Robust Image Processing with Risk Consideration on Small Exploration Rovers

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I. Introduction

Since the dawn of humanity, our ancestors were inspired by and observed stars and celestial objects in the night sky. When technological advancements made it possible humanity ventured into space. Benefits of space exploration include scientific knowledge, innovation and inspiring future generations to have interest in science. The first remote controlled rover to land on a celestial body was Lunokhod1 sent to the Moon by the USSR and operated for over 10 months. Even more impressive is NASA's Curiosity rover sent to Mars which is still operational after more than 7 years. Planetary and asteroid missions will continue to be an important part of space exploration in the future to gather knowledge that can help us understand our world. For economic and safety reasons exploration rovers hold a key role in this. In the International Space Exploration Coordination Group (ISECG) mission plan for the future, multiple missions can be seen planned for the Moon or Mars [1]. On the other hand there are only a handful of missions aiming to reach the asteroid belt (NASA's Lucy and Psyche spacecrafts) as well as Jupiter and its moons (NASA's Europa Clipper, ESA's JUICE). The fact that large distance missions are outnumbered by shorter distance missions show that the physical limitations of large distances are still a huge barrier in space exploration.

II. Motivation and Research Concept

Although recently emerging companies like SpaceX are aiming to reduce the cost of space missions, putting 1kg of payload in Earth orbit is still around 20,000$ [2]. There are multiple factors including the number and type of scientific instruments equipped, but if we look at the different exploration rovers sent to Mars by NASA in table I, a clear correlation can be seen between the weight of rovers and cost of missions.

With such enormous expenses, space exploration remains accessible only for governments of wealthy and large nations and/or collaborations between multiple nations. The projects are often accompanied with large delays and the failure rate of launches is still relatively high. However there is an emerging trend of smaller spacecrafts, probes and landers that are more affordable, and a general push towards commercial space exploration. Piggyback contract rides are becoming popular, meaning along with a primary load of the rocket, additional secondary payloads are added. With this opportunity, smaller groups can develop a small size spacecraft or rover and pay a smaller amount to the organization responsible for the launch. If we think about the small Sorato rover of team Hakuto developed for the Google Lunar X Prize competition that only weights 4 kgs [6], the small hopping rovers of rovers of MINERVAII1 spacecraft by the Japan Aerospace Exploration Agency (JAXA) [7], or the planned CubeRover modular platform inspired by the successful CubeSat form factor, an emerging different approach to space exploration can be seen focusing on the development of small probes and rovers. This paradigm shift can accelerate research by making space exploration more widely available and also may hold the key to long-distance missions where the importance of weight is even more significant.

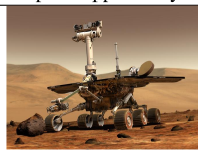
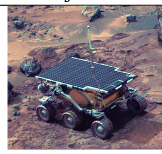
Name	Curiosity	Spirit/Opportunity	Sojourner
Image			
reference	[3]	[4]	[5]
Year	2012	2004	1997
Weight	899 [kg]	185 [kg]	11.5 [kg]
Cost	2500M [USD]	400M [USD]	40M [USD]

TABLE I: Comparing NASA Mars Exploration rovers

The main motivation for this research is to continue this trend of cost reduction by reducing the size and complexity of rovers, aiming to make space exploration affordable for smaller organizations, universities etc.

The difficulties of size reduction include increased difficulty of mobility caused by smaller wheel sizes in wheeled robots, difficulty of communication due to limited antenna sizes, difficulty of providing sufficient power and more. The scientific instruments used for exploration have to be limited and compromises have to be made with the sensors equipped as well. The safety and robustness of rovers however still have to be guaranteed. Conventional large exploration rovers use a number sophisticated and accurate sensors for navigation and obstacle avoidance. Since the rovers are heavy and carry sensible instruments, any mistake can have catastrophic consequences. This means that any risk is avoided altogether. On the other hand smaller rovers have to make compromises with the sensors carried, that increases the risk of unwanted events. On the other hand smaller size and less weight of rovers can be beneficial in the event of hitting obstacles, due to the smaller impact forces. This enables small rovers to take more risk during navigation to compensate for the lower abilities. This attitude means that instead of avoiding any risk, risks are evaluated and taken into consideration when designing the rover navigation system. By using less accurate sensors e.g. optical cameras instead of laser range finders, it is possible to cut down the weight and energy consumption of the rover, but also increases the risk of hitting obstacles while traveling. Images require more processing to compete with data acquired from more accurate sensors, but with more sophisticated algorithms they hold many possibilities. With the advancement of computational power and the ubiquity of optical cameras that are generally cheaper, lighter and more fail-safe present a low cost alternative in space exploration.

The concept of this research is to take the risk of using less accurate, but cheaper, lighter and smaller sensors (i.e. optical cameras) to make it possible to develop smaller rovers, but provide the same safety and robustness by evaluating risks using better image processing algorithms.

III. Robustness Improvement for Navigation of Small Rovers in Sparse Environments

In order to reduce the size of traditional wheeled exploration rovers compromises have to be made. The sensory system can be simplified to use only optical cameras and navigation can be performed using feature tracking based visual odometry. In small rovers the camera is closer to the ground providing worse image quality in unknown environments. Images are used for obtaining environmental data, then one or more distinct geographical features (landmarks) are extracted and tracked during movement. However it is difficult to determine what features are good to track during navigation. Conventional feature extraction techniques use corner or blob detectors such as SIFT, SURF and ORB. A study in 2017 found that SURF provided the best performance under Mars-like unknown environments [8].

However these extraction techniques use grayscale images. Therefore a novel landmark selection and tracking approach is proposed using textural distinctiveness based saliency detection and spatial information acquired from stereo data. Fig. 1 shows the overview of the proposed landmark selection and tracking system.

The goal of this research is to show that image processing methods can help to achieve a more robust navigation system using only optical cameras, creating a suitable method for smaller rovers with less resources. The presented landmark selection and tracking approach aims at selecting the best candidates for tracking and identifying obstacles in the environment to provide safe operation and make tracking more robust. The proposed landmark selection method is inspired by human vision traits i.e. understanding salient objects in the environment, even where distinct features are sparse to imitate what a real human operator would choose. While saliency detection is conventionally not used for feature point extraction, a saliency based approach can improve the results since it can add color and texture information. While conventional saliency detection algorithms value the center of the image more, in case of robot navigation the frames are only a projection of the 3D environment. To improve the robustness in long-distance navigation, landmarks that are more distant from the rover and along the travel path should be selected to avoid the sudden loss of landmarks due to frame-out. To quantify these requirements grayscale gradient maps are created, which are combined with the saliency map the create the landmark selection map. The most salient feature points are selected by an iterative algorithm from a textural distinctiveness based saliency map that is based on the algorithm proposed [9], [10], extended with spatial information, named Saliency Based Landmark Selection (SBLS). A repulsive potential field is created around the position of each already selected landmark for better spatial distribution of landmarks, further improving robustness by avoiding the loss of multiple landmarks in case of turning or occlusion. Fig. 2 shows an example of selected landmarks. In this particular image the white rocks stand out from the ground and the saliency of the landmarks can be confirmed easily. It can be concluded that the goal to prefer further and spatially distributed landmarks is achieved.

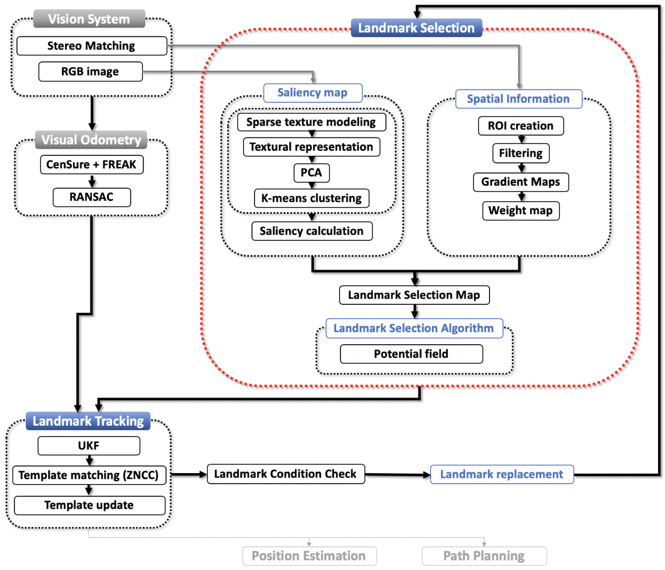


Fig. 1: System overview and the proposed landmark selection method marked red

Experiments were performed in a natural environment using the Micro-6 planetary exploration rover. The proposed method was compared with conventional extraction techniques based on the ability to match selected templates. Results conclude that the proposed method outperforms conventional methods especially in sparse environments. Long-distance tests concluded a robust operation and stable amount of landmarks visible at all times. The gradient map and potential field algorithm was applied to conventional methods as well and results show an improvement in the tracking robustness.

IV. Risk Consideration for Small Hopping Rovers

While traditional wheeled robots continue to be an essential part of space exploration, different approaches regarding motion types are also emerging. Space exploration rovers MINERVA-II1 launched by JAXA successfully landed and

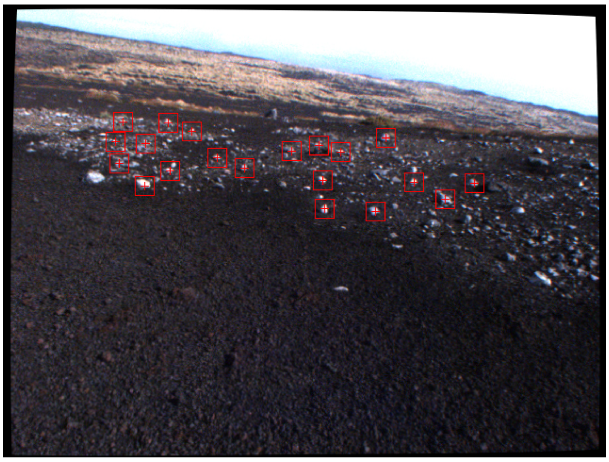


Fig. 2: Selected Landmarks

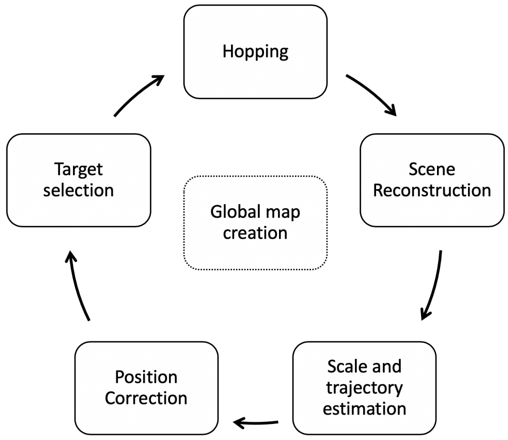


Fig. 3: Overview of the navigation system

recorded images of an asteroid surface the first time while moving with hopping motion [11]. The low gravity of such small celestial bodies make possible to utilize non-traditional movement types with low energy consumption. While in traditional rovers the wheel diameter limits the size of obstacles the robot can travel through, small jumping robots can simply hop over an obstacle eliminating the need for detour. However the increased risk of hitting obstacles have to be handled. By reducing the size of hopping rovers the energy requirements as well as possible impact forces can be greatly reduced.

For hopping rover navigation multiple approaches have been proposed including stereo camera systems such as the one on the spherical robot in [12], monocular camera system that use stereo cameras only for the initialization step [13] and systems that use multiple monocular cameras facing in different directions [14], [15]. While previous methods use multiple cameras, the proposed navigation system uses a single monocular camera to achieve the same while still providing safe and robust operation, showing that it is feasible to reduce the size of hopping rovers even further. This research uses a novel offline approach aiming at global consistency. Since during hopping we have no control over the rover, the reconstruction and localization step can be performed between jumps in an offline manner, making it possible to use every image taken during hopping at once instead of sequentially, improving accuracy and robustness.

Fig. 3 shows the overview of the proposed hopping rover navigation system. The proposed method is fully autonomous and is able to reconstruct the trajectory of the jump and create a map of the environment.

During hopping a monocular camera takes images of the environment. The camera poses and point cloud of the environment is reconstructed using a Structure from Motion (SfM) pipeline that provides detailed point clouds. The biggest difficulty of monocular camera systems is scale ambiguity. While some conventional methods utilize stereo vision for initialization before hops to determine the scale factor, the presented method relies only on monocular vision and solves this challenge by a trajectory and scale estimation method with the introduction of parabolic motion constraints and the a priori knowledge of the gravity vector that can be acquired by the accelerometers already equipped by the robot. Since no external forces work on the robot during flight, its center of gravity is moving along a parabola. The proposed algorithm finds the correct orientation and scale from the known gravitational constant and time of flight information and with these the scale factor is determined with high accuracy while eliminating the need for additional cameras. The reconstructed camera positions are projected to a plane using RANSAC to disregard outliers. Then a general conic section is fitted to the points using least squares method and after determining the orientation a parabola instead. The scale factor is calculated using the known gravity vector and time of flight and the point cloud and camera positions are scaled and transformed.

When landing the robot can hit the ground or an obstacle in a way that it bounces off to an unknown direction. However in successive jumps the launch position of a new jump is assumed to be the estimated landing position of the previous jump, because the uncertainty in landing deviation can be estimated but since the robot is too close to the surface at this point finding the exact position is challenging and unreliable using only camera images. To overcome this problem and make it possible to create an accurate global map and find the robot position in world coordinates, a position correction step is introduced using the created environmental point clouds of successive jumps. Alignment could be achieved by minimizing the difference between the two point clouds using the Iterative Closest Point (ICP) algorithm [16]. However conventional ICP algorithm performs poorly when there is only partial overlap between the point clouds. This problem is solved by matching only a smaller section of the clouds and iteratively eliminating the non-overlapping parts. With this method the aligned clouds can be used to create a seamless global map.

After estimating the current position of the robot it is necessary to select a suitable area for the next landing, taking into consideration the uncertainty of landing position to ensure the safety of the robot. The point cloud is projected to 2D creating a variable resolution image to preserve details and image processing is used to find landing position candidates. Obstacles and dangerous areas are identified with

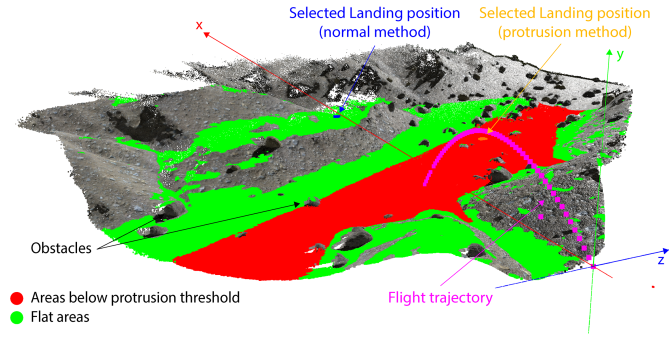


Fig. 4: Landing position selection methods based on protrusion and normals

two proposed methods based on the type of environment. For relatively flat surfaces a protrusion based method finds areas that are protruded from a ground plane, while a normal based method can identify slopes and obstacles using the normal vector of point cloud voxels. The uncertainties of motion is modeled and the resulting error ellipse is calculated for every pixel and used to find the possible landing areas. The best candidate is selected by using the distance transformed image of these areas combined with formulated gradient maps to ensure the ideal distance and direction of hops. Figure 4 shows the possible landing areas and selected landing position using the two different approaches in a rugged environment.

The proposed system was evaluated in the sandbox of a JAXA test facility to prove the feasibility of the method and that it can perform under low light conditions. Series of hops were reconstructed in a simulation where generated as well as photoscanned environments were recreated. Results conclude that the proposed navigation method is feasible and able to produce a detailed map of the environment.

V. Conclusions

From the experimental results it can be concluded that the proposed SBLS method is not only an alternative to conventional feature detectors but it can also outperform them, especially in sparse environments, making the navigation system more robust and lowering to risk of self position loss. A key element to the proposed method are the application of the weight map and repulsive potential field. The fusion of saliency map with weight map provides significantly better results and a more robust system. These results are further improved by the application of the repulsive potential field in the landmark selection algorithm. The robustness and adaptability to different environments also makes it suitable for outdoor navigation applications. The implemented system performs landmark selection in a few seconds depending on the input images which is fast enough for planetary exploration but not ideal for fast real-time applications, which is the main limitation of the system.

From the experimental results it can be concluded that the proposed navigation system for hopping rovers is feasible and makes it possible to use single monocular cameras simplifying hardware and widening the possibility for low-cost space missions. The proposed trajectory and scale estimation method is able to accurately determine the real scale and orientation of the environment for single hops and the introduced position correction method is able to eliminate errors caused by landing making long distance navigation and mapping possible. Furthermore both the protrusion and normal method based environment evaluation is able to identify and avoid obstacles ensuring the safety of the rover. The proposed target selection process can navigate the robot towards the desired direction with safety using the proposed error calculation model. The main limitation of the system is that path planning relies on the dense point cloud created in the previous hop since no other source of information is available about the environment.

Both proposed navigation systems show that by improving image processing algorithms, the size of exploration rovers can be reduced while maintaining the safety of rovers, making space exploration cheaper and more accessible that was the motivation for this research.

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