Towards sensing and perception for autonomous berthing – force-torque sensor and an algorithm for the gripping point pose estimation.

Paweł Paśko
Head of the Mechatronics Section @
PIAP Space

ASTRA 2023
Leiden, The Netherlands
19 October 2023

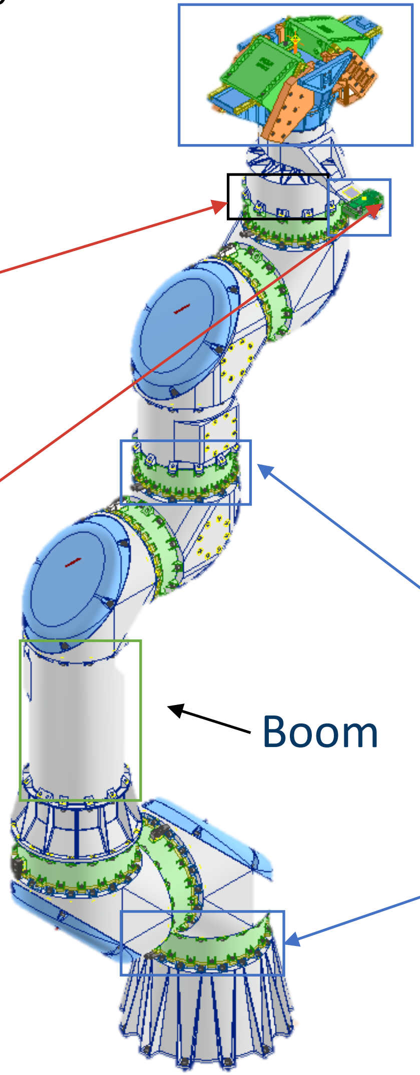
Key technologies for orbital and planetary robotics

- LARIS Gripper
- LARIS Docking System
- Standard Gripping Fixture
- Robotic Arm TITAN
- Force and Torque Sensor
- Vision System

IOS HEX (Credit: SAB Aerospace)

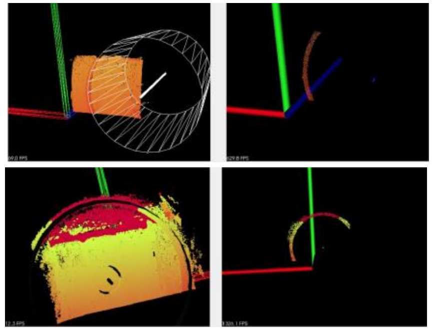
Context

TITAN Manipulator System



ORBITA

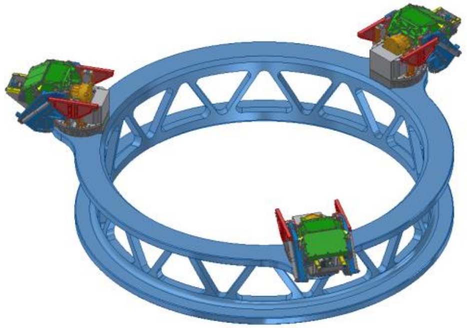
Force - Torque Sensor

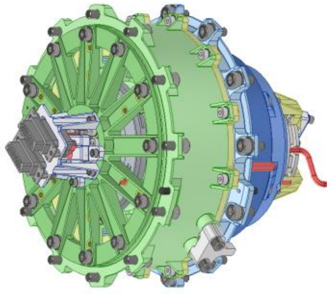


Vision System

LARIS Family

- LAR Gripper
- Docking System
- Standard Gripping Fixture (FGS)

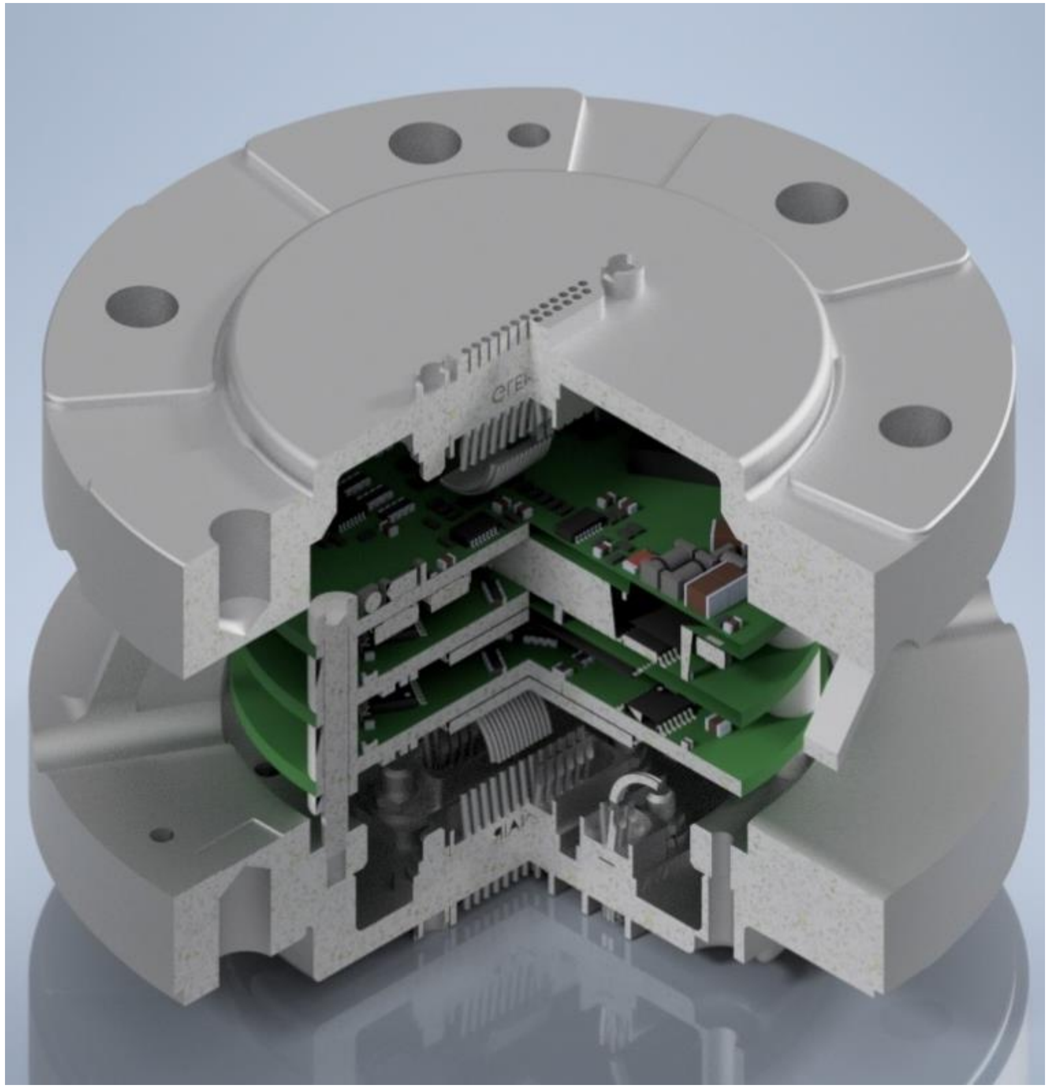




2 Joint sizes – Large and Small

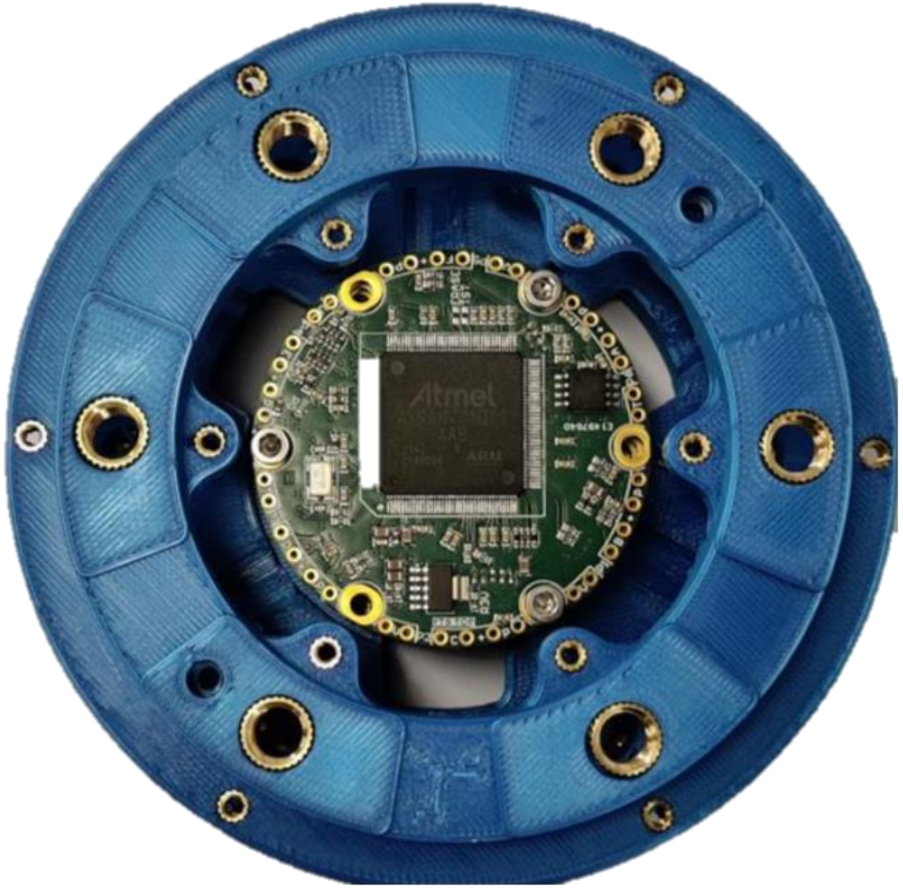
Control Electronics

PIAP Space Force and Torque Sensor



- **Redundant strain gauges and measuring channel** – fail safe
- **Custom-designed redundant electronic controller, fitted inside the body of the sensor** – path to fligth
- **Temperature monitoring and control** – accuracy and reliability
- **Calibration method** – wide range of measurments

FTS Parameters



- Measurement range of 50 N and 50 Nm,
- Overload capacity of 300%,
- Accuracy ≤3% (worst case)

- **Easy adaptation to different measurement ranges.**

- Operating range of -40/+100°C (survival range -100/+125°C)

- Φ125mm, 70mm height
- <1 kg

- More parameters in the paper!

FTS Principle of Operations

The sensor converts **force and torque input F** to signal **output U**. The sensor measures three components of forces and three components of torques in $\mathbb{R}3$.

$$\boldsymbol{U} \approx f(\boldsymbol{F})$$

$$\boldsymbol{F} = [F_x \quad F_y \quad F_z \quad M_x \quad M_y \quad M_z]^T$$

$$\boldsymbol{U} = [U_1 \quad U_2 \quad \dots \quad U_n]^T$$

Each signal output **U** is affected by each component of force and torque **F**, as **no sensor is perfectly decoupled**. This is shown by the **coupling matrix C**. The output signal is assumed to be proportional to applied load, as the sensor is designed to operate in range of elastic deformations.

$$\boldsymbol{U} \approx \boldsymbol{CF}$$

$$\boldsymbol{C} = \begin{bmatrix} C_{11} & \cdots & C_{16} \\ \vdots & \ddots & \vdots \\ C_{n1} & \cdots & C_{n6} \end{bmatrix}$$

Output signal is also affected by a **bias E** that was not fully compensated. This offset is assumed to be constant in whole measurement range and different for each output.

$$\boldsymbol{U} = \boldsymbol{CF} + \boldsymbol{E}$$

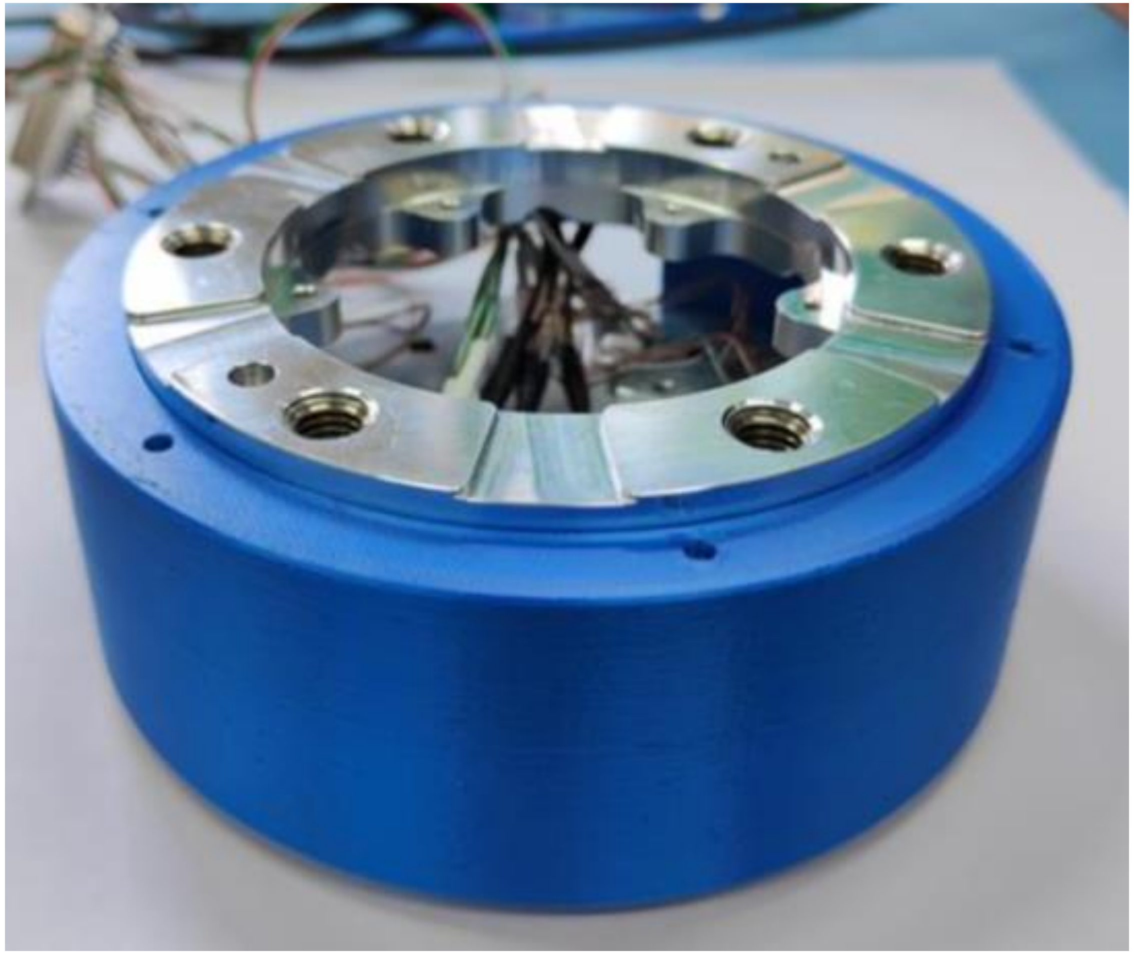
$$\boldsymbol{E} = [E_1 \quad E_2 \quad \dots \quad E_n]^T$$

A simple transformation is done to estimate forces and torques acting upon sensor. This operation can be employed in order to use the force and torque sensor as a measurement instrument.

$$\boldsymbol{F} = \boldsymbol{C}^{-1}(\boldsymbol{U} - \boldsymbol{E})$$

Mechanical structure and strain gauges

- Stewart platform like internal structure,
  - low non-linearity,
  - high accuracy
  - advantageous ratio of stiffness to mass.
- Redundant measurement channels,
  - vacuum compatible
  - extended temperature range.
- Both sets of strain gauge bridges are connected to individual, independent parts of controller with separate communication and power connections.

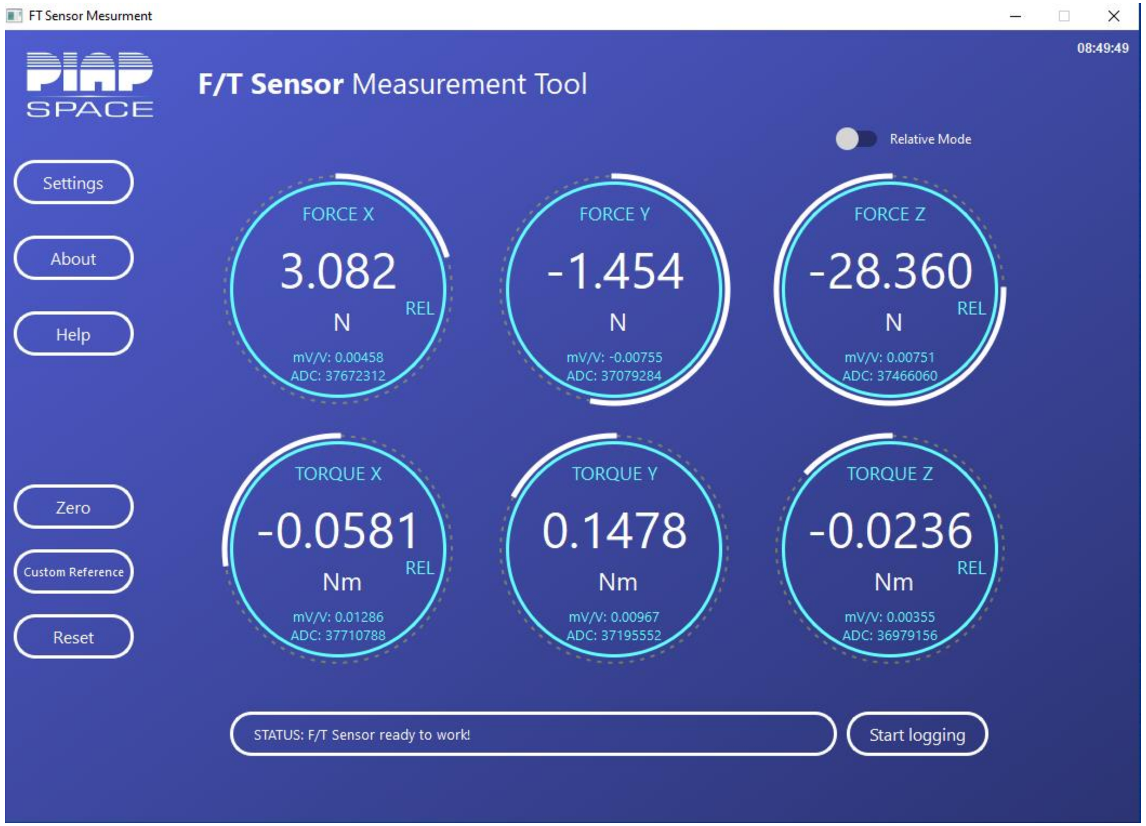


PIAP Space Controller

- Stacked PCBs fitted inside the FTS
    - prepared to use space rated components.
- Redundant architecture with two microcontrollers
- Software thermal compensation
- Sensor’s thermal control
    - temperature sensors redout and power heaters control

Controller Software

- Proprietary software for driving the controller, permitting data acquisition and visualization,
- CAN bus for communication and operates on Windows and Linux (Ubuntu 18.04) operating systems
- CANopen



FORCE X 3.082 N REL mV/V: 0.00458 ADC: 37672312

FORCE Y -1.454 N mV/V: -0.00755 ADC: 37079284

FORCE Z -28.360 N REL mV/V: 0.00751 ADC: 37466060

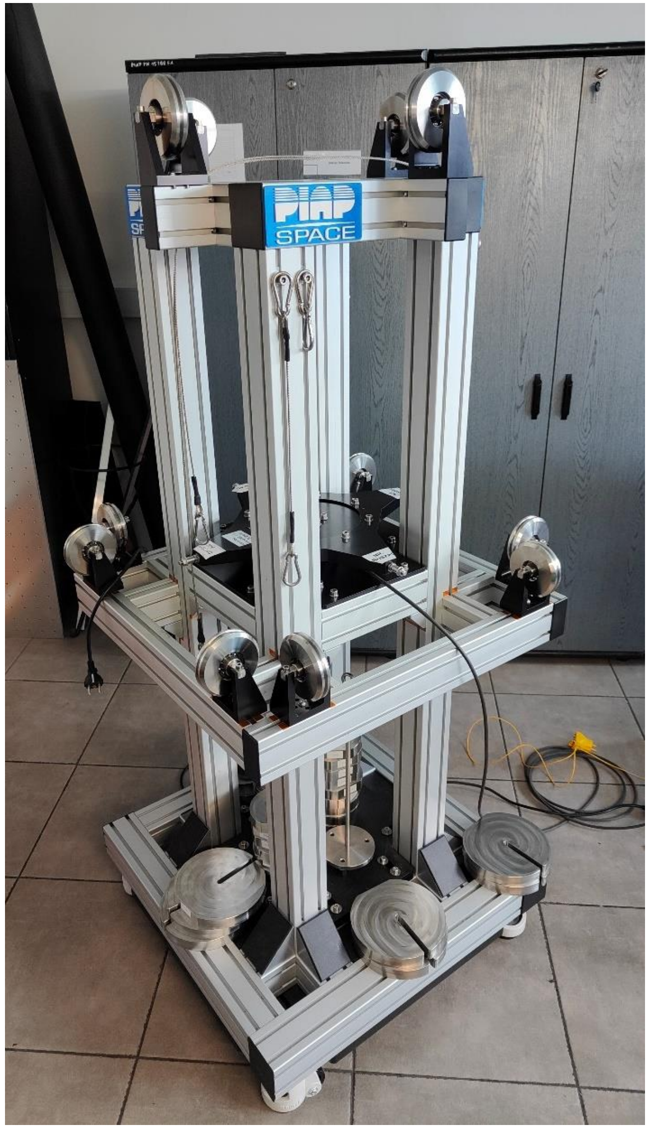
TORQUE X -0.0581 Nm REL mV/V: 0.01286 ADC: 37710788

TORQUE Y 0.1478 Nm mV/V: 0.00967 ADC: 37195552

TORQUE Z -0.0236 Nm REL mV/V: 0.00355 ADC: 36979156

STATUS: F/T Sensor ready to work!

Calibration Station

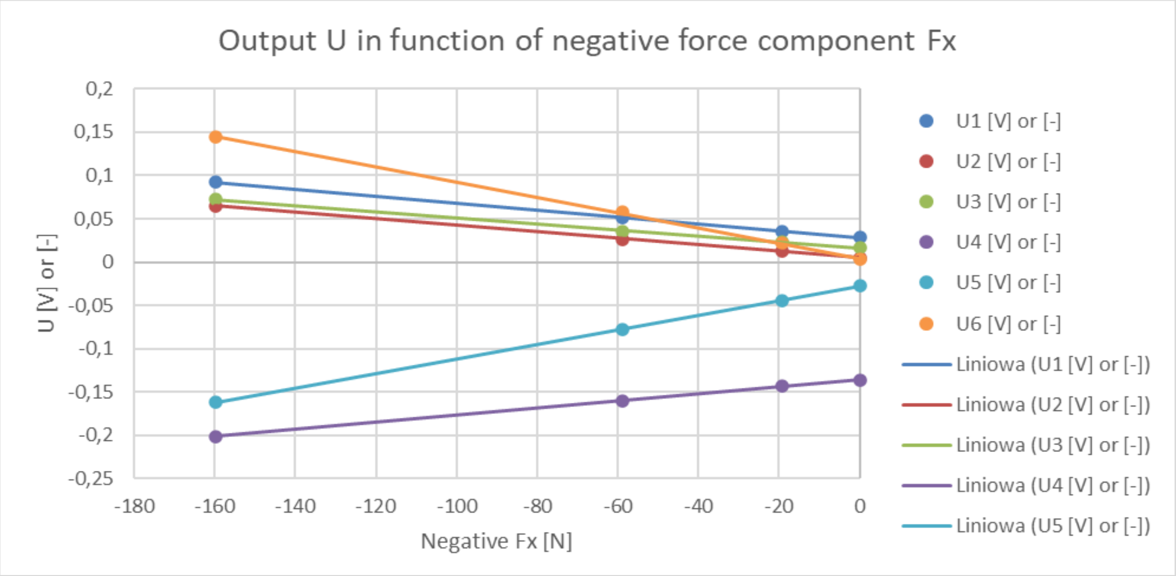


- Applying loads simultaneously in multiple axes,
- Compatible with climate chamber for calibrations at -40 and +40,

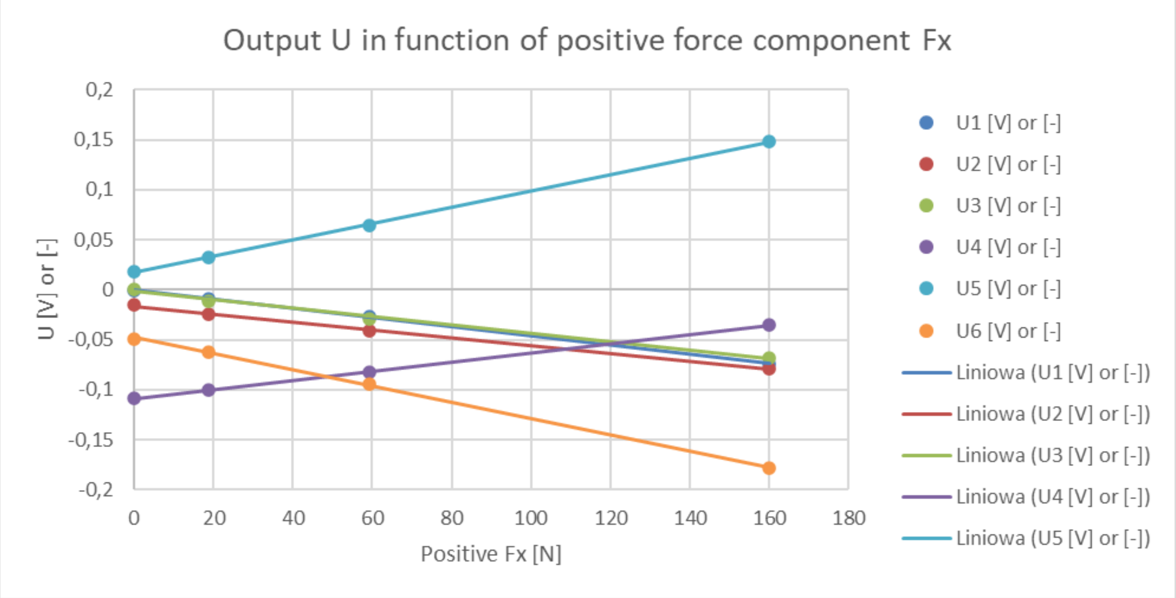
- Equipped with precisely machined weights, allow for application of loads from 15 N or 7,5 Nm up to 800 N or 400 Nm
- Calibrated dynamometers

- **Vacuum compatible Calibration Stations with much wider temperature range is planned.**

Calibration Results



Output U in function of negative force component Fx



Output U in function of positive force component Fx

- Full calibrations at temperatures -20, 0, 20 and 40°C
- Coupled but linear behavior

Tests Results

- Ageing in the range from -40 to +100 °C to reduce hysteresis of zero signals.
- Test in the full range of from -50 to 50°C.
- **TVAC tests are planned in upcoming months**

FTS Conclusions and Timeline

- **Q2 2023** - DM-1 off-the-shelf Force and Torque Sensor model calibrated and tested,
- **Q3 2023** – Custom electronics tested with DM-1 and DM-2 models
- **Ongoing** – tests and calibration of the customized DM-2 model with redundant channels
  - TVAC and vibration tests till end of the 2023 – **TRL 6**.

- **Calibration method validated!**
  - The proposed calibration may be used for any kind of force and torque sensor with linear output and with any number of outputs

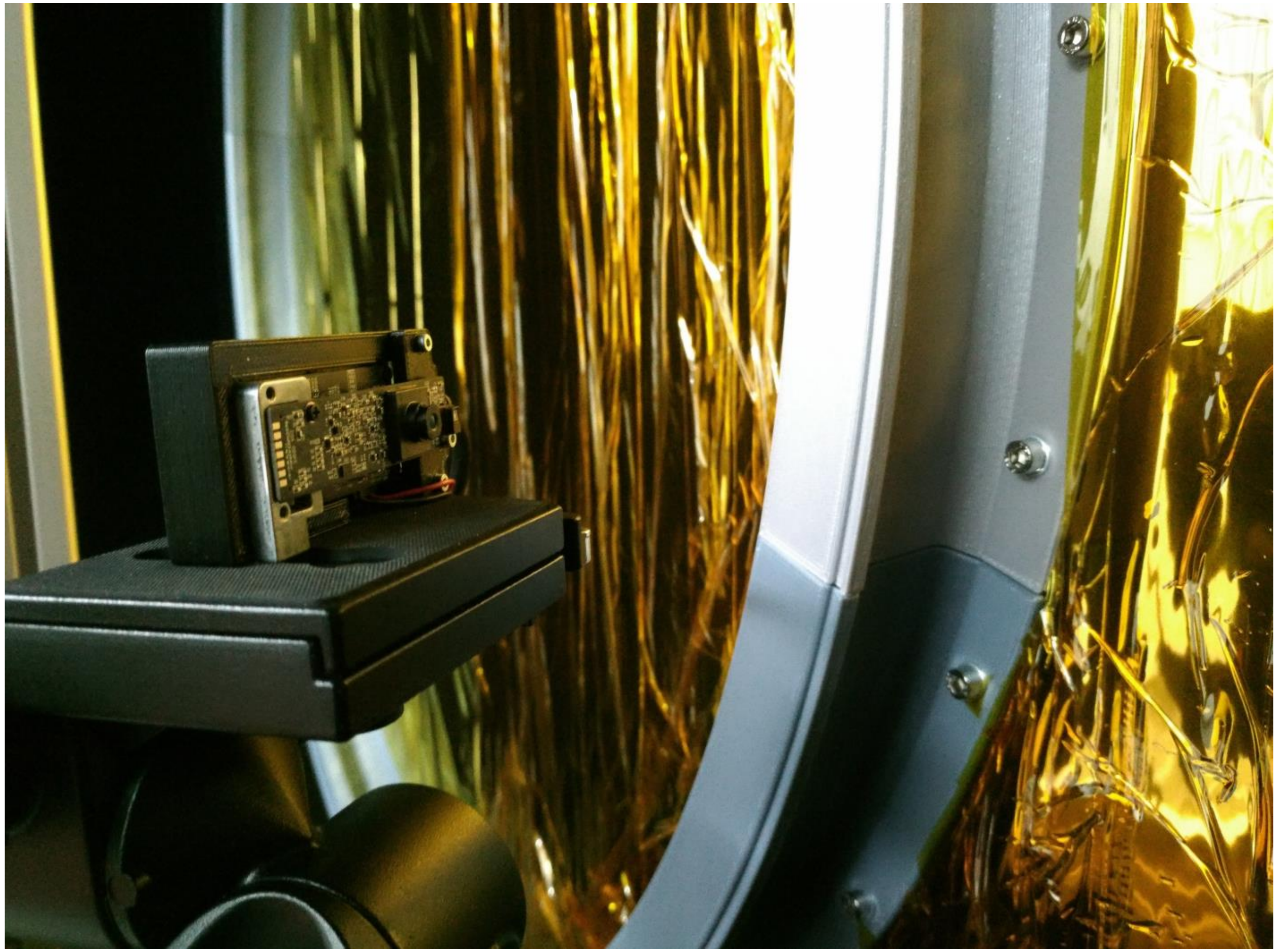
  - **TVAC calibration is planned to start in 2024.**

Vision System

- Vision system for estimation of LAR pose in 6 DOF **without markers** in close distance 0.2 – 1.2m
- LAR diameter and height has to be known

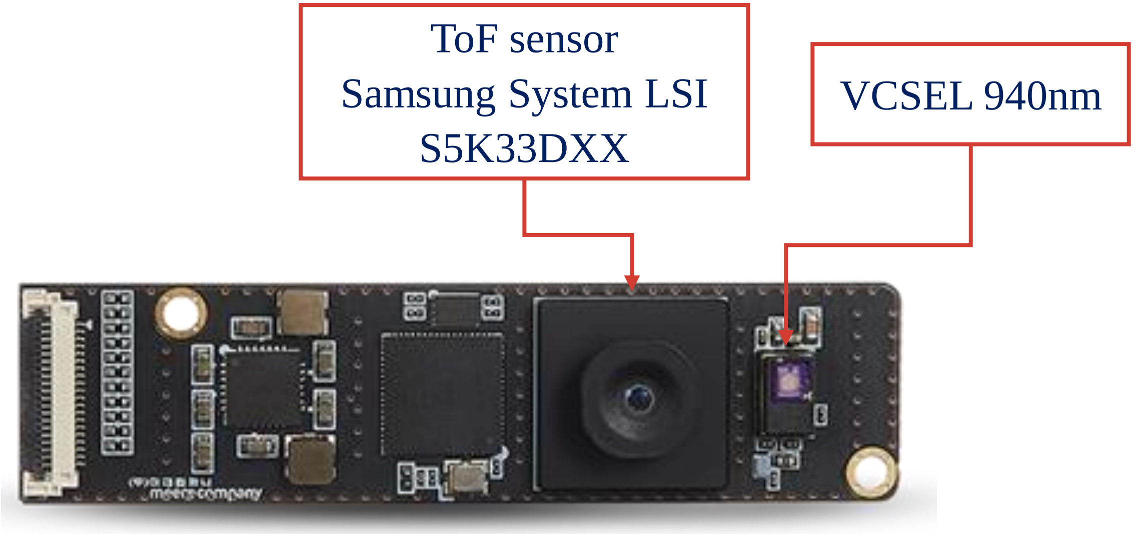
- Sensor to be mounted on robotic end-effector -> low mass & small envelope

- Linear accuracies:
    - 20mm@z=1,2m;
    - 10mm@z=500;
    - 4mm@z=250mm
- Angular accuracies:
    - 1deg@z=1,2m;
    - 0.5deg@z=500;
    - 0.2deg@z=250mm



Vision System Hardware

Hardware agnostic, but:



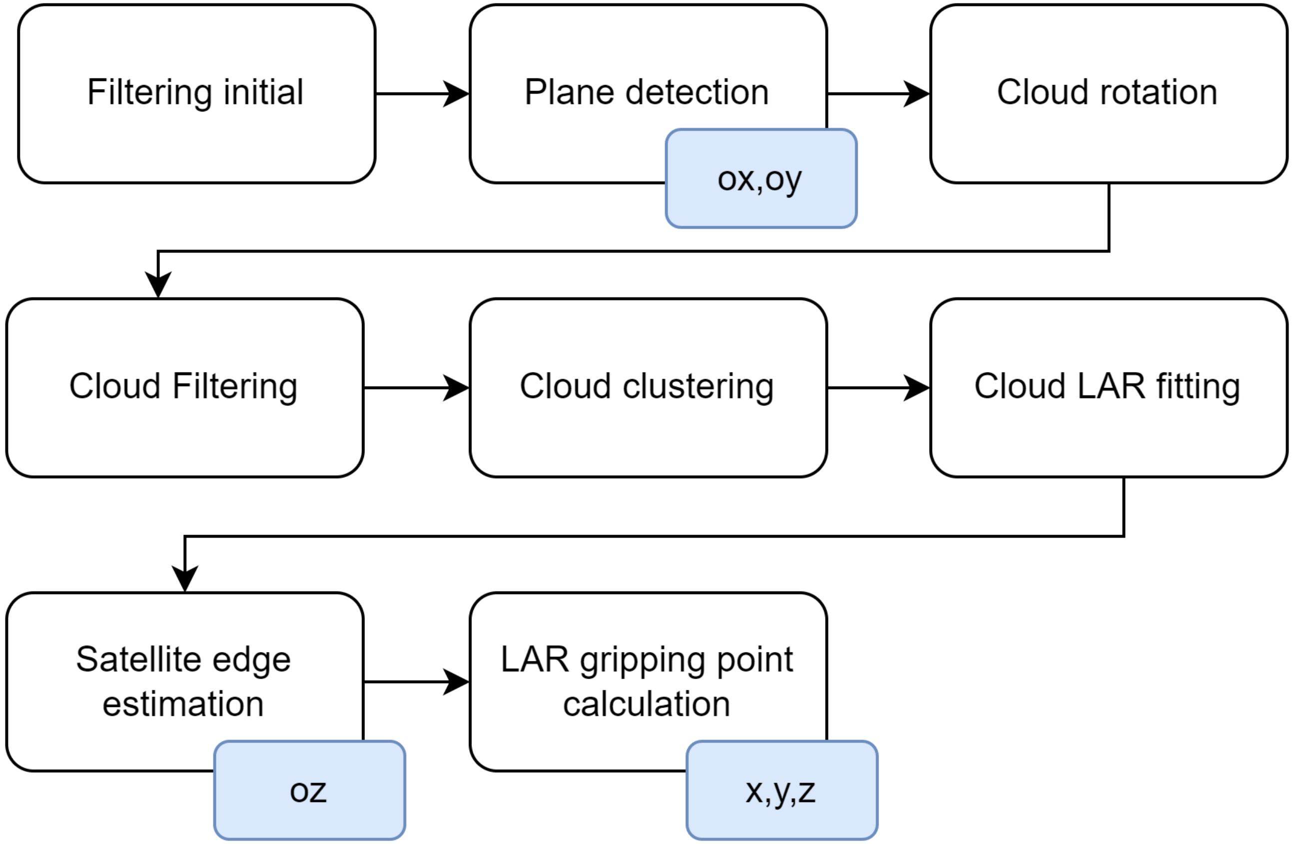
CubeEye/Meere Company S100D

- Indirect (phase-shift) ToF, 940nm
- Operating range: 0.2 – 4m
- FoV: 60x45 deg
- Resolution: 640x480
- Frame rate: max 30fps
- Not tested regarding space environment

Aetina AIE-CT41 Processing unit

- NVIDIA Jetson TX2 NX

Vision System Algorithm



- Using open-source PCL library
- Language: c++
- **Algorithm can be used on any point cloud map**
- Algorithm implemented in two application:
  - As EGSE (for parameters adjustment and inspection)
  - As module on Robotic arm (position feedback to motion controller)
- Additional filtering of results to correct stability

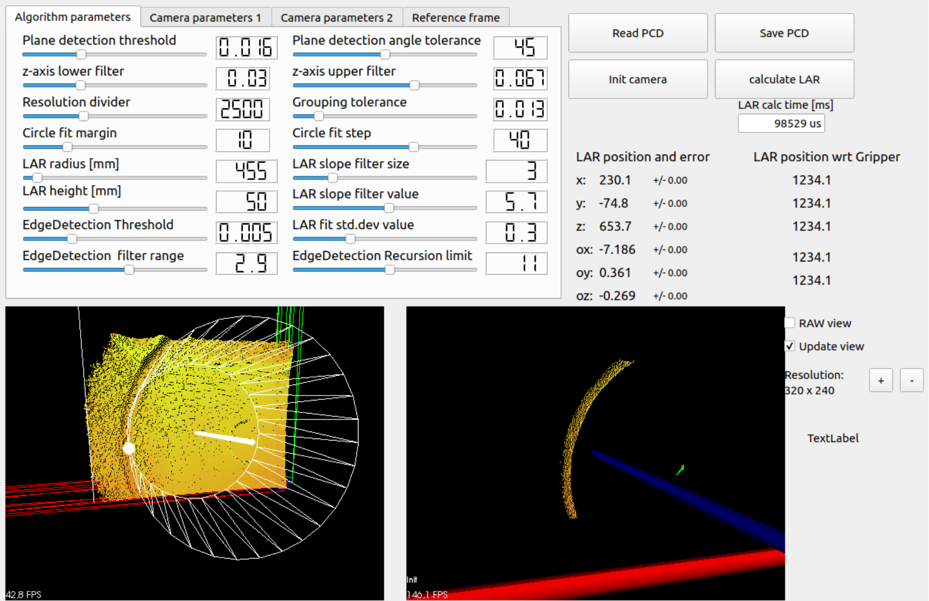
Vision System Software

SW-1

- GUI written on QT5
- **Fine tuning** of all algorithm and camera parameters
- Used mainly to verify algorithm behavior
- Works with saved point cloud data and with live camera data,

SW-2

- 2 modes (with/without visualization)
- **CAN-Open** implemented for communication with Motion Controller
- Optimized for performance
- Possibility to execute commands by terminal or GUI (in mode with visualization)

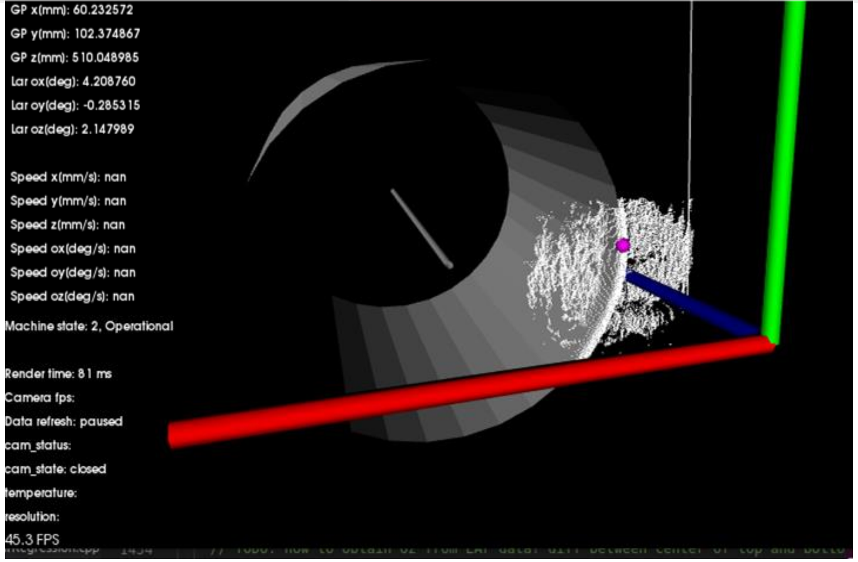


Plane detection threshold 0.016
z-axis lower filter 0.03
Resolution divider 2500
Circle fit margin 10
LAR radius [mm] 455
LAR height [mm] 50
EdgeDetection Threshold 0.005
EdgeDetection filter range 2.9
Plane detection angle tolerance 45
z-axis upper filter 0.067
Grouping tolerance 0.013
Circle fit step 40
LAR slope filter size 3
LAR slope filter value 5.7
LAR fit std.dev value 0.3
EdgeDetection Recursion limit 11

LAR calc time [ms]
98529 us

LAR position and error			LAR position wrt Gripper
x:	230.1	+/- 0.00	1234.1
y:	-74.8	+/- 0.00	1234.1
z:	653.7	+/- 0.00	1234.1
ox:	-7.186	+/- 0.00	1234.1
oy:	0.361	+/- 0.00	1234.1
oz:	-0.269	+/- 0.00	

☐ RAW view
☑ Update view
Resolution:
320 x 240



```
GP x(mm): 60.232572
GP y(mm): 102.374867
GP z(mm): 510.048985
Lar ox(deg): 4.208760
Lar oy(deg): -0.285315
Lar oz(deg): 2.147989

Speed x(mm/s): nan
Speed y(mm/s): nan
Speed z(mm/s): nan
Speed ox(deg/s): nan
Speed oy(deg/s): nan
Speed oz(deg/s): nan
Machine state: 2, Operational

Render time: 81 ms
Camera fps:
Data refresh: paused
cam_status:
cam_state: closed
temperature:
resolution:
45.3 FPS
```

Test set-up

- 3x3x3m aluminium cage covered with material absorbing IR radiation
- Printed version of LAR from Sentinel-3
- LAR mounted on flat Surface covered by Mylar + Kapton
- Additional **6 different MLI** material/components ready to test
- Handheld CMM used for accuracy measurements
- Camera mounted on rails (linear movement) and tripod head (angular movement)
- Different lightning conditions

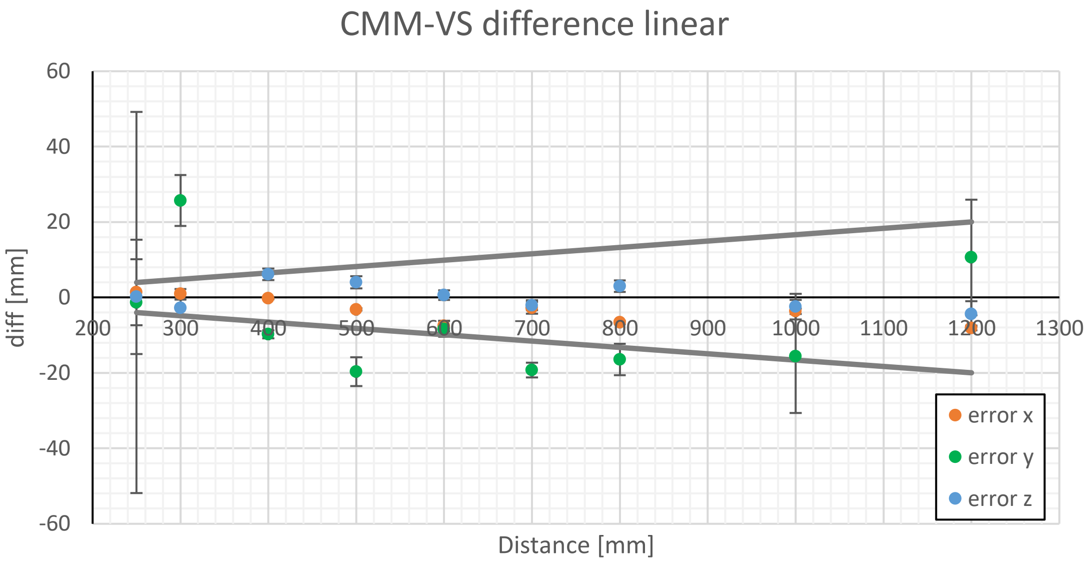
VS Verification

Verification procedure:

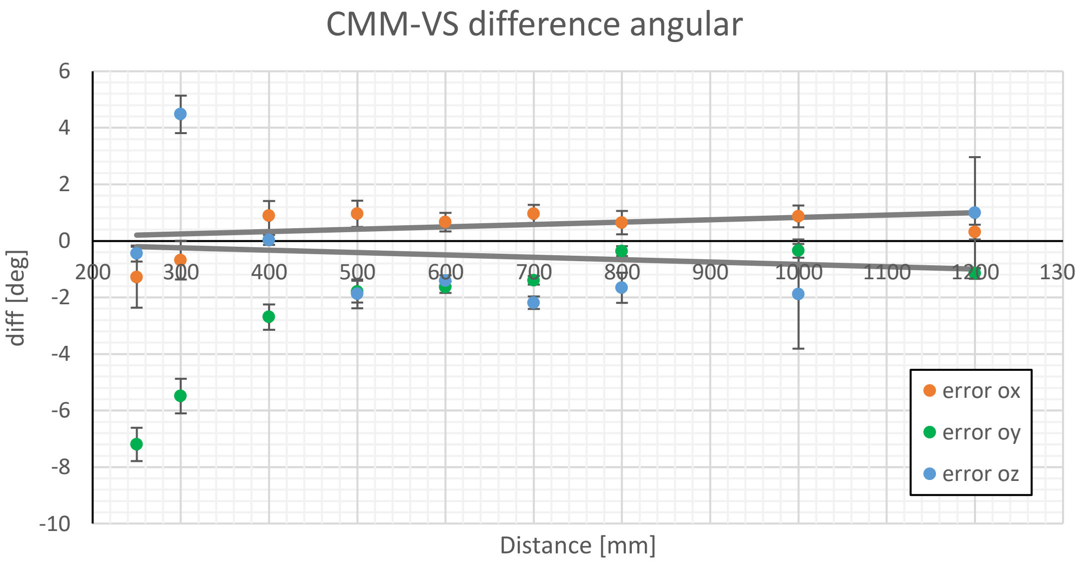
- Set camera position on rails and orientation on tripod head
- Perform batch of VS measurement
- Perform CMM measurement of the position of the LAR grasping points in the camera reference frame
- Compare results
- Repeat for different position on z axis

Test results I

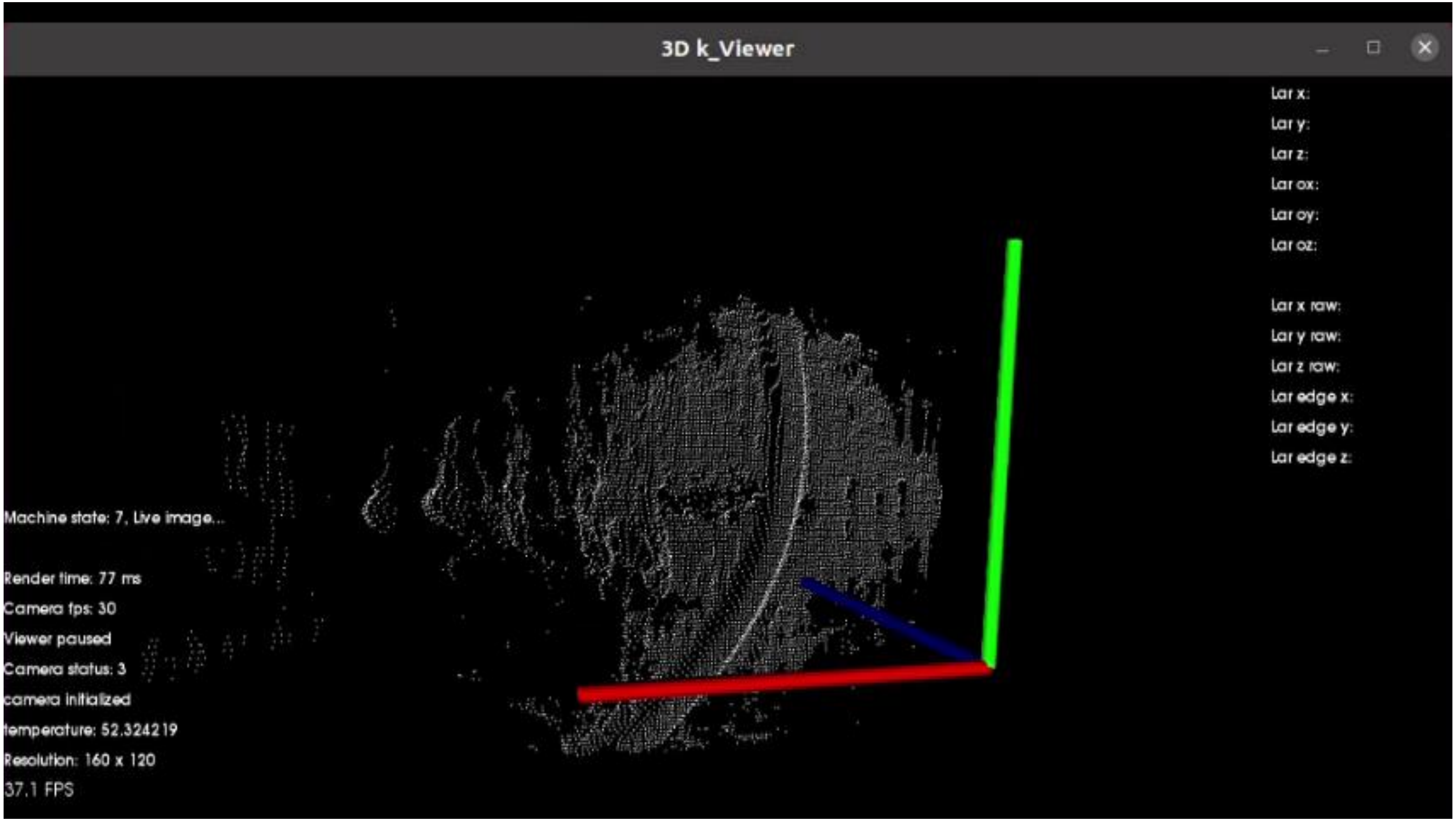
- Accuracy stable over distance
- X and Z accuracy below 6mm at whole range
- Accuracy of x and z ~1mm @z=250mm
- Accuracy on y axis outside required accuracy – in practice it's least significant
- Range currently limited from 250mm
- At z=250mm big instabilities



- Angular measurement repeatability not affected by distance
- Poor angular accuracy on close distance due to smaller dataset and higher noise
- VS performance supposed to be better with black Kapton MLI



Test results III



Lar x:
Lar y:
Lar z:
Lar ox:
Lar oy:
Lar oz:

Lar x raw:
Lar y raw:
Lar z raw:
Lar edge x:
Lar edge y:
Lar edge z:

Machine state: 7, Live image...

Render time: 77 ms
Camera fps: 30
Viewer paused
Camera status: 3
camera initialized
temperature: 52.324219
Resolution: 160 x 120
37.1 FPS

VS Summary

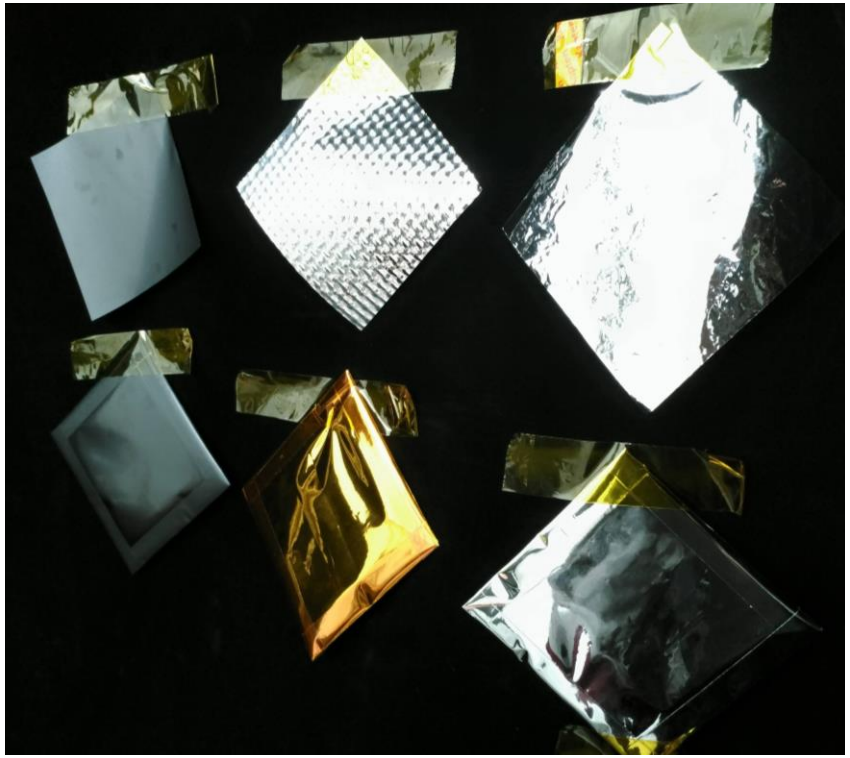
- VS works well enough to provide accurate movement for LAR grasping
- Calculation frequency is ~30Hz

- Algorithm can be further improved for better stability and accuracy

- Different MLI materials to be tested

- Plan to check ToF camera with wider FoV to increase repeatability in close range

- VS will be used during the TITAN tests



LET YOUR NEXT MISSION

BE OUR COMMON SUCCESS

We look forward to hearing from you

Paweł Paśko
Head of the Mechatronics Section
pawel.pasko@piap-space.com

(+48) 885 404 205
www.piap-space.com

The project "Development of the family of modular grippers for orbital and planetary applications – ORBITA".
POIR.01.01.01-00-0464/20-00