Abstract
論文の内容の要旨

論文題目　Study on Hopping Behavior Strategy for Planetary Exploration
（惑星探査のための跳躍移動戦略に関する研究）

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This thesis focuses on the hopping motion strategy for planetary exploration. Planetary exploration robots, called rover, have been developed by many space agencies and private companies. These robots have to act on rough terrains, such as sandy terrain, steep slope, or steps. Future missions require to explore such terrains where many scientists expected to get a lot of scientific evidences. However, these terrains are hard to traverse for conventional wheeled rovers. Hopping rover, called hopper, is one of the locomotion platforms which are expected to be able to traverse on rough terrains. Although many studies proposed and developed hopping systems, few planetary exploration missions using hopper still have been realized. In particular, there are no examples of hopping exploration missions on Moon and Mars. In order to realize the exploration by hopper, this thesis proposes a hopping behavior strategy with considering terrain conditions.

Planetary surfaces, such as the moon or Mars, are largely covered with rocks, stones, boulders and a fine-grained loose, soft soil called regolith. These natural terrains, unlike the hard or artificial ground, are mostly composed of rheologically complex soft material and easy to deform and hence the traversal efficiency of rover become low on flowable ground. Sometimes, this type of terrain can lead to unexpected hazards that can cause mission failure. To explore rough terrains, the interaction between the locomotive platforms and soil is one of the most important subjects. This challenge helps not only the explanation of physical

characteristics of soil, but also the design of mobility robots. The mechanics of wheel-terrain interactions have been investigated in the field of Terramechanics. The interaction between soil and non-wheeled locomotion, particularly dynamic locomotion, such as jumping or legged locomotion, has more challenges than the interaction between soil and wheels. Jumping is an intermittent locomotion. This characteristic requires the estimation of hopping track for motion control. This paper proposes a pressure-sinkage model based on the resistive force theory (RFT). Although the conventional RFT model helped explain the kinematics of slow-moving locomotors, some studies have also shown the importance of dynamic effects of highspeed interactions. This paper adds a velocity term into the RFT model as a dynamic effect. To demonstrate the effectiveness of the proposed approach, simulations and experiments were conducted. The simulations and experiments measure hopping distance and height. Comparing the experimental results to the simulated results, only the RFT simulations' values are estimated much lower than the experimental values for both height and distance. These results show that dynamic effects, such as for the velocity term, are also necessary for the estimation or analysis of hopping distance or height with any hopping direction on granular media. Comparing the simulation results with the dynamic effects, the error margin decreases with the error being about 7.5% at most. These results indicate that the proposed model is suit for hopping motion estimation better than than conventional models.

This paper also proposes novel foot pad designs for efficient traverse of hoppers using the proposed model. In order to improve locomotion efficiency of rovers on natural terrains, there are mainly two methods: an adaptive motion control depending on environments, and a hardware design which improve traversability. This paper focuses on hardware design because hardware designs greatly affects motion control. The performance of locomotion on granular media is lower than on hard ground, because it is harder to get friction than on hard ground. Thus, mobile robots require additional equipment for their locomotion on such terrain. The hopper used in this paper consists of two main parts: the hopper body and the contact part with the ground, called foot pad. The foot pad installs grousers to prevent slippage. First, the effectiveness of grousers is observed on hard ground and soft soil. It is thought that grousers better grip ground than flat pads on hard ground, and hence dynamic friction increases. Grousers also prevent slip by inserting into sand. In particular, the energy efficiency by using grousers is better on soft soil grousers than using flat pad. This paper presents the Soil interaction based (SIB) grouser shape as the solution of a multi-objective optimization problem (MOP) based on the proposed soil interaction model. The MOP decides the grouser shapes which are maximizing hopping distance and height on sandy terrains. The experiments are tested with only the injection angle 45 [deg], and compared with straight grousers, V-shape grousers and SIB grousers. The results show that all grouser pads perform much better than the flat pad.

Compared to the straight grouser pad, the V grouser pad and the SIB grouser pad improve the hopping distance: the V grouser increases about 4 [%], and the SIB grouser increases about 11 [%].

One of the challenges is the path planning problems. The detailed conditions of planetary surface cannot be known before robot has arrived on such and explore the celestial body. The environments have uncertainties of locomotion. In addition, planetary surfaces are almost covered with granular media, called regolith. The sandy terrains might cause the robot to get stuck. Therefore, hopping path planning algorithms are essential in order to investigate such terrains, or environments by the hopper. The proposed algorithm can calculate the optimized action in each state using the markov decision processes (MDPs). This means that when a hopper fails to follow the planned path, it is able to resume the locomotion immediately without re-calculating a path. The proposed algorithm is classified as a 2.5D path planning by adding the constraint of the hopping trajectory for collision check. MDPs define the motion uncertainty as probability. And calculate the optimal path which maximize the value function. This paper proposes a payoff function for hopping path planning. The proposed function includes a safety cost and an information gain. The safety cost is proportioned to the roughness of terrain. The information gain is proportional to the height of the terrain, because hopper can get the information about the environment around the hopper to make the map on high place, such as a rock or a step. The performance of the proposed algorithm is demonstrated by simulations. The simulation uses an artificial rough terrain which is expressed as digital elevation map. The simulations are tested for three cases: only prioritizing safety, only prioritizing information gain, and both. In the case of prioritizing safety, the path from the initial state selects the flat terrains. In the case of prioritizing information gain, the hopper makes the path what traverse on places as high as possible to get the information about the environment. The path considering both the information gain and the safety moves on relatively flat terrain at first. Then, coming near the goal, the hopper selects the path on the high place. The algorithm can generate a path in heterogeneous environment which has hard ground and sandy terrain.

One of the contributions of this paper is to validate the hopper performance in planetary-like environments using a 3D simulator. In order to develop the hopper, the validation of the performance using 3D simulator is important, because it is difficult to test in actual planetary environments. This work employs a two-wheeled robot equipped with a hopping mechanism. This design allows different modes of locomotion and improves the traversability of the robot on rough terrains. The robot uses the wheels on relatively flat terrain and gentle slopes, and to change directions. Hopping locomotion is used to clear an obstacle, step, cliff, or to escape from a stuck position. The results indicate that the larger hopping distance is, the smaller the gravitational level is. The robot needs three times hopping on the moon, and four times on the earth. However, the robot cannot reach the goal. The robot stuck on the sunken place and could not escape form the place. This is why the robot have to choose a hopping pattern depends on the terrain condition. In order to improve hopping performance, we use the reinforcement learning. Reinforcement learning is one of the most active field of machine learning. Robotics is one of the applications of reinforcement learning. The advantages of the reinforcement learning for robotics are that it does not depend on the environment, and it can be applied in case of changing the environment where a robot act. After finished learning, the weight of neural network is applied to the hopping simulation. Although the robot can reach the goal by reinforcement learning, the robot performs the unrealistic locomotion, such as driving on single wheel on slope. The result indicate that the locomotion by reinforcement learning needs constraints to generate the real motion.

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