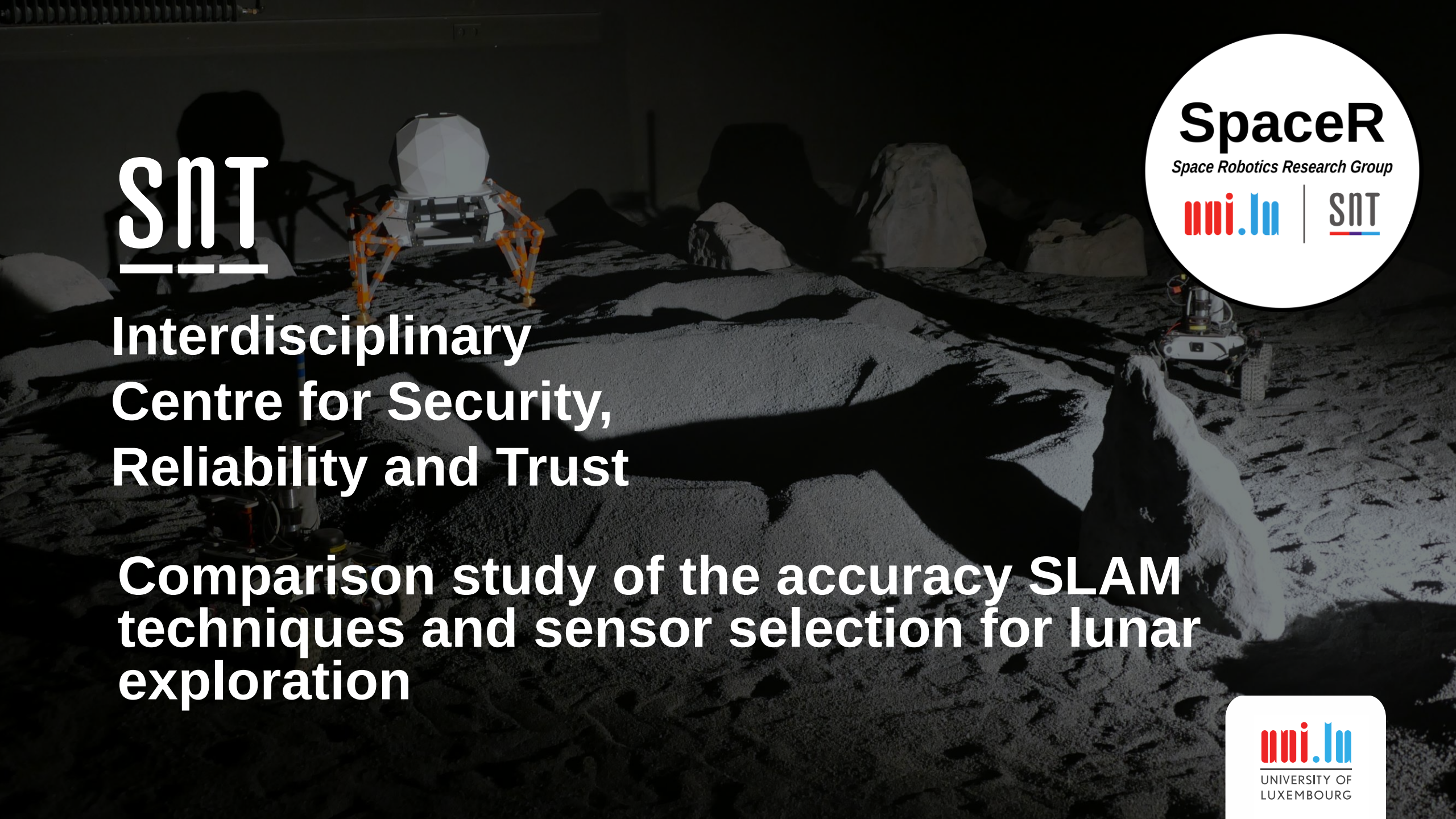

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Interdisciplinary Centre for Security, Reliability and Trust

SpaceR
Space Robotics Research Group
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Comparison study of the accuracy SLAM techniques and sensor selection for lunar exploration

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UNIVERSITY OF LUXEMBOURG

Agenda

1. Introduction
2. Methods and Materials
3. Experiments
4. Results
5. Conclusion

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1. Introduction

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UNIVERSITY OF LUXEMBOURG

Lunar robotics mission

- Lunar robotic missions relied on teleoperation
- Need for human operators during entire mission lifetime
- Labour and cost intensive

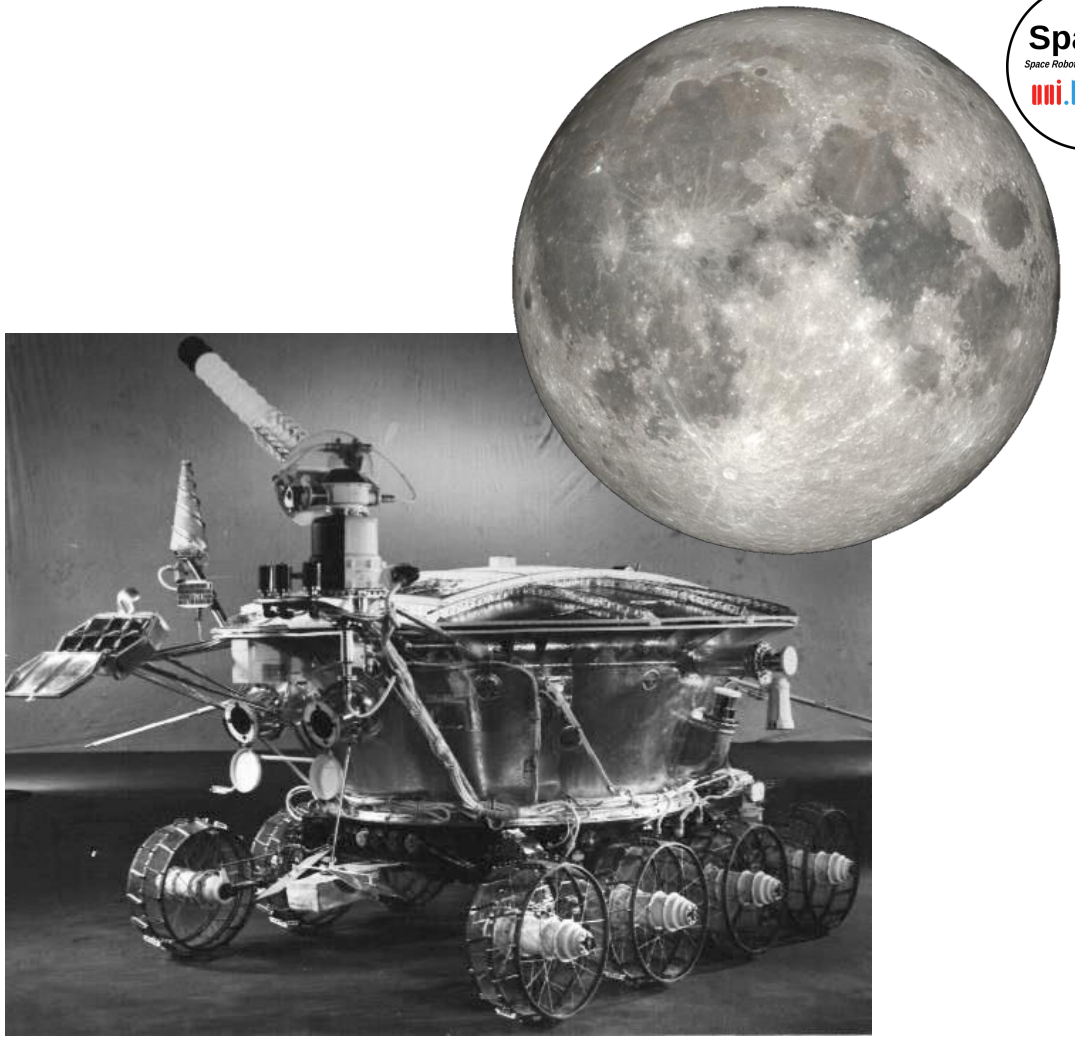

Figure 1 – Lunokhod rover

Source:
Space.com Lunokhod 1 https://www.space.com/35090-lunokhod-1.html
NASA Moon https://www.nasa.gov/image-feature/goddard/2021/nasa-gazes-at-the-strawberry-moon

Autonomous planetary robotics mission

- Mars Exploration Rovers use visual odometry
- Mars rovers have about 2.5% position error and 3° angular error

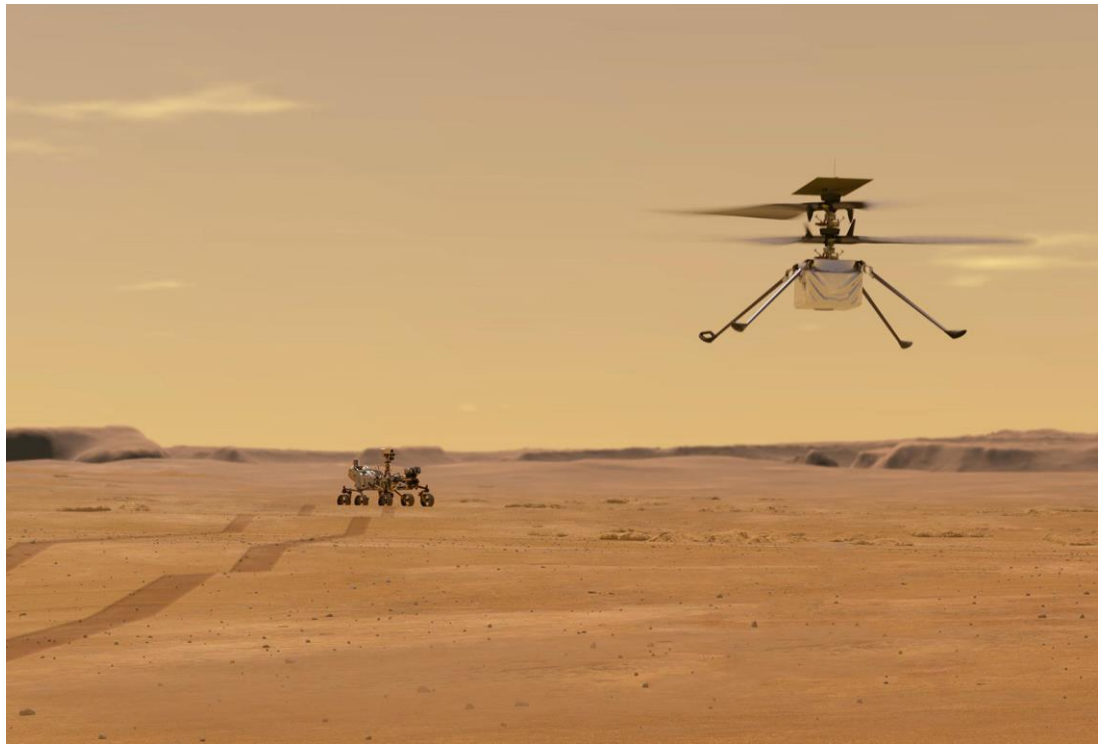

Figure 2 – Illustration of Perseverance rover and helicopter

Source:
NASA Perseverance and helicopter on Mars: https://www.nasa.gov/image-feature/jpl/helicopter-above-perseverance-on-mars

Source:
Yang Cheng, M. W. Maimone, and L. Matthies. Visual odometry on the mars exploration rovers – a tool to ensure accurate driving and science imaging. IEEE Robotics Automation Magazine, 13(2):54–62, 2006.

Challenges of Visual SLAM

- Lighting conditions
- Feature-poor environments
- Large scale environments

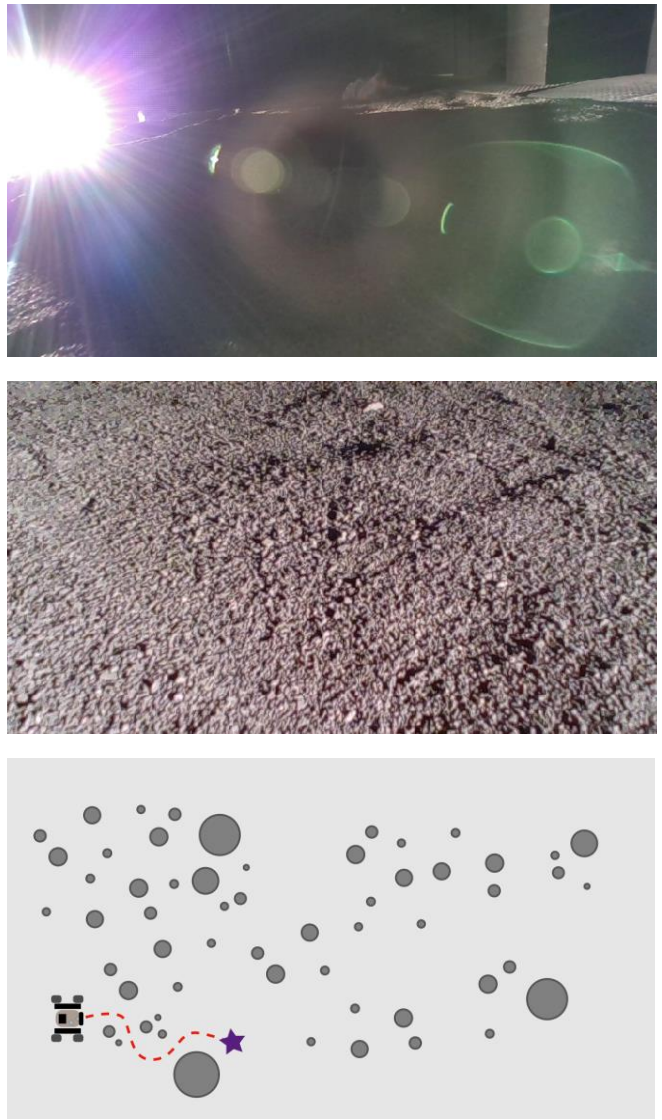

Figure 3 – Lens flares, feature poor environment and large scale environments

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2. Methods and Materials

LunaLab at University of Luxembourg

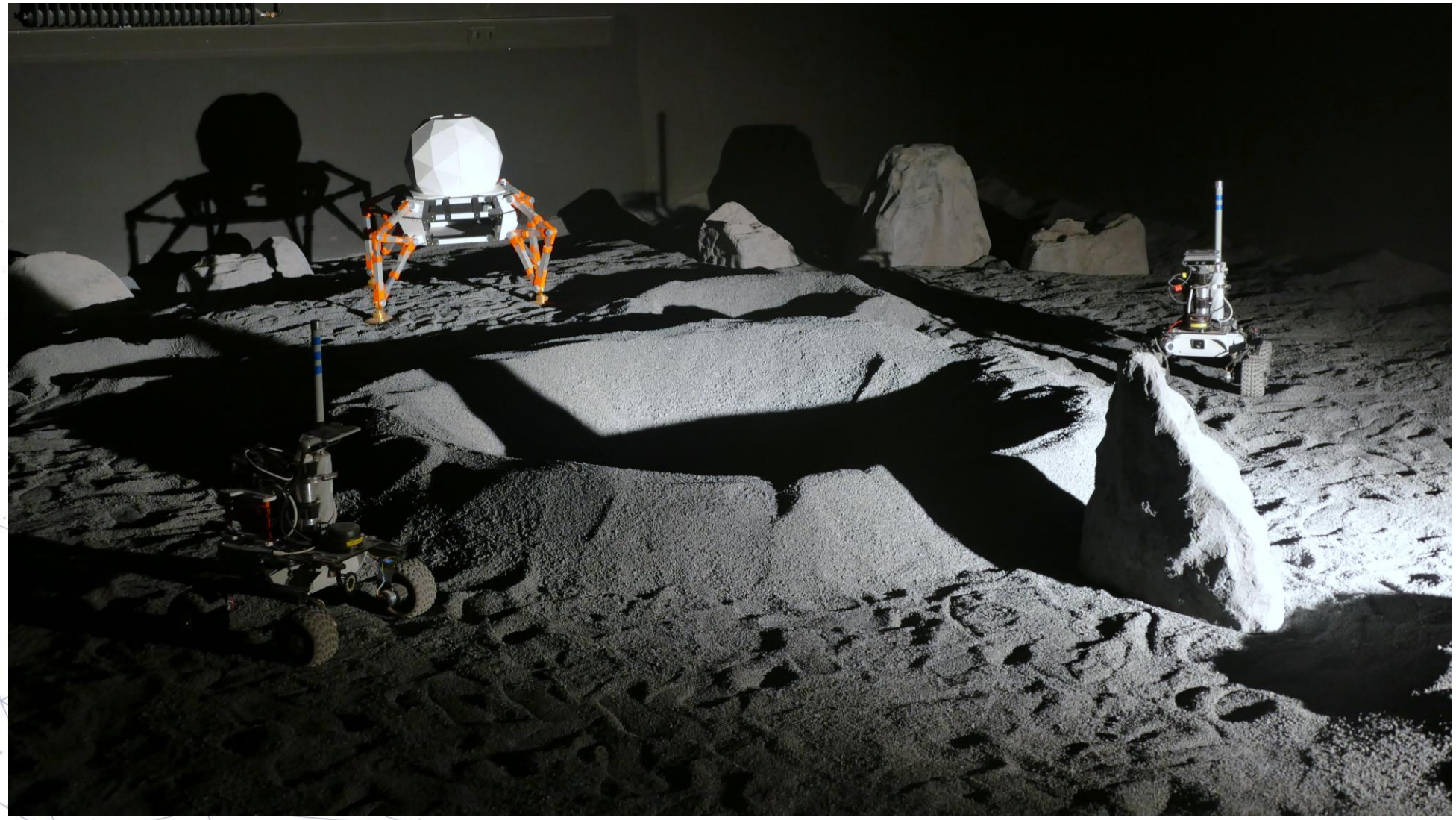

Figure 4 – LunaLab at University of Luxembourg

LunaLab at University of Luxembourg

Figure 5 – Light blocking curtains

Figure 6 – Artificial rocks

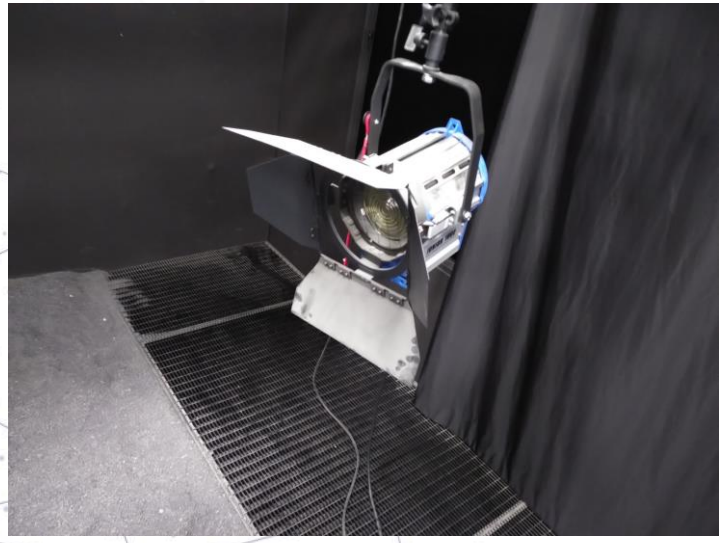

Figure 7 – Tungsten spot light

Figure 8 – Shadows in the LunaLab

Ground Truth

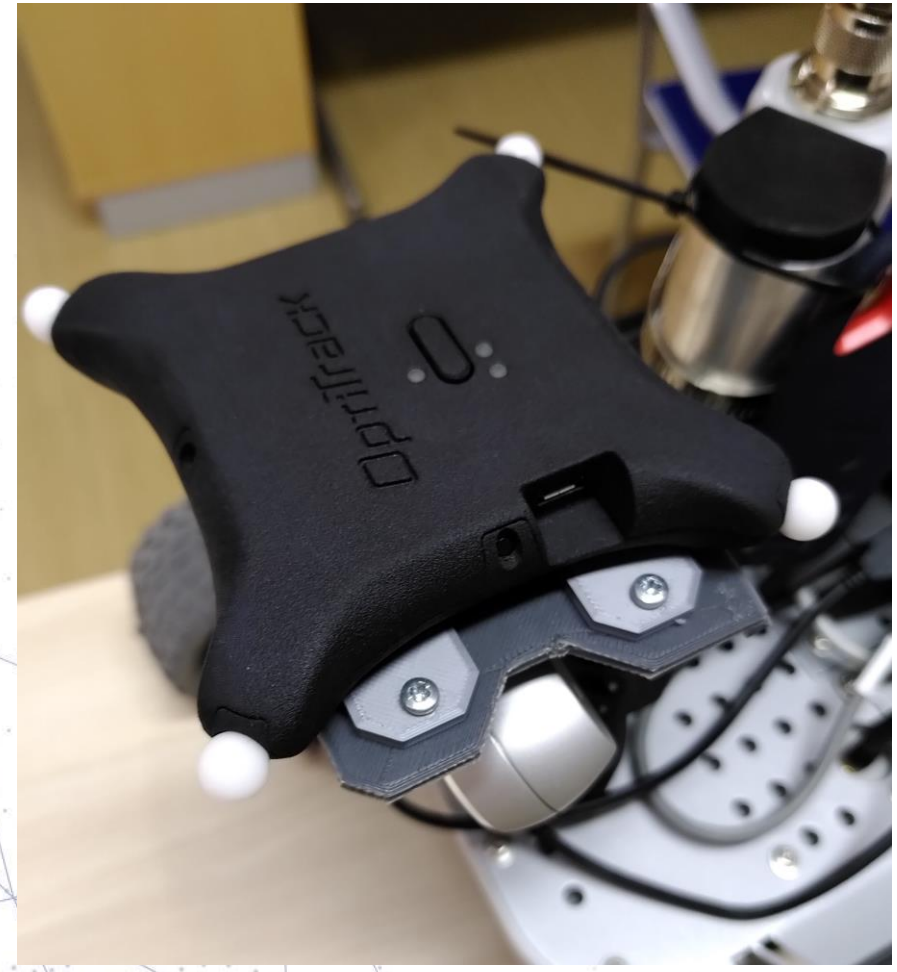

Figure 9 – OptiTrack active marker

Figure 10 – OptiTrack camera

Robotic Platform

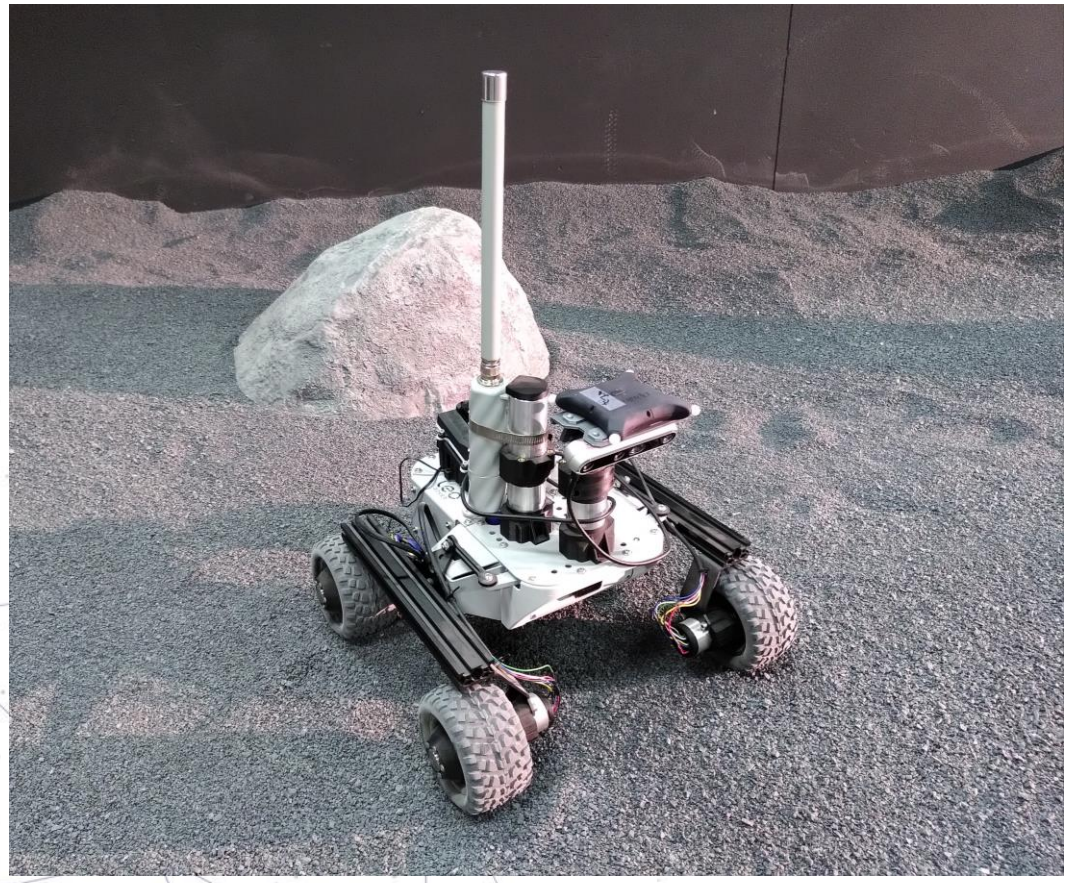

Figure 11 – Photograph of Leo Rover

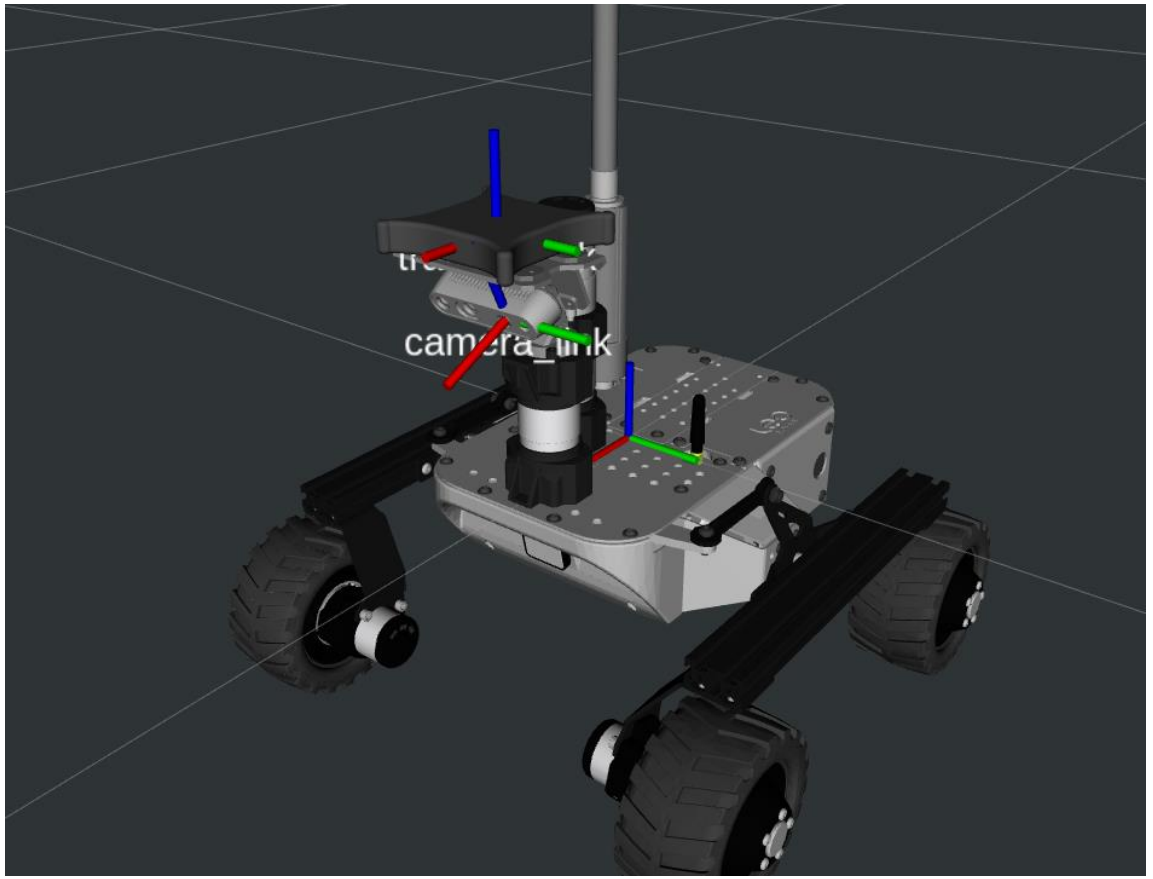

Figure 12 – URDF of Leo Rover

Stereo and Depth Cameras

Figure 13 – ZED 2 camera, RealSense D455, RealSense D435

Visual SLAM Algorithms

RTAB-Map

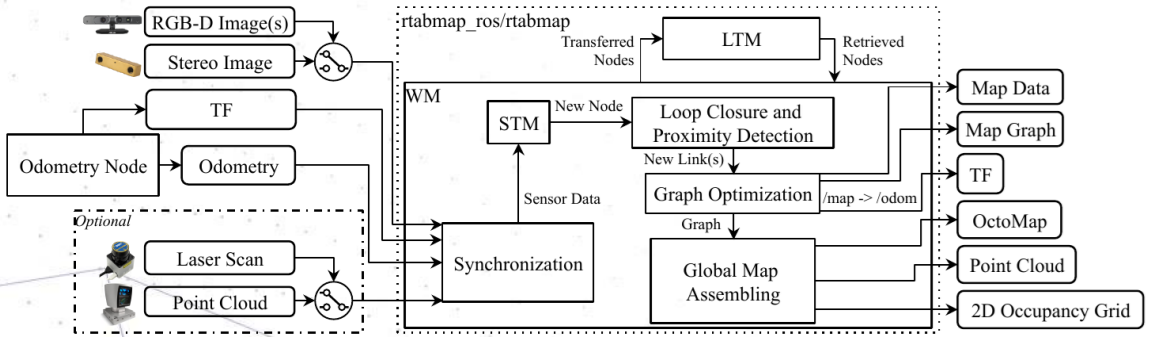

Figure 14 - Software diagram of RTAB-Map

ORB-SLAM2

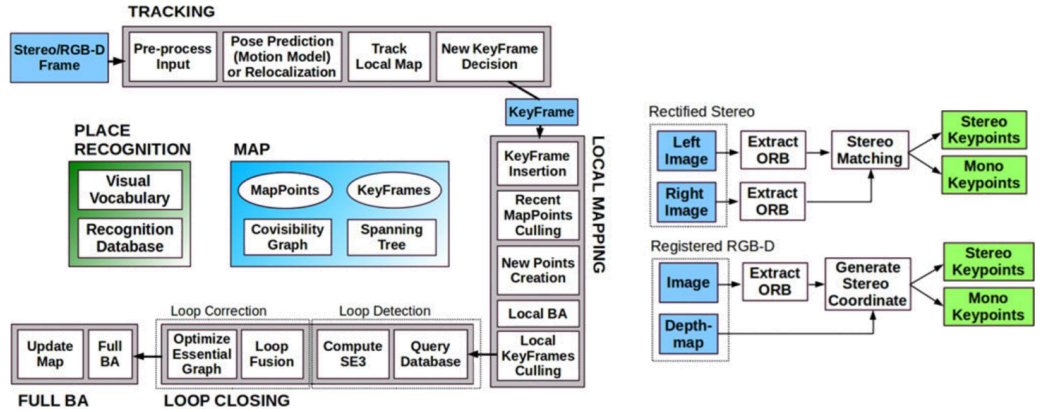

Figure 15 - Software diagram of ORB-SLAM2

Source:

Mathieu Labbe and Francois Michaud. “RTAB-Map as an open-source lidar and visual simultaneous localization and mapping library for large-scale and long-term online operation”. (2019)

Raúl Mur-Artal and Juan D. Tardós. “ORB-SLAM2: An Open-Source SLAM System for Monocular, Stereo, and RGB-D Cameras” (Oct. 2017)

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3. Experiments

Robot Trajectory

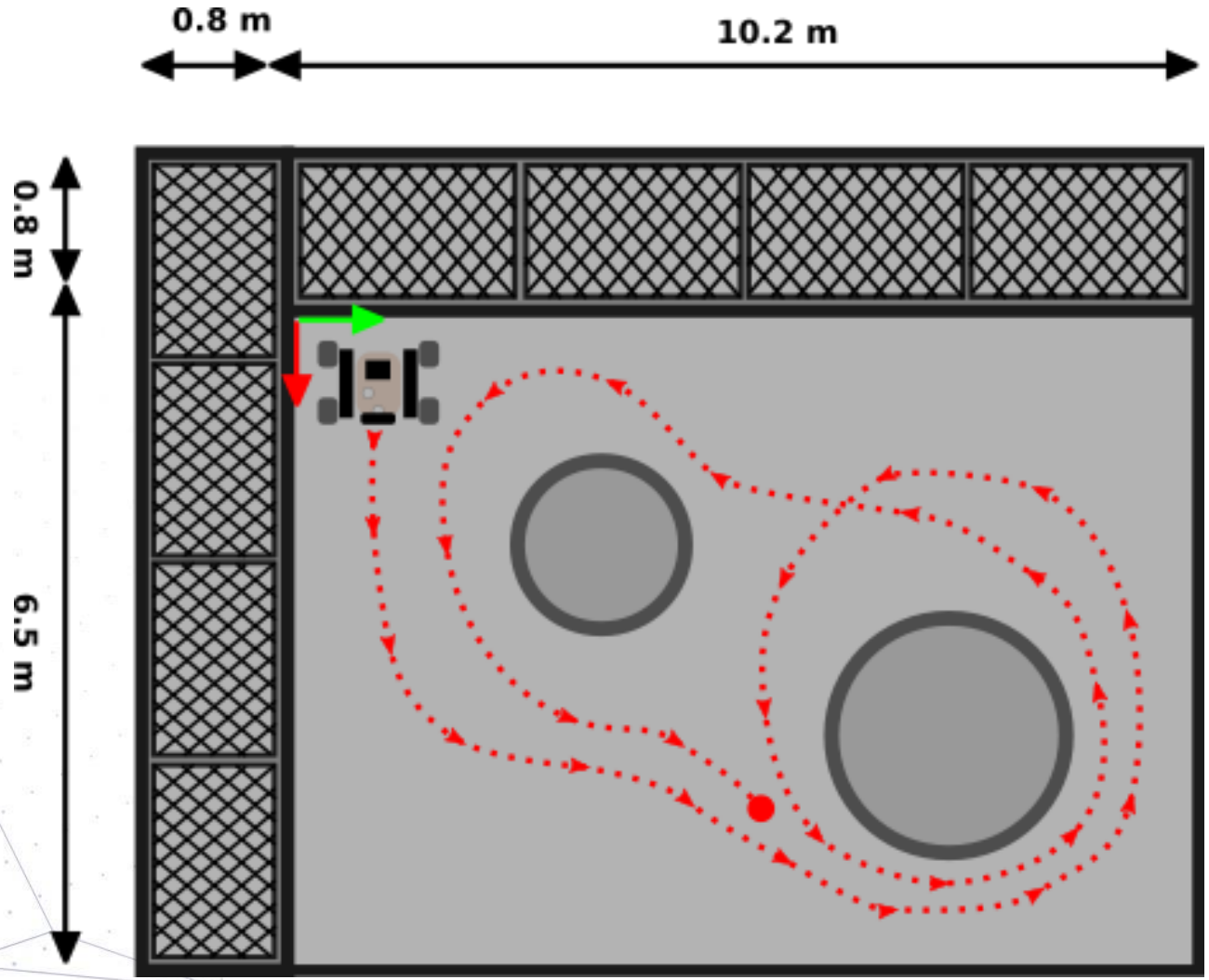

Figure 16 – Schematic of the robot trajectory during experiments

Different Surface Configurations

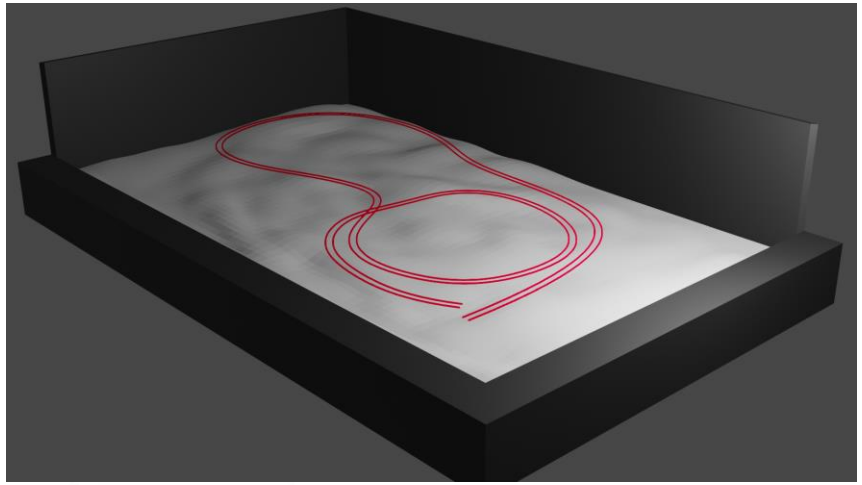

Figure 17 – Schematic of surface layout: Flat

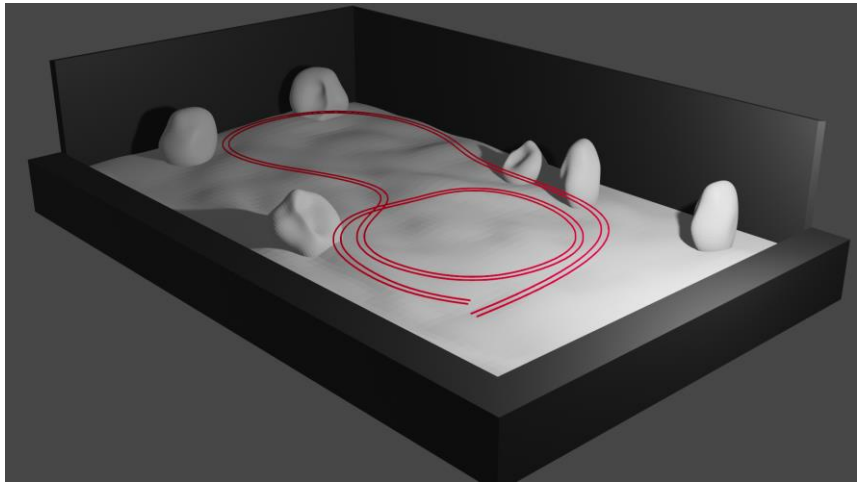

Figure 18 – Schematic of surface layout: Rocks

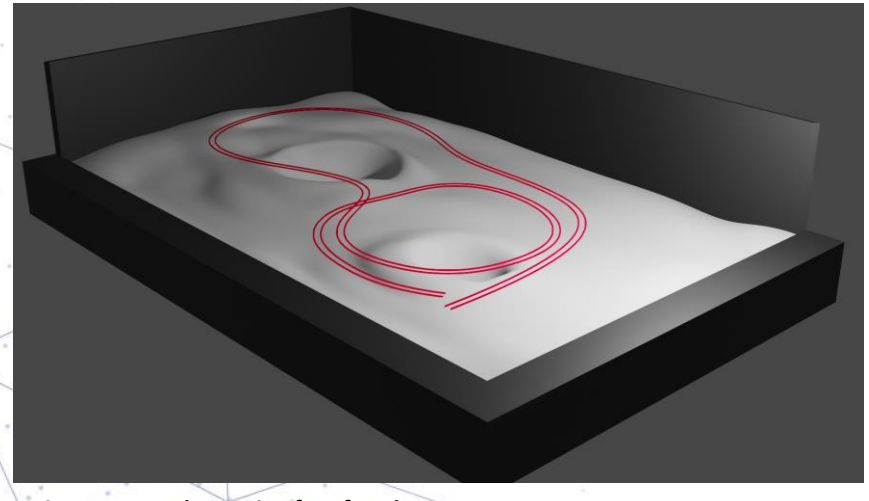

Figure 19 – Schematic of surface layout: Craters

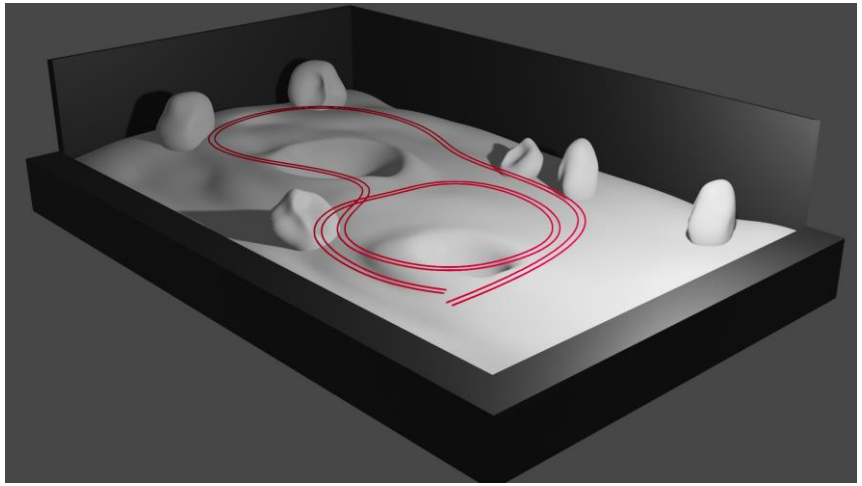

Figure 20 – Schematic of surface layout: Craters and Rocks

Lighting

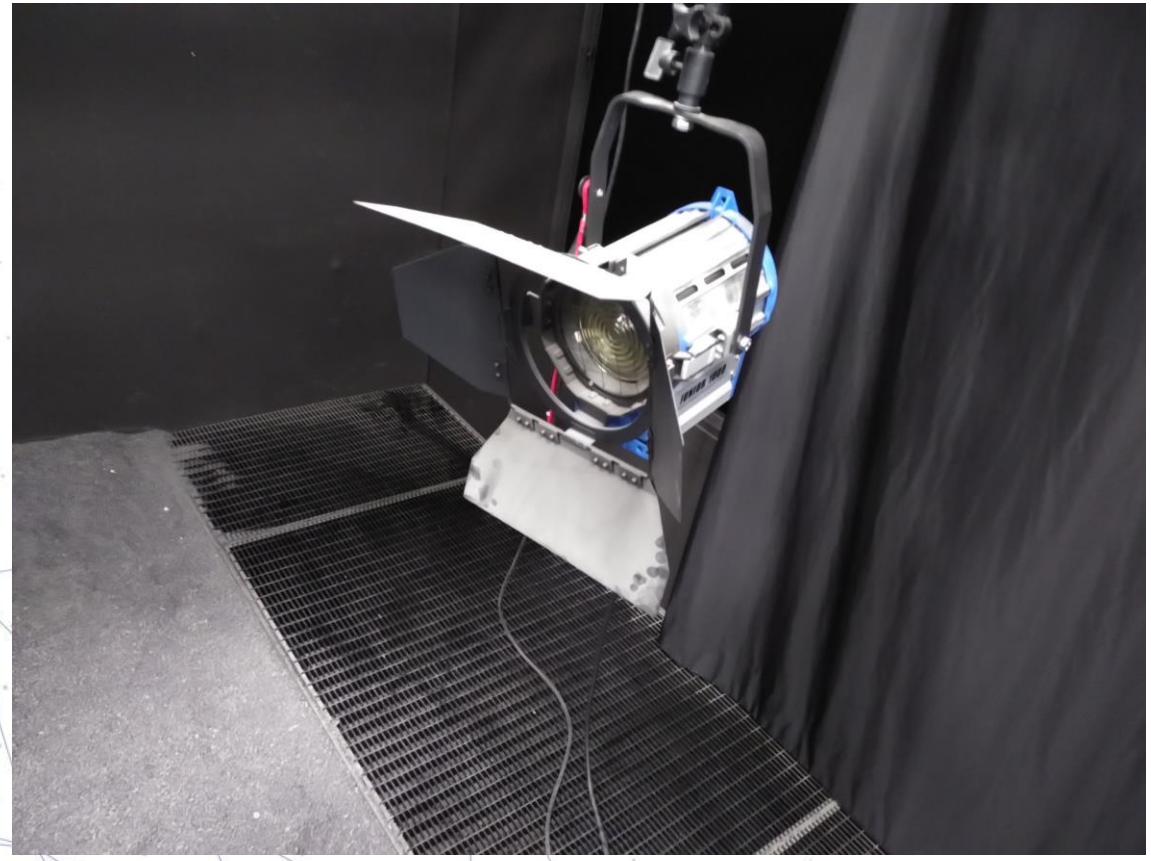

Figure 21 – Tungsten spot light to simulate the sun

Figure 22 – Tungsten spot light to illuminate the LunaLab from different angles

Total of 36 Recordings analysed with 2 Algorithms

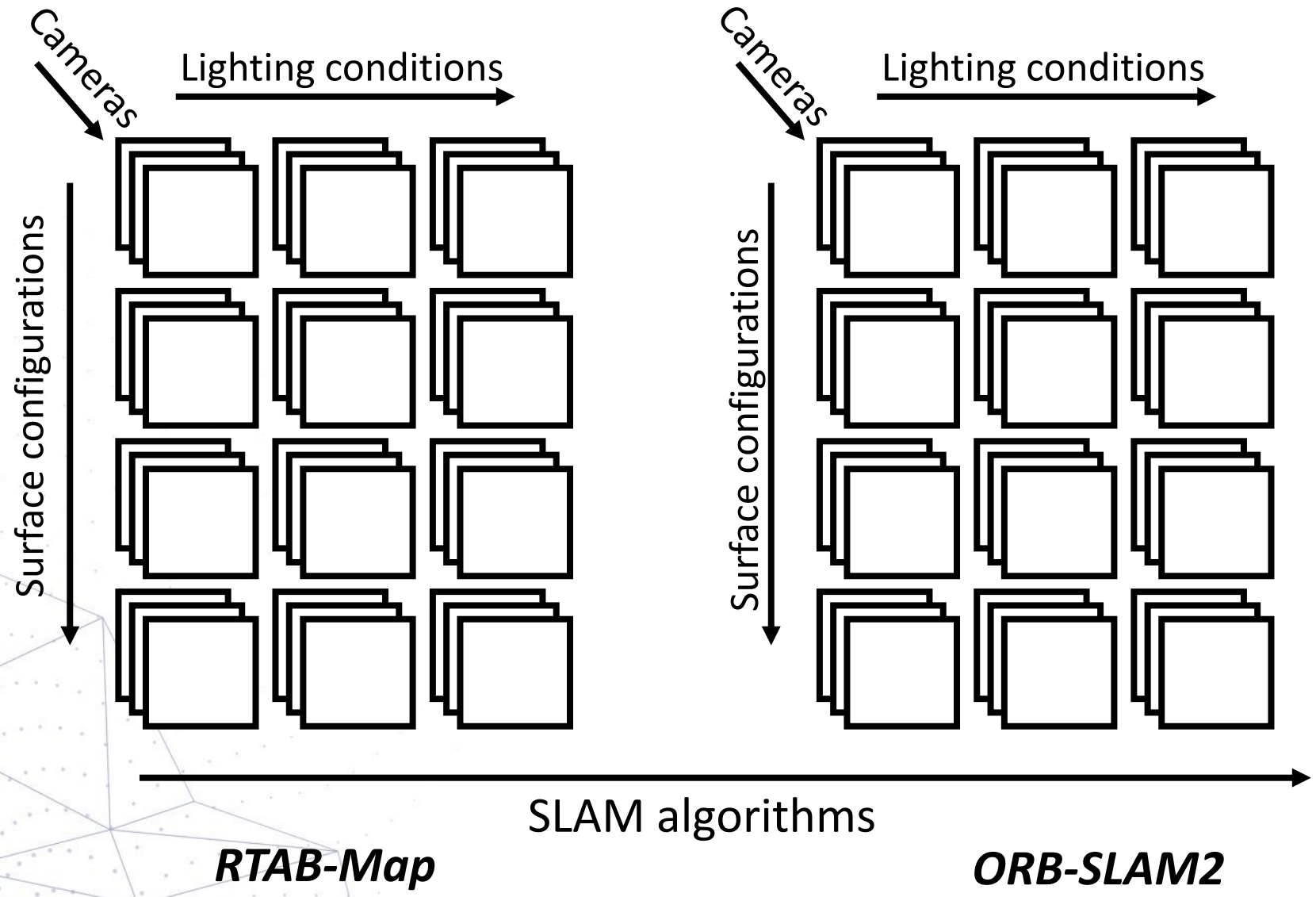

Figure 23 – Schematic to show the number of analysed trajectories

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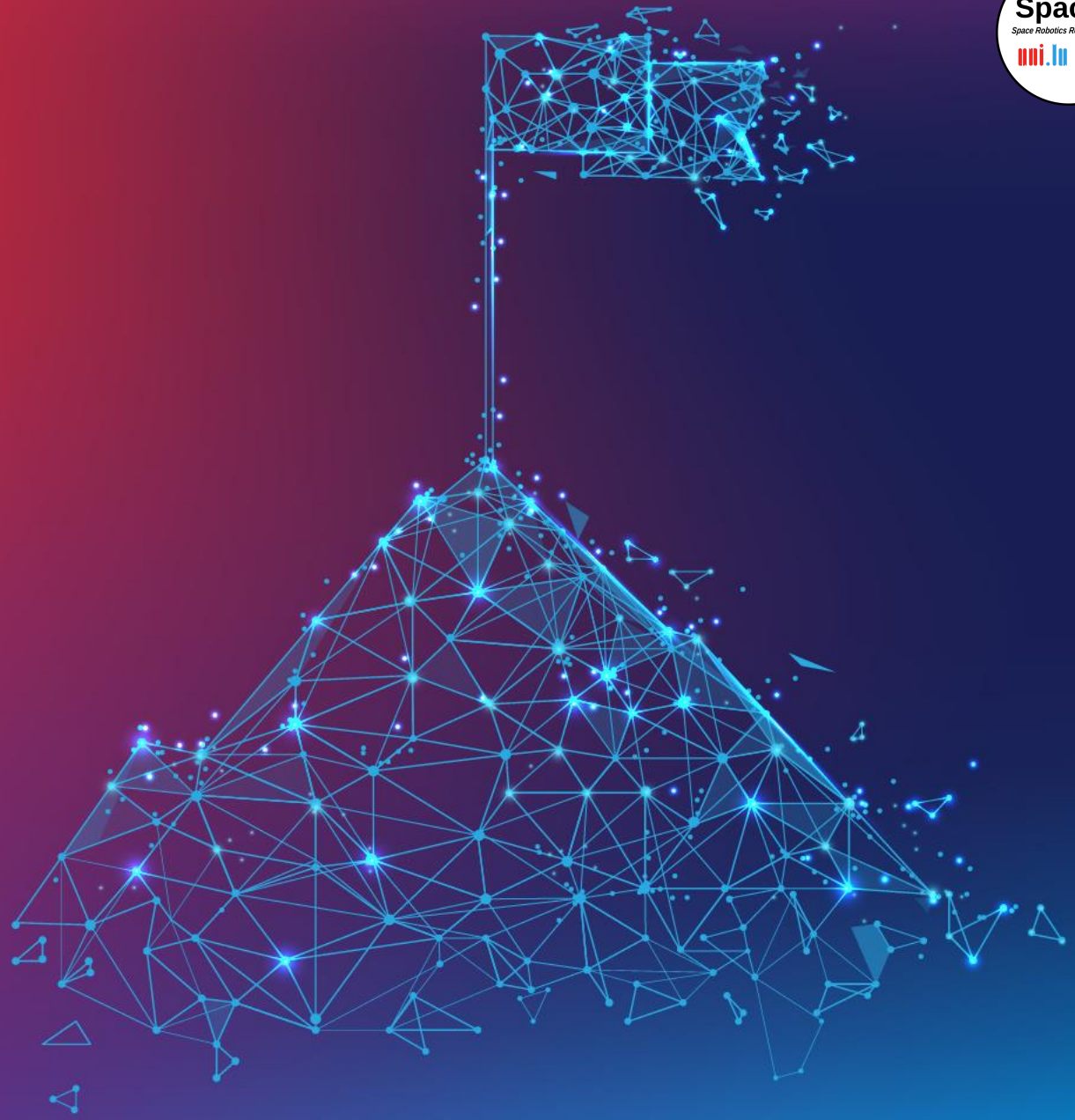
4. Results



Evaluation Criteria

1. Accuracy: How correct is the estimated trajectory?

2. Drift: How large are rotational drift and scale drift?

Rating	Symbol
Very bad	- -
Bad	-
Medium	+/-
Good	+
Very good	+ +

3. Odometry: Did the odometry get lost?

Rating	Symbol
Lost and not recovered	-
Lost and recovered	+/-
Not lost	+

Evaluation

- Very good tracking accuracy
- Very little drift
- No odometry loss

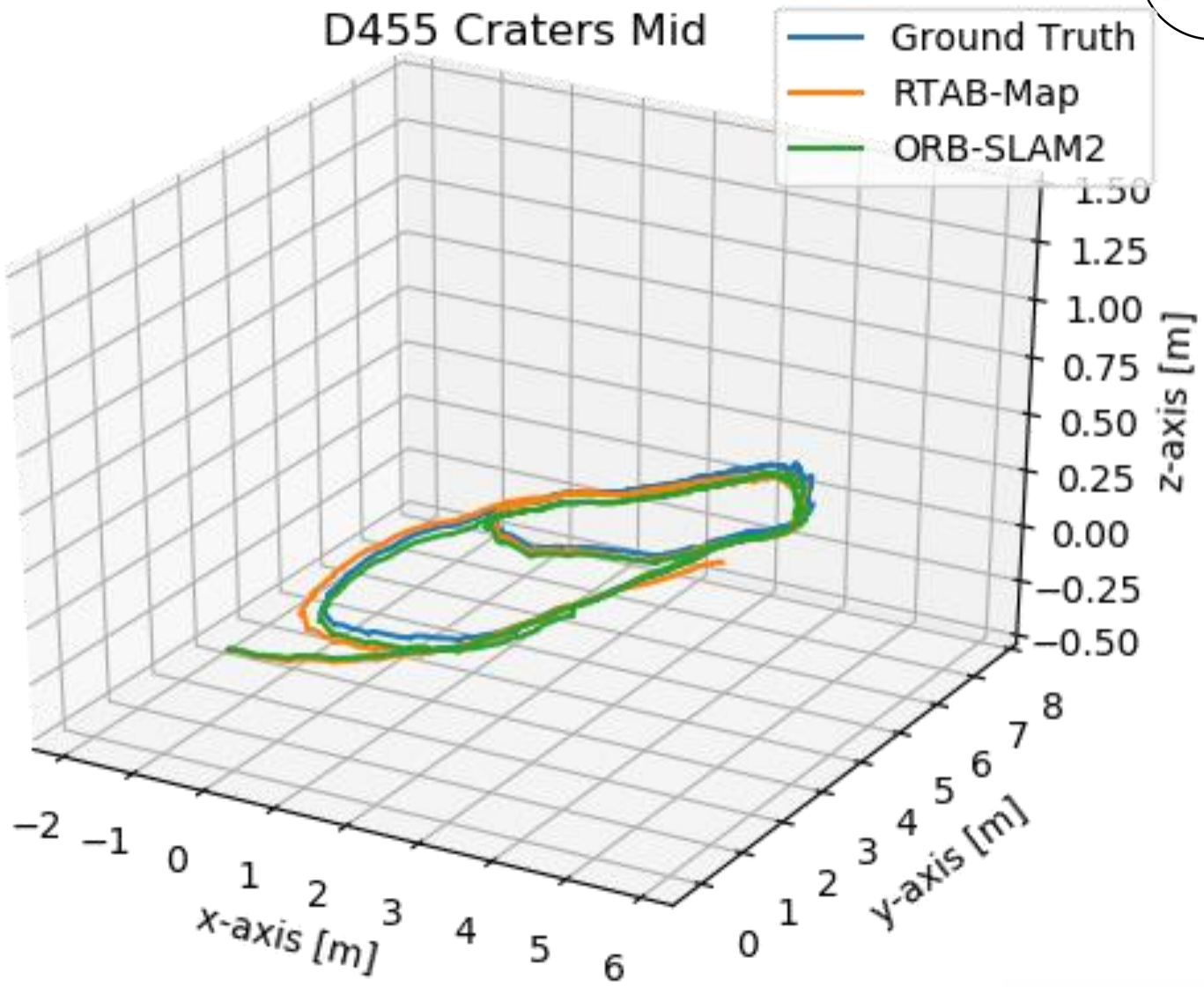


Figure 24 – Diagram of the trajectories with a D455 camera with craters and spot light in the middle position

Evaluation

- Bad rotational drift
- Bad tracking accuracy

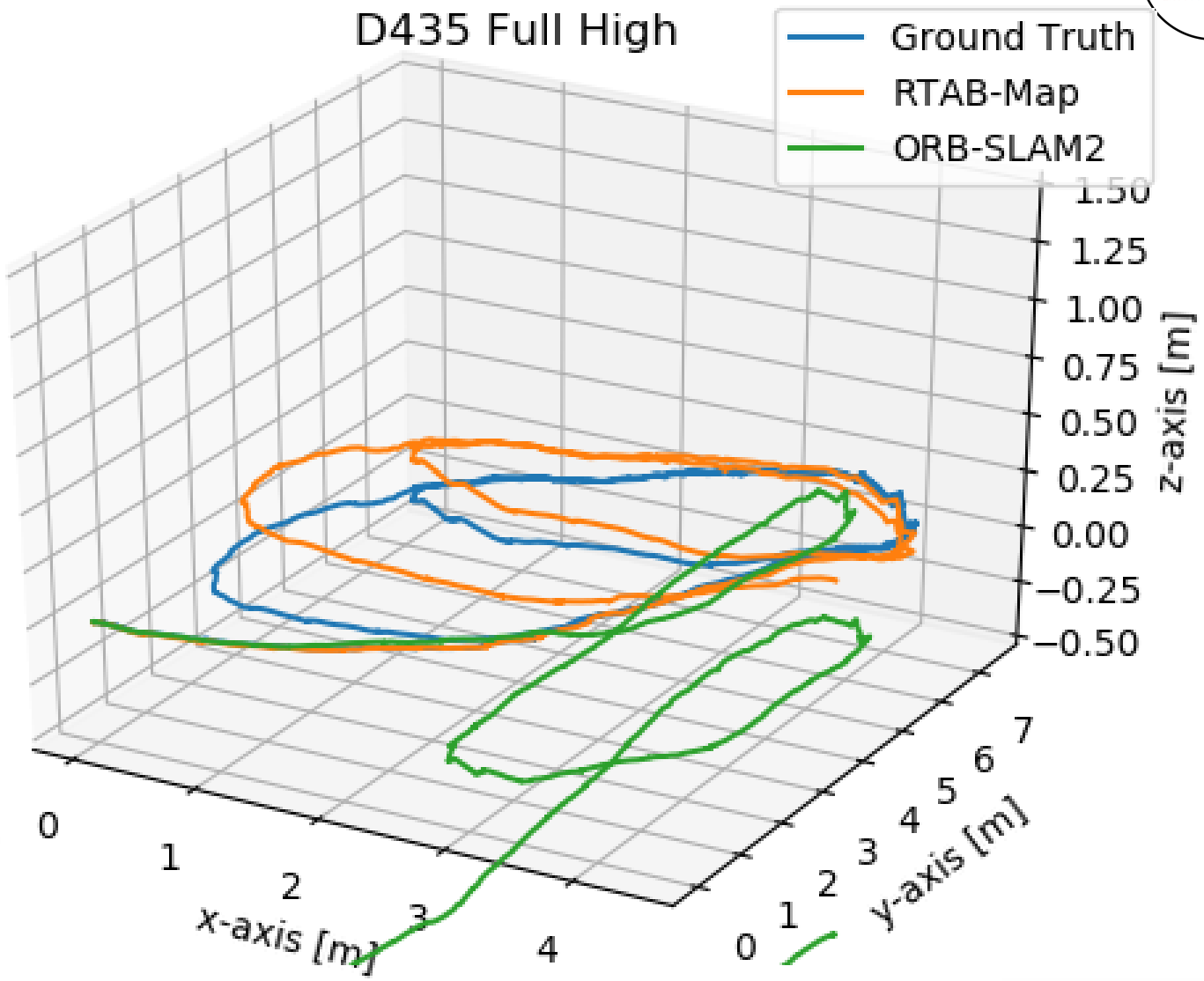


Figure 25 – Diagram of the trajectories with a D435 camera with craters and rocks and spot light in the highest position

Evaluation

- Odometry lost and recovered
- Odometry lost and not recovered

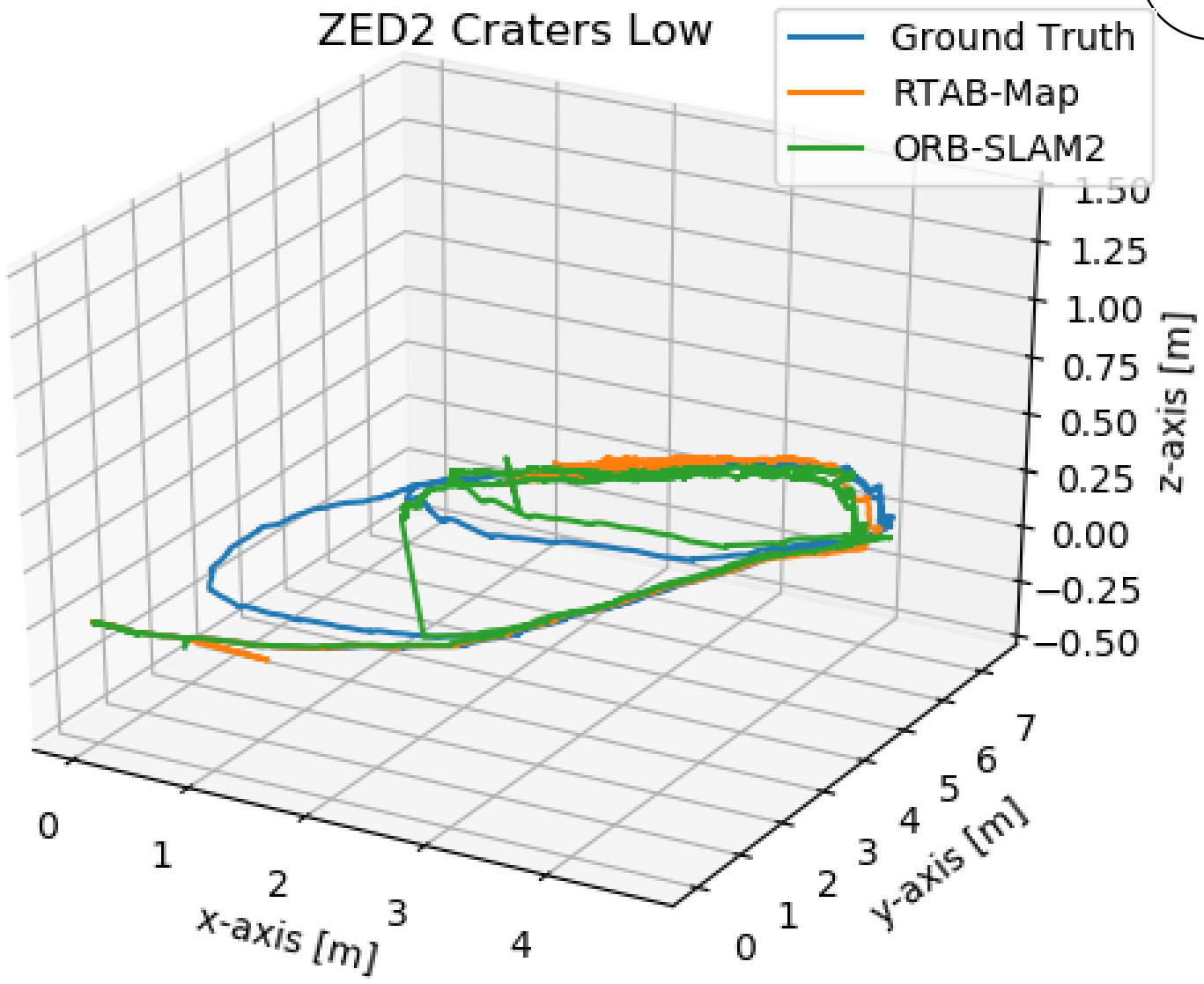


Figure 26 – Diagram of the trajectories with a ZED 2 camera with craters and spot light in the lowest position

Evaluation

	Cameras											
	D435				D455				ZED2			
	RTAB-Map		ORB-SLAM2		RTAB-Map		ORB-SLAM2		RTAB-Map		ORB-SLAM2	
Simple Landscape												
Light Low	A:	+/-	A:	-	A:	+	A:	+	A:	--	A:	++
	D:	+/-	D:	+/-	D:	-	D:	++	D:	--	D:	++
	O:	-	O:	-	O:	+	O:	+/-	O:	+	O:	+
Light Mid	A:	+	A:	--	A:	+	A:	++	A:	--	A:	++
	D:	+/-	D:	--	D:	+	D:	++	D:	--	D:	++
	O:	+/-	O:	+/-	O:	+	O:	+/-	O:	-	O:	-
Light High	A:	++	A:	-	A:	++	A:	++	A:	--	A:	++
	D:	-	D:	--	D:	++	D:	+	D:	--	D:	++
	O:	+	O:	-	O:	-	O:	+	O:	+	O:	+
Crater Landscape												
Light Low	A:	X	A:	X	A:	+	A:	+	A:	+	A:	+
	D:	X	D:	X	D:	++	D:	++	D:	+	D:	+
	O:	X	O:	X	O:	-	O:	-	O:	-	O:	+/-
Light Mid	A:	+	A:	--	A:	++	A:	++	A:	--	A:	++
	D:	+/-	D:	--	D:	+	D:	++	D:	--	D:	+
	O:	-	O:	+	O:	+	O:	+	O:	+	O:	+
Light High	A:	++	A:	-	A:	+/-	A:	+/-	A:	--	A:	++
	D:	-	D:	--	D:	+/-	D:	+/-	D:	--	D:	+
	O:	+	O:	+	O:	-	O:	-	O:	+	O:	+

Legend

A:	Accuracy
D:	Drift (scale/rotation)
O:	Odometry

Rating	Symbol
Very bad	- -
Bad	-
Medium	+/-
Good	+
Very good	+ +

Rock Landscape												
Light Low	A:	+	A:	-	A:	+/-	A:	+	A:	--	A:	++
	D:	+/-	D:	--	D:	-	D:	++	D:	--	D:	++
	O:	+	O:	+/-	O:	+	O:	+/-	O:	-	O:	+
Light Mid	A:	++	A:	+/-	A:	++	A:	+/-	A:	--	A:	+
	D:	++	D:	-	D:	+/-	D:	+/-	D:	--	D:	++
	O:	-	O:	+/-	O:	-	O:	-	O:	+	O:	+
Light High	A:	+	A:	--	A:	+	A:	+	A:	--	A:	+
	D:	-	D:	--	D:	+	D:	++	D:	--	D:	+
	O:	+/-	O:	+	O:	+	O:	+/-	O:	+	O:	+
Full Landscape												
Light Low	A:	--	A:	+	A:	-	A:	+/-	A:	--	A:	+
	D:	-	D:	--	D:	-	D:	+	D:	--	D:	++
	O:	+	O:	+/-	O:	+	O:	+/-	O:	+	O:	+
Light Mid	A:	++	A:	-	A:	++	A:	++	A:	--	A:	+
	D:	+/-	D:	--	D:	+/-	D:	++	D:	--	D:	++
	O:	-	O:	+	O:	-	O:	+/-	O:	+	O:	+
Light High	A:	+	A:	-	A:	+/-	A:	++	A:	--	A:	+
	D:	-	D:	--	D:	-	D:	++	D:	--	D:	+
	O:	+	O:	+	O:	+	O:	+/-	O:	+	O:	+

Evaluation

Legend	
A:	Accuracy
D:	Drift (scale/rotation)
O:	Odometry

Rating	Symbol
Very bad	- -
Bad	-
Medium	+/-
Good	+
Very good	+ +

	Cameras											
	D435				D455				ZED2			
	RTAB-Map		ORB-SLAM2		RTAB-Map		ORB-SLAM2		RTAB-Map		ORB-SLAM2	
Simple Landscape												
Light Low	A:	+/-	A:	-	A:	+	A:	+	A:	--	A:	++
	D:	+/-	D:	+/-	D:	-	D:	++	D:	--	D:	++
	O:	-	O:	-	O:	+	O:	+/-	O:	+	O:	+
Light Mid	A:	+	A:	--	A:	+	A:	++	A:	--	A:	++
	D:	+/-	D:	--	D:	+	D:	++	D:	--	D:	++
	O:	+/-	O:	+/-	O:	+	O:	+/-	O:	-	O:	
Light High	A:	++	A:	-	A:	++	A:	++	A:	--	A:	++
	D:	-	D:	--	D:	++	D:	+	D:	--	D:	++
	O:	+	O:	-	O:	-	O:	+	O:	+	O:	+
Crater Landscape												
Light Low	A:	X	A:	X	A:	+	A:	+	A:	+	A:	+
	D:	X	D:	X	D:	++	D:	++	D:	+	D:	
	O:	X	O:	X	O:		O:		O:	-	O:	+/-
Light Mid	A:	+	A:		A:	++	A:	++	A:	--	A:	++
	D:	+/-	D:		D:	+	D:	++	D:	--	D:	+
	O:	-	O:		O:	+	O:	+	O:	+	O:	+
Light High	A:	++	A:	-	A:	+/-	A:	+/-	A:	--	A:	++
	D:	-	D:	--	D:	+/-	D:	+/-	D:	--	D:	+
	O:	+	O:	+	O:	-	O:	-	O:	+	O:	+

Rock Landscape												
Light Low	A:	+	A:	-	A:	+/-	A:	+	A:	--	A:	++
	D:	+/-	D:	--	D:	-	D:	++	D:	--	D:	++
	O:	+	O:	+/-	O:	+	O:	+/-	O:	-	O:	+
Light Mid	A:	++	A:	+/-	A:	++	A:	+/-	A:	--	A:	+
	D:	+	D:	++	D:	+	D:	++	D:	--	D:	++
	O:	+	O:	+	O:	+	O:	+	O:	+	O:	+
Light High	A:	++	A:	++	A:	++	A:	+	A:	--	A:	+
	D:	+	D:	++	D:	+	D:	++	D:	--	D:	+
	O:	+	O:	+	O:	+	O:	+	O:	+	O:	+
Crater Landscape												
Light Low	A:	+	A:	+	A:	+	A:	+	A:	--	A:	+
	D:	+	D:	+	D:	+	D:	+	D:	--	D:	++
	O:	+	O:	+/-	O:	+	O:	+/-	O:	+	O:	+
Light Mid	A:	++	A:	-	A:	++	A:	++	A:	--	A:	+
	D:	+/-	D:	--	D:	+/-	D:	++	D:	--	D:	++
	O:	-	O:	+	O:	-	O:	+/-	O:	+	O:	+
Light High	A:	+	A:	-	A:	+/-	A:	++	A:	--	A:	+
	D:	-	D:	--	D:	+/-	D:	++	D:	--	D:	+
	O:	+	O:	+	O:	+	O:	+/-	O:	+	O:	+

A: ++ A: ++
D: + D: ++
O: + O: +

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5. Conclusion

Influence of Surface Configuration

- Surface
  - no significant effect on feature detection

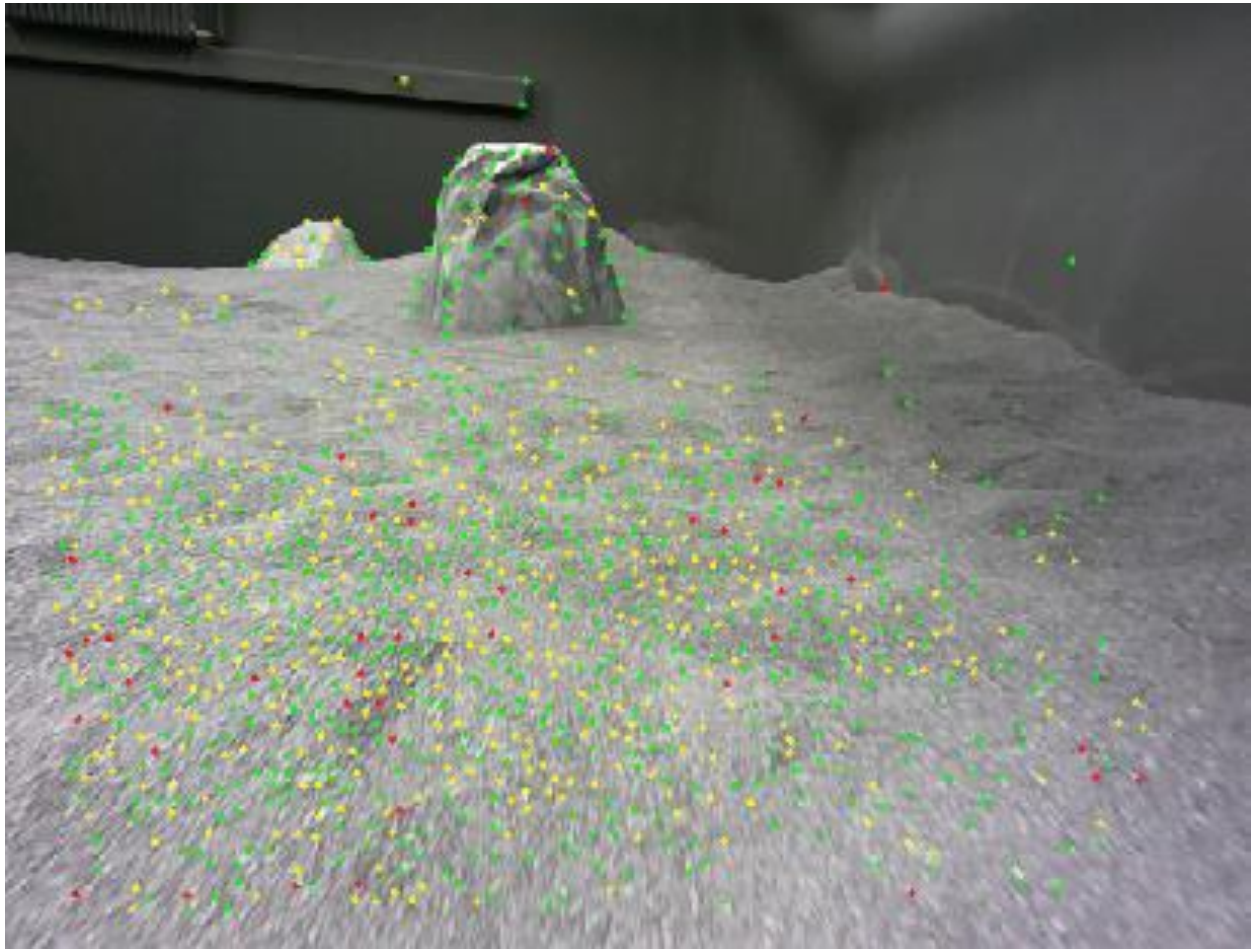

Figure 27 – Features detected on the ground

Influence of Illumination Angle

- Surface
  - no significant effect on feature detection
- Illumination
  - no limited effect on SLAM
  - low angle decreases SLAM

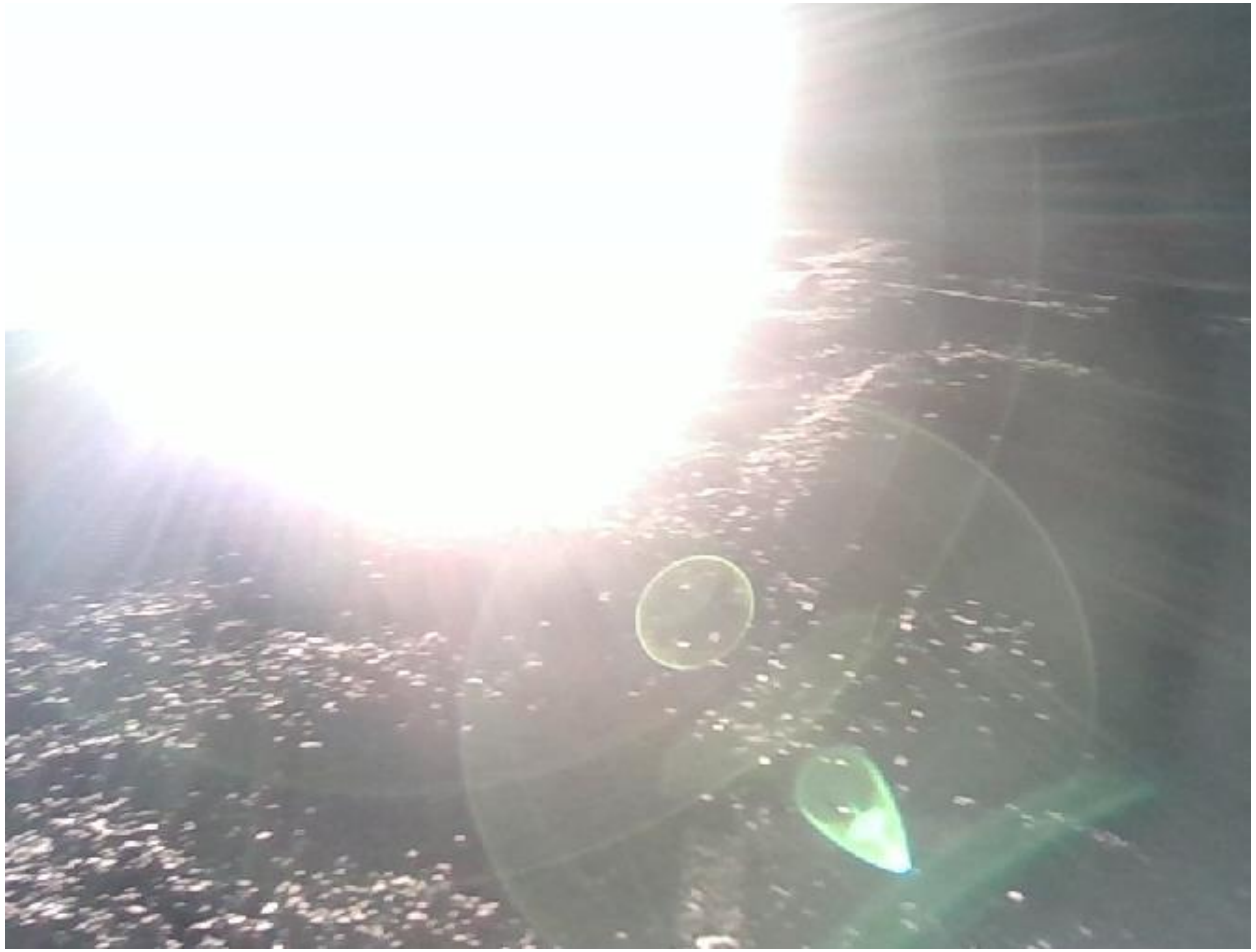

Figure 28 – Lens flares in visual odometry camera

Influence of Sensors

- Surface
  - no significant effect on feature detection
- Illumination
  - no limited effect on SLAM
  - low angle decreases SLAM
- Sensor
  - Wide baseline better
  - IMU can help

Figure 29 – ZED 2 camera, RealSense D455, RealSense D435

Influence of Algorithms

- Surface
  - no significant effect on feature detection
- Illumination
  - no limited effect on SLAM
  - low angle decreases SLAM
- Sensor
  - Wide baseline better
  - IMU can help
- Algorithm
  - High influence
  - Sensor fusion can help

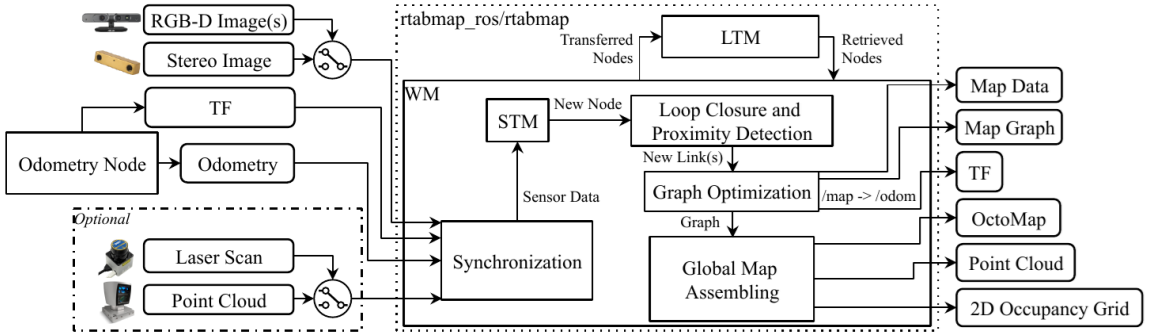

Figure 31 - Software diagram of RTAB-Map

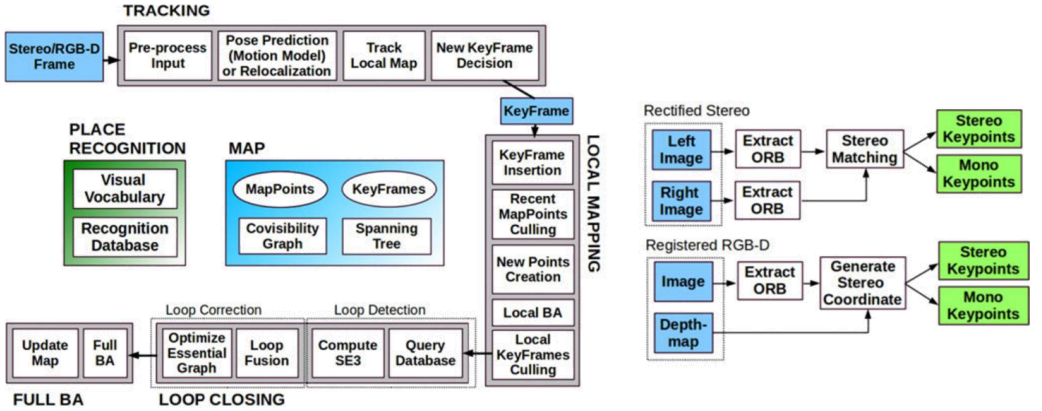

Figure 32 - Software diagram of ORB-SLAM2

Source:

Mathieu Labbe and Francois Michaud. “RTAB-Map as an open-source lidar and visual simultaneous localization and mapping library for large-scale and long-term online operation”. (2019)
Raúl Mur-Artal and Juan D. Tardós. “ORB-SLAM2: An Open-Source SLAM System for Monocular, Stereo, and RGB-D Cameras” (Oct. 2017)

3D Map generated by RTAB-Map

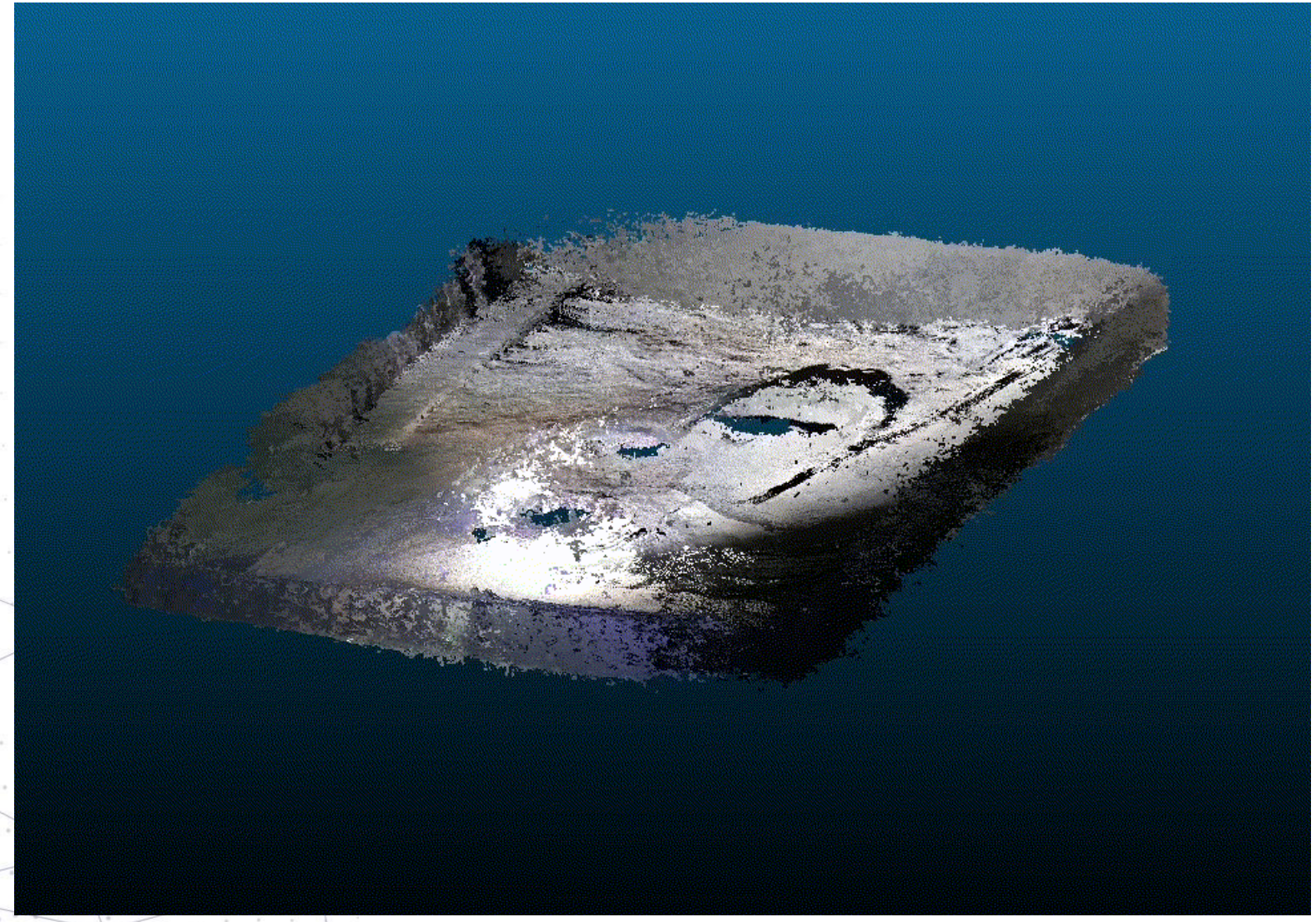

Figure 33 – Point cloud generated by RTAB-Map with D455 camera with craters and spot light in the middle position

SnT

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References

[1] N. N. Aeronautics and S. Administration. Lunokhod 02. https://solarsystem.nasa.gov/missions/lunokhod-02/in-depth/, 05 2018. Accessed on 2021-11-29.
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[4] Intel. Intel realsense product family d400 series. Report 337029-009, Intel, 2020.
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