Mapping and Navigation for Planetary Rovers Based on 3D Terrain Analysis

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論文内容要旨

Due to the success of the robotic exploration and scientific missions still being carried out by the Mars Exploration Rovers (MERS), the interest of the space exploration community has recently started to shift towards applying the lessons learned in Mars to the Moon. Since the Apollo era, multiple unmanned missions have flown into orbit or had impact with the Moon. The focus of these missions is now shifting to autonomous landing and surface locomotion by robotic devices on and around a specific area of scientific interest. Mobile robotic exploration can be a precursor for future human settlements on the Moon and In-Situ Resource Utilization (ISRU) is one important aspect in the selection process of candidate locations for such settlements. In order to continuously supply these future settlements with energy, water and other basic elements, it is necessary to find a location where these resources are plentiful. As proposed by Watson in the early 1960's, the characteristics of the Moon's equatorial plane position with respect to the Sun suggest deposits from which water can be extracted might be found at the bottom of craters located at its Polar regions.

Terrain elevation data of the surface of the Moon obtained from lunar orbiting missions can be used to generate a path for a wheeled mobile robot (WMR or rover). The rover can follow such a path to reach a given destination at the lunar Polar regions while negotiating any obstacles it encounters. Unfortunately, the resolution of the data gathered by these missions is rather low; hence, the path generated from these data can only be used as a guideline to the desired destination. This path, however, can be reconfigured through a local path computed using the data gathered by a Light Detection and Ranging device (LiDAR) system carried by the rover.

A significant issue that arises when gathering terrain elevation data of a given surface or environment with a LiDAR sensory system is the occlusion effect. Certain terrain features of the environment may produce this occluding effect on the ranging device, thus limiting the field of view of the sensor producing occluded or non-visible areas within the surveyed environment. Therefore, it is important to have the capability to estimate the topography of these occluded areas in order to provide the rover with a better understanding of its surroundings and the ability to navigate them accordingly.

In general, planetary exploration rovers are expected to navigate through long distances and perform complex scientific tasks in order to fulfill their challenging mission goals. The lunar soil presents various features, known as the maria, terrae, craters and the regolith. The irregular terrain presents the rover with mobility hazards that could damage the vehicle and the mission itself. Planning an appropriate local path to avoid these mobility hazards is vital for the exploration mission to be successful. This research, therefore, addresses: 1) the identification of the occlusion effect in any given mapped area, 2) the estimation of the topography of the identified occluded regions of a map, and 3) the provision of a path planning method that enables the navigation of the rover.

Maximizing the observable area within the space surrounding the vehicle in a poorly illuminated site such as the lunar Polar regions is very important. This dissertation approaches the occlusion problem to develop a criterion called the visibility index. This criterion is used to classify the different regions within a given local map based on the occlusion effect exerted on the ranging sensory system.

The occlusion present in the ranging measurements of a LiDAR device translates into a lack of information of the environment being mapped by the sensor. A method is proposed to estimate the topography of these occluded areas and to allow the reconstruction of the map that was generated upon the data gathered by the laser range sensor. Numerical simulations and experiments were carried out to validate this estimation method.

Having characterized the terrain, determined the occluded areas and estimated the topographic characteristics of these occluded regions, it is possible to calculate the destination at every local map the rover would go to. This position is called the next sensing position. This local goal represents the next destination of the robot, a place to where it can have the maximum the observable area in the next mapping procedure in order to locate the global desired goal within the line of sight of the LiDAR mounted on the vehicle.

The proposed path planning strategy creates a path as a collection of way points, starting from the rover's initial position and finishing at the next computed sensing position. The rover then implements the follow-the-carrot path tracking strategy to execute this collection of points until it reaches its final destination. While following the instructed local path, the mobile robot's knowledge of its own position can be affected by the characteristic incremental error present in dead reckoning techniques. One method to minimize this error is to find the movement between two consecutive data sets (in the form of a cloud of points) obtained from the implemented sensory system. This method is based on the Iterative Closest Point algorithm which finds the movement between data sets and then matches them based on the recognition of different features present in the measured environment. In natural terrain, however, the recognition of such features is a difficult task.

In this dissertation, a technique that considers this issue is developed and its numerical and experimental results are reported.

Finally, various sets of experiments that demonstrate the effectiveness of the proposed mapping and navigation system are explained and their results are presented.

The main contributions of this dissertation are summarized as follows:

- The different characteristics of a laser range sensor were addressed. In addition, a probabilistic model that can be used to determine the accuracy of its measurements was described.
- The concept of occlusion and its effects on laser range sensors in indoor and outdoor environments was explained and analyzed in detail. A methodology to determine the size of the areas affect by the occlusion was developed and validated.
- The quantification of the occlusion effect on a given local map enabled the classification of the map in order to determined the areas where a mobile robot may move and the areas that may represent a hazard to the vehicle.
- An algorithm to determine the position from which the vehicle can maximize the estimated non-occluded area in the next local map was developed.
- The estimation of the topographic parameters of natural terrain was described. The areas perceived by the laser range sensor as occluded were reconstructed using the proposed heuristic method.
- A path planning strategy that combines two different methodologies was put forward. This strategy includes the next sensing position and the characterization made by the quantification of the occlusion effect.
- An extension to the feature recognition procedure of the Iterative Closest Point algorithm was proposed and tested in indoor and outdoor environments.

These contributions are expected to further contribute to future mobile robotic planetary exploration missions by enabling the vehicle to determine the occluded areas within its known local and global maps. By estimating the occluded areas, the vehicle should be able to circumvent possible hazards, augment the local map and avoid hazards that would have been encountered if only a global path were to have been employed.

論文審査結果の要旨

ロボットによる月面探査計画が，各国の宇宙機関において議論されている。月面探査における興味のひとつは月の極域土壌中に存在可能性が指摘されている H_2O 氷の発見であり，もしも採掘可能な氷が発見されれば，今後の有人基地の開発や有人長期滞在へ向けて有益な資源となりうる。アポロ計画などこれまでなされてきた月面探査と異なり，無人ロボットによる極域氷探査を行うためには，暗闇の中において自律的に障害物を避けながら安全に目的地へ到達する能力が求められる。2007 年に打ち上げられた日本の探査機「かぐや」では，月の全表面に対して約 10m の精度の地形図が作られた。これは，グローバルな視点から探査目標を定めるのに有益な情報であるが，月面上に着陸したロボットが表面移動探査を行うためには，ロボットの視点からより高精度のローカルな地形図を作製し，グローバルな探査目標と整合をとりつつ自律ナビゲーションを行うことが必要である。

本論文は，月を含む様々な天体（惑星と総称する）において，照明条件によらずに 3 次元的に地形を認識し，ローカルな地図を生成しながら，与えられた目標点へ向けて自律的なナビゲーションを行うための手法について論じたものであり，全編 6 章よりなる。

第 1 章は序論であり，本研究の背景および目的を述べている。

第 2 章では，移動ロボットの運動学および動力学のモデル化について示し，本研究で用いる探査ロボットの力学モデルおよびシステム概要について述べている。

第 3 章では，照明条件によらずに 3 次元的に地形を計測可能とする方式として，赤外線レーザー光を用いた能動的な距離センサ（LIDAR）を用いることを提案し，以下の 3 点について論じている。第一に LIDAR 計測により構築される 3 次元地形図の精度について検討し，本研究で用いたセンサシステムによる測距性能を具体的に評価している。第二に，自然地形をモデル化する手法としてフラクタルを用いた方法を提案し，2 つのパラメータの組み合わせにより様々な地形を表現できることを示している。第三に，LIDAR 計測において，障害物の陰などのデータが欠損している領域を，地形フラクタルモデルに基づいて推定する手法を開発し，実用的に有効なことを示している。これらは非常に重要な提案および成果である。

第 4 章では，ロボット近傍の障害物によって陰の領域が計測できない問題（オクルージョン問題）を論じている。3 次元地形が与えられたとき，ある視点より LIDAR 計測が可能か否かを判定するアルゴリズムを開発し，計測可能な領域の広さを定量的に示す数値として Visibility Index と名づける指標を提案している。これは有用な提案である。

第 5 章では，障害物によるオクルージョン領域が多い場合において，効率的にローカルな移動経路を生成しナビゲーションを行う方法を提案し，その有効性をシミュレーションおよび実験により検証している。グローバルな探査目標に向かってローカルな移動経路を計画する問題に対し，LIDAR によりローカルな地形図を作製し，第 3 章において提案されたフラクタルモデルに基づいてオクルージョン領域の地形を推定し，第 4 章において提案された Visibility Index を評価指標として探査経路を決定する方法を開発している。Visibility Index が最大となるローカルな移動目標点を Next Sensing Point (NSP)と名づけ，NSP へ向けて障害物を回避しながら自律的に移動するアルゴリズムが示されている。現実的な屋外環境において LIDAR 計測，地形推定，NSP 決定，移動を繰り返し，ローカルな地形図を拡張しながら移動探査を継続し，グローバルな目標点に到達する実験を行い，提案する手法の有効性を検証している。これは非常に有益な成果である。

第 6 章は結論である。

以上要するに，本論文は，月惑星探査のための移動ロボットにおいて，照明条件によらずに 3 次元的に地形を認識し，ローカルな地図を生成し，障害物を推定しながら，与えられた目標点へ向けて効率的な自律的ナビゲーションを行う手法を開発し，実験によりその有効性を確認したものであり，航空宇宙工学および宇宙探査工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。