Ph.D Thesis

博士論文(要約)

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)

by

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Chapter 1

Introduction

Planetary surface exploration has been conducted using wheeled vehicle robots, called rover. Lunokhod 1 and 2, and Chang'E-3 and -4 had been developed to explore the Moon and succeeded in their missions. The Martian surfaces had been explored by Sojourner, Spirit and Opportunity, and has been being explored by Curiosity. Recently, various environments, such as a Recurring Slope Lineae (RSL), are expected to research by robots. However, such environments are often hard to traverse using wheeled rovers. Hopping locomotion is one of the solutions to perform on challenging terrains. In practice, a few hopping rovers have been designed to traverse difficult terrains in high-level gravity environments [1, 2, 3]. The effectiveness of hopping has been shown by a few missions for low- or ultra-low gravity celestial bodies: MASCOT developed by DLR and MINERVA-II in the Hayabusa-2 mission [4] succeeded their exploration on the Ryugu asteroid. As other hoppers, there are the MINERVA [5] in the Hayabusa mission and the PrOP-F [6] in the USSR Phobos-2 mission. Planetary surfaces are almost covered with granular media, called regolith. Although rovers have to traverse on such terrains, they have faced various difficulties by locomotion on soft soil. In fact, Spirit got involved in trouble when Spirit was moving on sandy terrain. The trouble is that Spirit got ‘stuck’ in sand, and could not escape from the embedding in sand.

In order to improve locomotion efficiency of rovers on natural terrains, there are mainly two methods: an adaptive motion planning depending on environments, and a hardware design which improve traversability. This paper presents the motion strategy of a hopping rover with wheels for planetary surface exploration. Hopping rovers have not been used for actual planetary exploration so far, because there are a lot of challenges to be tackled; hardware and software designs. Although some studies have proposed hopping mechanisms for planetary explorations, there don't consider the effect of sandy soil features. This study focuses on the hybrid rover design which considers the soil interaction and the motion uncertainty caused by sandy terrain.

The purpose of this study is to realize the lunar or planetary explorations by hopping rovers. In order to archive the purpose, this research discoveries about locomotion on natural terrains. This paper presents the four main results :

- Modeling the hopping-soil interaction
- A novel foot pad design to improve the hopping performance on soft soil.
- A hopping path planning algorithm with motion uncertainty
- Motion control of wheel and hopping in planetary environment

Section 2 introduces the soil interaction model to estimate the hopping motion on soft soil. Section 3 presents the proposed designs of the foot pads for effective hopping locomotion on granular media. Section 4 describes the hopping path planning with motion uncertainty. Section5 express the motion control of wheel and hopping locomotion in planetary environments. Finally, Section 6 summaries this paper.

Chapter 2

Hopping-Soil Interaction Model

This section introduces the proposed hopping-soil interaction model. The conventional soil interaction models, called "Terramechanics", are reviewed. And then, the details of the proposed model are explained and evaluated through the experiments and simulations.

2.1 The conventional model

The resistive force theory (RFT)[7] is based on empirical models from experimental results, in which the resistive forces of a small plate move freely in granular media. The strong points of this model are follows: i) a linear model in regards to sinkage despite soil materials, ii) being able to apply to any directional motions and any shape of mobility. RFT model is formulated as below:

$$F_{z,x} = \zeta \int \alpha_{z,x}(\beta, \gamma) z dA \tag{2.1}$$

where $\alpha_{z,x}$,dA, z, β, γ, and ζ denote the resistive stress per unit depth, the area of the stepper, the sinkage depth from soil surface, attack angle of intruder, intrusion angle of plate, the soil parameter called scaling factor (SF), respectively. Fig.2.1 shows the motion of a micro plate in granular media.

2.2 The proposed model

Although RFT has helped explain the kinematics of slow-moving locomotors, some studies[8, 9, 10] have also shown the importance of dynamic effects of high-speed

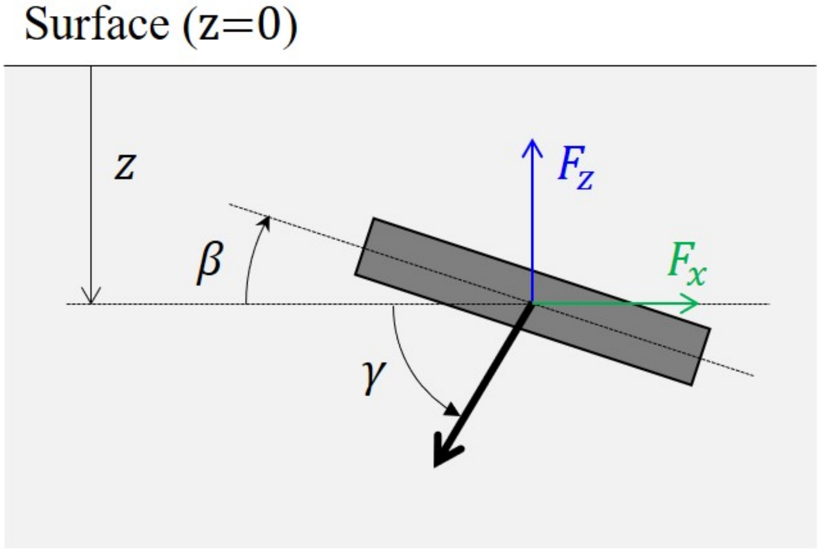


Figure 2.1: The image of RFT model.

interactions. Our studies had also confirmed that RFT cannot estimate the hopping motion on soft soil enough. The proposed model is described as:

$$F_{\mathrm{GM}} = F_{RFT} + \xi v^2 \tag{2.2}$$

where F_{GM}, F_{RFT}, ξ, and v denote the reaction force from granular media, the resistive force calculated by Eq.(2.1), the inertial drag coefficient, and the velocity of a micro plate.

2.3 Comparison study

To demonstrate the effectiveness of the proposed approach, I conduct simulations and experiments. The motion of the hopper is simulated numerically, and the hopping height and distance are calculated in the simulation. In this simulation, the hopper is treated as mass points and the attitude and rotation of hopper are not considered. The experimental setup and the hopper are shown in Fig.2.2. The initial position and angle are measured by a goniometer, and the errors on the initial angle were less than ±0.5 [deg]. The tested soil is silica sand which grain size ranges from 0.3 [mm] to 0.6 [mm], the angle of repose is 34.45±.92 [deg] (mean ± standard deviation (s.d.)), and the bulk density is 1.75 [g/cm^3]. Through hopping experiments, hopping height and distance are measured with various injection angles and foot angles. Then, by

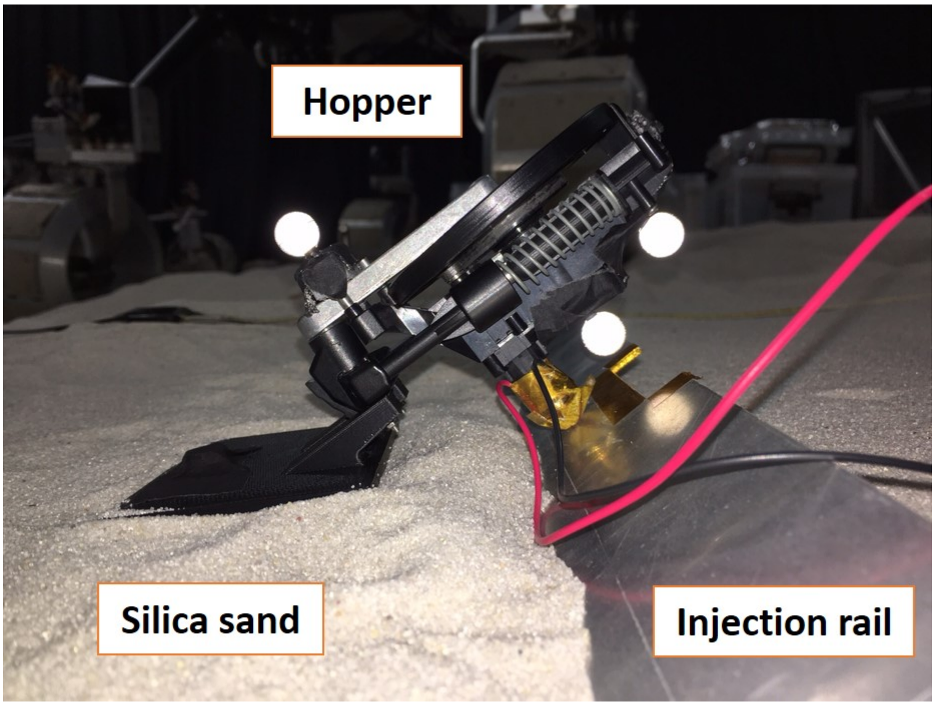
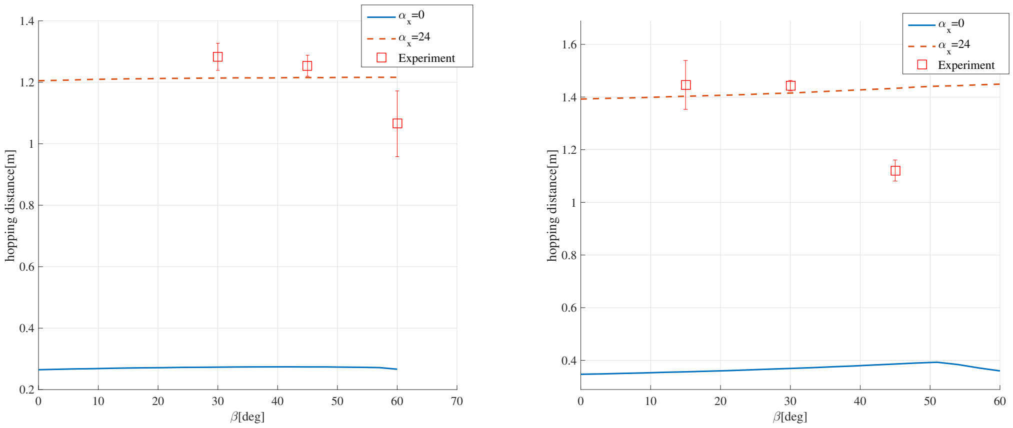


Figure 2.2: The experimental setup of hopper.

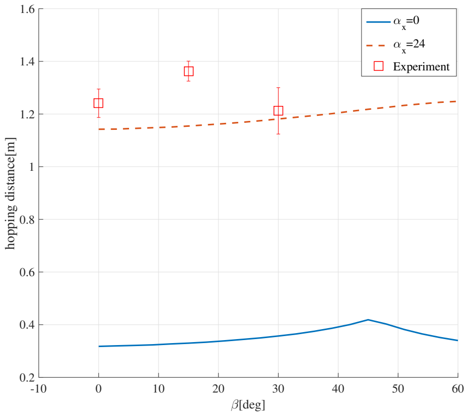
comparing simulation and experimental results, the validity of the theory is verified. In particular, the effect of velocity is evaluated by comparing two kinds of case; the RFT simulation only and the proposed approach. To discuss the comparison of the experimental results with simulation, the limitation of RFT approach and the effectiveness of proposed approach are described.

The results are shown in Fig.2.3. The hopper was installed on the injection rail to specify the injection angle η. Three injection angles (η = 30; 45; 60; degrees) and three incline angles are tested. In total, ten experiments were performed at each experiment. Comparing the experimental results to the simulated results, only the RFT simulations are estimated much lower than the experimental values. 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.

Although the proposed model simulates the hopping motion more accurately than the RFT, the angle dependency is not confirmed. The reasons are thought as follows: i) the proposed model uses the constant coefficient ξ, ii) the surface effect is hard to be explained physically. The first reason is noted that this model employs the SF of RFT as ξ. To the best of our knowledge, there is no method to determine ξ; this parameter is obtained artificially even in related works[8, 9, 10]. This requires more surveying



(a) Hopping distance at $\eta = 30$[deg]   (b) Hopping distance at $\eta = 45$[deg]



(c) Hopping distance at $\eta = 60$[deg]

Figure 2.3: The Compared results of hopping distance at each hopping angle. Bule soild line: RFT simulation; Red dash line: the proposed model; Red square: Experimental results

of properties of the coefficient which is related to angles of elements. The next one is more important for granular material physics. Unlike fluids, granular media are deformed plastically, in other words, they can memorised the effects of deformation. This phenomenon affect a “surface friction” which works on locomotor performance. Surface effects are displayed by nonlinear equations which cannot be incorporated into the RFT.

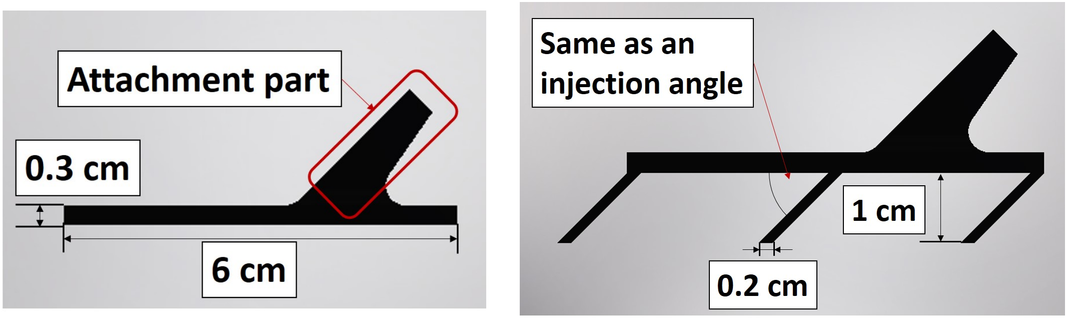
Chapter 3

Foot Pad Design based on Soil Interaction Model

This section presents the hopping performance evaluation on three types of terrains and novel foot pad designs for efficient traverse of hopping rovers. Inspired by the conventional wheeled vehicle design, treads, called grouser, are installed on the bottom of the foot pad. And the other novel grouser shape is designed based on the soil interaction model using a multi-objective evolutionary algorithm.

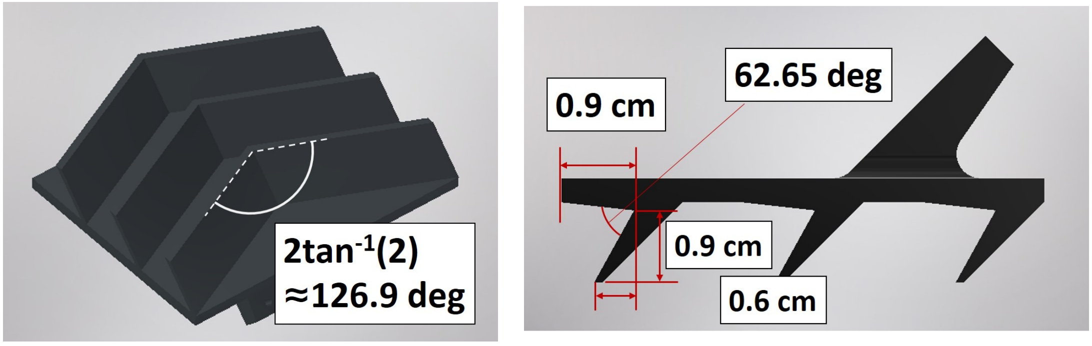
3.1 Related works

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 in order to improve their locomotion performance on such terrain. The Martian rovers have rigid wheels with low grousers. One of the examples is the wheel of Curiosity[11], which is 50 [cm] in diameter and 40 [cm] wide. The grousers on these wheels intrude into soil, and generate traction force by raking granular media. Axel rover showed the effectiveness of grousers by using simple physical analysis[12]. Axel has two wheels with paddles and can climb up/down steep slopes using tether from mother ship rover. Coyote II is a wheel-leg combination platform[13]. These legged-wheels sink in the soil shallower than conventional wheels, which can prevent them to be stuck in the sand. One of the examples using this interaction model is the foot pad of lander for celestial bodies[14]. This paper presents the effectiveness of RFT-based model to design landing-gear foot pads.



(a) The flat pad.

(b) The straight grouser pad.



(c) The V grouser pad

(d) The SIB grouser pad.

Figure 3.1: The CAD image of the proposed foot pads.

3.2 Foot pad designs

This section presents proposed foot pad designs for efficient hopping locomotion on soft soil. The hopper used in this study consists of two main parts: the hopper body and the contact part with the ground, called foot pad. In one of our our previous work, the authors observed that the hopping performance decreases on soft soil mainly due to slipping. In order to prevent slipping, some grousers are attached to the bottom of the foot pad. In the following sections, the foot pad without grousers is called “flat pad” (Fig.3.1a), and the foot pad with grousers is called “grouser pad”. This study uses three kinds of grousers: straight (Fig.3.1b), V (Fig.3.1c), and Soil interaction based (SIB) shape (Fig.3.1d). This paper described the SIB pad in detail.

The shape of SIB grouser is obtained as the solution of a multi-objective optimization problem (MOP) based on RFT. The objective functions are the hopping distance and the hopping height, because one of the most important challenges is to improve hopping performance. The hopping distance and height are simulated by calculating the resistive force using RFT. The MOP decides the grouser shapes which are maximizing these objective functions. The constraint is the grouser height to be 1 [cm].

The shape of the grouser is decided as follows: set 11 points per 1 [mm] between 0-10[mm] in the vertical direction (z-axis), then connect all points by drawing straight lines. These points can take any values between 0-10 [mm] in the horizontal direction (x-axis). These points are design variables. To solve this MOP, “ NSGAII ” is used , which is one of the multiobjective evolutionary algorithms (MOEAs). In this optimization, populations size is 300, and the number of evaluation is 20,000. Actually, the SIB grouser is designed so that one side is the optimized shape and the other side is parallel with the initial hopping angle. In order to minimize the resistance when the grousers are drawn out from the soil. The shape can be divided into two part; the upper part and the lower part. It is thought that the upper part increases the vertical resistive force in order to improve the hopping height and the lower part prevents slip in order to increase hopping distance.

3.3 Evaluation

This section describes the evaluation method of hopping performance and experimental results. In this model, hopping is caused by a spring which follows the Hooke’s law. The evaluation parameters are the follows: distance, angle, and energy efficiency. The hopper is same as the one which described in Section . This experiments were tested on three types of terrain: hard ground, bilayer ground, and soft soil. A wood-board is used as a hard ground. Bilayer ground represents the terrain which is hard ground covered with thinly sand or regolith. In this experiments, the constant weight of sand (200 [g]) is on a hard ground.

3.3.1 The performance of each grousers on soft soil

This section presents the effect of the V and SIB Grousers pads. The experiments are tested with only the injection angle $\eta_0 = 45$ [deg], because the main purpose of the experiments is to evaluate difference between the grousers shapes on/in soft soil. In addition, the hopping distance is the longest at the hopping angle $\eta = 45$ [deg], and the authors think that it is effective to improve the hopping performance around $\eta = 45$ [deg]. The results of the experiments are shown in Fig.3.2. These experiments were repeated five times. This figure includes the results of flat pad and straight grouser pad which was presented before for comparison. The mean values

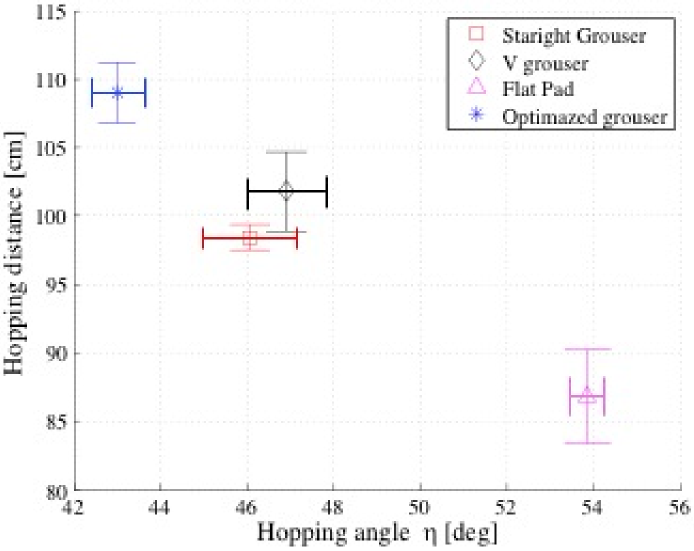


Figure 3.2: Comparative results of hopping distance and angle. Red squares: the result of the straight grouser pad; Black diamond: the result of the V grouser pad; Magenta triangle: the result of the flat pad; Blue asterisk: the result of the SIB grouser pad.

of the hopping distances and the actual hopping angles are plotted and the error bars show s.d. respectively. 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 [%]. This implies that the shape of grousers improve the hopping performance on soft soil. In particular, a shape based on the interaction model is effective. However, it is considered that optimizing the shape of grouser is difficult. This is because that optimization depends on the physical model used, hence being careful in the choice of such model should use.

Chapter 4

Hopping Path Planning in Uncertain Environments

Robotic autonomies are emphasized to enable efficient surface exploration in order to traverse on complex terrain safely, and efficiently. Path planning, or motion planning is one of the autonomous navigations. This section proposes the hopping path planning algorithm to explore uncertain environments.

4.1 Conventional algorithms

Path planning algorithms have been studied and improved by many researchers. Here, the conventional path planning algorithms are listed.

Unlike urban environments, locomotions on natural terrains include a lot of uncertainty because of the interactions with the terrain surface. Model based algorithms reduce the uncertainty arising from terrains using the interaction model. State lattice algorithm[15] is applied in rough terrain. The algorithm uses the grid of state, called state lattice. Based on the mobility model or the terrain interaction, the input parameters are optimized. The method often use the lookup table or neural networks for estimating the parameter. Therefore, the validity of the results of optimization depends on the lookup table or the used model.

4.2 Problem description

This section presents the assumptions of environments and the conditions of hopper. Then, the proposed algorithm is described. This study employs the Markov Decision

Process (MDP) method. The reasons are that the hopping is a discrete motion, and hence the uncertainty is relatively large. In addition, it is difficult to control the attitude and trajectory while the hopping. Therefore, the best action should be pre-calculated in all states.

4.2.1 Assumptions

The surface is covered with granular media, such as regolith, which causes the slip. Therefore, the motion on such surface has uncertainties. This study assumes that the uncertainty of the landing point are expressed by probabilistically. It is assumed that the hopper act on sandy terrain. Hence, the slip may reduces the estimated hopping distance. Although there are the right and left shift, the possibility is lower than the above. The composition of the soil is assumed homogeneous, and hence the probability of the uncertainty is constant. In addition, the environment has some rocks. The uncertainty of the hop on a rock is lower than the hop on the sand.

4.2.2 Hopper conditions

The hopper can hop any horizontal directions (360 degrees) and some vertical directions (45 – 90 degrees). The hopper also is installed springs which generate the hopping force, and stereo cameras to perceive the environments. This study assumes that the hopper can know self position and attitude using arbitrary localization method. Therefore this paper do not discuss a localization.

4.2.3 Markov Decision Processes

This section describe the basic concept of the MDPs and the application. MDPs assume that robots can observe the state fully, i.e., the the perceptual model $p(z|x)$ is deterministic. Where z and x denote the measurement and state, respectively. The MDPs define the probabilistic action model $p(x_t|u_{t-1}, x_{t-1})$, where u denotes the action.

The key technique of the MDPs is the way of designing the payoff function $r(x,u)$. The details of the $r(x,u)$ is described later. This study employs the value iteration method in order to calculate the best control policy.

4.2.4 Payoff Function

In general, payoff functions is defined numerically in MDPs. The function is designed by considering the above assumptions and hopping features. The proposed function is expressed as:

$$r(x, u) = w_1 S(x, u) + w_2 I(x, u) \tag{4.1}$$

where $S(x, u)$ and $I(x, u)$ denote the Safety cost and the Information gain, respectively. The w_1 and w_2 are the weight coefficients.

The Safety of the rover operations depends on the interaction between the mobility and the environments, such as slope, obstacles, terrains and so on. The Safety cost is proportioned to the roughness. The reasons are that hoppers can ride on rocks, and get over steps. These indicate that hoppers can access more dangerous area than wheeled rovers can access. Therefore, the function of the safety cost is described as below:

$$S(\mathbf{x}_p, u) \propto \sum_{i=-1}^{1} \sum_{j=-1}^{1} \tan^{-1} \left| h(x_p, y_p) - h(x_{p+i}, y_{p+j}) \right| \tag{4.2}$$

where $h(x_p, y_p)$ denotes the height of the terrain at a point (x_p, y_p) in a DEM. The roughness on an point (x_p, y_p) of terrain is formulated as the summation of the gradient around the (x_p, y_p).

The information gain is also key to exploration. When a robot traverse in unknown environment, a robot need to perceive the environment around the robot and mapping in order to make a path or decide a next motion. Exploring in planetary environments, a hopper can perceive the environments around the hopper by riding on a high place, such as a rock or a step. In this paper, the information gain is expressed simply as:

$$I(\mathbf{x}_p, u) \propto h(x_p, y_p) \tag{4.3}$$

This equation means that a hopper look the environment on a height more than on a ground.

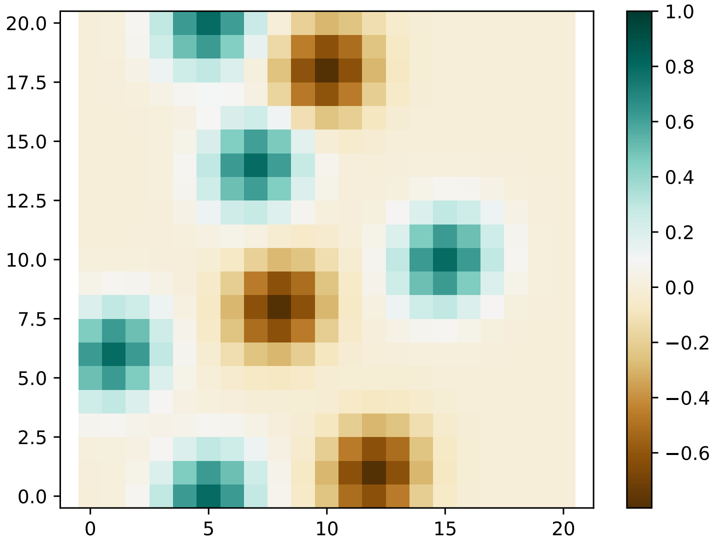
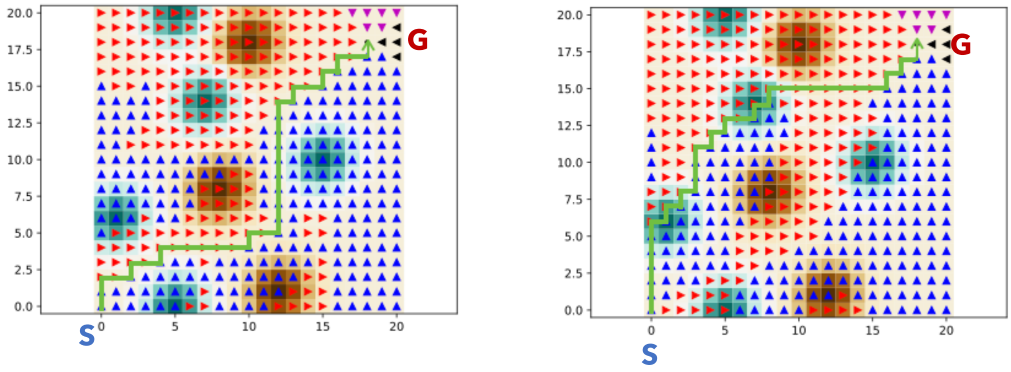


Figure 4.1: The artificial simulation environment.

4.3 Simulation Study

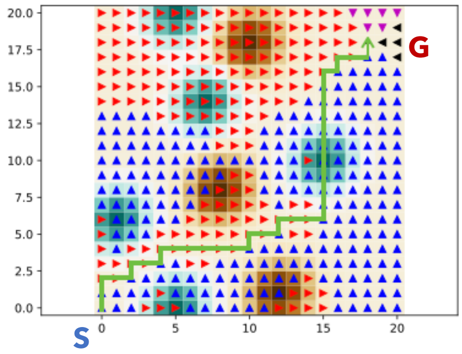
This section evaluates the proposed algorithm using an artificial digital elevation map(DEM). The map range is square of 20[m], and the resolution is square of 1[m]. The DEM is shown in Fig.4.1. The undulations of terrain is expressed a color bar. The highest point is 1[m] and shown in green. The lowest point is -1[m] and shown in brown. The hopping performances are follows: enable to hop 1[m] horizontally, and 0.5[m] vertically. The uncertainty is formulated as below: landing on the estimated point in 70%, 1[m] behind the estimated point in 15%, diagonally right and left behinds the estimated point in 7.5% each. The simulation results are shown in Fig. 4.2 and Fig. 4.3. The arrows indicate the actions the hopper chooses at each state. The green lines show the path that start from the initial state. In the case of prioritizing safety (Fig. 4.2a), the path from the initial state selects the flat terrains. The hopper also selects the flattest route possible at the start. However, the actions in some states near the goal show that hopper should go through the slopes. It is assumed that the hopper gets more payoff to traverse on slopes than to make a detour in order to reach the goal.

The part of sandy terrains are figured as translucent grey. Two paths started from the initial state avoid to traverse on sandy terrains from Fig. 4.3b and Fig. 4.3c. No path is shown in Fig. 4.3a, because the hopper doesn't reach the goal from the start. The main difference between the Fig. 4.3b and Fig. 4.3c is the actions on the elevated



(a) The case of prioritizing safety.

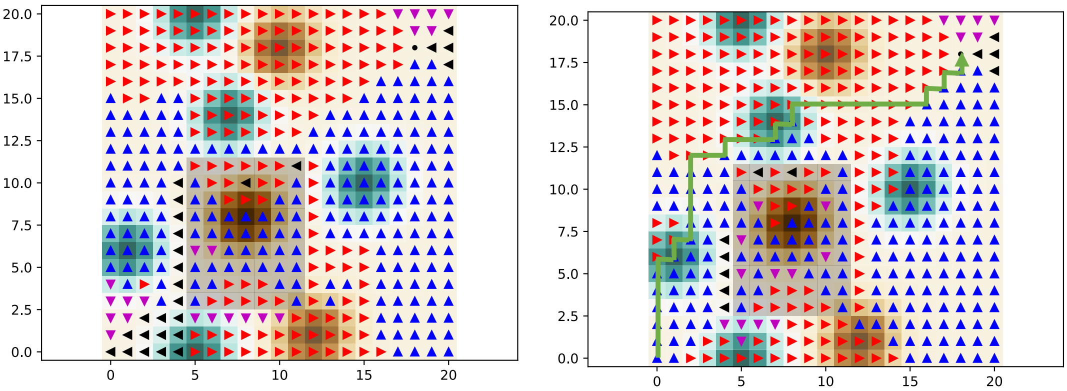
(b) The case of prioritizing information.



(c) The case of including both.

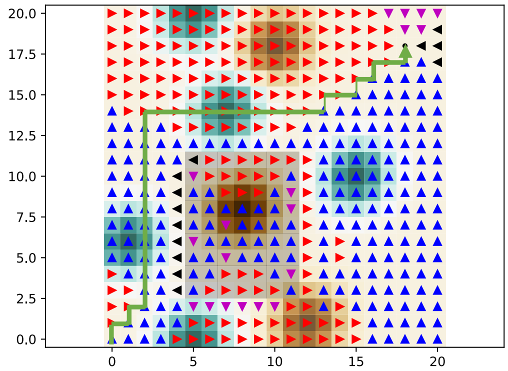
Figure 4.2: The path planning results.

regions. Figure 4.3b shows the path passes on the two tops of the hills in order to maximize the information gain. Figure 4.3c indicates the hopper selects a safer path than the Fig. 4.3b. Finally, the vertical hopping actions are confirmed. This section use the other environment in the simulation. Figure 4.4 illustrates the new environment and the simulation result. The result of this simulation shows that the path can include the vertical hop at the $(x, y) = (9, 8)$. The vertical hopping actions are plotted as green arrows. The path includes the vertical hopping shown in a green curve. The other vertical hopping actions around the low rock. The hopper can get on the low rock to gain the information about the environment around the hopper. The actions around the tall rock avoid collisions by calculating the hopping trajectories.



(a) The case of prioritizing safety.

(b) The case of prioritizing information.



(c) The case of including both.

Figure 4.3: The results on the heterogeneous terrain.

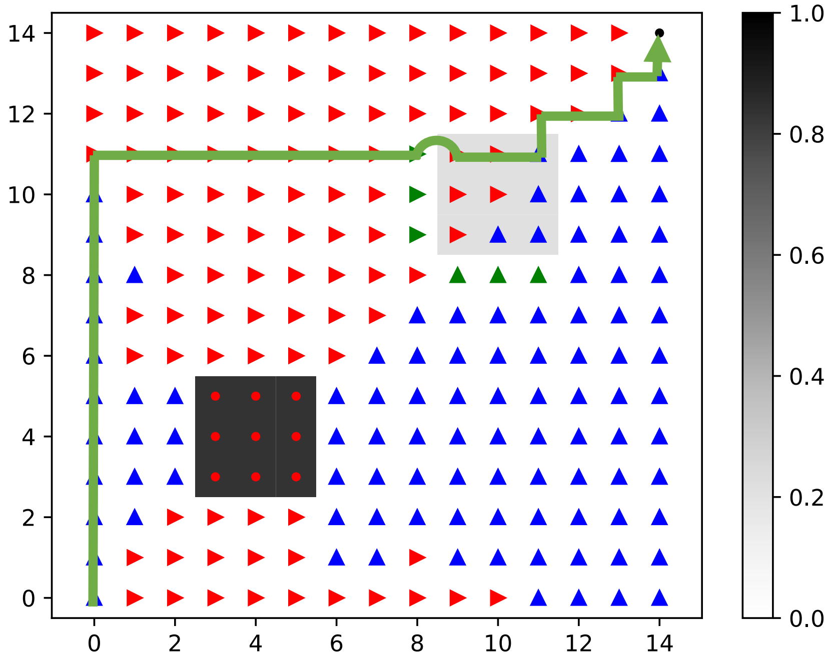


Figure 4.4: The environment for the vertical hopping simulation.

Chapter 5

Motion Control of wheel and hopping locomotion

The contribution of this section 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 the actual planetary environments. First, the design of the hopper is shown. Next, the performance of the hopper is tested in various terrains. Finally, the hopping locomotion generated by reinforcement learning is described.

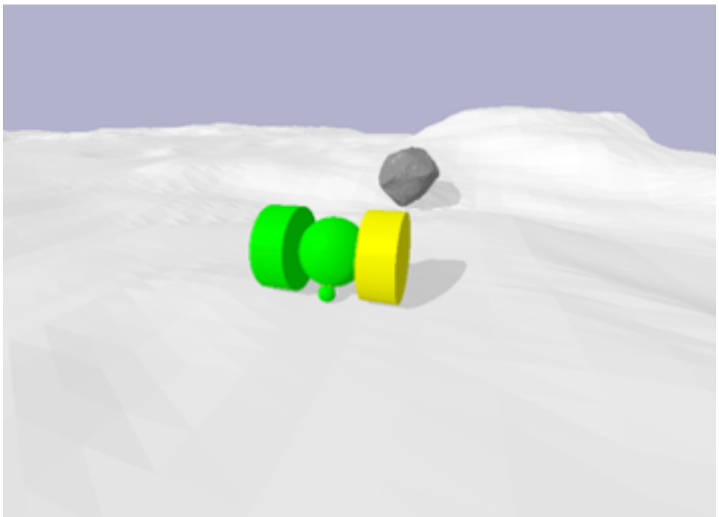
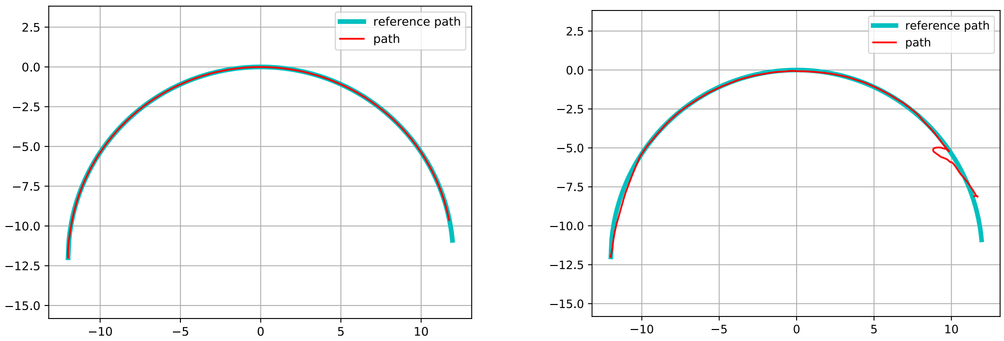


Figure 5.1: The image of the hopping robot and the planetary like terrain.



(a) On flat plane.

(b) On rough terrain.

Figure 5.2: The performance of the pure pursuit.

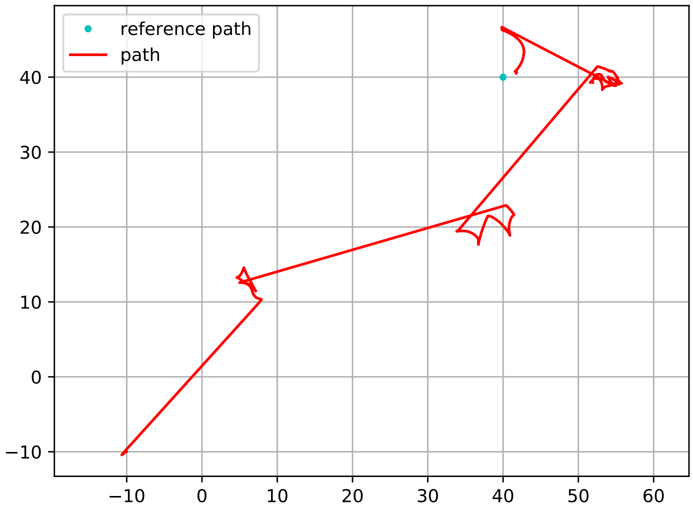


Figure 5.3: The hopping locomotion trajectory.

5.1 Conventional controller

This work employs the hopping and two wheeled robot as shown in Fig.5.1. This is because to improve the traversability of the robot on rough terrains. The robot uses the wheels on relatively flat terrain, gentle slopes, and change directions where the robot goes. The hopping locomotion is tried to clear an obstacle, step, cliff, or to escape from a stuck. The control method of the wheeled motion is the pure pursuit algorithm. This path following algorithm minimize the angle error between the robot position (x_r, y_r) and the target point (x_{ref}, y_{ref}). Figure 5.2 shows the results of the performance of the pure pursuit. Although the algorithm works well on flat plane, the robot cannot follow the path with accuracy in planetary-like environments because of the roughness. This results indicate that the pure pursuit suit for the wheel control

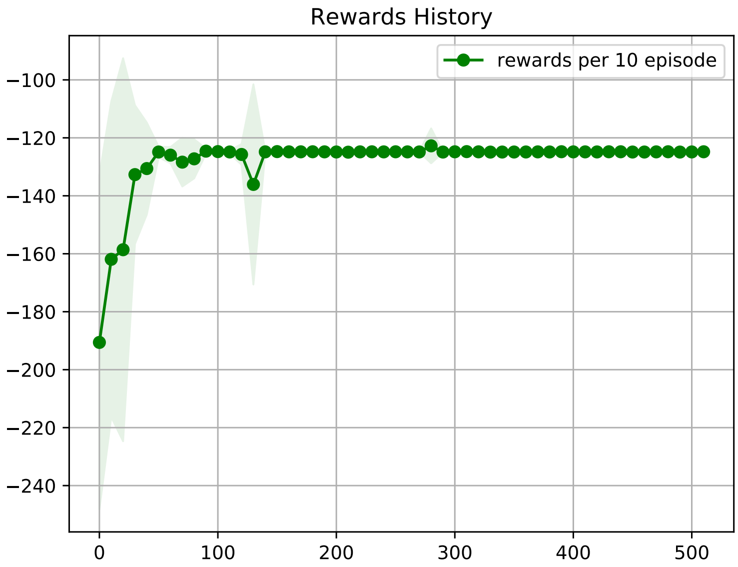


Figure 5.4: The reward history.

on relatively flat terrain. However, wheeled locomotions become a low accuracy in proportion to the roughness of the terrain. Figure 5.3 shows the result of the hopping locomotion in a planetary-like environment. The robot can reach to the goal. The result shows that a combination of hopping and wheels is efficient as a locomotion on rough terrain. However, it takes relatively much time to change the direction. In addition, there are some unnecessary hopping. It indicates that it is essential to improve the motion strategy for efficient locomotion in order to reach the goal.

5.2 Reinforcement Learning for hopping locomotion

In order to improve the locomotion in planetary-like environments, this work have applied the reinforcement learning to the simulations. Advantages of the reinforcement learning are that: i) Less environment oriented programming, ii) works in changing environment. This work used a policy gradient method to learn a policy by maximizing the expected value . Policy gradient methods update a learning parameter directly, which is suitable for coutinuous value control, such as robot motor control. The reward function is difined as $r = 1/d$. where d denotes the distance between the robot position and the goal. In addition, the robot get +500, if reach the goal, -500 if , and -400 if the simulation time is over 40 secs. As an action list, the robot choose the following actions: hopping, spin, and straight moving. Figure5.4 shows the generated hopping locomotion by reinforcement learning, and the reward history. The robot had trained

510 times, and the reward function converged to -125. After trained, the robot can move to the goal, but it takes 55 seconds to reach the goal. This is because the reward is negative. The robot learned the way of using wheels, however the robot does not use the hopping. The reasons are that i) the robot have not got the payoff ofz hopping, ii) hopping locomotion becomes over easily. In order to improve the performance, the following works are needed: (a) to modify the reward function, (b) to add the constraints to the actions, (c) to add a penalty or a payoff to the actions.

Chapter 6

Conclusion

This paper presents the hopping motion strategy for exploring uncertain planetary environments. The following subjects have been studied: i) the modeling of soil-hopping interaction, ii) a novel foot pad design based on the interaction model, iii) a hopping path planning which consider the motion uncertainty caused by environments, and iv) motion control of wheel and hopping in planetary environment. The effectiveness of this study is verified by the hopping experiments on various terrains, and the simulations.

For more contributions, the future works need to be tackled: formulating the payoff functions, testing the proposed algorithm in various environments, and developing the hopper which can move continuously on soft soil. The proposed payoff function uses the constant coefficients. However, the actual environments are very complex and various. Therefore, the coefficient have to be variable depending on the environments. In addition, combining the perception and mapping algorithms is essential to traverse in unknown environments. It is important for more efficient path planning to consider the soil properties. Finally, the effectiveness of proposed path planning algorithm will be demonstrated through the experiments using the hopper.

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