TESTING ENVIRONMENTS FOR LUNAR SURFACE PERCEPTION SYSTEMS; COMBINING INDOOR FACILITIES, VIRTUAL ENVIRONMENTS AND ANALOGUE FIELD TESTS.

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ABSTRACT

This paper describes the different approaches which can be used to test vision systems for operations on robotic lunar surface missions. We investigate validating systems in virtual environments, lab environments and analogue outdoor environments and demonstrate that a combination of all three approaches is needed to sufficiently test systems for the lunar surface.

1. INTRODUCTION

Reliably testing robotics systems for the lunar surface can be challenging because unlike most robotic systems, we cannot test them in their intended operating environments. Instead, we must develop different testing environments which mimic the actual surface of the Moon as accurately as possible. Additionally, knowledge of the expected surface environment of most landing sites is limited, due to the low resolution of available orbital imagery. Consequently, we are not only testing for a single environment, but for a range of different scenarios which could be encountered by a rover mission on the lunar surface.

1.1. Methodology:

We present various environments which are divided into three different categories: controlled indoor lab environments, virtual simulation environments [1] and outdoor analogue testing [2]. We analyse different existing solutions, including our own test configurations for each category. Also, the different setup possibilities for each category will be described as well as their strengths and weaknesses with regards to their similarities to the moon. The primary focus of this research lies in perception sensors which are required for autonomous navigation problems, including mono and stereo camera systems, infra-red projection depth cameras, inertial measuring units, lidar sensors and time of flight sensors. Lastly, we consider the type of testing that is performed, as some applications can rely on recorded data, while others require constantly generated data based on the experiments output. As such, pure localisation algorithm accuracy tests may be conducted on recorded data, while autonomous driving tests or remote operations tests change the position of the camera based on the progress of the test.

Figure 1: Rover exploring an indoor lunar environment of the University of Luxembourg

2. VIRTUAL ENVIRONMENTS

Virtual environments present the simplest way to test robotics systems with very little financial overhead. Of the numerous robotics simulators, a handful have been configured for planetary surface operation testing, such as Pangu [3], Gazebo [4] and 3drov [5].

2.1. Games Engines

Most robotics simulation environments are built for integration with robotic systems, or for high fidelity physics simulations. For testing vision-based perception systems, however, the primary requirement is the visual fidelity of the generated camera images. Therefore, we have taken a new approach to utilise a commonly used computer game engine instead. Currently, there are two major game engines to choose from: *Unreal Engine 4* (www.unrealengine.com) and *Unity* (www.unity.com).

While realistic dynamics also play a vital role in robotics, they are less important for navigation systems, which is why we rely on the existing physics simulations within the game engine. However, integration with existing hardware and software systems remain a significant consideration when selecting a game engine. In terms of fidelity, game engines are closer to the state of the art of realistic rendering than simulators. Currently, no simulator can rival the ray-tracing capabilities of *Unreal Engine 4* and *Unity*. This is an approach to 3d rendering where rays of light are simulated according to their physical properties in order to calculate the final scene image. Until recently, this approach was only available to non-real-time applications, but it is now finding its way into computer games, in order to deliver more realistic lighting. When it comes to environment size, there is also a significant difference, as games are already optimized to display large scale gaming areas, while most simulators only focus on the direct surroundings of the robot.

2.2. Bridge with existing systems

Before setting up any simulation environment, one needs to first establish which other systems will interface with the simulation, and which parameters should be tested. This could potentially include direct streaming of data to a robotic platform for hardware in the loop testing or streaming to mission control systems in order to test remote operation capabilities. A more limited approach could also be reduced to recording data to disk for later usage by other systems.

Both of the presented computer games engines have open source bridges to Robotics Operating System (ROS), which is widely used for operating experimental rover hardware. These existing links can be used for a simple connection to existing infrastructure. For Unreal, there are two different implementations: ROSIntegration [6] and Airsim [7]. For Unity, there is ROS# (https://github.com/siemens/ros-sharp).

As ROS transmits data over a TCP/IP link, data can then also be easily shared with other devices, including with the actual test platform hardware. In addition to this, control commands may also be sent back to the simulator to move the test platform inside the simulation. This allows for testing, where the navigation system can run on its dedicated hardware, while receiving real-time sensor data from the simulation environment

2.3. Simulator Landscape

While the rendering engine is responsible for the technical part of simulating sensors, we also need to provide an environment where we can perform tests. Ideally, this environment is as close as possible to the environment of that on the moon. When using computer game engines, this problem has already been partially resolved, as one can easily buy moon-like environments for both Unreal Engine and Unity, which offer large scale testing grounds with randomly generated surface textures and rock distributions. One such example can be found here: www.unrealengine.com/marketplace/the-moon

Figure 2: Virtual Unreal Engine environment

For our setup, we have made use of this example environment which provides an area of 64 km^2 with different rock and soil distributions, as well as larger and smaller rocks. This allows for a range of different scenarios where a rover can spawn and enables the validation of new algorithms with statistical significance. The same environment was also used to generate training data for a machine learning approach to localisation [1]. The scale of the environment is an advantage that game engines have, which can currently not be matched by other proposed solutions, i.e. Gazebo.

3. Real data

For a higher degree of accuracy, environments should however be based on real data from the intended landing site on the lunar surface. Current Digital Elevation Models (DEM) have a resolution of up to 1m/px, which is not enough for surface perspective simulations. Instead, a resolution around at centimetre level is needed. Since such DEM's are currently not available for the lunar surface, existing ones need to be post processed and enhanced artificially. In order to do this, we can look at the distribution of rocks and craters at a larger scale, and we make assumptions about the distribution of smaller rocks and craters. Rocks can then be added procedurally to the environment, while craters require the modifications to the existing DEM. An example of such post processing can be found here [4].

3.1. Ground truth data

When it comes to ground truth data, simulation environments are particularly interesting, because we always have perfect knowledge of all the parameters in our systems. This also enables another use case with data collection for machine learning applications. Due to the perfect system knowledge, the generation of training datasets can be automated, and therefore does not require time-consuming labelling of data. This includes data types such as perfect depth maps, or pixel accurate semantic segmentation images.

3.2. Procedural parameter testing

The virtual environment allows for added flexibility where parameters can be changed in a scripted manner, allowing for automated testing. In doing so, modifications to parameters may be made in an automated way: starting location, rover configuration, rock distribution and Sun positioning, to name a few. This type of testing would be difficult to reproduce accurately in a real environment.

3.3. Advantages & limitations of Simulation Environments

The primary limitations of simulators are that they provide data which is too perfect. There is generally very little noise in simulated data, or it must be generated in addition to the produced data. The terrain resolution of virtual environments is also not without limits, especially when dealing with large-scale landscapes. When approaching objects up close, this can lead to sharp edges through the low polygon count on these objects.

In terms of advantages, the simulator provides large scale environments which can easily be modified. The testing is also deterministic and reproducible, which is crucial when trying to modify specific parameters in isolation, and is especially interesting for trouble shooting. Additionally, the perfect ground truth knowledge is great for accurate benchmarking, as well as for generating training data for machine learning applications.

4. ANALOGUE LAB ENVIRONMENTS

Indoor testing environments allow for a lot of flexibility, because they allow for regular testing, under controlled conditions. There are a number of examples of such facilities across the world, some of which are smaller in scale, while using regolith simulant [8], others that focus more on the difficulty of the terrain and lastly facilities which focus more on mechanical properties of the surface material [9].

4.1. Material

Ideally, lunar regolith simulant is used for such a facility [10], because the material is the closest replication of the regolith on the lunar surface. It does, however, limit the operation of the facility, as regolith simulant is made from fine ground sharp particles of basalt rock, which are also a carcinogenic. Additionally, it is expensive to produce, which limits the size of the facility. For daily testing, one can use rocks, gravel and sand of volcanic origins, which is sufficiently accurate, and easier to work with. It is still recommended to install a filtered ventilation system, as sand of any type tends to get everywhere, including the mechanical components of robotic systems. For our tests, we have used a combination of basalt sand (0.1-2mm) and basalt gravel (2-5mm).

4.2. Surface Shape:

The design of the facility surface will depend on the area of the Moon considered for testing. The lunar surface varies widely between smoother areas within maria regions, with low density of craters (approx. 73 craters per 1 million km^2; e.g. Apollo landing sites) to the rough and rocky areas with high density of craters (approx. 442 craters per 1 million km^2) [11]. Since direct surface observations are lacking for most areas of the Moon, we need to extrapolate data to build an assumption of what specific area could look like. When it comes to the crater and rock distributions, we look at the distribution of larger craters and boulders visible in high-resolution remote sensing images and make assumptions for the smaller craters and rocks [12].

When manually crafting craters, they should be bowl-shaped and perfectly circular as described in [13] (p58). At least half a meter of material depth is recommended, to increase the flexibility when designing craters or more mountainous regions with small hills which can cast longer shadows. This also allows for testing more edge cases with regards to localisation, but also the overall mobility of the system.

Another interesting approach is to rely on computer simulations to generate random surface lunar surfaces and rock distributions. This is useful to guarantee randomness of a facility setup, especially when trying to test as many configurations as possible [8]. This is however more difficult to setup, as such software is currently not commercially available.

4.3. Illumination

To reproduce the optical properties of the lunar surface as accurately as possible, the illumination and the cast shadows play a significant role. Therefore, a single lighting source should be used to illuminate the complete environment, as opposed to using multiple light sources, which would cast multiple shadows in different directions.

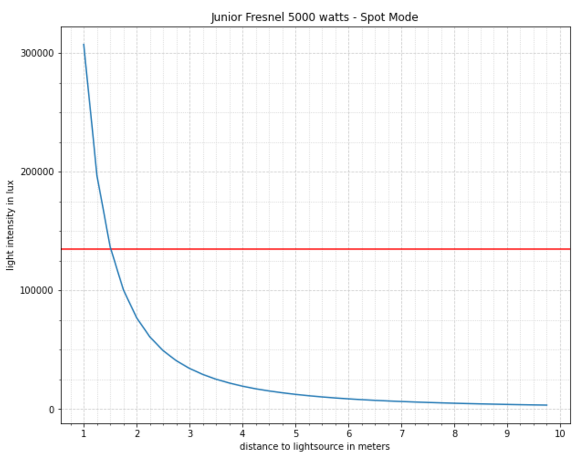

Figure 3: Calculations of the light intensity relative to the distance to the light source. The red line indicates the solar constant.

Lights used in the film industry are suitable for this use case, as they provide enough power to illuminate the whole environment from a single light source. Even on the cheaper end, tungsten lightbulbs are perfectly suitable to illuminate a lunar yard. While they cannot exactly match the spectrum or our sun, they cover the visible spectrum and the IR spectrum well, while being somewhat weaker in the UV part of the spectrum. When considering the strength of a lightbulb, commercial lights are given in lux output at a specific distance. With the quadratic fall-off of light, we may then calculate (*Figure 3)* the distance at which the light source can achieve the solar constant of 135000 lux.

Another element to examine is the directional light one can find on the Moon. Due to the large distance from the Sun to the Moon, it appears that the Sun's rays and the shadows they cast are parallel. In order to replicate this effect, the light source should be positioned as far from the scene as possible. However, this is not very practical as it requires additional space and a more powerful light source due to the quadratic falloff of the light intensity. For most computer vision applications, this is less of a concern and at least for our applications, we consider this factor to be secondary.

4.4. Solar spectrum

The solar illumination is fairly consistent throughout the year, due to the near circular orbit of Earth, resulting in a distance between 1.01671033 AU and 0.935338 AU. For our calculations, we use a solar illumination constant for the Moon which is equal to 135.000 lux [14]. This is the approximate illumination intensity found on the lunar surface, before the sunlight is reflected of the ground. The combined illumination can be derived from the direct and indirect lighting in the target environment. For both types of illumination, we need to consider the sun inclination throughout the lunar day. For the indirect illumination, we also need to estimate the reflective properties of the surface material. We can estimate the landing site material properties from the albedo values as measured by the Diviner lunar radiometer experiment [15]. If the sun angle, the sun intensity and the reflectivity properties of the surface are modelled correctly, we can reproduce the illumination conditions to a high degree of fidelity.

For most computer vision problems, the illumination intensity is not directly an impacting factor, as most cameras can adjust intensity through aperture, shutter speed, sensor sensitivity and ND filters. However, problematic factors could be present, which include motion-blur through longer exposure times as well as interference with active illumination sensors. While passive sensors such as cameras are barely affected by this, active sensors, such as projection-pattern based systems, time-of-flight cameras or LIDARs, can only work properly if the signal they send out to measure distances is not overpowered by the Sun [16]. When performing field testing with such sensors outdoors, one should keep in mind that the atmosphere not only diminishes the overall power of the sunlight, but that it also filters out certain wavelengths at a higher rate than others. As such, sensor manufacturers for outdoor LIDAR systems specifically pick wavelengths which work favourably with

Earth's atmosphere. For this type of testing, indoor facilities with better control over the illumination conditions are, therefore, more beneficial.

4.5. Facility walls

Figure 5: ispace lunar yard in Luxembourg

On the lunar surface, there is very little light bouncing from other objects into shaded areas. This is because the Moon does not have an atmosphere, nor any tall structures to reflect light from. In an indoor lunar yard, the biggest sources of reflecting light are the walls and the ceiling. In order to have less light bouncing into the shaded areas, as we would on the Moon, the walls and the ceiling should be painted matte black. This results in darker shadows, which can also be observed in *Figure 1* where the contrast between illuminated and non-illuminated areas is much stronger. In comparison, we can look at *Figure 5* where the shadows are brighter. This effect has an impact on the localisation system because darker areas are less suitable for localisation systems to detect features. It also influences the auto exposure system on cameras, which now have to deal with more extreme values in a single picture.

It is also important that the walls remain featureless and not covered with horizon images, as any features will be picked up by the camera systems and provide ideal points for depth estimation. Whilst on the Moon, stereo cameras will also see the horizon, but these features are not within the stereo depth estimation range and can thus, only marginally contribute to better localisation accuracy.

4.6. Sun position and movement

The angle of the Sun should be positioned with regards to the expected latitude for operation on the Moon. Landing sites in the equatorial region will endure mostly top-down illumination with limited shadows through a large part of the day. In the polar regions, the Sun will remain on the horizon throughout the day, casting long moving shadows. The simulation of equatorial regions requires facilities with a higher ceiling to mount the light source sufficiently far away from the terrain.

Due to the slow movement of the Sun's positions in the lunar sky, a moving Sun position depends on the scenario to be tested. The Sun's relative position moves approximately 28 times slower than on Earth. For most types of surface navigation, this means the movement is negligible. Nonetheless, for SLAM systems, it is important to consider if loop closure algorithms will still function accurately, should a rover revisit a location during various time periods. To examine these results, one should move the Sun's position to simulate a different time of day. To assist with these changes in positioning, robotic sunlight mounts can also be considered for repeatable configurations [17].

4.7. Localisation ground truth

To test any type of localisation, an external system is needed to accurately measure the actual position of the testing platform. For this purpose, we rely on a motion capture system, as such systems can typically determine a rover's position with sub-millimetre precision. Such systems use reflective IR markers which are clearly visible with IR cameras. Next, we position multiple IR cameras around the testbed. Through triangulation, the system will then determine the position of each marker and consequentially, the position and orientation of the mobile platform with 6 degrees of freedom. In order to achieve this, the motion capture system requires at least 3 cameras and 3

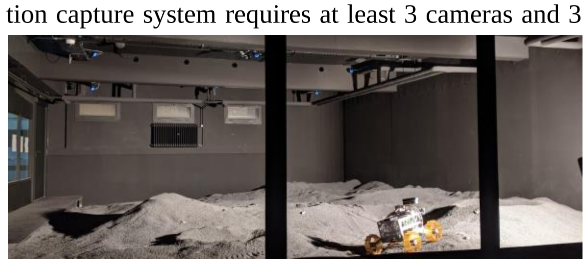

Figure 4: Lab facility at the University of Luxembourg, showing the localisation system on the ceiling.

markers. By using more cameras and more markers, the precision of the measurement can be improved. This also helps in avoiding occluded markers, which can lead to the loss of the position tracking. When placing the markers, they must be placed in an asymmetrical fashion, in order to guarantee that the system does not confuse left/right or front/back of the test platform. The sub-millimetre precision of the ground truth is required because of the small scale of such facilities. Since the roving space is limited, the localisation error must be measured at a smaller scale as well. However, one factor to note with such systems, is the illumination interference with IR based systems, such as IR cameras or Time-Of-Flight cameras. In order to circumvent this problem, active IR markers can be used to limit the IR illumination of the scene to an absolute minimum, while still maintaining the accuracy of the system.

4.8. Advantages & limitations of indoor testing grounds

Indoor testing facilities are great for regular testing where real sensor data can be gathered. Since these tests are being held in a controlled environment, they are also suitable to configure specific scenarios and edge cases. On the other hand, the size of these facilities is problematic for navigation purposes. The range of most sensors easily exceeds the size of most such facilities, and often the walls are being detected by localisation systems, regardless of active or passive sensor approaches. Additionally, the small environment can lead to only a limited number of navigation scenarios being tested. Nevertheless, testing in such locations will still yield favourable results with a good indication on the accuracy and the functionality of a navigation system on the lunar surface.

4.9. Existing datasets

One notable dataset of an indoor facility is the POLAR dataset [10]. It has been recorded at the NASA Ames lunar yard, specifically to test the robustness of stereo camera systems with regards to the lunar lighting conditions, and the material properties of lunar regolith. The dataset also provides a LIDAR based ground truth, to validate the stereo depth estimation.

5. OUTDOOR ANALOGUE FIELD TESTS

Before flying any system to the Moon, a long-range outdoor field test should be performed, to make sure the developed system has no bias towards the simulation environment or the indoor testing environment. A good example for the necessity of such tests is the development of the Mars Exploration Rover's (MER) HAZCAM visual odometry system, where the system performed well during indoor tests, but unfortunately, turned out to be biased towards features on the wall of the testing facility [18]. Once presented on the surface of Mars, the system did not perform as anticipated. Therefore, it is crucial to test outside of lab facilities, in order to detect any potential bias towards the testing environment.

5.1. Ideal locations

Ideal locations for testing are volcanic environments because the surface materials and rocks have similar optical properties as the ones on the Moon. There is also a limited amount of vegetation. This is especially significant because vegetation moves with the wind, creating moving features which would not be present on the lunar surface. Buildings should also be avoided as they produce very angular shapes and shadows, which are also not observed on the Moon. For example, volcanic areas such as Hawaii (USA), Cape Verde or Lanzarote (Spain) are good lunar analogue

Figure 6: Robex dataset from Mount Etna

locations. Alternatively, desert-like unstructured environments with little vegetation may also be useful, such as the Atacama (Chile) or Mojave (USA) deserts. For the latter, the optical properties may not be quite as accurate, but the bare unstructured environment is still useful, as it provides few visual features for navigation systems to properly localise.

5.2. Other locations to consider

Ultimately, it is not always a feasible option to travel to remote locations to perform the testing. When considering locations with easy access and/or closer in proximity, quarries are the most straight forward solution. To maximize the similarity between the analogue site and the lunar surface, it is advisable to look for an abandoned or out-of-hours basalt quarry with limited buildings and vegetation. The sand dunes of beaches and coastal areas can also be used for testing purposes if there is limited vegetation moving with the wind.

5.3. Existing datasets

Due to the cost and time needed for field testing, initial research can also be conducted on existing field test datasets. While they probably do not match your rover's size and sensor configuration, they are a good place to start testing algorithm and software implementations, before a testing platform is available. They can also be used as validation dataset, in order to test the software robustness in an additional environment. An example of such a lunar analogue dataset was recorded on mount Etna [2] (*Figure 6*).

Mars analogues should also be considered, as the primary difficulty of lunar navigation systems lies in the repetitiveness of the environment and the limited number of visual features that be used for tracking and matching. One such Mars analogue is available for the Moroccan desert [19].

5.4. Ground truth

There are two types of ground truth sources which can be used for outdoor field testing: differential GPS or optical surveying equipment [20]. The RTK-GPS solution gives a lot of flexibility, because it works in most places with good visibility of the sky and is capable of providing centimetre-level accuracy. If two GPS receivers are paired on the robotic platform, both position and orientation may also be estimated. However, the GPS signal can be subject to interference from other electronic systems onboard the testing platform. In such cases, shielding or receiver masts should be considered. The surveying equipment provides both position and orientation, but direct line of sight with a base station always needs to be guaranteed. Most total station surveying equipment can cover distances up to 1500 meters at an accuracy of up to 1.5 mm accuracy.

Particularly with GPS systems, longer traverses should be considered, in order to ensure that the constant ground truth error is smaller than the localisation error that we are trying to measure.

5.5. Advantages & limitations of field testing

The primary disadvantage of field testing remains the time and effort to organise a location, as well as the travel and delivery of the equipment. In addition, the illumination conditions of a field test cannot be fully controlled, as the Earth atmosphere scatters light, particularly in the blue spectrum. Our atmosphere also blocks certain parts of the IR spectrum which affect testing of active IR sensors such as LIDAR. This can be mitigated to an extent by testing at night with a controlled light source, which, in turn, limits the range of the field test. The main advantage of a field test is the longer range of the tests which can not be replicated in a lab environment. The outdoor tests are also necessary to make sure the tested systems are not bias towards our other testing environments.

6. CONCLUSION

When addressing the different options for testing navigation systems, it is important to consider all available options to mimic the environment of the lunar surface. Coming up with different testing strategies is an integral part when it comes to developing systems for space in order to cover all possible edge cases. Especially for lunar surface missions, this is difficult, because there is no single testing facility which can reliably reproduce all the environmental conditions encountered on the Moon.

Of the approaches presented, all have strengths and weaknesses when it comes to the fidelity of the testing. Indoor facilities, while producing accurate lighting conditions and a certain degree of repeatability but suffer from the small surface area of the test setup. Virtual environments can be configured at a large scale and allow for perfect repeatability for testing different parameters. However, they still experience limitations when it comes to reproducing environment detail and sensor artefacts. Outdoor analogues help with large scale environment testing, while having downsides with control over environmental conditions as well as a significant organisational overhead.

The outcome of this work provides a qualitative assessment of different testing approaches which can be used to test perceptions systems for the lunar surface. While none of the described environments can perfectly recreated the lunar surface, each approach has its own specific advantages. We therefore rely on the combination of all three methods to better assess the reliability of our systems. We also note that convenience is also a major factor, as time consuming test setups can significantly slow down the development process. Accurate and frequent testing remains a priority in order to deliver reliable systems, especially when developing systems for the lunar surface.

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