6DOF estimates from 3D camera data matched with robotic positioning data.

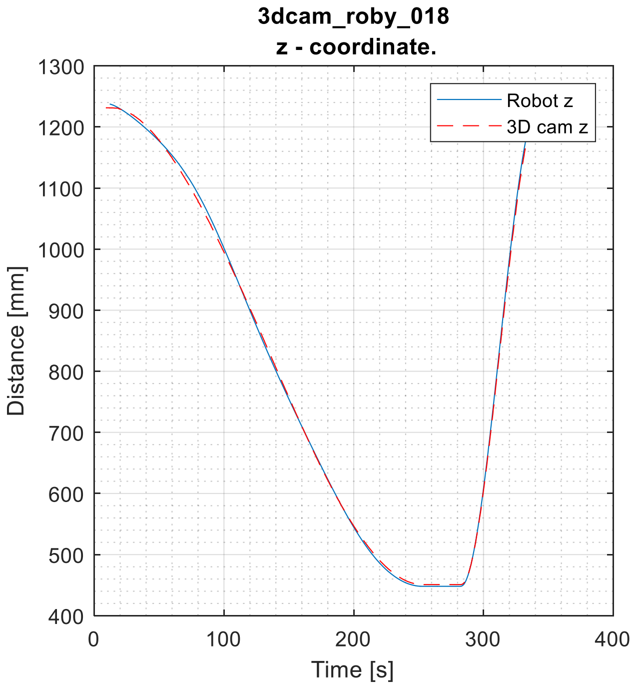


6DOF accuracy better than 1%

- Example trajectory below shows highly overlapping results.
- Trueness to within 1 % of distance across all tests, including motion up to 70 mm / s for ranges 400 - 1500 mm distance.

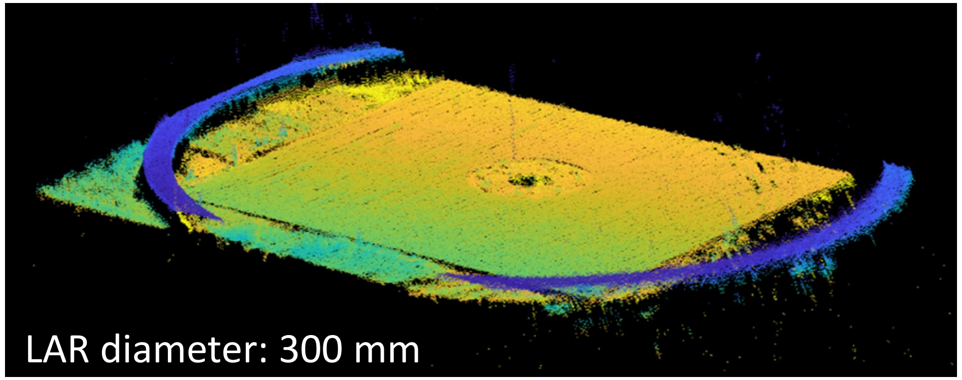


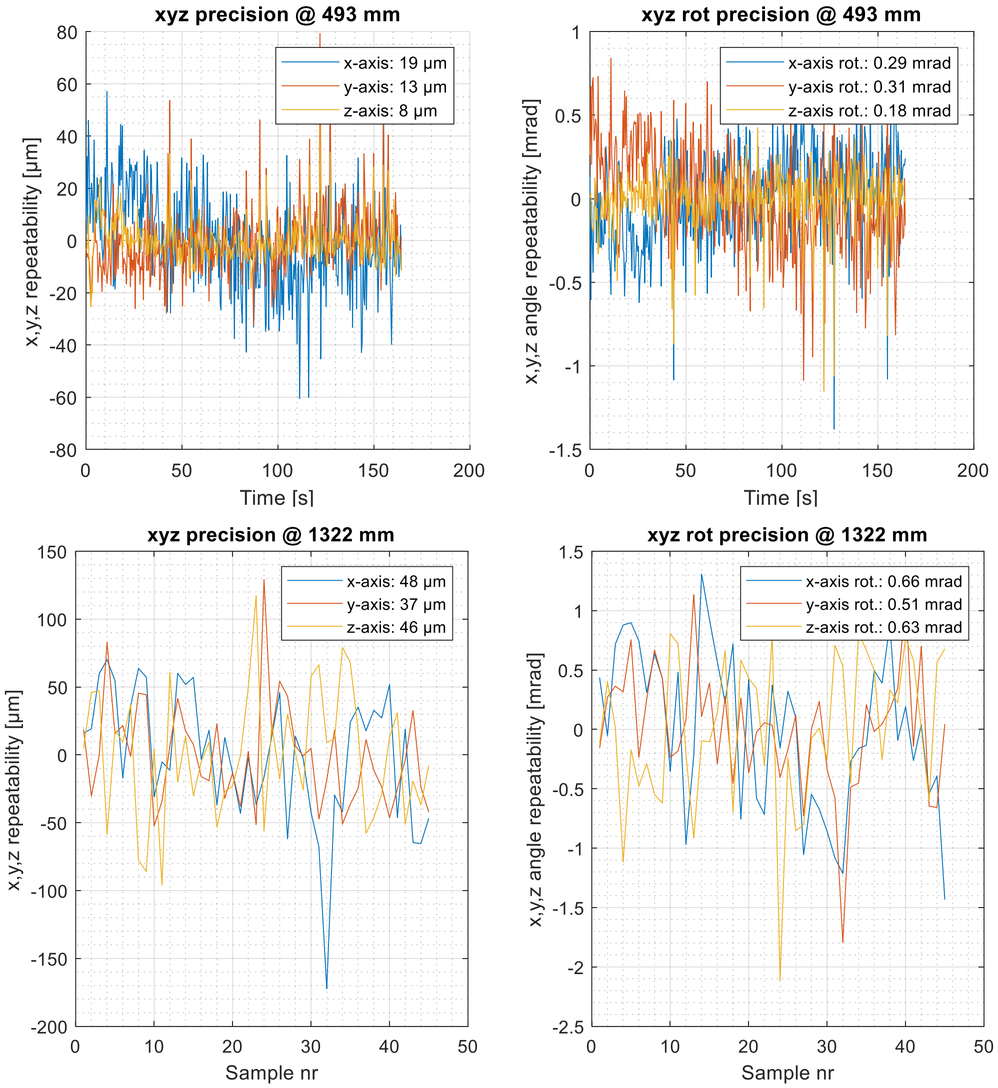




6DOF precision better than 50 um, 1 mrad

- Test target: 8x8x8 cm aluminium cube
- 6DOF precision better than 50 um, 1 mrad @ 1.3 meters.
- Larger objects could improve precision even further.





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Flight materials compatibility tests

Surface compliance table	
Tolerant at all angles:	- Brushed metal surfaces - Plastic and 3D printed surfaces - Composite materials
Tolerant at surface normals >10 degrees away from camera z-axis:	- MLI surfaces - Polished metal surfaces - Glossy paint
Limited compliance / best effort at surface normals >10 degrees away from camera z-axis:	- Highly specular surfaces (solar panels etc).
Non-compliance:	- Mirroring surfaces (Optical Solar Reflectors etc.)

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Capabilities matching robotic interaction

Capability	Advantage
Strong sunlight tolerance	Improved mission efficiency. No need to orient satellite etc relative to direction of sunlight to ensure shadow / correct illumination
Compact, robust, low power	Easy integration. Suitable for e.g. on-arm mounting.
Sub-mm dense 3D	Superior 3D data/6DOF quality. Ability to interact also with objects of unknown shape. Robustness in object recognition.
Motion tolerance	Can be used for closed-loop arm guidance for e.g. grasping/manipulation.
Material compliance	Many relevant flight materials can be reliably 3D imaged without significant efforts.

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Summary and outlook

- Highly compact, power-efficient 3D camera with active projector.
- Dense 3D images @ 10 Hz with sub-mm accuracy
- Example configuration for next step:
  - On-arm camera for robotic manipulation.
  - On-board 6DOF estimation
  - FPGA implementation
- Technology itself is flexible and adaptable for use case. (Power, field-of-view, range, size, …)
- Enabling technology for robust, efficient, and safe space robotics

	Current prototype	Optimized version
Resolution	500x500 pix	500x500 pix
Field-of-view	15x15 deg	15x15 deg
Capture time	150-450 ms	75-200 ms
Compute time	< 100 ms	< 100 ms
Size, mass	175 x 125 x 88 mm	145 x 80 x 50 mm
Mass	2 kg	0.4 kg
3D point precision	0.1 mm at 0.6 m	0.1 mm at 0.6 m
3D trueness	<1 % of distance	<1 % of distance
6DOF precision	<50 µm, <1 mrad	<50 µm, <1 mrad
Power incl. stereo reconstruction	30 W @ 10 Hz	10 W @ 10 Hz

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