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Robotic Systems Lab
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Master Thesis

Autonomous Vision-based Safe Proximity Operation of a Future Mars Rotorcraft

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Contents

List of Acronyms

- **UAV:** Unmanned Aerial Vehicle
- **SFM:** Structure From Motion
- **LSD:** Landing Site Detection
- **LS:** Landing Site
- **BA:** Bundle Adjustment
- **DEM:** Dense Elevation Map
- **OMG:** Optimal Mixture of Gaussian
- **LOD:** Level Of Detail
- **HiRISE:** High Resolution Imaging Science Experiment
  (High Resolution Satellite Imagery on the Mars Reconnaissance Orbiter (MRO))
- **LRF:** Laser Range Finder
- **GT:** Ground Truth
- **LSM:** Landing Site Manager
- **FSM:** Finite State Machine
- **BT:** Behavior Tree

Abstract

An autonomous rotorcraft literally stands or falls on its reliable landing capabilities. When that same rotorcraft is on Mars, this procedure cannot fail even once. The LORNA (Long Range Navigation) project tackles this problem by introducing a Landing Site Detection (LSD) mechanism which aggregates Structure From Motion (SFM) point clouds into a multi resolution elevation map and performs landing site segmentation on the collected depth information. In this master's thesis we incorporated this landing site detection pipeline into an autonomy framework and implemented a behavior tree based landing mechanism to safely and efficiently select, verify and discard detected landing sites. Furthermore, the pipeline was enhanced using a stereo camera depth input alternative to SFM for lower altitudes to remove the necessity of lateral motion in order to perceive depth. The software was tested extensively in a gazebo simulation on different synthetic as well as recorded environments and different behaviors were considered and analyzed throughout various Monte Carlo iterations. The contributions in this work aim at enabling future Mars rotorcrafts to autonomously and reliably land at safe locations thus enabling a more daring aerial exploration of the red planet.

Chapter 1

Introduction

With the Ingenuity rotorcraft's lifecycle coming to an end, the question about future Mars rotorcrafts and their capabilities draws ever closer.
For the future NASA develops two different rotorcraft Mars concepts.

- Mars sample return helicopter concept

  The first is associated with the Mars Sample Return mission in which NASA's Perseverance rover collects Mars rock and sand samples in test tubes. These tubes are subsequently brought back to a sample retrieval landing platform from which a small rocket (Mars Ascent Vehicle) launches them into Mars orbit. There, ESA's Earth Return Orbiter will enclose them in a highly secure containment capsule and deliver them to Earth.

  In case that the Perseverance rover won't be able to collect the test samples and deliver them to the lander, a Mars Sample Return helicopter concept is envisioned. This is a rotorcraft for low altitudes equipped with a mechanical gripper in order to offer an alternative way of transporting Mars samples to the retrieval station should the Perseverance rover fail to do so.

- Mars Science Helicopter (MSH)

  Secondly, for future exploratory large distance missions, NASA is conceptualizing a Mars Science Helicopter (MSH) project. The aspirations for such a rotorcraft are on one hand to cover farther distances at high altitudes with accurate state estimation and on the other to land safely, autonomously and reliably in previously unknown terrain. These two feats allow a helicopter to perform much advanced science missions compared to Ingenuity.

The Long Range Navigation (LORNA) project that I have been involved with is working on a concept to tackle the second project's challenges while dealing with the constraints that rotorcraft missions on Mars provide us with. These are namely a limitation on the size and weight of the drone, a constraint on computational power due to the deployment on limited embedded processors and lastly a large delay in communication which makes adaptive remote control from Earth impossible.

1.1 Objective

The conclusive high level objective of the LORNA science concept is the achievement of long range safe navigation including global localization, safe landing site detection and full system autonomy. The navigation endeavor is tackled using a laser-range-finder augmented visual-inertial odometry state estimator which uses

map based localization to achieve global localization. Landing site acquisition is achieved using a structure from motion based 3D reconstruction of the terrain which is fed into the creation of a multi resolution dense elevation map used for landing zone segmentation. Finally, a state machine-based autonomy framework orchestrates the entire procedural workflow.
The endeavor in this thesis was to create a front to back landing mechanism that combines the existing vision based landing site detection algorithm with the autonomy framework. In order to accomplish this, both the landing site detection algorithm and the autonomy had to be altered. Last but not least, given that the structure from motion depth generation depends on lateral movement, which is less desirable for a drone navigating at low altitudes in unfamiliar surroundings, the utilization of a stereo camera for low altitude 3D reconstruction presents a viable solution to attain real-time depth perception without necessitating lateral displacement. A stereo camera is thus a light-weight solution which allows a drone to perceive depth statically as well as in vertical and lateral motion.

1.2 My Contribution

In this work, I established the interface between the vision based landing site detection algorithm and the autonomy framework in order to make informed landing decisions based on detected landing sites. A safe and efficient landing mechanism was implemented in the existing autonomy. This mechanism utilizes a novel stereo camera 3D reconstruction procedure to avoid lateral motion at low altitudes.

- **Stereo Camera Depth**

  A stereo camera was implemented in the simulated drone model in order to get stereo camera images. Additionally, a stereo camera depth node was put in place as an augmentation of SFM to supply the landing site detection algorithm with a point cloud at low altitudes without the need for lateral motion.

  An automatic switch was inserted between the SFM node and the stereo camera depth node by utilizing the already present laser range finder sensor on board. This allows for minimal computational overhead as only one depth creation node runs at a time.

- **Ground Truth**

  A ground truth depth node was created for two reasons. First it allowed the validation of the stereo camera depth output. Second, having a perfect point cloud of the terrain, specific testing of the autonomous landing behavior itself was possible.

- **Autonomy LSD Interface and Landing Site Handling**

  The landing site detection output initially only consisted of a one single site's location. This output was enhanced to utilize many more characteristics already present in the landing site detection algorithm in order for the autonomy to make a more informed decision in regard to what spot to select. These landing site properties are

  - Terrain roughness
  - Size
  - Terrain uncertainty
  - Detection altitude

  - Obstacle height

  The autonomy framework was expanded to correctly receive and sort incoming landing sites based on their individual heuristic score. Additional landing site handling mechanisms like re-detection, verification and banishment were introduced.

- **Behavior Tree for Adaptive Decisions**

  Using the existing behavior tree structure from the autonomy, an adaptive landing procedure consisting of both existing and novel actions was implemented. The implementation of the landing behavior optimized for both safety and efficiency.

- **Simulation Setup**

  As just recently the switch was made to Gazebo Garden the entire visual pipeline (SFM + LSD) had never run with this simulation environment before. Therefore, I implemented the changes necessary to run the landing site detection procedure on the Gazebo sensor input.

- **Deployment of LSD Pipeline onto an Embedded Processor**

  Currently, the used processor on the drone is modalAI's voxl2. Both the structure from motion and the landing site detection software did not run out of the box having an incompatible dependency handling with the voxl's AARCH architecture. Resolving these dependency issues, I was able to run the landing site detection pipeline with the structure from motion depth supply on the voxl2 using a collected rosbag of images and respective poses from the xVIO state estimator.

1.3 Organization of this Thesis

- **Related Work**

  As is custom, I will introduce the reader to what has been done in this area. Main focus will be placed on vision-based landing site detection procedures and previous work on autonomous landing.

- **System Overview**

  The entire project architecture will be outlined. Emphasis lies on the methods that I have heavily interacted with in this thesis. These are mainly the structure from motion depth generation, the landing site detection mechanism and the autonomy framework.

- **Methodology**

  Here I conceptually lay out the high level structure of the implemented work in this thesis. The two key contributions stereo depth and autonomous landing are introduced as well as the ground truth used.

  I will go into the reasoning of why a stereo camera is necessary as a low altitude depth alternative. Additionally, I analyze the stereo option theoretically and conclude its usage domain.

  I explain the ground truth depth source used in this work both in order to compare stereo with and to test the autonomous pipeline without the possibility of insufficient depth information. Additionally, I analyze the ground truth's comparability to SFM to ensure adequate testing of the autonomous landing pipeline.

Lastly, I outline the prerequisites for the implementation of the autonomous landing behavior and introduce the methodology of the final implementation in the behavior tree structure of the autonomy.

- **Stereo Camera Depth Alternative**

  This chapter elaborates on the stereo camera depth implementation. A coordinate frame overview is given and the entire process from sensor data handling to point cloud generation is discussed. Lastly it is qualitatively compared to a depth camera based ground truth.

- **Autonomous Landing Procedure**

  Here I will lay out the core contribution of this project which combines the existing system with the novel contributions of this work in order to put together a front to back autonomous landing procedure. First, I describe the interface between the autonomy and the landing site detection pipeline. Then I introduce the conceptual implementation of the landing procedure before I show its implementation in the form of a set of actions structured in a behavior tree. Lastly the working pipeline is shown in a case example of a science mission flown in simulation.

- **Evaluation**

  Here I introduce the test setup according to which I performed repeated randomized simulation flights. I introduce the outcome defining metrics and the results of the test flights. Lastly these results are analyzed numerically as well as visually considering the final choices of landing sites.

- **Conclusion**

  I summarize the novel contributions of this work and conclusively assess the characteristics and quality of the final landing pipeline. Shortcomings of the approach are pointed out and remedies are discussed.

- **Outlook**

  Further enhancements of the current systems are laid out and alternatives for future iterations are discussed. Also, emphasis is placed on current insufficiencies and the necessity of resolving them.

Chapter 2

Evaluation

2.1 SFM Insufficiencies

SFM is part of the LORNA pipeline and proofed to be a valid option for the endeavor tackled by LORNA. Prior to this work however, it was never tested extensively, especially at high altitudes (100 m).
Though very well performing when initialized successfully at low to mid-altitudes, SFM often had issues during startup and showed frequent insufficiencies when the drone rotated or when switching the key frames used for the stereo at high altitudes.

2.2 Experimental Setup

The pipeline was tested by repeatedly flying a mission with randomized initial conditions.
The performed experiments were flown on the following two maps:

- Arroyo Map - Map from the Arroyo Seco area outside the East entrance of the Jet Propulsion Laboratory. Predominantly used map during development

- Rough Test Map - A control environment designed to prevent LSD from detecting any landing site unless a landing platform is specifically spawned. It was created using blender and applying white noise perturbations to the elevation of a plane. Note that there is no texture projected onto the terrain. Therefore, on this map only ground truth was used.

Figure 2.1: Map of the Arroyo Seco area outside the Jet Propulsion Laboratory

Figure 2.2: Close Up of the Arroyo Map

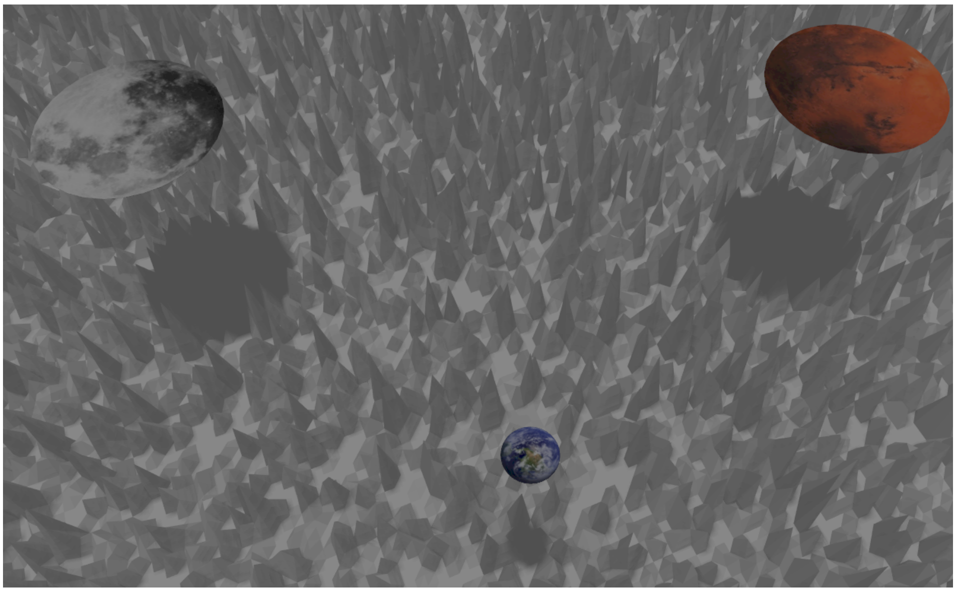

Figure 2.3: Synthetically created map with no landing sites apart from inserted landing platforms.

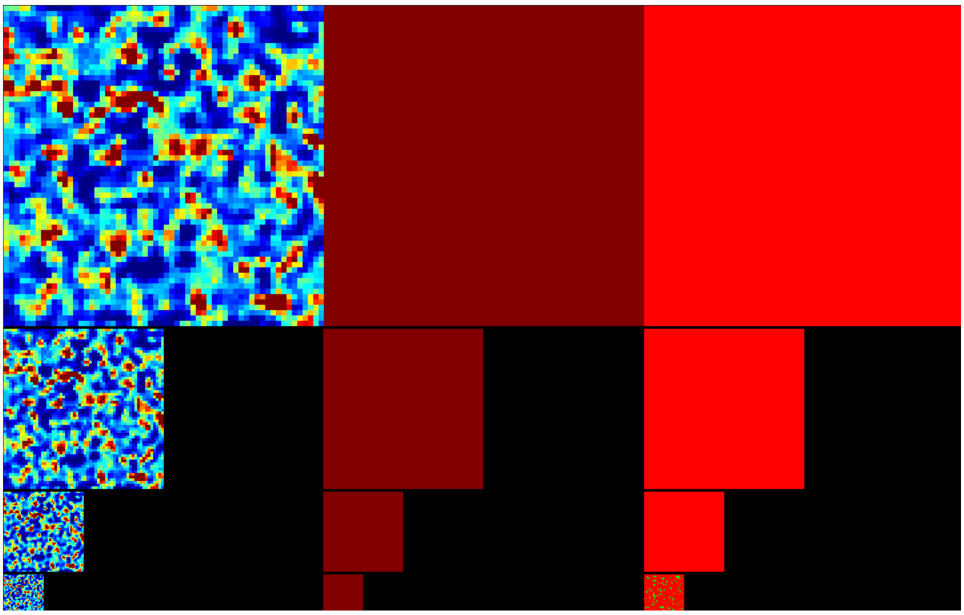

Figure 2.4: LSD debug output shown of the plain rough environment

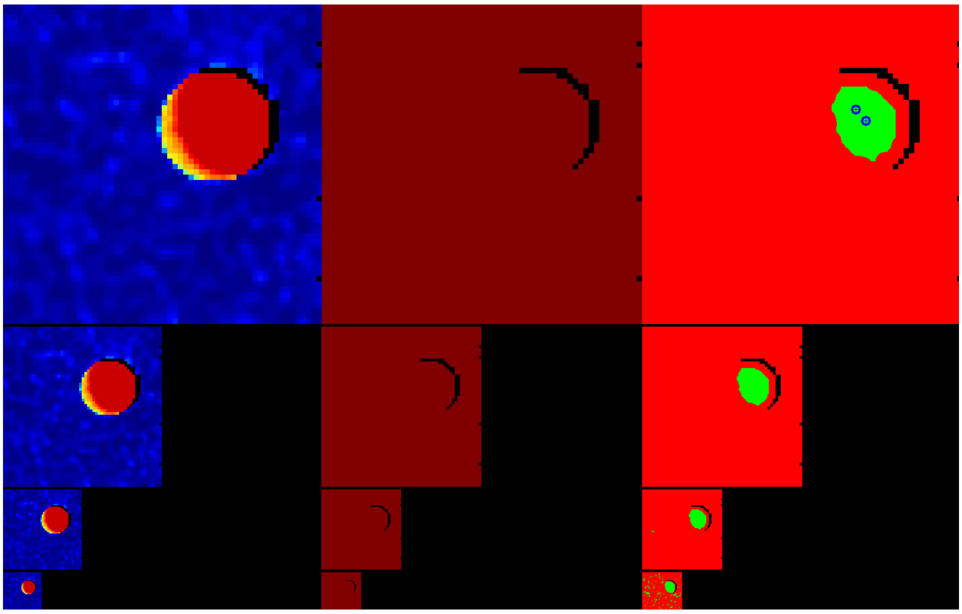

Figure 2.5: LSD debug image of the rough control map with spawned landing platforms

2.2.1 Drone Spawn

The drone was either spawned repeatedly from a default location on the ground (The start location from when the actual fields tests were performed) or from a random location. For a simplicity way of avoiding terrain collisions, the drone was spawned on a randomly positioned disk at 40 m altitude. The start disk's size was only 0.5 m in diameter which prevented it from being considered too good of a landing site by LSD. This is important because the platform implicitly gains quality due to the fact, that it is located higher up than the terrain, leading to a lower distance to the drone when flying at mission altitude.

Figure 2.6: Arroyo Map with Fixed Start Position

Figure 2.7: Arroyo map with randomly positioned spawn platform

2.2.2 Depth Source

As mentioned in ??, at the time of this work SFM was very fragile as an individual module. Because of this and to evaluate the merged pipeline as opposed to the depth generation module, ground truth depth was used at high altitudes unless specified otherwise. Regardless of whether ground truth or SFM was used, the verification at low altitudes was always performed using the point clouds from the stereo camera depth node.

2.2.3 Success Conditions

To determine whether a flight was successful or not, two main metrics were considered. First, whether the landing action in the autonomy was initiated (this happens only after the landing site selection and verification were both successful) and secondly to infer the safety of the rotorcraft, a rosbag was collected and analyzed to check whether either the roll or pitch value exceeded the crash threshold. In practice, a threshold of 1.2 radians or shortly below 70°proved to be an accurate decision boundary to detect a drone crash.

Home Landings

The drone lands at the home position in the two following cases:

- No landing sites exist to be chosen.

  This happens when very few landing sites were detected yet failed verification and were therefore banned or when no landing sites were detected in the first place.

  The latter case occurs in two scenarios:

  - The overflown terrain simply does not have a single landing site of decent quality. (see the rough map introduced in section 2.2)
  - The landing site detection algorithm failed to detect landing sites.

  In both scenarios, going home is the desired behavior. However, if LSD does not detect landing sites, the run cannot be counted as a success regardless of whether the drone landed safely after taking off.

  Looking at the Arroyo map shown in fig. 2.2 and speaking from development experience, sufficient landing sites should be found on this map. Therefore, landing at home when flying on the Arroyo indicates a landing site pipeline issue.

- A landing site is chosen at the home position.

  This is possible as the stereo camera detects landing sites on the takeoff location when ascending. However, given that the last mission waypoint is sufficiently far away from the takeoff location, the drone should land at a closer location.

2.2.4 Visual Analysis

To further analyze the randomized flights in a bit more detail, visual landing attempt projections are used. Such an analysis image is shown in fig. 2.8.
The green points indicate successful verifications which lead to the initiation of the landing action shortly after. (If no rotation above a failure threshold was detected, this is considered a successful landing.)

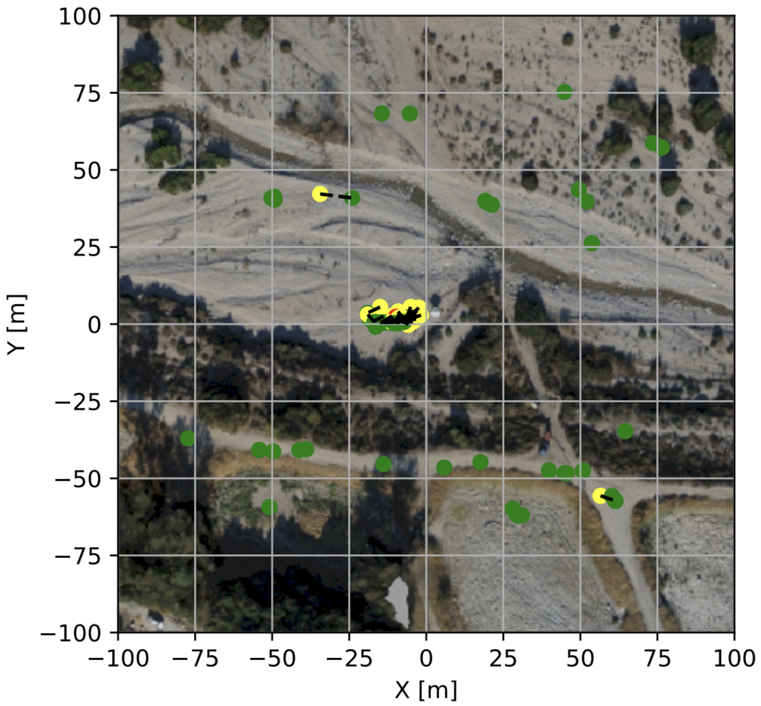

Figure 2.8: Landing Attempt dummy image - Green: successful landing, Yellow: verification failure, Blue: landing at home position

The yellow points are landing attempts, where a chosen landing site was not verified and thus banned from further consideration. It is crucial to note that not being able to verify a landing site is no issue at all. Landing sites detected at high altitudes merely provide a preliminary indication of potential landing zones. It is the subsequent phase, responsible for verifying these sites, that yields the refined final landing site knowledge used for landing. So selecting a landing site at high altitude, not being able to verify it and subsequently choosing a close by landing site detected during verification might even be called the most promising chain of actions in the pursuit of autonomous landing.
Lastly, blue points indicate successful landings achieved through the trigger of the landing-at-home action. As previously mentioned, When flying on a map with obvious landing opportunities, triggering the landing-at-home action indicates an issue with the landing site detection mechanism.
In the case of multiple attempts at verifying a landing site, connection lines are drawn between the failed attempts and the final landing indicating which subsequent sites were chosen.

2.2.5 Off Board Mode connection Issues

As will be presented in the following, connection failures between the PX4 flight controller and the autonomy occurred, leading to the deactivation of the off board mode and therefore the loss of control of the autonomy over the rotorcraft. These issues arose most likely because the MAVROS connection in between failed to send a necessary heartbeat repeatedly and thus the connection was intercepted.
Self-evidently, this did not result in a successful landing and was not counted as such. However, as these connection issues did not occur due to insufficiencies in the

pipeline presented in this work, they were not considered failures of the pipeline either.

2.3 Test Flights

2.3.1 Arroyo - Randomized Waypoints

When starting 100 times from the fixed position indicated in fig. 2.6 and flying to random mission waypoints at 100 m altitude in a 70x70m vicinity on the Arroyo map, the following results were achieved:

Table 2.1: Results with fixed takeoff and random waypoint

# Flights	# Successes	# Timeouts	# Crashes	# Home Landing
100	99	1	0	0

The landing attempt numerics are shown here:

Table 2.2: Landing attempts with fixed takeoff and random waypoint

# Flights	# Landing on first attempt	# 2 attempts	# 3 attempts
100	48	45	7

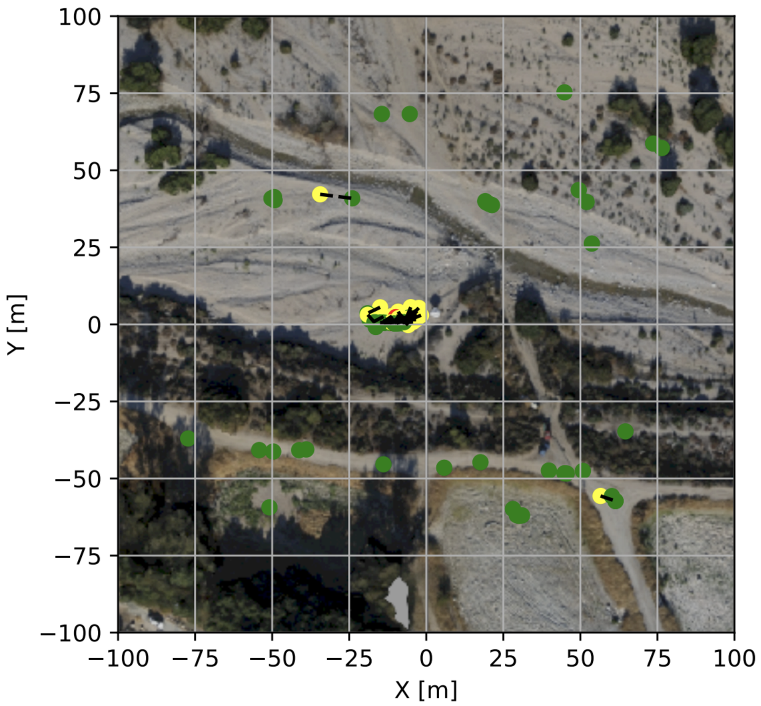

Figure 2.9: Landing Attempts - Green: successful landing, Yellow: verification failure, Blue: landing at home position

Numeric Discussion

table 2.1 shows the numeric outcome of the flights. 1 timeout occurred but each performed flight by the autonomy was a success, landing safely and controlled. No home landings were necessary which, as described above, indicates a very robust LSD performance. A high number of flights where two landing site verification attempts were performed is also well within acceptable boundaries because the first landing site might as well be used as an indicator to draw the drone closer to an area where high quality sites can be detected using the stereo camera.

Visual Discussion

Let's consider the landing image 2.9. The final landing sites indicated in green span exclusively decent landing areas. The verification attempts that fell short are indicated with yellow and annotated by a line connection to the successful attempt thereafter. Subsequent landing sites were always detected short distances away from failed candidates which is exactly the correct behavior in order to not lose time pursuing a far away landing site. As indicated in **??** this is thanks to the verification altitude which incentivizes the selection of other landing sites detected at the current verification altitude. Lastly the attempt which timed out is hardly visible indicated in red.
The last thing to mention is the clustering of the landing sites around the takeoff location. The reason for this is twofold:

- **Quality**: The takeoff position was also the takeoff position for the physical flights in performed in the field. It was chosen exactly because of its even and smooth characteristics. Therefore, it is no surprise that many landing sites were detected around that location.
- **OMG Conversion**: During ascent, when using either stereo or ground truth depth, the same area is perceived repeatedly. This leads to a convergence in certainty in the map aggregation step of LSD. As landing sites have a higher chance of being detected on terrain with a low uncertainty, the takeoff position is most likely selected until it leaves the rolling buffer map.

This test is a very clear demonstration of the applied chosen heuristics. The best landing site detected is very likely one that is detected at the takeoff position. Around this clustering of landings there is notable space of no attempts performed. This can be attributed to the competing motives of the landing site selection. The quality of the landing site defines the autonomy's choice until the drone's distance to that landing site is too big, and a closer one is chosen.

2.3.2 Arroyo - Randomized Takeoff and Waypoints

In this set of test flights, randomized takeoff positions were used as shown in fig. 2.7. Missions were built using a randomized waypoint in a 70x70m surrounding.
The numerical results look as follows:

Table 2.3: Results with random takeoff location and random waypoint

# Flights	# Successes	# Timeouts	# Crashes	# Home Landing
100	99	1	0	0

And the visual outcome:

Numeric Discussion

Exactly the same success rate was reached as in section 2.3.1. Notably however, many more attempts landed at the first site considered.

Table 2.4: Landing attempts with random takeoff and random waypoint

# Flights	# 1 attempt	# 2 attempts	# 3 attempts	# 4 attempts
100	78	15	5	2

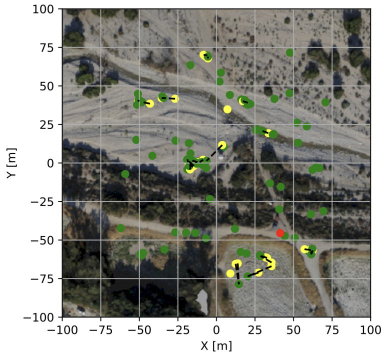

Figure 2.10: Landing attempts with randomized drone spawn - Green: successful landing, Yellow: verification failure, Blue: landing at home position

Visual Discussion

Compared to fig. 2.9, the landing attempts are more spread out over the map. Fewer landings were attempted at the takeoff position. This is the case because the area wasn't always covered by the mission's trajectory and the flights spent less time above that area as the drone spawned randomly. Thus, the pipeline did not converge at that location leading to a smaller chance of landing sites being detected there. As for the fixed spawn location, the second attempts were always at landing sites close by which is desirable.

2.3.3 Rough Map - Random Waypoints over Platforms

In this test, the drone flew a randomized two-waypoint pattern which always covered the synthetically added landing platforms. The idea behind this experiment was to eliminate other landing possibilities and test, whether the approach at hand would be able to detect the controlled good landing sites.
The numerical result thereof is displayed below:

Table 2.5: Results - Rough map with platform coverage

# Flights	# Successes	# Timeouts	# Crashes	# Home Landing
20	19	1	0	0

As both the spawn platform and the landing platforms where spawned randomly, evaluating the visual outcome is redundant. For sake of completion however, it is still displayed.

Numerical Discussion

One timeout occurred, but each attempt at landing resulted in a success.

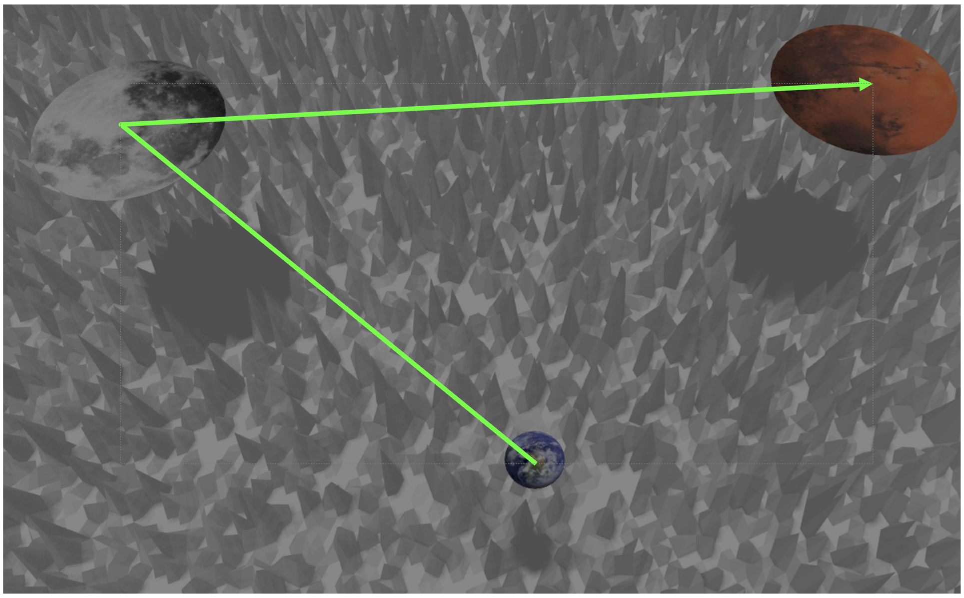

Figure 2.11: Test flights on rough map with waypoints covering the landing sites

Table 2.6: Landing attempts rough map with platform covering mission

# Flights	# Landing on first attempt	# 2 attempts	# 3 attempts
20	20	0	0

This proves that LSD does in fact not perceive convincing landing sites where there should be none. Additionally, as the drone never went home, this proves that LSD also detects landing sites where there should be safe landing zones.
Each landing site selected was verified. This convincing result is not surprising as the inserted landing sites are perfect landing sites and are therefore unlikely to trigger a verification failure.

2.3.4 Rough Map - Completely Random Waypoints

Changing the setup a bit, in this test, the drone flew a completely randomized two-waypoint pattern without the guarantee of flying over a safe landing site. This test set analyzed the pipeline's capabilities to deal with the case when no landing sites are detected initially.
The numerical result thereof is displayed below:

Table 2.7: Results - Rough map with platform coverage

# Flights	# Successes	# Timeouts	# Crashes	# Home Landing
20	19	1	0	6

Numerical Discussion

Notably, the drone went to the home position 6 times. This is the desired behavior, when no landing site was found and is therefore to be considered a success. Like

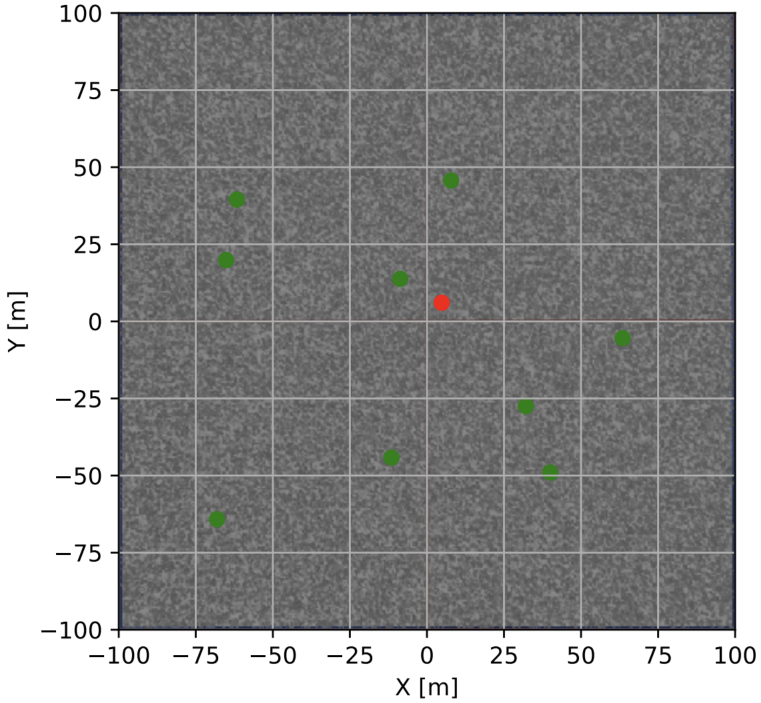

Figure 2.12: Landing attempt locations for the rough map with platform covered by the mission

Table 2.8: Landing attempts rough map without platform covering mission

# Flights	# Landing on first attempt	# 2 attempts	# 3 attempts
20	13	1	0

for the case when the platforms were covered by the mission, the landing sites were always verified as they were by design of high quality. One timeout remained also in this run.
In this test the setup was the same as for section 2.3.2 with the exception, that SFM was used for the depth generation.
The numerical result thereof is displayed below:

Table 2.9: Results - Rough map with platform coverage

# Flights	# Successes	# Timeouts	# Crashes	# Home Landing
20	19	1	0	0

As both the spawn platform and the landing platforms where spawned randomly, evaluating the visual outcome is redundant. For sake of completion however, it is still displayed.

Numerical Discussion

One timeout occurred, but each attempt at landing resulted in a success.

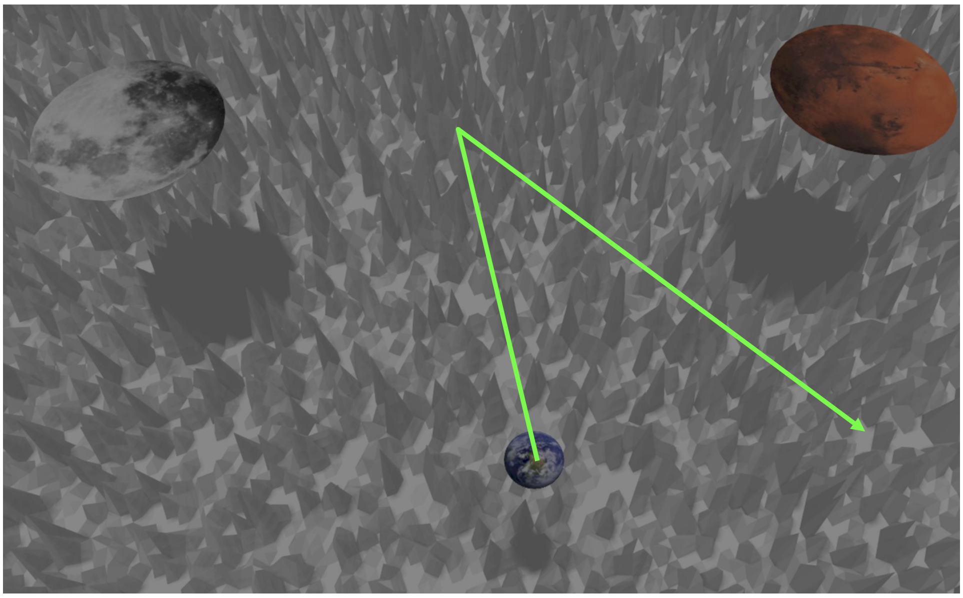

Figure 2.13: Test flights on rough map with waypoints covering the landing sites

Table 2.10: Landing attempts rough map with platform covering mission

# Flights	# Landing on first attempt	# 2 attempts	# 3 attempts
20	20	0	0

This proves that LSD does in fact not perceive convincing landing sites where there should be none. Additionally, as the drone never went home, this proves that LSD also detects landing sites where there should be safe landing zones.
Each landing site selected was verified. This convincing result is not surprising as the inserted landing sites are perfect landing sites and are therefore unlikely to trigger a verification failure.

2.4 Theoretical Edge Cases

section 2.3 shows that the implemented landing procedure performs well only terrain that is roughly comparable to that on Mars. These tests represent rather ordinary cases though. In the following, a number of theoretical edge cases are introduced and their handling by this work's pipeline discussed.

2.4.1 Arrival on Mars

One concept for the rotorcraft arrival on Mars is its takeoff during the descent of the main payload. In the Mars Sample Return mission which has since been aborted for instance, this payload would have been the landing platform to return the Mars samples to. From that lander the rotorcraft would take off mid-descent and land on its own.
Playing this scenario through, a small mission or pattern needs to be flown in order to move laterally and thus detect landing sites. Additionally, as the platform from which we took off is descending with neck-breaking velocity, we need to consider a different location for the choice of our home position. This can be done prior to

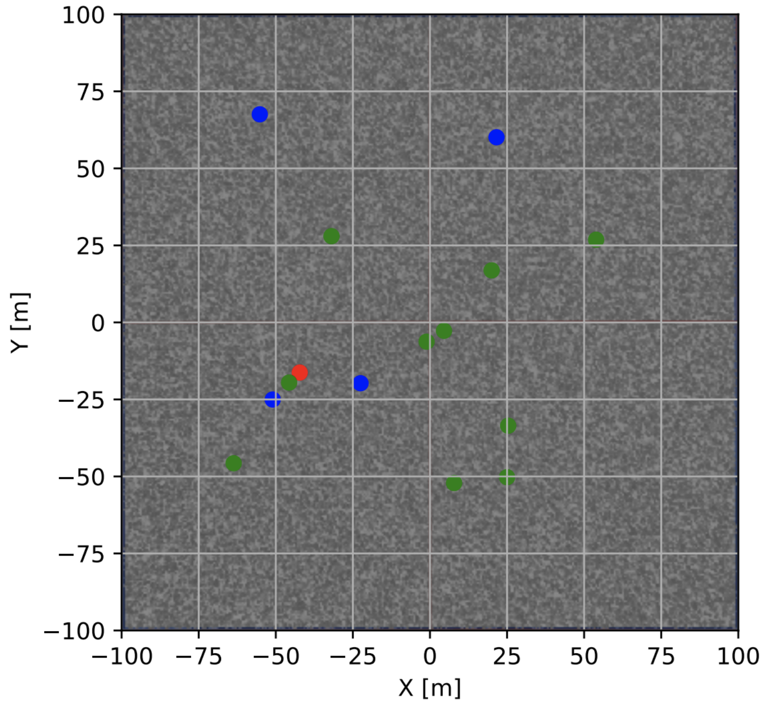

Figure 2.14: Landing attempt locations for the rough map with completely random missions

the flight using a mixture of HiRISE orbiter images and information provided by Opportunity and Ingenuity. The ladder two options also ensure a sufficient image resolution to safely determine a home position.
In case of successful landing site detection during this mission, the landing procedure is initiated as usual. If no candidates for suitable landing areas were found however, further landing site search patterns at random locations are flown. If the landing site buffer remains empty still, the aforementioned synthetic home position is navigated to and landed at.

2.4.2 Flying on Large Scale Inclined Terrain

The tests performed all happened on generally even terrain with rough and inclined areas spread throughout. What happens however, when we want to fly the drone over large scale inclined terrain? An example of this could be flying out of the Jezero crater which is where the Opportunity rover was deployed.
In this case, the necessary precautions must be taken during the mission planning stage. Assuming a mission was created at a cruise altitude high enough to allow lateral traversal to the farthest mission waypoint without danger of collision, the landing behavior would be the same.
Two possible break points exist however:

- Lack of number and quality of landing sites

  On inclined terrain fewer landing sites are detected. Secondly, a blind spot of the pipeline are unstable landing sites like larger rocks. Though the probability of landing on such a rock and thus making it fall over are very small, they exist. Even more so on inclined terrain.

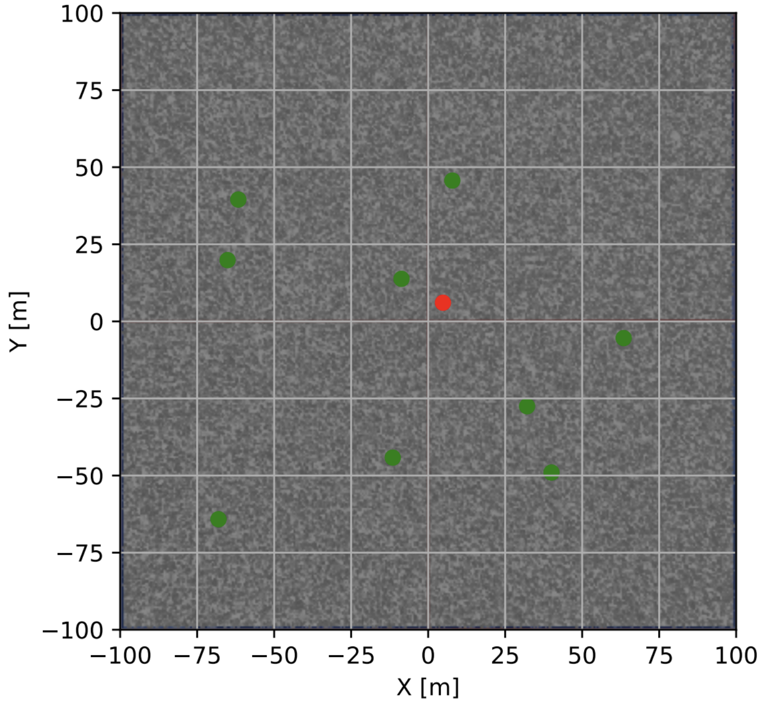

Figure 2.15: Landing attempt locations for the rough map with platform covered by the mission

- Collision danger when flying LS search patterns

  The mission waypoints are set deterministically. Therefore, the terrain can be accounted for during their creation.

  This is not the case for the random flight patterns execute when no landing sites are available. The center point of a rectangular search pattern is set randomly at a fixed distance from the location where the action was invoked. If during the mission a landing site was found at a very high altitude and turned out to be a false candidate, the LS search is initiated at that location. This case is schematically depicted in fig. 2.16. Note how the found landing site was detected at a significant distance from the last mission waypoint.

One more break case for the presented pipeline is overhanging terrain. In that case the ascent to a clearing altitude does not constitute a safe approach.
It has to be noted that the exploration of terrain as advanced as overhanging ground and cave systems is not considered part of the LORNA endeavour.

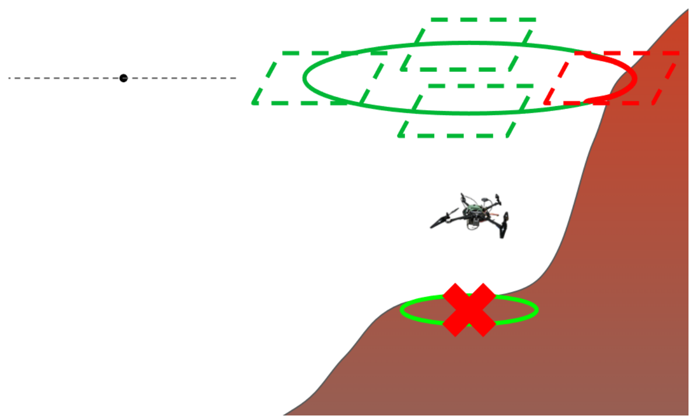

Figure 2.16: Break case of landing site search pattern. The black dot indicates the last mission waypoint at cruise altitude. The bright green circle with the red cross show an invalid landing site and the circle above the drone shows the possible center points of search patterns.

Bibliography