COMPARISON STUDY OF THE ACCURACY OF SLAM TECHNIQUES AND SENSOR SELECTION FOR LUNAR EXPLORATION

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ABSTRACT

Robotics navigation on the lunar surface is crucial for future lunar prospection missions. Visual Simultaneous Localisation And Mapping (vSLAM) bears several advantages over traditional Simultaneous Localisation And Mapping (SLAM) methods, such as mitigating wheel slip and using sensors with space heritage. Still, extreme environments create challenges for optical sensors. This work proposes a qualitative analysis of which elements influence the performance of vSLAM for lunar environments through an experimental approach in an analogue lunar facility.

Key words: lunar surface; visual simultaneous localisation and mapping; vSLAM; rtabmap; orbslam2; illumination.

1. INTRODUCTION

Space missions rely on robotic agents to support or fully replace human operations, reducing the risk for humans. Early space missions required teleoperation from the control room to enable robots to function [1, 10, 12]. A higher level of autonomy is required to reduce permanent human supervision and eliminate transmission delay from the Earth to the Moon. Early rovers relied mainly on wheel odometry, which made the position estimation of the robots unreliable due to wheel slip [12, 10]. Terrestrial Simultaneous Localisation And Mapping (SLAM) sensors contained rotating parts that were prone to wear and failure due to the intense vibrations during the rocket launch. Furthermore, the Moon was considered a GPS-deprived environment [9] without any additional infrastructure for SLAM. Therefore, cameras were an interesting alternative regarding their wide use in space missions [10].

The Mars exploration rovers Opportunity and Spirit were the first to use visual odometry [2] using stereo cameras. The MER rovers used an Inertial Measurement Unit (IMU) for Visual Inertial Odometry (VIO) and achieved an attitude drift of less than 3° [12]. NASA JPL also tested the Visual Odometry (VO) approach with the Rocky 8 rover in their lab facilities. The error was 2.5% in position, and less than 5° in attitude [12]. VO had the advantage that it worked independently from the terrain properties and was not prone to wheel slip. Since VO was still a form of dead-reckoning, it was prone to accumulated drift over time. When VO was introduced to the MER twin rovers, they were still suffering from accumulated drift [2]. Pure VO without Visual Simultaneous Localisation And Mapping (vSLAM) did not correct the accumulated drift.

The state-of-the-art of vSLAM allowed the use of stereo cameras and RGB-D cameras as an input source for vSLAM algorithms that allowed tracking the motion of the robots while mapping the surroundings. The next step to further increase the level of autonomy was the use of a SLAM algorithm that uses the VO as input, hence vSLAM.

This work seeks to analyse on a qualitative level how available terrestrial vSLAM techniques can be used for lunar robotics exploration and the challenges that should be addressed to increase the localisation and mapping quality. Given the high interest in robotics space applications on the lunar surface, vSLAM is an essential step for developing autonomous robotics applications. Experiments in a lunar analogue facility focusing on high optical fidelity give insights into the suitability in feature-poor environments with high dynamic range lighting conditions similar to the lunar surface.

This study focuses on two state-of-the-art vSLAM approaches: Real-Time Appearance Based Mapping (RTAB-Map) [5] and ORB-SLAM2 [7] as highlighted in section 2. Section 3 elaborates the experiments conducted for this project. Section 4 shows the results taken from the experiments and section5 highlights the lessons learned from this qualitative study.

2. MATERIALS AND METHODS

The experiments take place in an analogue lunar facility focusing on visual fidelity. A robot records the camera data and the ground truth data. The recorded data is then played back on a separate system to run the vSLAM algorithms.

2.1. Laboratory setup

This project is implemented in the LunaLab [6] of the University of Luxembourg in collaboration with Centre for Security, Reliability and Trust (SnT) and the Space Robotics (SpaceR) research group. The LunaLab is a 8×11 m^2 test bed focusing on optical fidelity. The LunaLab is equipped with a 1 kW spotlight to emulate the sunlight. This spotlight can be displaced horizontally and vertically to change the light's angle of incidence. The testbed is filled with 20 tons of basalt so that the surface can be changed and equipped with fake rocks to add more visual features to the environment. The LunaLab is suitable to simulate a similar environment to the lunar surface, as shown in Figure 1. An OptiTrack motion capture system provides the ground truth for the experiments.

Figure 1: Rock with cast shadow inside the LunaLab.

The LunaLab is prepared to simulate four different landscapes: One landscape contains rocks and craters, one only contains craters, one only contains rocks, and one contains no additional features. Additionally, three different angles of incidence are chosen for the spotlight to illuminate the surface: high, middle and low.

2.2. Robot setup

As a robotic platform, a Leo Rover [3] is used with ROS Melodic [8]. This robot is equipped with one of three cameras: a RealSense D435, a RealSense D455 [4] and a Stereolabs ZED2 [11] camera. The rover is equipped with an NVIDIA Jetson Nano running ROS Melodic to receive and record the data from the cameras.

The Jetson Nano runs a node to receive the ground truth data from the OptiTrack system. Furthermore, the embedded system runs a script to follow a pre-recorded trajectory automatically, shown in Figure 2, with a maximum velocity of 0.05 m/s. The relevant data is recorded inside a database file called "rosbag". These rosbags are then played back on a desktop computer to publish the date for the vSLAM algorithms.

The vSLAM algorithms used are RTAB-Map [5] and ORB-SLAM2 [7]. These algorithms are running on a desktop computer where the rosbags are played back to avoid any performance limitations due to the limited hardware of the rover.

3. EXPERIMENTS

3.1. Motivation of the experiments

The experiments conducted in this research serve to find the strengths and weaknesses of vSLAM algorithms applied to lunar analogue environments. The algorithms used are presented in subsection 2.2. A single light source is positioned at different angles of inclination to mimic the illumination conditions on the Lunar surface. Furthermore, the landscape of the experiments is modified between sets of experiments to simulate different amounts of visual features, based on the presence of rocks or craters. Lastly, the experiments are conducted using different cameras to find potential differences in the performance of the sensors and their suitability for vSLAM in lunar environments. The vSLAM algorithms are developed for terrestrial applications in urban environments such as cities or indoor environments. The main objective of this research is to identify the suitability of these systems in the lunar environments.

3.2. Experiment setup

For each experiment, the rover starts with a fully charged battery and is placed at the same starting position. The surface of the lunar environment is brushed to smooth out the tracks of the previous experiments. The trajectory made by the rover is defined in the environment containing rocks and craters. As a result, the rover follows the same trajectory by reaching a set of predefined waypoints, avoiding the rocks and craters. During the consecutive experiments, the following variations are introduced in that order: alteration of the position of the light source, exchange of cameras, and landscape modification. After completing all the experiments in the four landscapes, 36 experiments have been recorded in total.

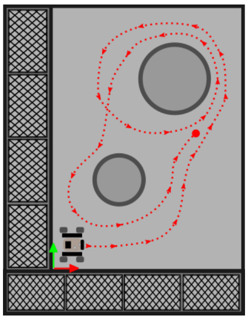

Figure 2: Trajectory of the Leo Rover inside the LunaLab.

The rover's camera and IMU topics are recorded in a rosbag file together with the pose data collected from the OptiTrack system. Then, the rosbags are copied to a desktop computer, where they are played back to serve as input for the vSLAM algorithms. The algorithms return the odometry of the rover, based on the visual input. This odometry is stored in a file for later evaluation and comparison with the ground truth data from the OptiTrack system.

4. RESULTS

4.1. Evaluation of the data

To evaluate the data, the odometry results from the two algorithms and the ground truth data are displayed in a 3D graph. By analysing visually the odometry data from the two algorithms in each situation based on different landscapes and illumination conditions, the odometry is evaluated by the following criteria points:

1. Accuracy: How correct is the estimated trajectory?
2. Drift: How large are rotational drift and scale drift?
3. Odometry: Did the odometry get lost?

The accuracy is evaluated to be very good (++) if the estimated trajectory shape is close to the ground truth and very bad (–) if the estimated trajectory shape does not correspond to the ground truth. The drift is evaluated to be very good (++) if the estimated trajectory aligns with the ground truth and very bad (–) if the estimated trajectory is off in scale or if the estimated trajectory deviates from the ground truth. Table 1 shows how the accuracy and drift are evaluated.

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

Table 1: Legend for the evaluation of accuracy and drift

The odometry is evaluated as not lost (+), lost and recovered (+/-) or lost and not recovered (-). It is possible that the odometry is lost in a difficult part of the trajectory but then recovered while revisiting that part of the trajectory again. Table 2 shows how the accuracy and drift are evaluated.

The odometry data of the landscape, including rocks and craters, where the light is in the middle, recorded with the RealSense D455 camera is represented in figure 3. The graph shows that there is a moderate amount of drift for RTAB-Map and only a small amount of drift for ORB-SLAM2. The shape of the trajectory is clearly recognisable when compared to the ground truth.

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

Table 2: Legend for the odometry evaluation

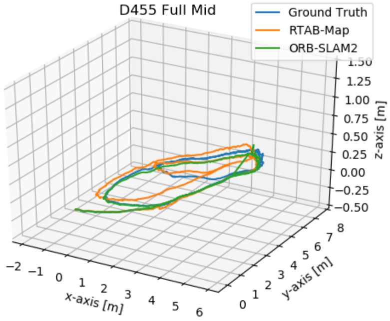

Figure 3: Visual odometry based on D455 camera with rocks and craters and light in the middle

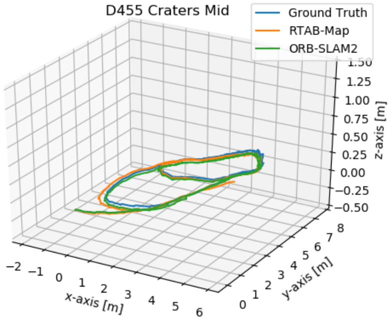

Figure 4: Visual odometry based on D455 camera with only craters and light in the middle

The odometry data of the landscape, including only craters where the light is in the middle, is recorded with the RealSense D455 camera, which is represented in figure 4. The graph clearly shows that the accuracy is high for both algorithms, and the drift is minimal compared to the ground truth value.

4.2. Trajectory estimation

After analysing all 36 scenarios for both algorithms, resulting in 72 different trajectory estimations, the results of the evaluation have been summarised in Table 3.

	D435		D455		ZED2	
	RTAB	ORB	RTAB	ORB	RTAB	ORB
Simple Landscape						
Low	A: +/-	A: -	A: +	A: +	A: --	A: ++
	D: +/-	D: +/-	D: -	D: ++	D: --	D: ++
	O: -	O: -	O: +	O: +/-	O: +	O: +
Mid	A: +	A: --	A: +	A: ++	A: --	A: ++
	D: +/-	D: --	D: +	D: ++	D: --	D: ++
	O: +/-	O: +/-	O: +	O: +/-	O: -	O: -
High	A: ++	A: -	A: ++	A: ++	A: --	A: ++
	D: -	D: --	D: ++	D: +	D: --	D: ++
	O: +	O: -	O: -	O: +	O: +	O: +
Crater Landscape						
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: +/-
Mid	A: +	A: --	A: ++	A: ++	A: --	A: ++
	D: +/-	D: --	D: +	D: ++	D: --	D: +
	O: -	O: +	O: +	O: +	O: +	O: +
High	A: ++	A: -	A: +/-	A: +/-	A: --	A: ++
	D: -	D: --	D: +/-	D: +/-	D: --	D: +
	O: +	O: +	O: -	O: -	O: +	O: +
Rock Landscape						
Low	A: +	A: -	A: +/-	A: +	A: --	A: ++
	D: +/-	D: --	D: -	D: ++	D: --	D: ++
	O: +	O: +/-	O: +	O: +/-	O: -	O: +
Mid	A: ++	A: +/-	A: ++	A: +/-	A: --	A: +
	D: ++	D: -	D: +/-	D: +/-	D: --	D: ++
	O: -	O: +/-	O: -	O: -	O: +	O: +
High	A: +	A: --	A: +	A: +	A: --	A: +
	D: -	D: --	D: +	D: ++	D: --	D: +
	O: +/-	O: +	O: +	O: +/-	O: +	O: +
Full Landscape						
Low	A: --	A: +	A: -	A: +/-	A: --	A: +
	D: -	D: --	D: -	D: +	D: --	D: ++
	O: +	O: +/-	O: +	O: +/-	O: +	O: +
Mid	A: ++	A: -	A: ++	A: ++	A: --	A: +
	D: +/-	D: --	D: +/-	D: ++	D: --	D: ++
	O: -	O: +	O: -	O: +/-	O: +	O: +
High	A: +	A: -	A: +/-	A: ++	A: --	A: +
	D: -	D: --	D: -	D: ++	D: --	D: +
	O: +	O: +	O: +	O: +/-	O: +	O: +

Table 3: Overview of experiment results

The results show that the influence of the landscape and lighting conditions is very limited. The influence of the camera and the algorithm are much stronger. The ZED2 camera works very well with ORB-SLAM2 but shows significant tracking issues with RTAB-Map. The RealSense D455 camera shows better results than the D435 camera. The D455 camera shows better results with RTAB-Map than the D435 camera.

5. CONCLUSION

This work presents the analysis of 36 datasets recorded in different landscapes in an analogue lunar facility under different lighting conditions, using three different cameras. The environments contain craters or rocks, a combination of both or no features. The recorded datasets are analysed using two different vSLAM algorithms to estimate the trajectory of the rover and to create a map of the environment.

The analysis of the estimated trajectories shows that the features in the environments, such as rocks and craters, have little influence on the tracking accuracy. The lighting conditions have a limited effect, though the data shows that very low angles of incident cause a challenge for vSLAM. The largest influence on the accuracy of the trajectory estimation is given by the choice of camera and the choice of the vSLAM algorithm to do the trajectory estimation.

This work highlights that the most promising areas of research to improve planetary mapping capabilities for the lunar surface lie in developing specialised algorithms and selecting sensors adapted to the challenges of the lunar surface.

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