SOLAR X

WP8: Airborne LCC monitoring system pilot implementation

September 2025, CYI | Kypros Milidonis, Ismail Loghmari

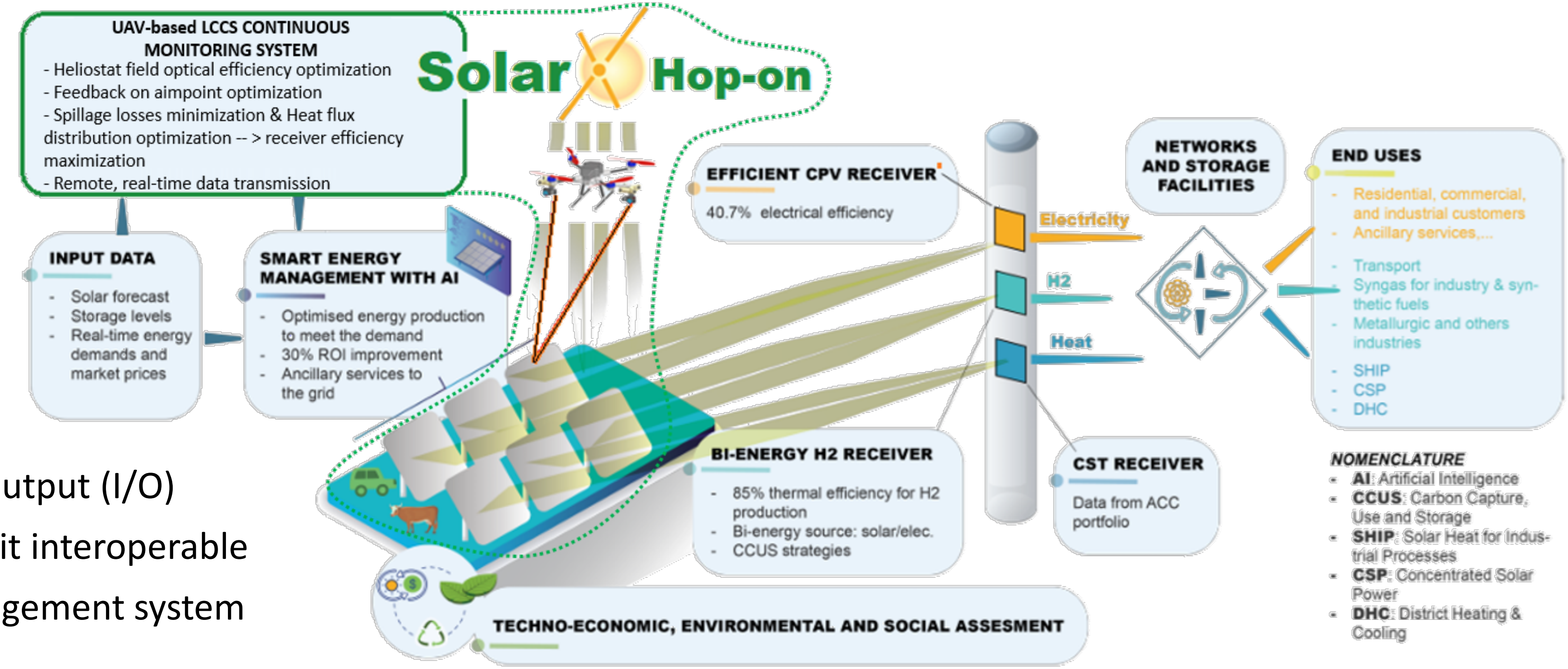
SOLAR X Hop-On

Funded by the European Union

Funded by the European Union under the Horizon Europe Framework Programme (Project name: SOLARX; grant number: 101084158). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them. The project is also supported by the Swiss State Secretariat for Education, Research and Innovation (SERI).

The SolarX-Hop-On overview

- The SOLAR X **Hop-On** project's main objective is to enhance the first key technological element of SolarX, i.e. the smart solar resource management algorithm, by:
  - Developing a pilot of an airborne, Unmanned Aerial Vehicle (UAV) based system for the continuous monitoring of the Light Collection and Concentration sub-system of the solar tower plant.
  - Testing of the pilot at TRL 4 at a relevant Environment
  - Development of a digital virtual twin of the system
  - Tuning the pilot's input/output (I/O) interface accordingly to make it interoperable with the smart resource management system



UAV-based LCCS CONTINUOUS MONITORING SYSTEM
- Heliostat field optical efficiency optimization
- Feedback on aimpoint optimization
- Spillage losses minimization & Heat flux distribution optimization --> receiver efficiency maximization
- Remote, real-time data transmission

INPUT DATA
- Solar forecast
- Storage levels
- Real-time energy demands and market prices

SMART ENERGY MANAGEMENT WITH AI
- Optimised energy production to meet the demand
- 30% ROI improvement
- Ancillary services to the grid

EFFICIENT CPV RECEIVER

40.7% electrical efficiency

NETWORKS AND STORAGE FACILITIES

END USES
- Residential, commercial, and industrial customers
- Ancillary services,...

- Transport
- Syngas for industry & synthetic fuels
- Metallurgic and others industries

- SHIP
- CSP
- DHC

BI-ENERGY H2 RECEIVER
- 85% thermal efficiency for H2 production
- Bi-energy source: solar/elec.
- CCUS strategies

CST RECEIVER

Data from ACC portfolio

TECHNO-ECONOMIC, ENVIRONMENTAL AND SOCIAL ASSESMENT

NOMENCLATURE
- **AI**: Artificial Intelligence
- **CCUS**: Carbon Capture, Use and Storage
- **SHIP**: Solar Heat for Industrial Processes
- **CSP**: Concentrated Solar Power
- **DHC**: District Heating & Cooling

The technical concept

- The efficiency of the heliostat field is of outmost importance being the first components to interact with the sunlight in the energy harnessing process

- The mirror's optical errors (whose quantification is an highly difficult task) constitute the most important energy loss
  - Direct effect on the achieved concentration level and irradiance distribution on the receiver
  - Spillage increase due to bad aiming
  - Non-linear energy losses and to improper flux distribution, influencing plants efficiency

Need for a continuous monitoring system, which will provide the smart solar resource algorithm with dynamic, real-time continuous feedback on the status of the LCC.

SolarX-Hop-On, focused on complementing, augmenting, and dynamically enhancing the SolarX's algorithm by developing such a system to a TRL 4.

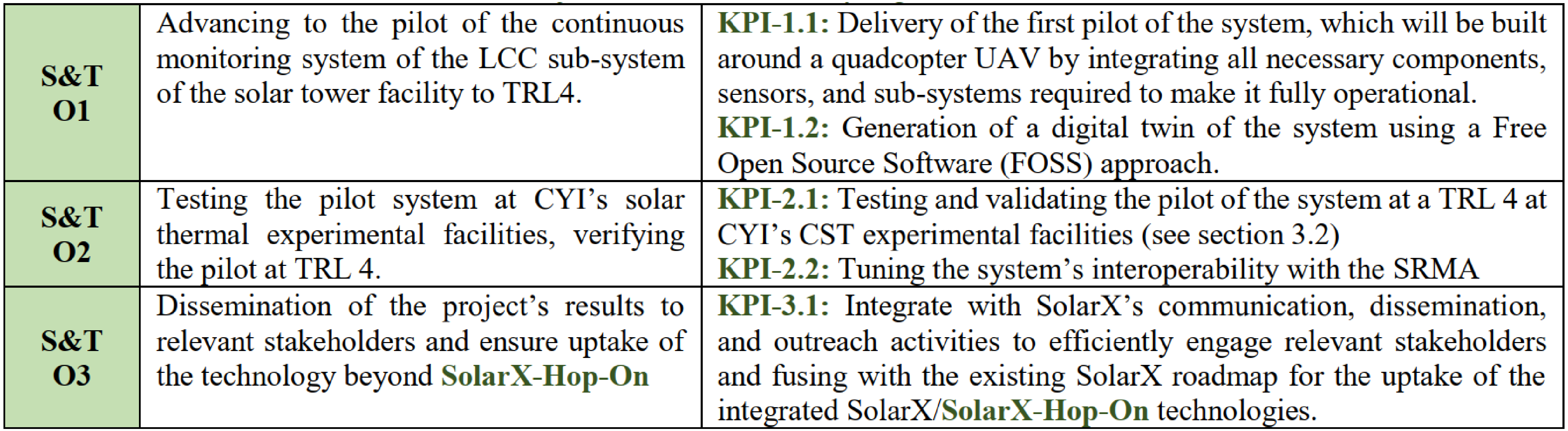
Align modular production potential with solar resource and energy demand	**KPI-2.1**: Develop one algorithm for real-time management of multiple energy vector production from a single tower, based on solar resource nowcasting and energy demand (electricity, heat and H$_2$ market prices). **KPI-2.2:** Enhance plant operation through development of an adaptive aiming strategy, supported by a ray tracing model and camera-based aim point detection by 5% optical efficiency compared to conventional control

Main objectives

- To ensure the successful attainment of these objectives, **SolarX-Hop-On** focuses on the following specific measurable scientific and technical (S&T) objectives (O), which will be monitored by targeted Key Performance Indicators (KPI's).

Two main objectives:

- Development of a first physical prototype of the system
- Parallel development of the digital virtual twin of the system



S&T O1	Advancing to the pilot of the continuous monitoring system of the LCC sub-system of the solar tower facility to TRL4.	**KPI-1.1:** Delivery of the first pilot of the system, which will be built around a quadcopter UAV by integrating all necessary components, sensors, and sub-systems required to make it fully operational. **KPI-1.2:** Generation of a digital twin of the system using a Free Open Source Software (FOSS) approach.
S&T O2	Testing the pilot system at CYI's solar thermal experimental facilities, verifying the pilot at TRL 4.	**KPI-2.1:** Testing and validating the pilot of the system at a TRL 4 at CYI's CST experimental facilities (see section 3.2) **KPI-2.2:** Tuning the system's interoperability with the SRMA
S&T O3	Dissemination of the project's results to relevant stakeholders and ensure uptake of the technology beyond **SolarX-Hop-On**	**KPI-3.1:** Integrate with SolarX's communication, dissemination, and outreach activities to efficiently engage relevant stakeholders and fusing with the existing SolarX roadmap for the uptake of the integrated SolarX/**SolarX-Hop-On** technologies.

Overview of the patented mirror characterization methodology

- Method based on stereo vision geometry and computer vision algorithms. Assuming a drone equipped with two cameras, each mounted on its respective gimbal mechanism, then:
  - The normal to any point of the mirror can be determined if the directions are known:

$$\mathbf{n}_\mathrm{M} = -\frac{\mathbf{d}_\mathrm{A} + \mathbf{d}_\mathrm{B}}{|\mathbf{d}_\mathrm{A} + \mathbf{d}_\mathrm{B}|}$$

  - The point of the mirror can be determined by the intersection of two rays:

$$\begin{cases} \mathbf{r} = \mathbf{r}_\mathrm{A} + t_\mathrm{A}\mathbf{d}_\mathrm{A} \\ \mathbf{r} = \mathbf{r}_\mathrm{B} + t_\mathrm{B}\mathbf{d}_\mathrm{B} \end{cases}$$

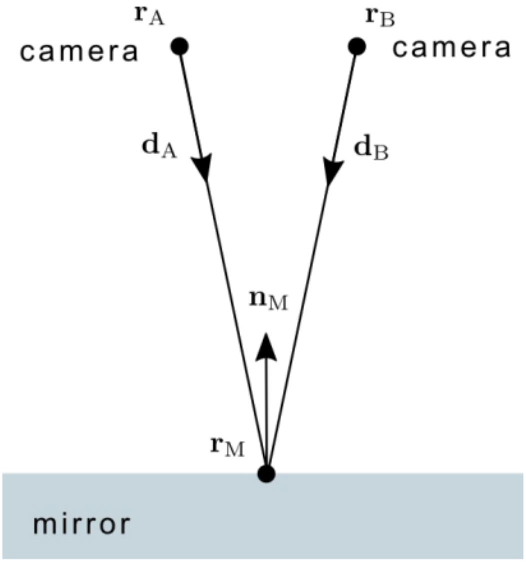
rA = origin of ray
dA, dB = directions of propagation
r = rM = ray end point
tA, tB = distance from origin

  - 3 scalar equations for 2 variables (tA and tB):

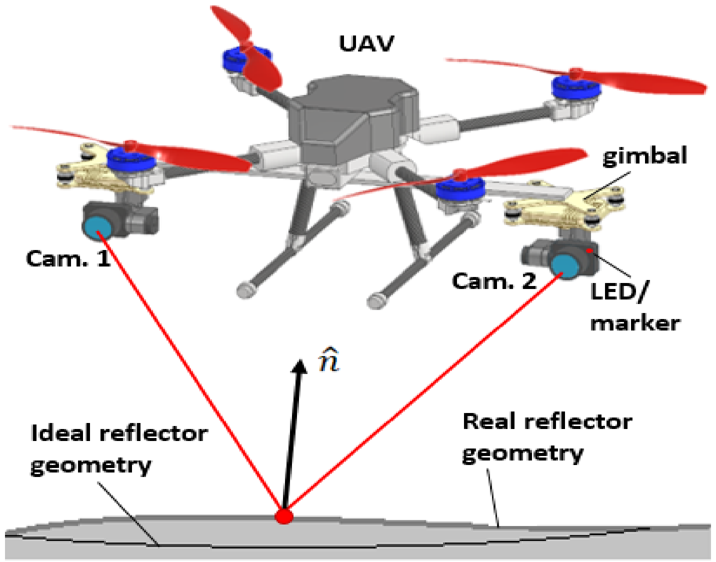
$$t_\mathrm{A}\mathbf{d}_\mathrm{A} - t_\mathrm{B}\mathbf{d}_\mathrm{B} = \mathbf{r}_\mathrm{B} - \mathbf{r}_\mathrm{A}$$

  - 2 equations for 2 variables:

$$\begin{cases} t_\mathrm{A} - (\mathbf{d}_\mathrm{A} \cdot \mathbf{d}_\mathrm{B})\, t_\mathrm{B} = \mathbf{d}_\mathrm{A} \cdot (\mathbf{r}_\mathrm{B} - \mathbf{r}_\mathrm{A}) \\ (\mathbf{d}_\mathrm{A} \cdot \mathbf{d}_\mathrm{B})\, t_\mathrm{A} - t_\mathrm{B} = \mathbf{d}_\mathrm{B} \cdot (\mathbf{r}_\mathrm{B} - \mathbf{r}_\mathrm{A}) \end{cases}$$



Simplified mathematical model of the method



Simplified schematic representation of the pilot system

  - Mirror point vector:

$$\mathbf{r}_\mathrm{M} = \frac{(\mathbf{r}_\mathrm{A} + t_\mathrm{A}\mathbf{d}_\mathrm{A}) + (\mathbf{r}_\mathrm{B} + t_\mathrm{B}\mathbf{d}_\mathrm{B})}{2}$$

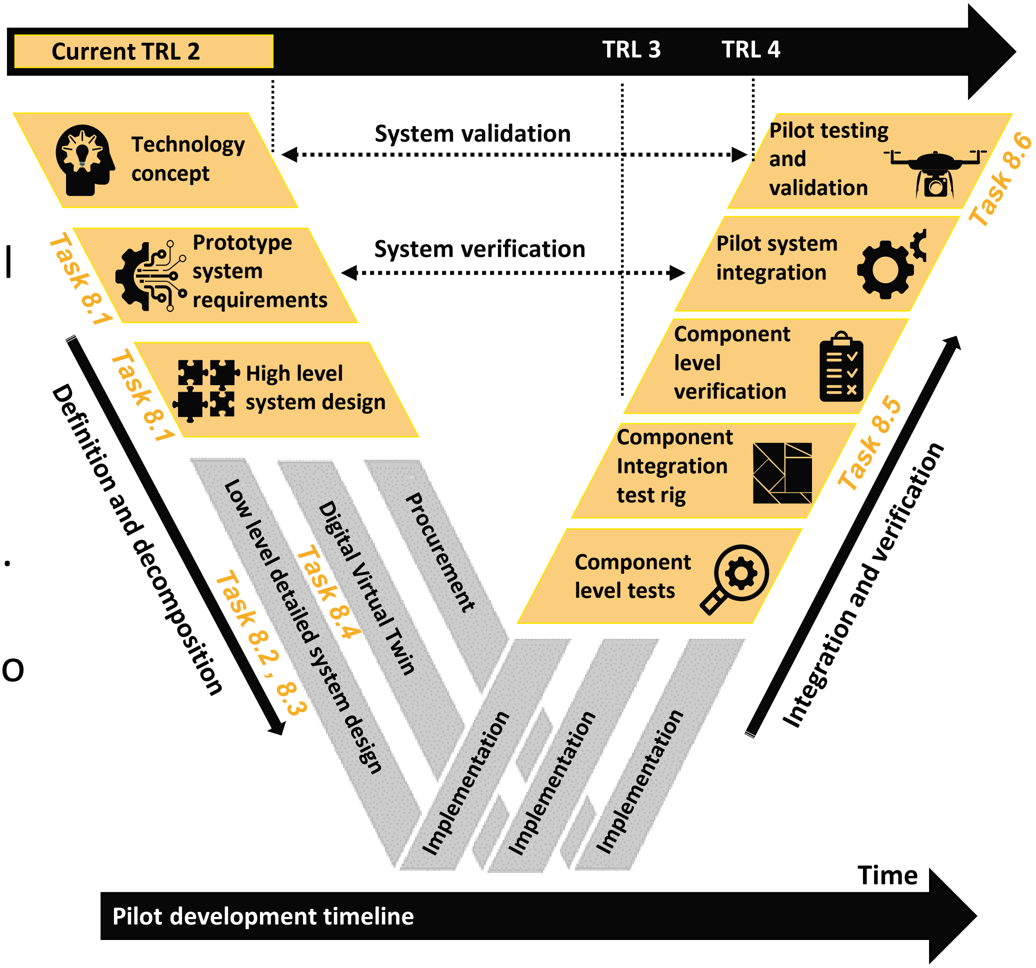
System Engineering of the pilot

- The physical pilot of the system was designed on the basis of a quadcopter (UAV) /drone and through a V-form System Engineering methodology
  - Major design concerns:

i) Efficient payload capacity, integration of RTK technology, dual gimbal platform and control, data transmission, etc.

ii) Suitable of the shelf components were used in developing the UAV pilot (motors, propellers, electronic speed controllers, flight controllers, IMU, batteries, on-board sensors, radio transmitters, etc.

iii) Positioning accuracy is critical: Terrestrial based techniques proven to achieve fine-grained accuracy down to mm-level were explored to assess their potential to achieve the required accuracy

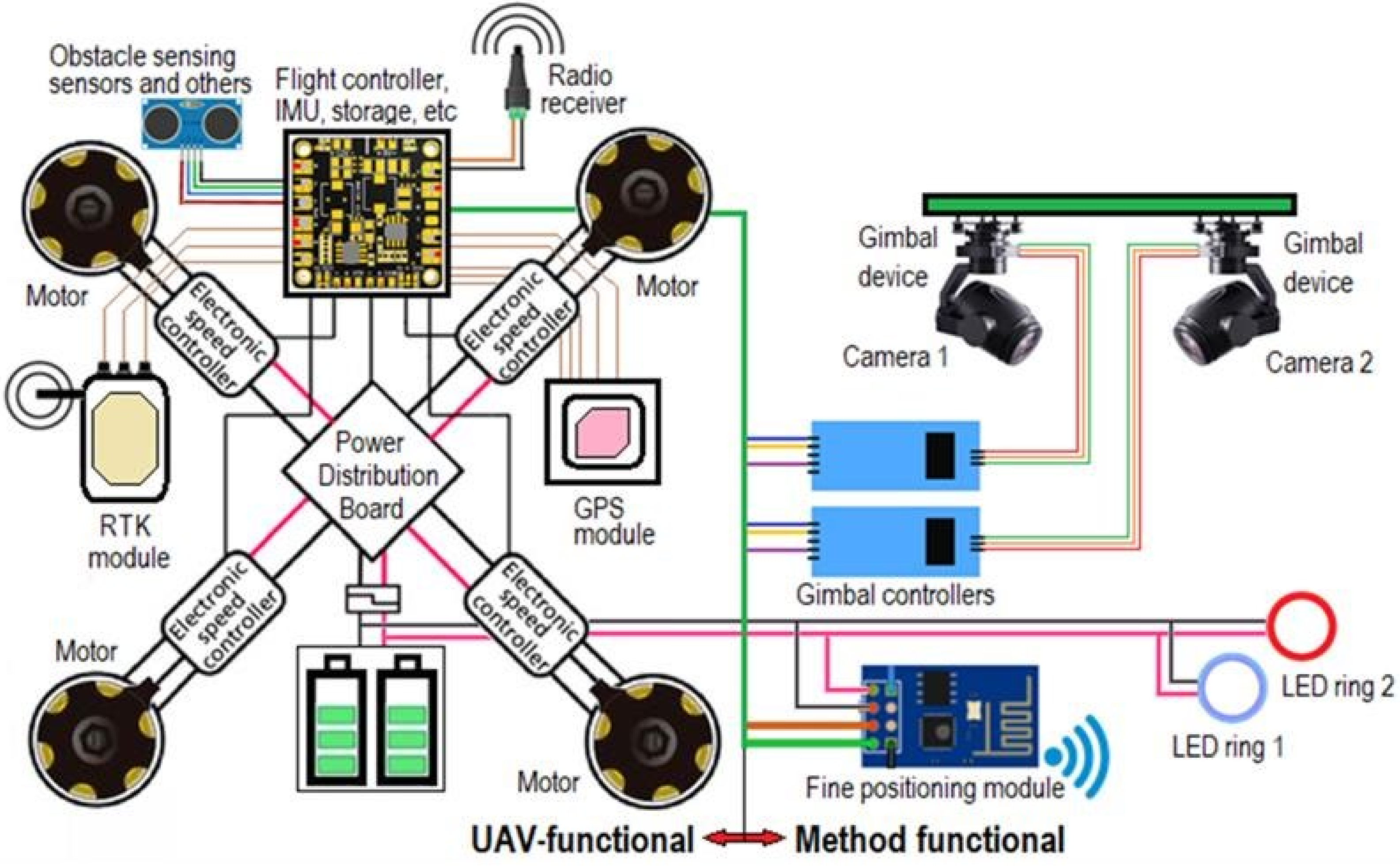


Implementation of the physical pilot system

- Physical pilot of the system is separated into the two major sub-assemblies:

    1. The ***UAV-functional characteristics*** which include all components needed to the operation of the UAV

    2. The ***method-functional characteristics*** that enable the patented characterization method to operate



Implementation of the pilot

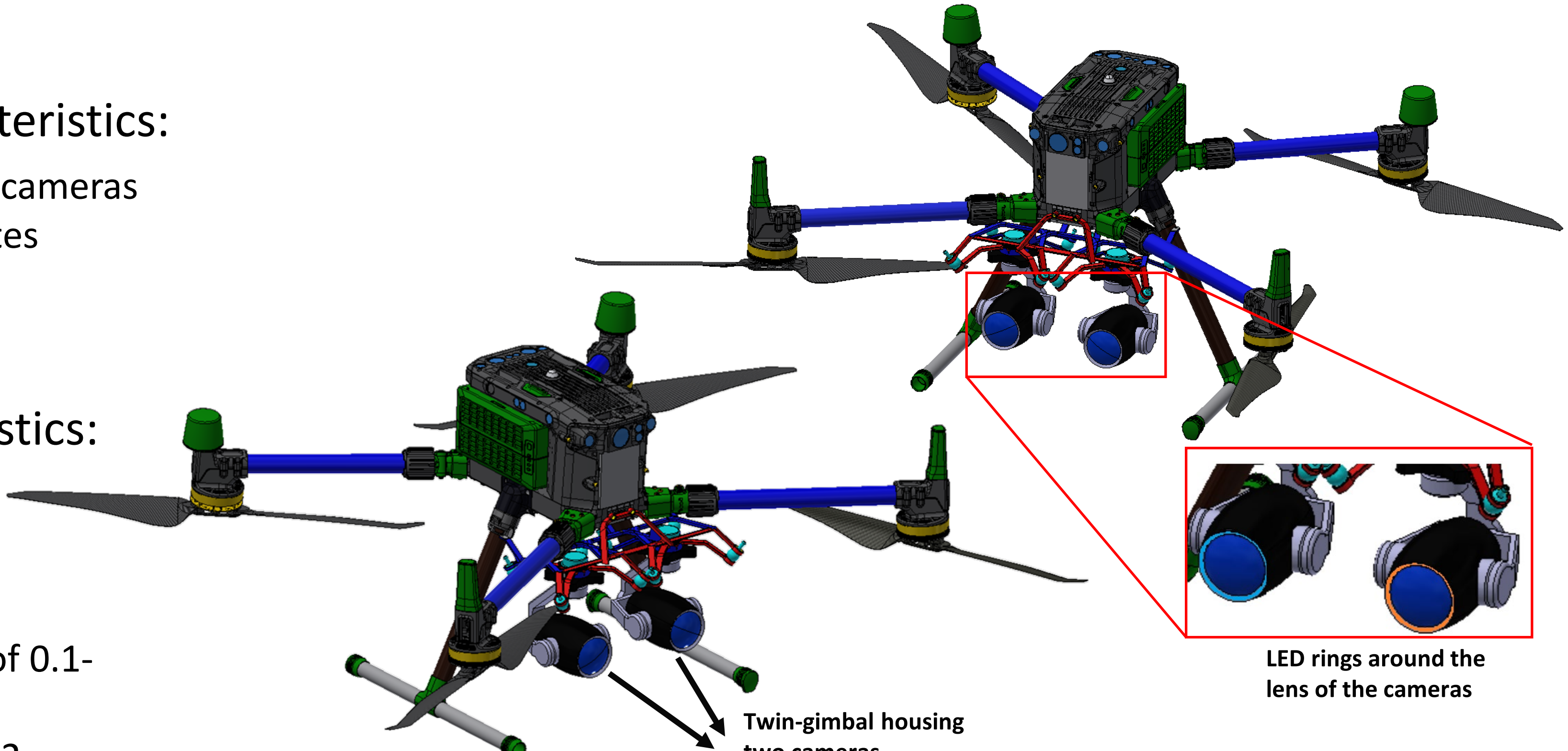
SOLAR X

- Main UAV-functional design characteristics:
  - Twin gimbal for supporting two individual cameras
  - Operational battery time at least 25 minutes
  - Payload capability of at least 1.5kg
  - UAV flight path optimization algorithm
- Main method-functional characteristics:
  - Cameras

i) Best mirror characterization methods determine normals with an accuracy of 0.1-0.2 mrad

ii) It was calculated that to get at least 0.2 mrad with the pilot system, the angular resolution of pixels must be about 0.1 mrad

Zoom: 180X Hybrid Zoom, 30X Optical Zoom
Resolution: 4K Ultra HD
Sensor: 8MP 1/2.7-Inch Sony CMOS, with **FOV:** Diagonal 65.4°, Horizontal 58.1°
Rotation capabilities: 540-Degree Yaw Axis Rotation, roll ±45-degree



Twin-gimbal housing two cameras

LED rings around the lens of the cameras

- Positioning system

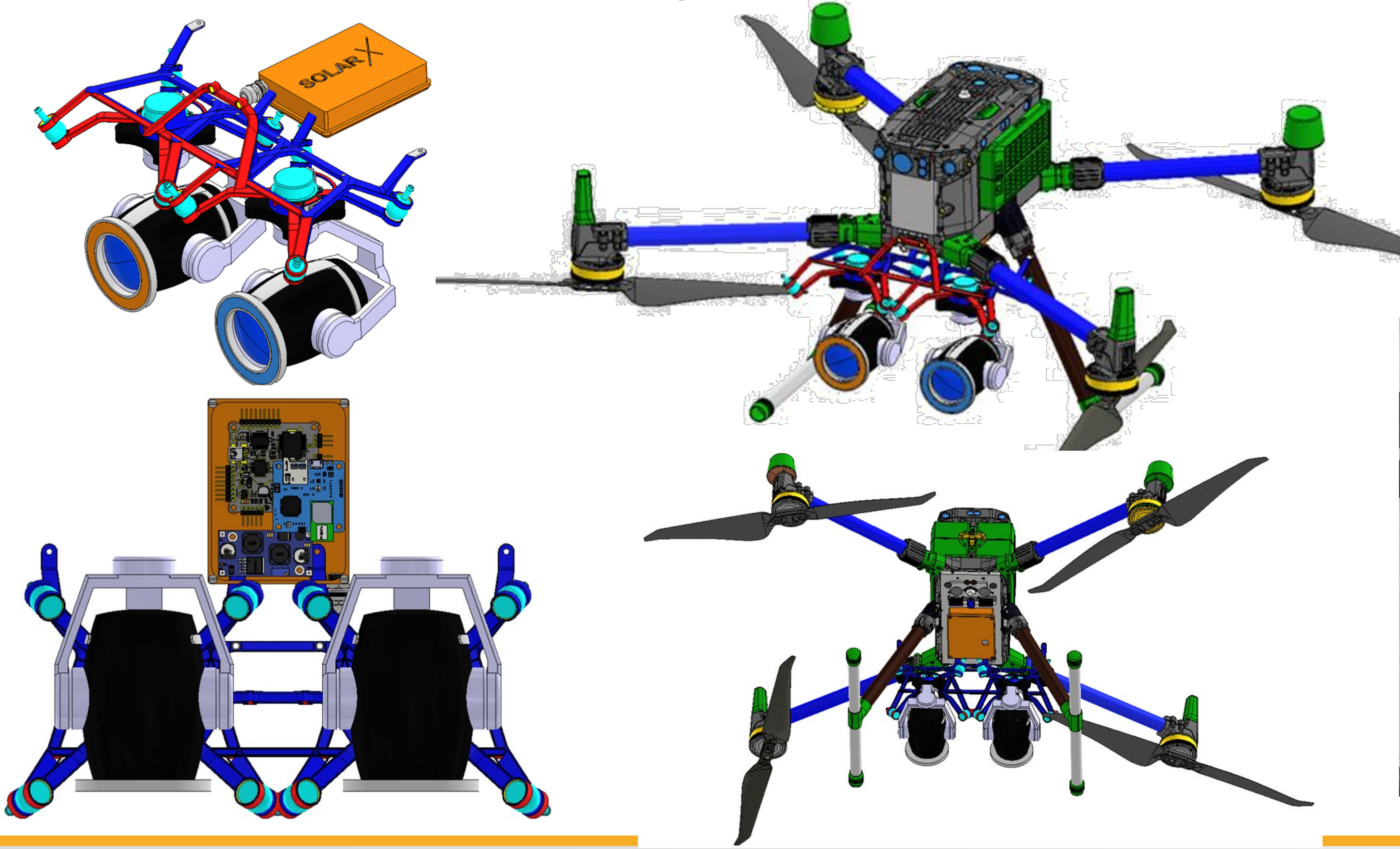
i) Positioning accuracy is critical for the accuracy of the reconstruction of the mirror’s geometry

ii) Fine positioning system developed based on the u-blox ZED-F9P dual band CGNS modules

Implementation of the pilot

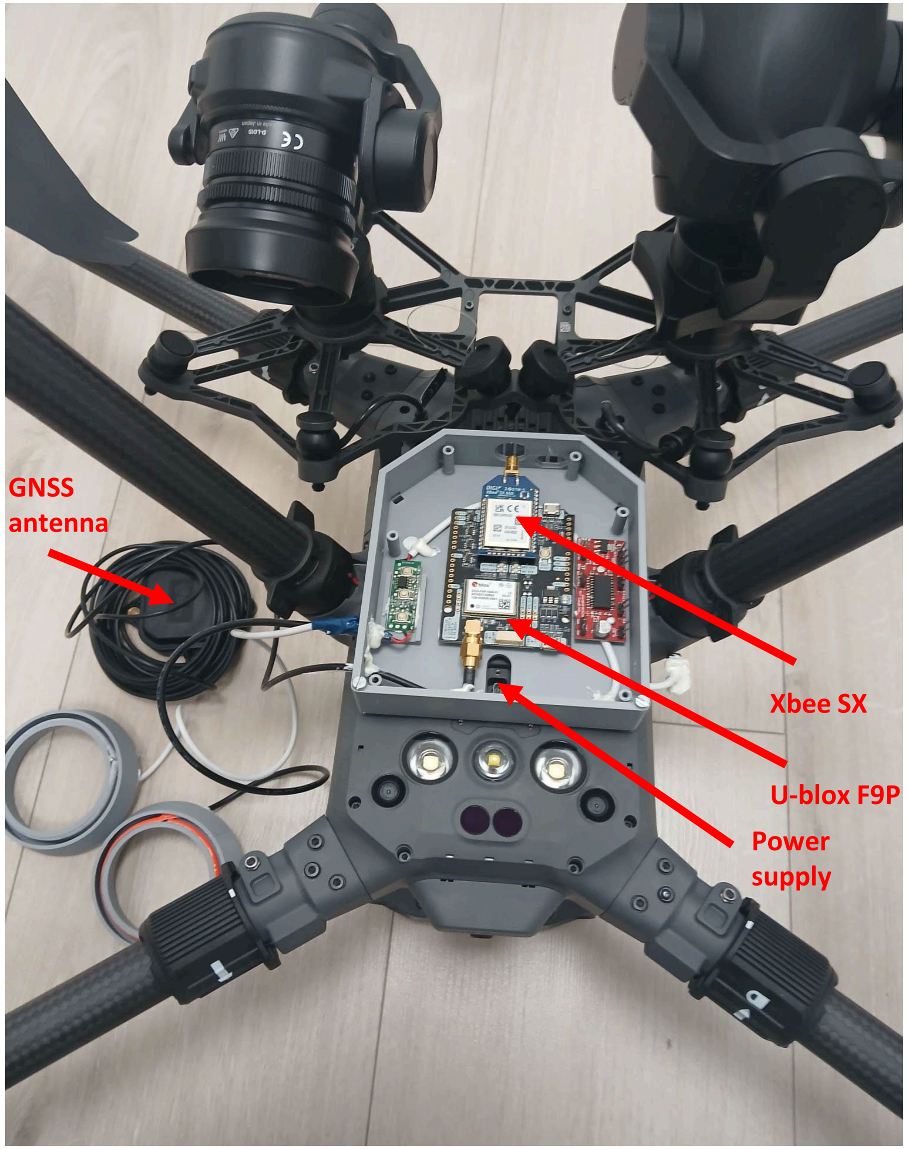
KPI-1.1: Delivery of the first pilot of the system, which will be built around a quadcopter UAV by integrating all necessary components, sensors, and sub-systems required to make it fully operational

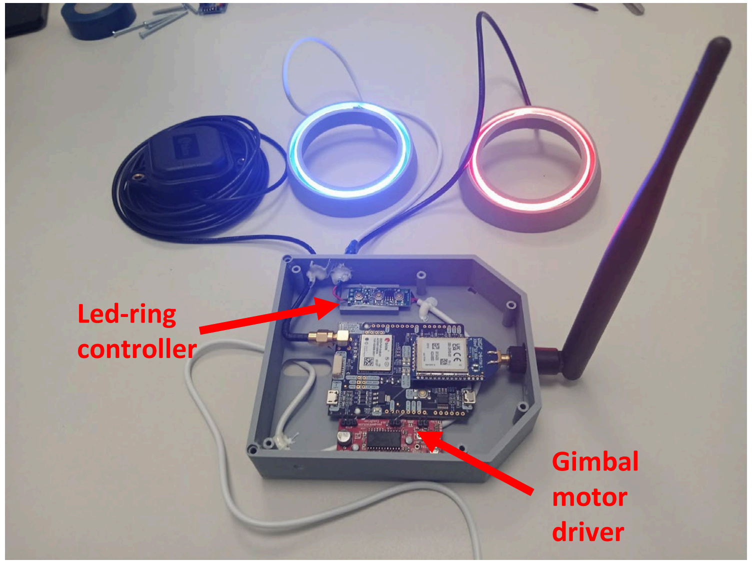
- System pilot completed and ''UAV-functional'' components tested and validated (**M8.1:** Testing and validation of the pilot)
- Currently performing tests on the physical system while running ''co-simulations'' on the digital twin

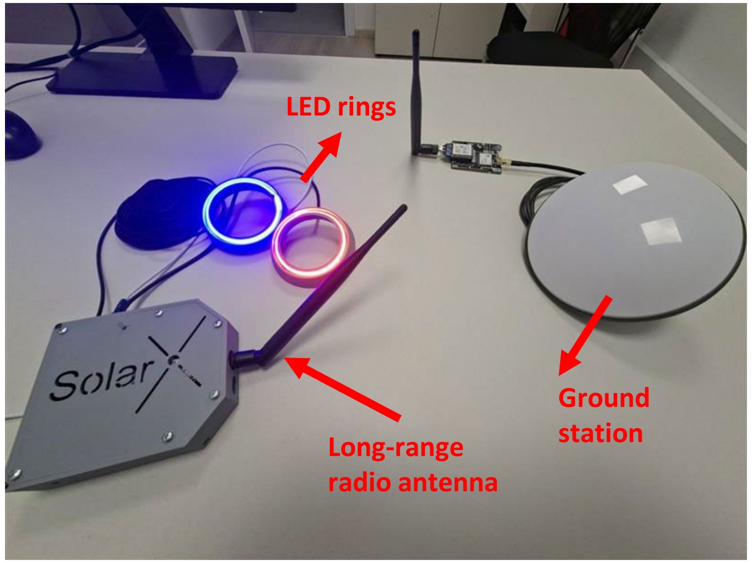


Implementation of the pilot

- Method-functional components developed
- All components tested on the bench before installing on the UAV
- Fine positioning system based on the **u-blox ZED-F9P** (dual band RTK GNSS), the **Digi XBee SX series** long-range radio module and a ground station





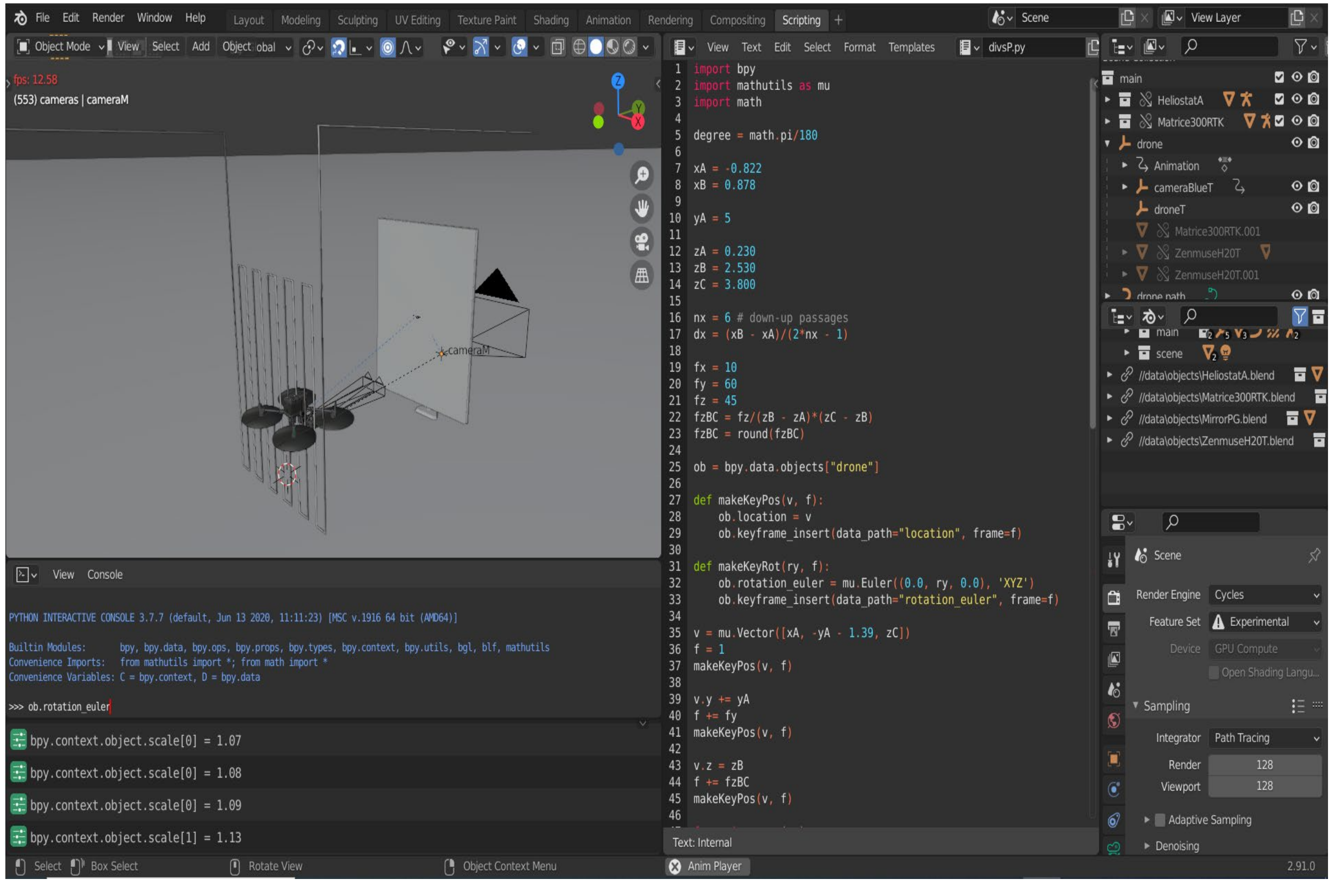


Implementation of the pilot

- Complete system pilot

Digital twin of the pilot

- The development of the system’s digital twin is finalized and validated. Continuous testing in parallel with the testing of the physical system’s pilot is being performed.
  - The digital twin was being built with free open source software
  - It uses a combination of Python programming language, OpenCV (Open Computer Vision) and Blender software, which supports the entirety of the 3D pipeline—modeling, rigging, animation, simulation, rendering, compositing and motion tracking, and video editing.
  - Blender has an API for Python scripting, enabling full customization of the digital twin.
  - After testing and calibrating and the digital twin with using a perturbed parabolic mirror as a test case, this was then applied to real mirror surfaces to fine tune and validate the digital twin model.



```
import bpy
import mathutils as mu
import math

degree = math.pi/180

xA = -0.822
xB = 0.878

yA = 5

zA = 0.230
zB = 2.530
zC = 3.800

nx = 6 # down-up passages
dx = (xB - xA)/(2*nx - 1)

fx = 10
fy = 60
fz = 45
fzBC = fz/(zB - zA)*(zC - zB)
fzBC = round(fzBC)

ob = bpy.data.objects["drone"]

def makeKeyPos(v, f):
    ob.location = v
    ob.keyframe_insert(data_path="location", frame=f)

def makeKeyRot(ry, f):
    ob.rotation_euler = mu.Euler((0.0, ry, 0.0), 'XYZ')
    ob.keyframe_insert(data_path="rotation_euler", frame=f)

v = mu.Vector([xA, -yA - 1.39, zC])
f = 1
makeKeyPos(v, f)

v.y += yA
f += fy
makeKeyPos(v, f)

v.z = zB
f += fzBC
makeKeyPos(v, f)
```

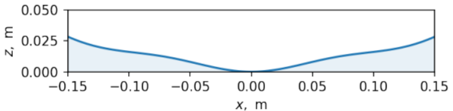
```
PYTHON INTERACTIVE CONSOLE 3.7.7 (default, Jun 13 2020, 11:11:23) [MSC v.1916 64 bit (AMD64)]

Builtin Modules:       bpy, bpy.data, bpy.ops, bpy.props, bpy.types, bpy.context, bpy.utils, bgl, blf, mathutils
Convenience Imports:   from mathutils import *; from math import *
Convenience Variables: C = bpy.context, D = bpy.data

>>> ob.rotation_euler
```

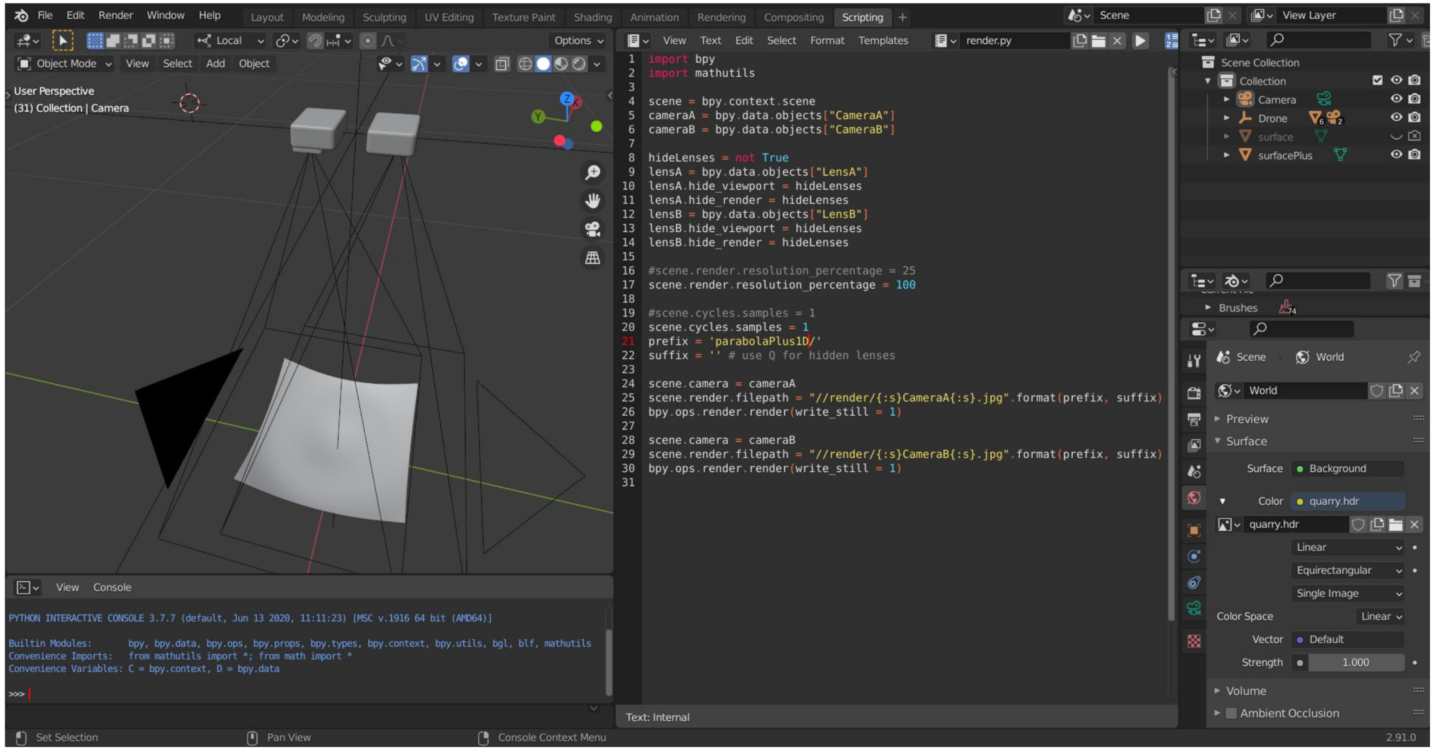
```
bpy.context.object.scale[0] = 1.07
bpy.context.object.scale[0] = 1.08
bpy.context.object.scale[0] = 1.09
bpy.context.object.scale[1] = 1.13
```

Render Engine: Cycles
Feature Set: Experimental
Device: GPU Compute
Open Shading Langu...
Sampling
Integrator: Path Tracing
Render: 128
Viewport: 128
Adaptive Sampling
Denoising

Digital twin of the pilot / Testing and calibration

- The perturbed parabolic mirror serves as a test case / worst case scenario to explore the digital twin’s operational capabilities, limits and accuracy
- The perturbed parabolic mirror surface consists of 3 focusing (concave) and 2 defocusing (convex) parts

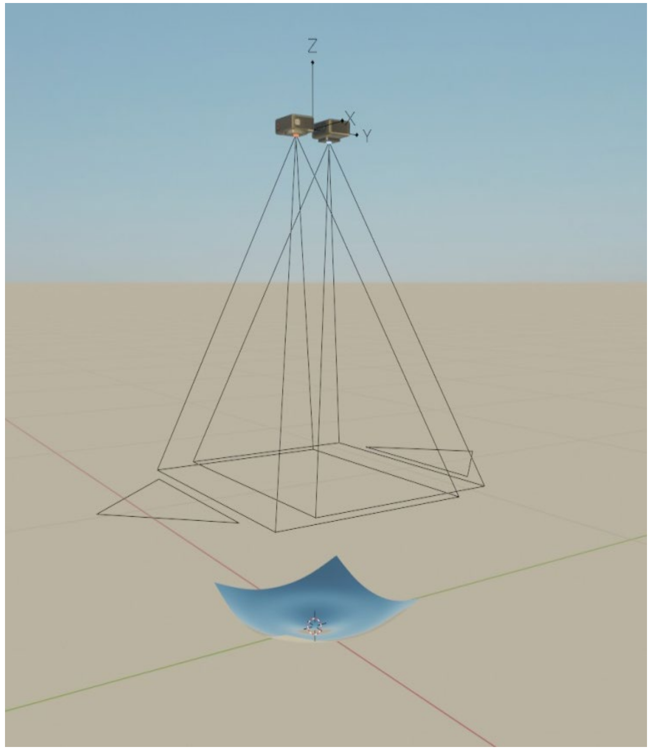


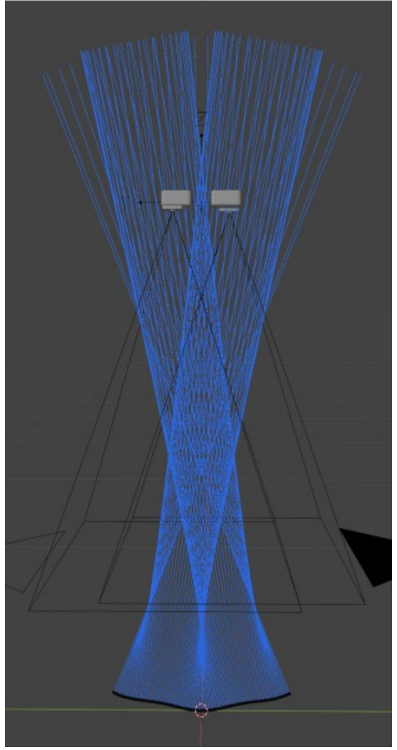


```python
import bpy
import mathutils

scene = bpy.context.scene
cameraA = bpy.data.objects["CameraA"]
cameraB = bpy.data.objects["CameraB"]

hideLenses = not True
lensA = bpy.data.objects["LensA"]
lensA.hide_viewport = hideLenses
lensA.hide_render = hideLenses
lensB = bpy.data.objects["LensB"]
lensB.hide_viewport = hideLenses
lensB.hide_render = hideLenses

#scene.render.resolution_percentage = 25
scene.render.resolution_percentage = 100

#scene.cycles.samples = 1
scene.cycles.samples = 1
prefix = 'parabolaPlus1D/'
suffix = '' # use Q for hidden lenses

scene.camera = cameraA
scene.render.filepath = "//render/{:s}CameraA{:s}.jpg".format(prefix, suffix)
bpy.ops.render.render(write_still = 1)

scene.camera = cameraB
scene.render.filepath = "//render/{:s}CameraB{:s}.jpg".format(prefix, suffix)
bpy.ops.render.render(write_still = 1)
```

```
PYTHON INTERACTIVE CONSOLE 3.7.7 (default, Jun 13 2020, 11:11:23) [MSC v.1916 64 bit (AMD64)]

Builtin Modules:       bpy, bpy.data, bpy.ops, bpy.props, bpy.types, bpy.context, bpy.utils, bgl, blf, mathutils
Convenience Imports:   from mathutils import *; from math import *
Convenience Variables: C = bpy.context, D = bpy.data

>>>
```

Surface: Background
Color: quarry.hdr
quarry.hdr
Linear
Equirectangular
Single Image
Color Space: Linear
Vector: Default
Strength: 1.000



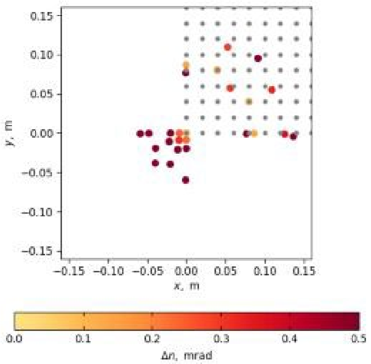


Digital twin of the pilot

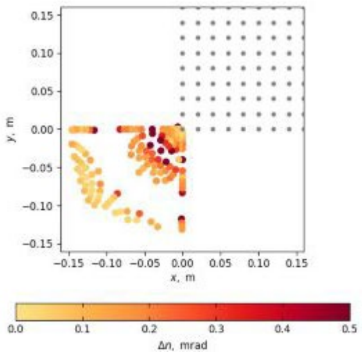
/ Evaluation of key parameters

- Objective: Quantify how each parameter affects angular error in surface-normal reconstruction.
- Methodology: One-factor-at-a-time sweep across 7 parameters, each tested at 4 levels.
- Evaluated Metric: Root-Mean-Square angular error RMS(Δn).

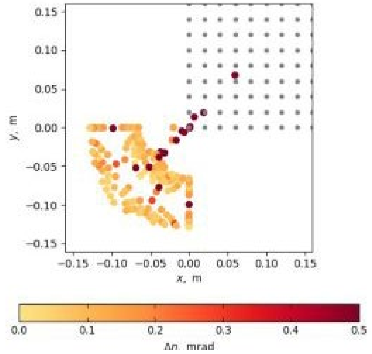
Flight height=0.4m



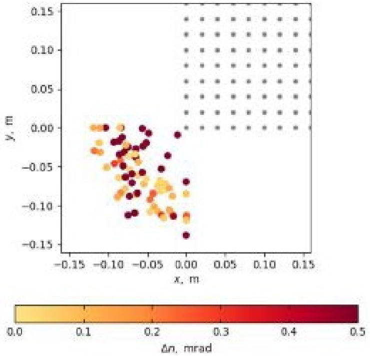
Flight height=0.8m

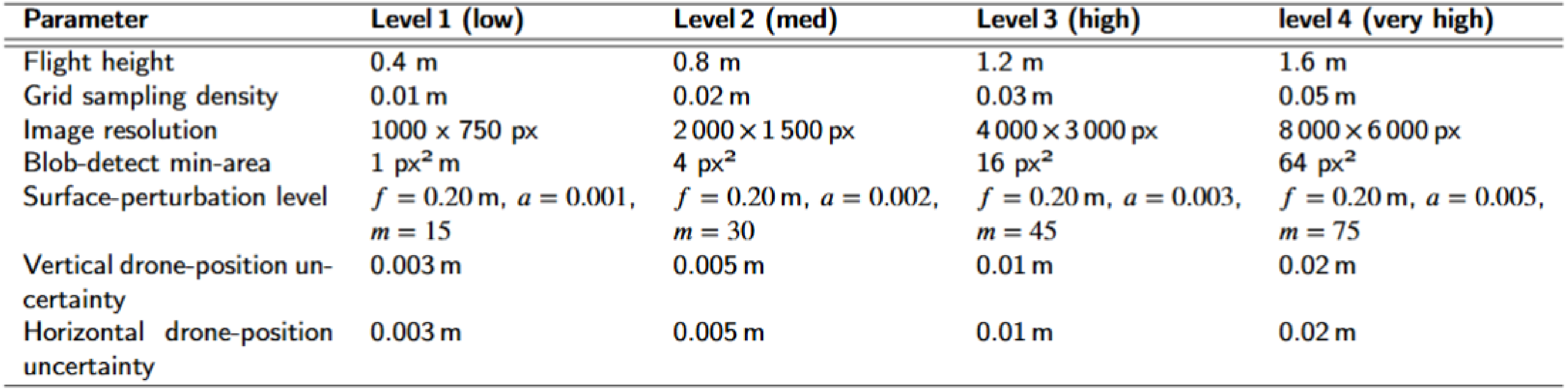


Flight height=1.2m



Flight height=1.6m





Parameter	Level 1 (low)	Level 2 (med)	Level 3 (high)	level 4 (very high)
Flight height	0.4 m	0.8 m	1.2 m	1.6 m
Grid sampling density	0.01 m	0.02 m	0.03 m	0.05 m
Image resolution	1000 × 750 px	2 000 × 1 500 px	4 000 × 3 000 px	8 000 × 6 000 px
Blob-detect min-area	1 px² m	4 px²	16 px²	64 px²
Surface-perturbation level	$f = 0.20\,\mathrm{m}$, $a = 0.001$, $m = 15$	$f = 0.20\,\mathrm{m}$, $a = 0.002$, $m = 30$	$f = 0.20\,\mathrm{m}$, $a = 0.003$, $m = 45$	$f = 0.20\,\mathrm{m}$, $a = 0.005$, $m = 75$
Vertical drone-position uncertainty	0.003 m	0.005 m	0.01 m	0.02 m
Horizontal drone-position uncertainty	0.003 m	0.005 m	0.01 m	0.02 m

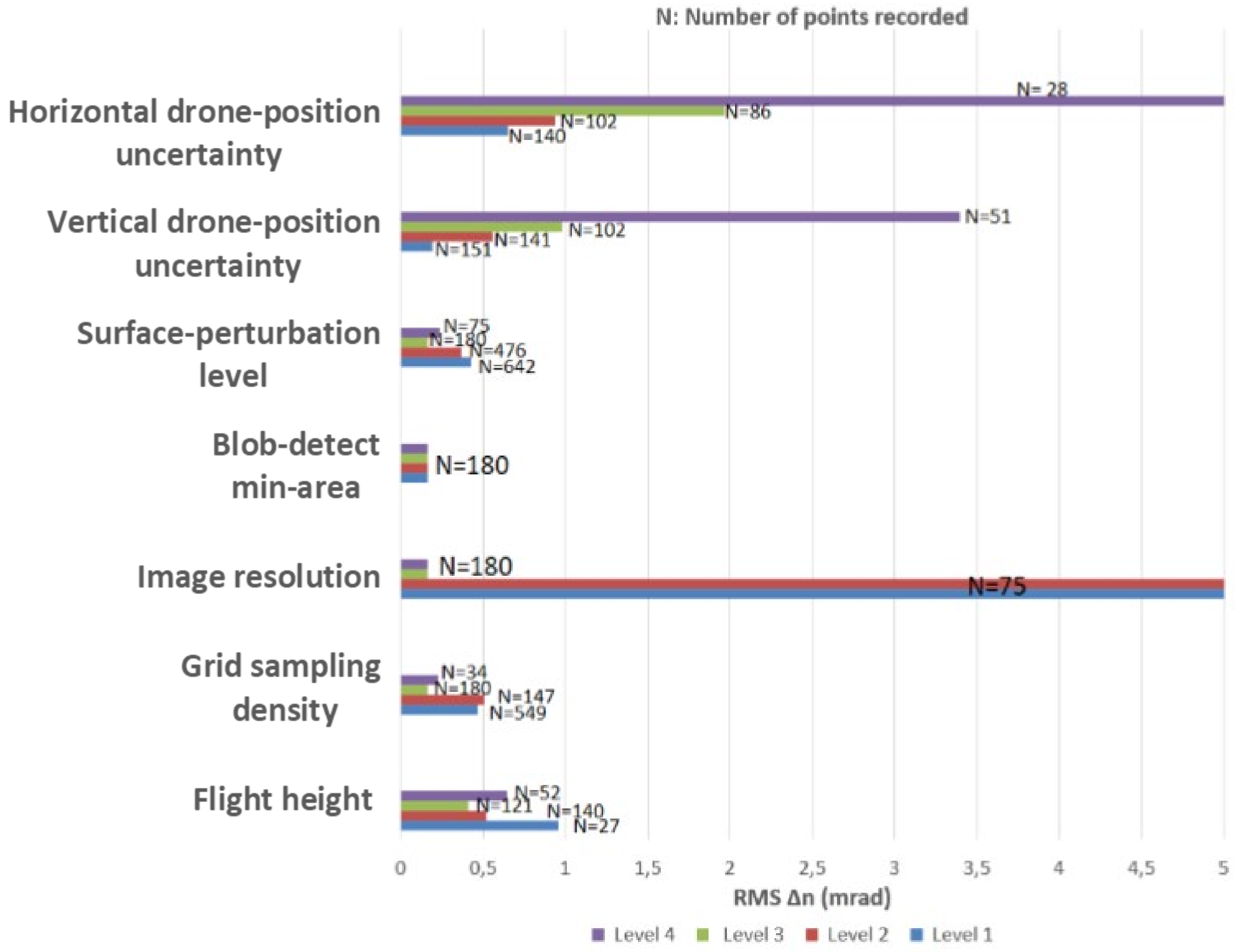
Parameters investigated:

- Flight height
- Grid sampling density
- Image resolution
- Blob-detect min-area
- Surface perturbation level
- Vertical drone-position uncertainty
- Horizontal drone-position uncertainty

Digital twin of the pilot

/ Evaluation of key parameters

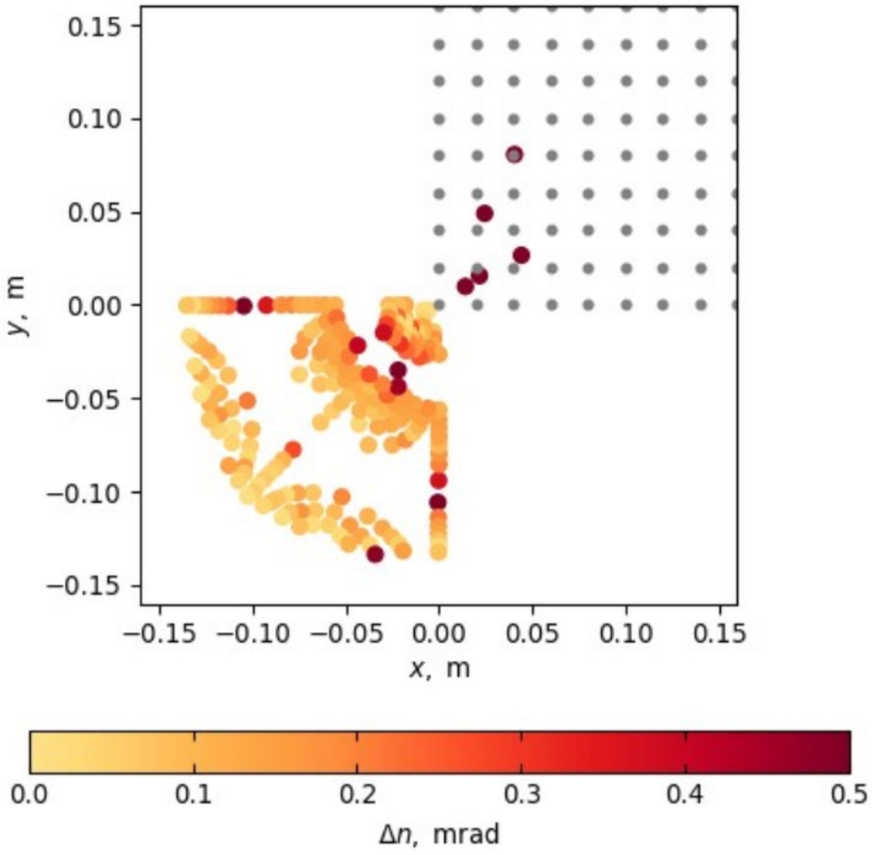
- Flight height: Optimal at medium altitudes (0.8-1.2m above mirror)
- Grid density: Best trade-off at 0.02-0.03m
- Image resolution: Strong threshold – high resolution (>4k) crucial (decrease the error to 0.16 mrad)
- Blob-detection threshold: Minimal influence
- Surface perturbation: Mild-moderate ok; strong ripples increase the error
- Drone-position uncertainty: Most critical – large shifts cause error >3-5 mrad and data loss



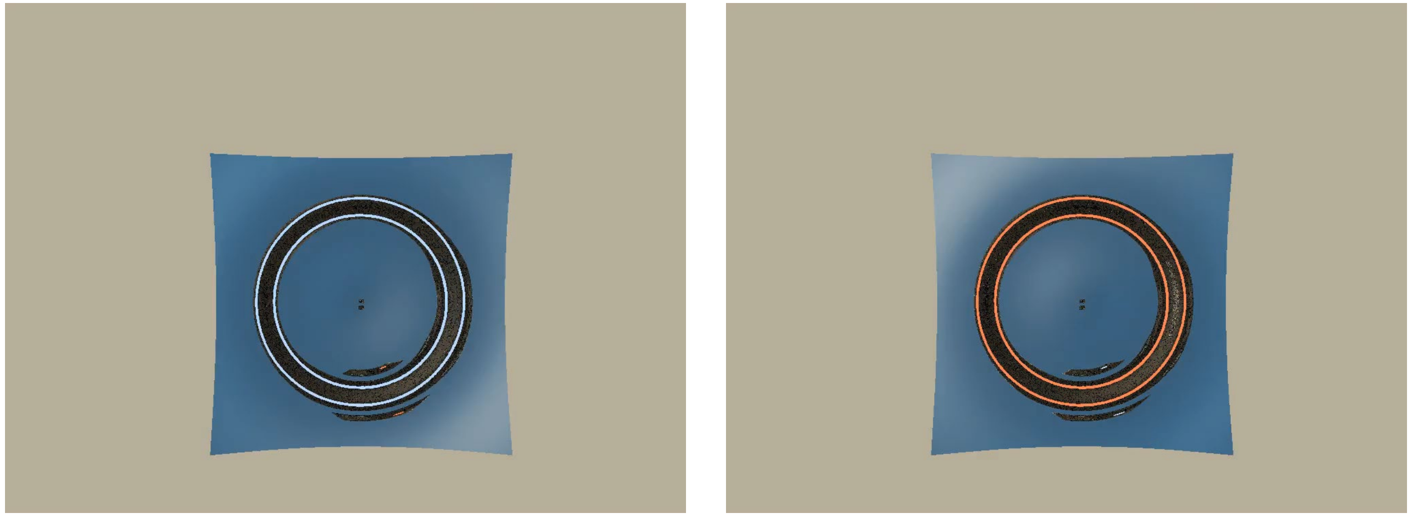
Digital twin of the pilot

/ Evaluation of key parameters

- Surface characterization of perturbed parabola:



Accuracy of reconstructed normals (z = flight height = 1 m).

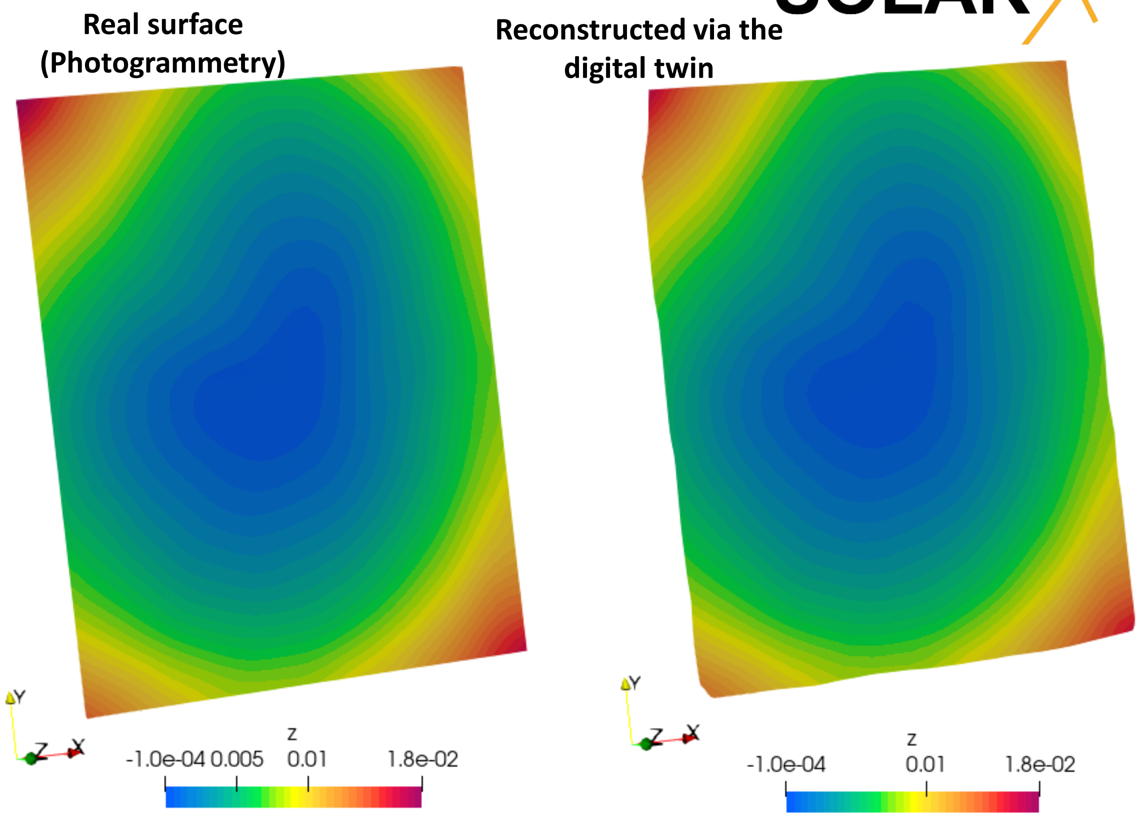


- Gray points correspond to drone positions
- Colored points show the calculated accuracy of the reconstructed normals
- Possible to achieve 0.1 mrad in the absence of position and rotation errors
- Accuracy is dominated by image resolution, surface perturbation, and positional uncertainty.
- Other parameters (grid density, flight height) need balancing for efficiency vs accuracy.

Digital twin of the pilot

/ Validation through real data

- Objective: Benchmark the performance of the digital twin to reconstruct the geometry of a real heliostat geometry
- Rectangular CSIRO heliostat mirror (2440×1850 mm). Its exact geometry was reconstructed through close-range photogrammetry



Real surface (Photogrammetry)

Reconstructed via the digital twin

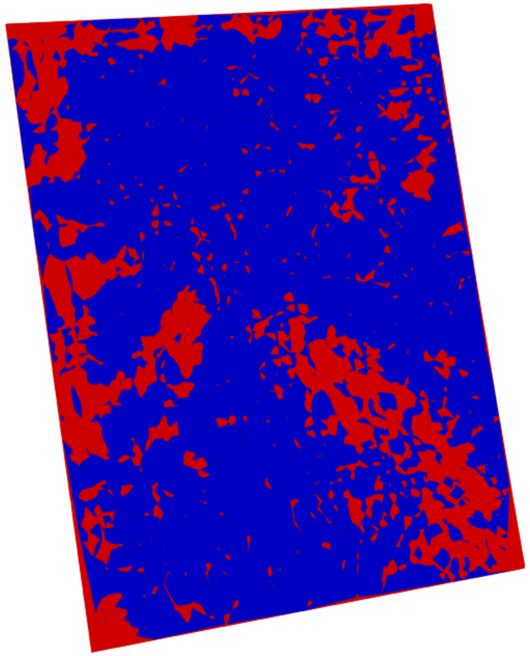
Next steps:

- Preliminary results show good agreement, but we are now focusing on fine tuning the digital twin parameters to get enhanced results
- Testing the effect of the positioning accuracy and other operating parameters

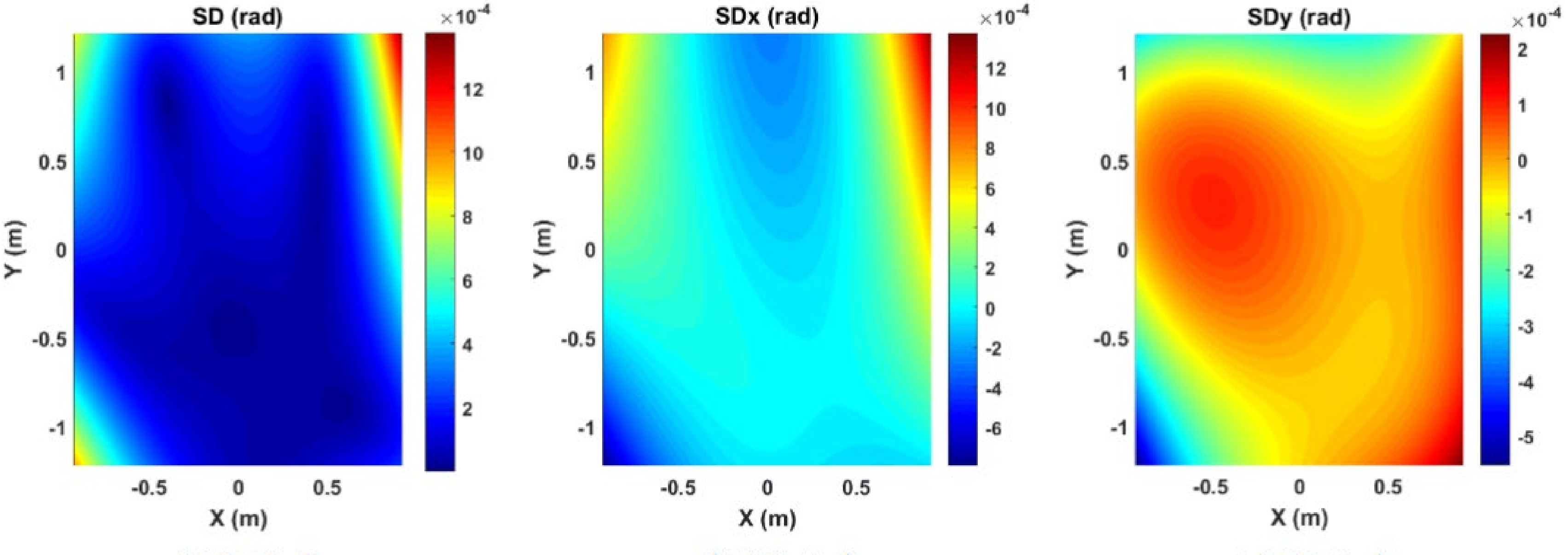
Digital twin of the pilot

/ Validation through real data

- **Comparison Metric:** Slope Deviation (SD, SDx, SDy).



Superposition of the two mirror surfaces (red: real surface, blue: digital twin reconstruction)



(a) SD (rad)   (b) SD_x (rad)   (c) SD_y (rad)

- The slope deviation errors of the reconstructed surface are very small, slightly higher close to mirror edges (in absense of any gimbal inclination and drone positioning)

On-going work

- Testing the physical pilot in parallel with the digital twin of the system at PROTEAS solar tower heliostat field.
  - Evaluate the accuracy of the system in the presence of real uncertainties, including the UAV’s positioning errors
  - Evaluate the overall time of reconstructing a complete heliostat mirror in real conditions

Time: While the physical data collection, e.g. capturing images at predetermined grid points at a predetermined flight path is a rather fast procedure, processing the images to get the normal is a rather time consuming procedure

Contact

Kypros Milidonis
The Cyprus Institute
k.milidonis@cyi.ac.cy

SOLARX

Dispatchable concentrated Solar-to-X energy solution for high penetration of renewable energy

www.solarx-project.eu

Funded by
the European Union

Funded by the European Union under the Horizon Europe Framework Programme (Project name: SOLARX; grant number: 101084158). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them. The project is also supported by the Swiss State Secretariat for Education, Research and Innovation (SERI).