Online Slip Estimation for Mobile Robot Localization and Reactive Path Planning on Rough and Deformable Terrain

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論 文 内 容 要 旨

Since the high-magnitude earthquakes of March 2011, the eruption potential of many active volcanoes in Japan has increased. Once a volcano erupts, it induces severe disasters, such as pyroclastic and debris flows. To efficiently evacuate an area threatened by a volcanic disaster, the onsite observation of active volcanoes is desired to generate real-time hazard maps. However, when the eruption alert level is high, approaching such volcanoes is prohibited because human observation is difficult and dangerous. Therefore, mobile ground exploration robots are desired and currently being developed.

For a volcano exploration mission, a specific scenario was assumed in this research. As the first step of the assumed scenario, the operator brings the robot to the outer border of the alert area. The operator then defines the goal position or area for the observation. Thereafter, the robot begins to travel to the desired goal autonomously. During the autonomous exploration, the robot obtains a map of the surrounding terrain using the on-board sensor (sensing). Based on the obtained environmental information, the robot plans a path that avoids wheel-terrain slippage (path planning). The robot estimates its position and attitude (localization) while traveling through the unknown terrain (mobility). An autonomous exploration is required for the scenario because the target environment is unknown, which makes it difficult to obtain and present sufficient environmental information to the remote operator. In addition, because of the eruption, communications may be unstable. The terms in parentheses indicates the main technologies required for the scenario. As shown in the scenario, various types of technologies must be developed and integrated for the volcano exploration system.

In these cases, the robot systems need to travel on unknown terrain. However, traveling on unknown terrain causes many problems. One of the biggest problems is caused by wheel-terrain slippage on rough and deformable terrain. Because the terrain is unknown, it is difficult to make assumptions about the slippage states and assess the traveling performance beforehand, because wheel-terrain interaction on an unknown terrain is too complex and uncertain to estimate. In such an environment, the localization accuracy decreases significantly.

In addition, when the slippage peaks, the wheels of the robot run idle. Obviously, such a condition must be avoided for mobile robot. This means that a robot traveling on rough and deformable terrain should plan a path to prevent occurrence of large slippage. However, estimating quantitative slippage occurrence on rough and deformable terrain beforehand is difficult, especially on unknown terrain. This research focused on the above two problems, localization and path planning in consideration of the wheel terrain slippage.

Localization, which accurately estimates the current position and attitude of a mobile robot, is fundamental to such robots because accurate localization is mandatory for accurate mapping or path planning. One of the most basic localization methods is wheel/gyro-based odometry. The accumulation of error, which is mainly caused by wheel-terrain slippage, is innate to and unavoidable in odometry. It is therefore widely accepted that odometry should be combined with another localization method such as a global positioning system (GPS), using a particle filter algorithm. This is known as Monte Carlo localization (MCL). The author implemented a general example of an MCL algorithm and performed several field experiments on rough and deformable terrain to confirm its validity and limitations. The results showed that the occurrence of the wheel-terrain slippage may have decreased the reliability of the odometry motion model, which led to the difference between the positions of the used particles and the measured GPS positions. Assuming a large uncertainty in the motion model is one of the ways to prevent this difference. However, this is equal to decreasing the reliability of the odometry motion model. To develop an accurate motion model for a mobile robot traveling through an unknown outdoor environment, it is essential to take the wheel-terrain slippage into consideration. If the slippage could be roughly estimated online, it could be used to significantly enhance the reliability of the motion model.

When planning a safe path to the desired position, the wheel-terrain slippage is also an important problem for such robots in an unknown outdoor environment. Path planning for such environments requires an evaluation of the expected traveling performance in the target environment. However, in an unknown environment, defining the quantitative traveling performance is difficult because the wheel-terrain interaction on unknown terrain is too complex and uncertain to model. Quantitative evaluation criteria for the traveling performance are required for the path planner.

The above two problems — the occurrence of error in the motion model caused by the wheel-terrain slippage and the evaluation of the quantitative traveling performance − are independent problems. However, the author assumes that the essential issue for these problems is accurately expressing a specific unknown, wheel-terrain interaction, quantitatively. If it was possible to use the expression, the role of the wheel-terrain interaction could be modeled in the odometry motion model, and the traveling performance on the planned paths could be evaluated quantitatively.

Wheel-terrain slippage is generally digitalized as the "slip ratio," which is determined from the wheel rotational velocity and the actual observed velocity. To estimate the slip ratio, the author focused on the relationship between the slip ratio and the slope angle. The correlation between the slip ratio and the slope angle is quasi-linear, except when the slope angle is very large. As long as the environment is uniform, an almost accurate slip ratio can be estimated from the slope angle once the relationship is obtained. The set of the two parameters (the gradient and offset) used to express this simple relationship is called the slippage property. This is the key property for solving the above two problems in this research. Considering rough and deformable terrain, the purposes of this research are, to develop an accurate localization method based on the wheel-terrain slippage in the odometry motion model, and to develop a path planner based on the quantitative evaluation of the traveling performance.

The idea of the slippage property is integrated into the general MCL algorithm. Though there are a variety of filtering algorithm based on a particle filter, the author uses a well-known basic particle filtering algorithm, the sequential, importance, and resampling (SIR) filter, as the basis of the filter. The general MCL algorithm is extended to estimate the slippage property online. The proposed algorithm estimates not only the position and orientation but also the slippage property. Because the slippage property parameters are initially unknown, they are uniformly distributed in the particles. After the robot begins to move, each particle assumes a specific slip ratio based on its slippage property and the pitch angle of the robot at that time. Each particle is then transited based on an adjustment in the odometry readings using the derived slip ratio. After several instances of updating the particles using the filtering algorithm, those that survive are the ones that more accurately evaluate the position, orientation, and slippage property.

In this research, the combination of odometry and GPS was selected for the fused localization based on a particle filter algorithm. The proposed method was implemented in our mobile robot, and several field experiments were conducted in desert environments to validate it. The experimental results indicated that the proposed filtering algorithm can compensate for the error in the motion model caused by wheel-terrain slippage and prevent a decrease in the localization accuracy even on rough and deformable terrain, compared with the general MCL. In addition, the proposed method can also estimate a roughly accurate slip ratio online based on the estimated slippage property and the pitch angle.

Although the slippage property used the parameters to improve the motion model of the mobile robot, it can also be used as an index for the traveling performance, because it expresses the specific relationship between the robot and the terrain at the time. A novel cost function for the path planner is proposed to involve the online-estimated slippage property. Based on this cost function, the proposed path planner can plan a path that minimizes the online-estimated slippage on the path. Based on the above strategy, the author proposed a path planning scheme that consists of three steps: construction, propagation, and extraction. In the first step, an extended elevation map (EEM) is constructed. EEM is a voxel-based environmental expression and has a 3-D space defined by the X, Y, and orientation as the axes of the coordinates. Then, in the next step, the reach cost of the voxels in EEM is determined by accumulating the results of the transition cost function, which determines the cost to transit from one voxel to another voxel based on the distance, turning motion, and slip ratio, in turns in ascending order from the lowest reach cost. This propagation is repeated from the start voxel until the propagation reaches the goal voxel or its neighbor voxels. Finally, the third step extracts the path from the goal to the start based on the registered cost. Because the cost function of the path planning uses the specific parameters of the slippage property, when the robot detects a change in the parameters while following the path, it is necessary to re-plan the path based on the newly obtained parameters for the slippage property. Based on this approach, the planner can plan a safe path even across the unknown terrain.

The proposed method was implemented and several simulations were performed to confirm the paths planned by the proposed method by comparing the conventional path planner with the general simple cost function. The simulation results confirmed that the path planned by the proposed method differed from that by the conventional one. In addition, the planned paths also differ relying on the difference of the slippage properties on the terrain. From these results, it was confirmed that the proposed reactive path planning scheme plans a path to prevent the occurrence of the high slip ratio even across unknown terrain that involves the various distribution of the true slippage property.

The research outcomes described above are expected to contribute to develop the future mobile exploration robots working on rough and deformable unknown terrains. By importing the slippage property in the odometry motion model of a mobile robot, the robot can adapt to the wheel-terrain interaction states even across the dynamically changing unknown environment. In addition, by using the slippage property as the parameters of the cost function of the path planner, the planner can estimate a safe path based on not only the terrain shape but also the states of the wheel-terrain interaction.

論文審査結果の要旨

2011年の東日本大震災以降，我が国の火山活動は活発化しており，火山噴火時の情報収集のため，火口付近の立入禁止区域において，自律的に移動探査が可能な移動ロボットの実現が望まれている。しかしながら，火山表面は細かな砂や砂利で覆われた軟弱斜面であるため，車輪と地面との間にスリップが生じやすく，このスリップが，移動ロボットの自律移動に必要不可欠である自己位置推定の精度低下をもたらすことが知られている。そこで，本研究では，スリップ現象と斜度の関係を表現するslippage propertyという指標を考案し，これを用いた軟弱斜面における移動ロボットの自己位置推定精度の向上ならびに，この指標の不整地経路計画への応用について論じている。本論文は，これらの研究成果をまとめたものであり，全編5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，移動ロボットの位置推定に幅広く利用されているparticle filterを用いた自己位置推定手法と，これを軟弱斜面で利用する際の問題点について述べている。移動ロボットが軟弱斜面を走行する際，スリップ現象が発生することでparticle filterで利用するモーションモデルと実際の現象の乖離が大きくなり，自己位置推定が破綻する場合があることを，実際の軟弱斜面における移動ロボットの長距離走行実験により明らかにしている。これは重要な知見である。

第3章では，軟弱斜面でのスリップによる移動ロボットの位置推定精度の低下問題を解決するため，移動ロボットのスリップ現象と軟弱斜面の斜度との関係を表すslippage propertyという指標を提案している。これをparticle filterを用いた自己位置推定手法のモーションモデルに組み込み，この指標をオンライン推定することで，軟弱斜面における精度の高い移動ロボットの自己位置推定手法を提案している。さらに，複数の軟弱斜面における移動ロボットの長距離走行実験により，提案手法の有効性を示している。これは，重要な成果である。

第4章では，オンライン推定されたslippage propertyを評価関数に加えることで，スリップの発生を低減する経路を生成することが可能な，新たな移動ロボットの不整地経路計画手法を提案している。この手法は，移動ロボットの走行にともなってslippage propertyが変化した場合にも，適宜経路の再計画を可能とするため，土壌変化に頑強な経路計画手法となっている。シミュレーションによりこの手法の妥当性が示されており，これは有用な成果である。

第5章は結論である。

以上要するに，本論文は，軟弱斜面で走行する移動ロボットのスリップ現象と斜度との関係を表すslippage propertyという指標の提案ならびに，その指標を用いた，移動ロボットの自己位置推定精度の向上と不整地経路計画への応用について論じたものである。シミュレーションならびに実機実験により，提案手法の妥当性が示されており，その成果は，航空宇宙工学及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。