VISION-BASED NAVIGATION TECHNIQUES IN
PLANETARY ROVERS

Hans Baumgartner 6153583
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<tr>
<td>CCD</td>
<td>Charge-Coupled Device</td>
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<tr>
<td>CMOS</td>
<td>Complementary Metal Oxide Semiconductor</td>
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<td>DTM</td>
<td>Digital Terrain Model</td>
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<td>GPS</td>
<td>Global Positioning System</td>
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<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<td>MB</td>
<td>Mega Byte</td>
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<td>MER</td>
<td>Mars Exploration Rover</td>
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<tr>
<td>RAM</td>
<td>Random Access Memory</td>
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<td>RTK</td>
<td>Real Time Kinematic</td>
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1. INTRODUCTION

Planetary rovers are vehicles designed to move on the surface of a planet or another astronomical object. An essential part of a rover is navigation. Because rovers are located far from the Earth, real-time communication between the Earth operating center and rover is normally not possible. At the moment the most popular navigation technique in planetary rovers is based on visual sensors and vision-based navigation algorithms.

This report concentrates on vision-based localization techniques. Basic functions and phases used in navigation are discussed. The only active rover mission at the moment (2010) is Mars Exploration Rovers (MER), so especially techniques used in this mission are discussed.
2. PLANETARY ROVERS

Planetary rovers are vehicles designed to move on the surface of a planet or another astronomical body. There are two types of rovers, vehicles designed to transport humans (on the surface of the Moon) and partially or fully autonomous robots. This report concentrates only on the autonomous robot rovers designed to explore foreign planets. [1]

2.1 History

Rovers are very flexible exploring devices compared to stationary landers or orbiting spacecrafts. Because rovers are able to move, they can explore much wider area than stationary landers and be directed to interesting targets. Also physical experimentations are possible to make to analyze the surface and gases in the atmosphere. Some disadvantages of rovers compared to orbiting spacecrafts are the higher chance to failure, due to landing and other risks, and the limited and approximately anticipated exploring area. [1]

The first successfully landed rover was Soviet Lunokhod 1 landed on the Moon in November 1970. Lunokhod 1 was the first remotely controlled robot to land on any celestial body. Another significant milestone in the history of planetary rovers was the landing of Mars Pathfinder on July 1997. Mars Pathfinder included Sojourner rover which was the first rover on the surface of Mars. Pathfinder lander and Sojourner rover sent over 20 000 images from Mars. At the moment (2010) active rover missions in Mars are Mars Exploration Rovers involving two rovers, Spirit and Opportunity. The mission has been active since January 2004. [1]

![Figure 1](image1.jpg)  Examples of planetary rovers. Lunokhod 1 in the left most figure, Sojourner in the middle and Spirit/Opportunity in the right. [1]
2.2 Sensors in rovers

Rovers have plenty of different sensors to measure the environment of the planet. Many of the sensors are only for scientific measurements, but many of the sensors can also be used to help in navigation. This report examines vision-based navigation techniques in planetary rovers so only sensors used somehow in the navigation are discussed.

2.2.1 Vision-based sensors

In vision-based navigation the most important sensors are vision sensors. These sensors are devices designed to detect visible photons. There exist two main vision sensor technologies, CCD (Charge-Coupled Device) and CMOS (Complementary Metal Oxide Semiconductor). Both sensor types are devices organized as arrays of photo detectors which measure the amount of photons on the pixel surface during integration time. Sensors are made from silicon and they use the photoelectric effect in silicon to react photons. [2]

CCD technology was invented in 1969 and is the dominant technology used in commercial camera devices. The newer CMOS technology has some benefits over CCD, such as more efficient pixel reading, ease of production and smaller power consumption. However, CMOS cells are less sensitive than CCD and they provide lower resolution. [3]

2.2.2 Another sensors

In addition to cameras, vision-based navigation requires also other sensors to help to observe environment and the states of actuators. Examples of another sensors used in planetary rovers are wheel speed and position sensors, force/torque sensors, localization sensors and ranging sensors. These sensors are used help the vision-based navigation algorithm to get feedback values from the environment. These sensors together with the main cameras are used to move the rover. [3]

2.3 Autonomous navigation

Planetary rovers are used to explore the surface of an astronomical object far away. Nowadays and near future the most interesting planetary rover missions are executed in the planet Mars. Because of the distance between Earth and Mars, real-time controlling of the rover is not possible. Also, because of the difficulty in communication, autonomy may be needed for a vehicle on the far side of the Moon. For example the Mars Exploration Rover
vehicles are typically commanded only once per solar day using a prescheduled sequence of precise metrically specified commands (e.g., “drive forward 2.34 m, turn in place 0.3567 radians to the right, drive to location X,Y, take color pictures of the terrain at location X,Y,Z”)[4][5]

A basic vision-based navigation procedure consists of several functions: localization, mapping, mission planning, path planning and acting. In the localization phase the rover determines its present location. Mapping phase includes the mapping of the environment based on data from orbital satellites and former locations of the rover. In mission and path planning functions the goal and way to reach it is determined and finally the acting phase executes the plan. [3]
3. LOCALIZATION

Localization is a key function in autonomous robots. Keeping track of a vehicle’s location is one of the most challenging aspects of planetary rover operations. On the surface of Earth, a simple and common localization method is to use GPS (Global Positioning System) receiver. A real time kinematic (RTK) GPS can reach an accuracy of 1 cm if enough satellites are visible. Unfortunately, satellite positioning system is available only on the planet Earth so another localization technology has to be used in planetary rovers. [6]

3.1 Wheel odometry

Wheel odometry is a relative positioning system, which uses wheel encoders and a simple method called “odometry” to estimate linear movement. Since wheel revolutions correspond to linear travel distance, on smooth and flat terrain odometry is reliable and reasonably accurate method to measure the travelled distance. However, on off-road terrain, especially on soft, sandy soil, odometry is not very reliable, because the wheels slip and the measurement of wheel rotations does not corresponds to travel distance anymore. Figure 2 shows an illustrative example of wheel odometry error accumulation. [7]

![Figure 2](image)

**Figure 2** Wheel odometry error during straight line motion of 30 meters on a gravel surface. [8]

As can be seen in figure 2 travel error caused by the wheel slippage accumulates very fast. In real environment, such as Mars, the terrain is usually sand or gravel so wheels slip frequently. Some correction methods to avoid accumulating odometry errors have been developed. For example by measuring the currents of the electrical motors rotating the wheels, slips can be detected and some level of error correction made. Also by comparing the rotation speeds of
different wheels or by using gyroscopes, slipping is possible to detect and error correction made. [7] [9]

3.2 Visual odometry

Because of the poor performance of the wheel odometry, other localization methods have been developed to improve the rover localization accuracy. Vision-based approach is one of the most attractive solutions. In addition to localization information, it is also possible to use the vision system for 3D modeling. NASA’s two Mars Exploration Rovers have used visual odometry since their landing in 2004. Visual odometry is not used alone to localize the rover, but to assist wheel odometry. After moving a small amount on a slippery surface, the rovers are normally commanded to use visual odometry to correct the wheel odometry estimation. [10]

In planetary rovers, visual system consists of two cameras providing stereovision. Also an omnidirectional camera is possible to use but in planetary rover missions this solution has not been used. For example the MER visual odometry system comprises onboard software for comparing images from two stereo cameras. The resolution of the MER navigation cameras is 256 x 256 pixels. [10]

The basic operating principle of visual odometry is as follows: for a given pair of frames, (1) detect features in each frame (corner detection), (2) match features between frames (sum of absolute differences), (3) find the largest set of self-consistent matches and (4) find the frame-to-frame motion that minimizes the re-projection error for found features. Figure 3 tries to visualize the basic principle of visual odometry based on stereovision and pixel tracking. [11]
One major problem in pixel tracking is the choice of suitable pixels. In order to avoid wrong correspondence, one must make sure that the pixels can be faithfully tracked. One method to select the tracked pixels is to do pixel selection in three steps. An *a priori* selection is done on the basis of an error model of the stereo algorithm; an empirical model of the pixel tracking algorithm is used to discard the dubious pixels during the tracking phase; and finally an outlier rejection is performed when computing an estimate of displacement between two stereo frames. MERs use also the on-board wheel odometry as an approximation of the movement to find probable locations of the tracked pixels. [12] [13]

Even though visual odometry is much more complex method to localize a rover, its accuracy is better than the accuracy of wheel odometry. Figure 4 presents test results from a four wheel rover travelling on a paved surface.
Figure 4  Test results showing a path of a four wheel rover run on a paved surface of a parking lot. Red line is the real travelling path, dashed green line estimation of a wheel odometry and dashed blue line estimation from visual odometry. [8]

As can be seen in figure 4, visual odometry alone can provide better accuracy than wheel odometry. The cumulative error in the estimated position over the distance of 4.5 m for wheel odometry is over 24\% and for visual odometry 3.6\%. [8]
3.3 Mapping

In active planetary missions (Mars Exploration Rovers) mapping is made before landing, and during and after the rover operation. Cartographical map of the landing site can be made by using the data from orbiting satellite. These maps can be produces in advance, long time before landing. When the rover has landed, locally taken high-resolution images are matched with the landmarks in the orbital images. Only the essential computations for moving and local mapping is made on the rover computers, other calculations, image processing and image matching is made on the orbiting satellite or on Earth. [13]

Images from the on-board cameras are used to construct a local map of the rover’s surrounding terrain. Mars Exploration Rovers use panoramic images to generate orthophoto maps (aerial maps), each of which covers an area of 60 x 60 meters. Detailed rock locations, orientation, and map scale are all presented in the orthophoto maps. Constructive orthophoto maps connected along the traverse describe the large-scale topography across the landing site. These orthophoto maps are used after construction in path planning. Figure 5 shows one orthophoto map constructed by Spirit MER. [14]

![Mars Exploration Rover orthophoto map of Laguna Hollow (60 x 60 m, 1 cm/pixel)](image-url)
4. MISSION AND PATH PLANNING

After maps have been constructed, interesting targets to explore can be found. After suitable target has been determined, the best path to reach it needs to be found. Suitable path is found with the help of maps constructed by the on-board cameras. Part of the terrain model is a goodness map, which is a grid based map, presenting an overhead view of the mapped terrain. Each grid cell in the map contains a goodness value. High goodness values indicate easily traversable terrain, and low goodness values indicate hazardous or unreachable areas. Figure 6 shows a principle of a goodness map. [15]

![Goodness Map Diagram](image)

**Figure 6** Basic principle of a goodness map. In left image is presented an overhead view of the rover. The middle image is the correspondent goodness map and a Field D* map is shown in the right image. [15]

The right most image in figure 6 presents a Field D* map. Field D* algorithm is a path planning algorithm that calculates the best path between two map locations. Algorithm uses a grid based map representation of an environment to calculate the path. Each grid cell is assigned a cost value, which indicates how hard/easy it is to travel through the cell. The algorithm generates a path between two locations, with the aim of minimizing the cost of traversing that path. [15]

As can be seen in figure 6 the goodness map and Field D* cost map are very similar. However, there are some major differences between these maps. Field D* plans on a global scale and must therefore store a much larger map. The goodness map is always centered on the rover location, and stores only information about the local terrain. Goodness map also
moves along with the rover, whereas Field D* map is fixed to the environment and does not move along with the rover. [15]

Field D* map is initialized before use. Initializing cells to a low cost means the rover will be much more inclined to explore unseen regions. Initializing to a high cost means that the rover will prefer to stay in regions it has already seen. The grid size of the goodness and Field D* cost maps are same and the map updating is made in concert. At each step of the traverse, the position of the goodness map inside the larger Field D* cost map is determined. Then each known goodness cell is translated into a cost value and placed into the corresponding cost map cell. [15]

Path computations are made by using the onboard computers. The computational power is very limited; the onboard computer uses a radiation hardened RAD6K processor running at 20 MHz and has 128 MB of RAM. The computer needs to handle 97 tasks, so the path planning algorithms are highly optimized. Also the bandwidth to send data to the Earth is limited. The data can be grouped into two categories; engineering data and science data. Engineering data is used to monitor the rover status and science data contains information about Mars that is of interest to scientists. Because the aim of Mars missions is to collect as much scientific data as possible, it is desirable to limit the engineering data to a minimum in order to maximize the amount of scientific data. [15]
5. CONCLUSION

Vision-based navigation techniques are the most efficient way to navigate a rover in foreign planetary environments. At the moment, the most interesting concerns are the existing and future planetary rovers in the planet Mars. Vision-based navigation algorithms have been developed more than twenty years, but the performance of the algorithms is not as good as it might be. Especially practical problems in image processing and pixel tracking are very challenging. To teach a computer to find interesting targets from a pixel based images is challenging and erroneous tracking occurs. In addition, the very limited computation power available in planetary missions restricts the algorithm complexity. Due to the difficulties and restrictions in vision-based navigation, rover movements are also relatively slow.

However, vision-based navigation is now days the most attractive navigation method. Despite the complexity and difficulties in the technology, successful mission in Mars has been made and good results achieved.
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