Design Method of Rough Terrain Detection and Avoidance in Unknown Environment for Space Rover

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***Abstract*—This paper describes the guidance and control method for an exploration rover in an unknown planet where a rough area exists. A mission of a space rover is sometimes interrupted when the rover falls into the rough area. To overcome this problem, we propose the method that detects and avoids rough terrain by an observer without the use of images of a camera mounted on the rover. The observer, which is based on Disturbance Accommodating Control (DAC) method, estimates nonlinear terms including running resistance and slip ratio because nonlinear term changes by rough terrain such as high soil resistance area. Therefore, the proposed method enables to detect and avoid the rough terrain automatically without the use of vision sensors. Space rover also should identify its position during a mission because of a non-GPS environment. Expanded Kalman Filter - simultaneous localization and mapping (EKF-SLAM) is applied to a space rover. The numerical simulation is conducted to verify that a space rover detects and avoids the rough terrain smoothly by using the proposed method.**

***Index Terms*—rough terrain, potential function, EKF-SLAM, DAC method, space rover.**

I. INTRODUCTION

It is effective to apply a space rover that can explore finely in an unknown environment such as a planet. The conventional design method of a trajectory for a space rover mission uses geographic information transmitted from an artificial satellite. However, it is difficult to design the trajectory in advance, due to occur any delay in mutual communication between a satellite and space rovers. We have applied potential function method to a space rover without the use of any image data and a predesigned trajectory [1][2]. The method generates guidance law to avoid obstacles and to steer a space rover to the desired position by using data from sensors mounted on the vehicle. However, it is hard to carry out the exploration by using sensors such as camera because, in unknown planet, there are rough terrain such as soft soil which can be not detected by sensors. Therefore, a space rover is sometimes interrupted at the terrain due to its high running resistance.

In this paper, we propose the method of detection of rough terrain in the unknown environment without visual sensor. An observer based on DAC [3][4] method is treated for the detection. The guidance law to steer a space rover and to avoid the rough terrain is obtained by using an artificial potential method. The observer is designed to estimate the nonlinear term that includes a running resistance and slip ratio of a space rover because the nonlinear term on dynamics of a space rover changes when the rover falls into a rough terrain. Using this change, a space rover can detect and avoid a rough terrain with a moving repulsive potential function. The nonlinear term estimated by the observer based on DAC is used for the linearization of the rover dynamics by applying dynamic inversion (DI) method [4]. Moreover, a space rover requires the self-localization on an unknown planet where it is difficult to obtain a map information. Thus, EKF-SLAM [5] is employed for the localization and the mapping. The validity of the proposed method is verified by the numerical simulation.

II. CONTROL SYSTEM

A. *Equation of Motion* [4]

Fig.1 shows the definition of the coordinate system and state variables of a space rover. Then, equations of the translational motion and the rotational motion are obtained as follows:

$$m\ddot{x}_b = -R_x \mathrm{sgn}(\dot{x}_b) - (a_1F_1 + a_2F_2) + (F_1 + F_2) \tag{1}$$

$$J\ddot{\psi} = b\{(a_1F_1 - a_2F_2) - (F_1 - F_2)\} \tag{2}$$

where m is the mass of a space rover, J the moment of inertia, and R_x the coefficient of a running resistance. The running resistance between of space rover is expressed by the following equation [4].

$$R_x = R_{fx} + R_{cx} + R_h \tag{3}$$

Manuscript received February 25, 2018; revised October 30, 2018.

doi: 10.18178/ijscer.8.1.63-68

$$R_{fx} = \tfrac{1}{2}\mu_x mg \tag{4}$$

$$R_{cx} = \frac{1}{(n+1)\left(k_c + b_w k_\phi\right)^{\frac{1}{n}}}\left(\frac{mg}{2l}\right)^{\frac{n+1}{n}} \tag{5}$$

$$R_h = uQ_a \tag{6}$$

where R_{fx} is the friction resistance, R_{cx} the compressive resistance, and R_h the excavation resistance. Parameters k_c, k_ϕ, and n are soil constant parameters that express the coefficient of adhesive force [4], the coefficient of the internal frictional force of the soil, and the hardness of soil, respectively. Parameters μ_x, b_w, u, and Q_a are constants with respect to each resistance.

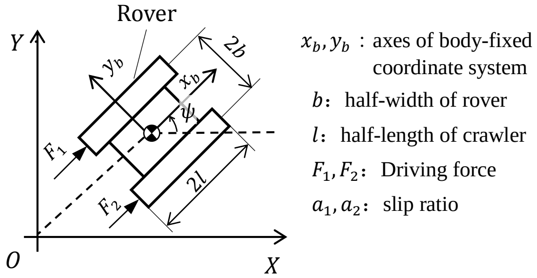


Figure 1. Top view of space rover and definition of its state variables and coordinate systems

B. Linearization of Translational Motion

The position error $\mathbf{x}_e$ in the inertial coordinate system is calculated by the difference between the current position $\mathbf{x}$ and the target position $\mathbf{x}_c$ to follow the target value.

$$\mathbf{x}_e = \mathbf{x} - \mathbf{x}_c = [x - x_c \;\; y - y_c]^T \tag{7}$$

The second time derivative of $\mathbf{x}_e$ is expressed as

$$\ddot{\mathbf{x}}_e = \ddot{\mathbf{x}} - \ddot{\mathbf{x}}_c = \ddot{\mathbf{x}} \tag{8}$$

It is noted that the vector $\ddot{\mathbf{x}}_c$ is zero because the vector $\mathbf{x}_c$ is assumed to be constant. The position error $\ddot{\mathbf{x}}_e$ is translated to the body-fixed coordinate system by using the translational matrix $\mathbf{C}^{B/I}$. Then, the translated position error $\ddot{\mathbf{x}}_{be}$ is written as the following equations.

$$\ddot{\mathbf{x}}_{be} = \mathbf{C}^{B/I}\,\ddot{\mathbf{x}}_e = [\ddot{x}_{be} \;\; \ddot{y}_{be}]^T \tag{9}$$

$$\mathbf{C}^{B/I} = \begin{bmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{bmatrix} \tag{10}$$

The vector $\mathbf{x}_{be}$ is the position error in the body-fixed coordinate system. Therefore, the error equation of the space rover is expressed by the following equation.

$$\ddot{x}_{be} = z_{t1} + \tfrac{1}{m}(F_1 + F_2) \tag{11}$$

$$z_{t1} = -R_x \mathrm{sgn}(\dot{x}_b) - (a_1 F_1 + a_2 F_2) \tag{12}$$

where z_{t1} denotes the nonlinear term of the rover dynamics. When applying DI method for linearizing the nonlinear dynamics, the thrust of the space rover F_1 and F_2 can be written by the equation including the nonlinear terms.

$$U_c = F_1 + F_2 = m(-z_t + v_t) \tag{13}$$

where v_t can be considered as the new control input for the linearized system. The error equation in terms of the translational motion of the space rover is linearized by using DI method.

$$\frac{d}{dt}\begin{bmatrix} x_{be} \\ \dot{x}_{be} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} x_{be} \\ \dot{x}_{be} \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} v_t \tag{14}$$

C. Linearization of Rotational Motion

In the same way as the translational motion, the rotational equation of space rover is linearized by using DI method. The error of heading angle of the rover ψ_e in the inertial system is defined as between the current heading angle ψ and the target heading angle ψ_c.

$$\psi_e = \psi - \psi_c \tag{15}$$

The time derivative of the second order of ψ_e is expressed as

$$\ddot{\psi}_e = \ddot{\psi} - \ddot{\psi}_c = \ddot{\psi} \tag{16}$$

It is assumed that $\ddot{\psi}_c$ is zero since ψ_c is constant. The heading angle error ψ_e is the error in body coordinate system. Therefore, the error equation of space rover is expressed as

$$\ddot{\psi}_e = z_{r1} - \tfrac{b}{J}(F_1 - F_2) \tag{17}$$

$$z_{r1} = \tfrac{b}{J}(a_1 F_1 - a_2 F_2) \tag{18}$$

The nonlinear term in (2) is denoted by z_{r1}. Applying DI method to (2), the thrust of space rover F_1 and F_2 is expressed by the equation including the nonlinear term.

$$M_c = b(F_1 - F_2) = -J(-z_{r1} + v_r) \tag{19}$$

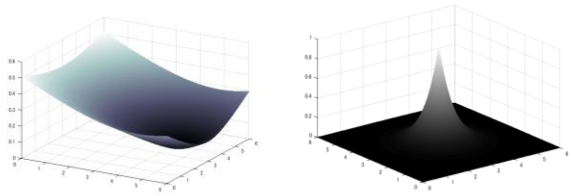
It can be considered that v_r is the new control input for the linearized rover dynamics. The rotational error equation of the space rover that is linearized by using DI method is derived as follows:

$$\frac{d}{dt}\begin{bmatrix} \psi_e \\ \dot{\psi}_e \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} \psi_{be} \\ \dot{\psi}_{be} \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} v_r \tag{20}$$

III. Guidance and Navigation

A. Guidance Law

The potential function method, which is one of the useful methods to obtain a guidance law, is treated to steer the space rover to a destination and to avoid obstacles. The method is applied to the avoidance of a rough terrain area on an unknown planet.



(a) Steering potential (b) Repulse potential

Figure 2. Potential functions

The potential function is classified into two functions, i.e. a steering potential and a repulsive potential as shown in Fig.2. The former is designed to guide the space rover to a destination on an unknown planet. The latter is a repulsive potential that is designed to avoid obstacles. Each potential field $U^s(\mathbf{X}_{r,d})$ and $U^R(\mathbf{X}_{r,j})$ is defined as the following equations.

$$U^s(\mathbf{X}_{r,d}) = C_s\sqrt{\left|\mathbf{X}_{r,d}\right|^{\mathbf{2}} + L_s} \tag{21}$$

$$U^R(\mathbf{X}_{r,j}) = C_r \cdot e^{\frac{-\sqrt{\left|\mathbf{X}_{r,j}\right|^2}}{L_r}} \tag{22}$$

where $\left|\mathbf{X}_{r,d}\right| = [x - x_d \quad y - y_d]^{\boldsymbol{T}}$ is the relative distance between the space rover and a destination, C_s the impact gradient strength of steering potential, L_s the range of steering potential, $\left|\mathbf{X}_{r,j}\right| = [x - x_j \quad y - y_j]^{\boldsymbol{T}}$ the relative distance between a space rover and obstacles, C_r the gradient strength of repulsive potential, and L_r the impact range of repulsive potential. The gradient field of the potential function is treated as a velocity field. Then, velocity commands for the space rover are expressed by the partial differentiation of the potential function relative to X and Y.

$$v_x = -\frac{\partial U^s(\mathbf{X}_{r,d})}{\partial X} - \frac{\partial U^R(\mathbf{X}_{r,j})}{\partial X} \tag{23}$$

$$v_y = -\frac{\partial U^s(\mathbf{X}_{r,d})}{\partial Y} - \frac{\partial U^R(\mathbf{X}_{r,j})}{\partial Y} \tag{24}$$

Using these equations, the velocity command v_c, the heading angle command ψ_c, and position commands x_c and y_c for reaching the destination while avoiding obstacles are defined as follows:

$$v_c = \sqrt{{v_x}^2 + {v_y}^2} \tag{25}$$

$$\psi_c = \tan^{-1}\left(\frac{v_y}{v_x}\right) \tag{26}$$

$$x_c = x + v_x \cdot e^{-\frac{1}{|x - x_d|}} \tag{27}$$

$$y_c = y + v_y \cdot e^{-\frac{1}{|y - y_d|}} \tag{28}$$

where x_d and y_d are the desired position of the space rover in the inertial coordinate system.

B. Guidance Law

1) Detection

The observer, which is based on DAC method, is employed to detect the rough terrain area on an unknown planet. We propose that the observer estimates the nonlinear term including the running resistance and the slip ratio of the rover. It can be considered that the time variation of the nonlinear term is the change of the running resistance and the slip ratio.

The parameter z_{t1} is assumed to be a polynomial of the time t[3].

$$z_{t1} = c_1 t + c_2, z_{t2} = \dot{z}_{t1} = c_1, z_{t3} = \dot{z}_{t2} = 0 \tag{29}$$

where c_1 and c_2 are coefficients. Then, the DAC observer can be expressed as the following discrete equation by using the zero-order hold.

$$\begin{gathered}\hat{\mathbf{z}}_{t1}(k+1) = \mathbf{A}\hat{\mathbf{z}}_{t1}(k) + \tfrac{1}{m}\mathbf{B}u + \mathbf{L}(y(k) - \hat{y}(k)) \\ \hat{y}(k) = \mathbf{C}\hat{\mathbf{z}}_{t1}(k)\end{gathered} \tag{30}$$

$$\mathbf{A} = \begin{bmatrix} 1 & \Delta T & \Delta T^2/2 \\ 0 & 1 & \Delta T \\ 0 & 0 & 1 \end{bmatrix}, \hat{\mathbf{z}}_t(k) = \begin{bmatrix} \dot{\hat{x}}_{be} \\ \hat{z}_{t1} \\ \hat{z}_{t2} \end{bmatrix}, \mathbf{B} = \begin{bmatrix} \Delta T \\ 0 \\ 0 \end{bmatrix}, \mathbf{L} = \begin{bmatrix} L_{t1} \\ L_{t2} \\ L_{t3} \end{bmatrix}$$
$$\mathbf{C} = [1 \quad 0 \quad 0]$$
$$u = F_1(k) + F_2(k)$$

where $\mathbf{L}$ is an observer gain that is obtained by LQR, ΔT the sampling time, and $\hat{\mathbf{z}}_{\boldsymbol{t}}$ the estimated parameter in the translational motion. If the estimated parameter changes suddenly, it can be considered that the space rover detects the rough terrain area.

DAC observer can be also applied to the rotational motion of the space rover. The estimation equation of the motion is defined as

$$\begin{gathered}\hat{\mathbf{z}}_{r1}(k+1) = \mathbf{A}\,\hat{\mathbf{z}}_{r1}(k) + \tfrac{b}{J}\mathbf{B}u + \mathbf{L}(y(k) - \hat{y}(k)) \\ \hat{y}(k) = \mathbf{C}\,\hat{\mathbf{z}}_{r1}(k)\end{gathered} \tag{31}$$

$$\mathbf{A} = \begin{bmatrix} 1 & \Delta T & \Delta T^2/2 \\ 0 & 1 & \Delta T \\ 0 & 0 & 1 \end{bmatrix}, \hat{\mathbf{z}}_{r1}(k) = \begin{bmatrix} \dot{\hat{x}}_{be} \\ \hat{z}_{r1} \\ \hat{z}_{r2} \end{bmatrix}, \mathbf{B} = \begin{bmatrix} \Delta T \\ 0 \\ 0 \end{bmatrix}, \mathbf{L} = \begin{bmatrix} L_{r1} \\ L_{r2} \\ L_{r3} \end{bmatrix}$$
$$\mathbf{C} = [1 \quad 0 \quad 0], u = F_1(k) - F_2(k)$$

2) Avoidance

It is necessary that the new repulsive potential is designed to avoid the rough terrain area. It is desirable to design that the repulsive potential approaches gradually the space rover. Thus, a sigmoid function is used at the same time as the detection of a rough terrain in this paper. The repulsive potential function is defined as the following equation.

$$x_i = \frac{(x + R\cos\psi)}{f(\hat{z}_{t1})} \tag{32}$$

$$y_i = \frac{(y + R\sin\psi)}{f(\hat{z}_{t1})} \tag{33}$$

$$f(\hat{z}_{t1}) = \frac{1}{1 + e^{-\gamma(|\hat{z}_{t1}| - \bar{z}_{t1})}} \tag{34}$$

$$U^{Ri}(\mathbf{X}_{r,i}) = C_r(\hat{z}_{t1}) \cdot e^{\frac{-\sqrt{\left|\mathbf{X}_{r,i}\right|^2}}{L_{ri}}} \tag{35}$$

$$L_{ri} = L_r \cdot f(\hat{z}_{t1}) \tag{36}$$

where x_i and y_i are positions on repulsive potential, R the distance between the space rover and the repulsive potential when a space rover falls into rough terrain. $|\mathbf{X}_{r,i}| = [x - x_i \quad y - y_i]^{\boldsymbol{T}}$ the relative distance between the space rover and repulsive potential, $\bar{z}_{t1}$ the threshold means that the range of rough terrain is defined as to avoid the area, γ the strength of gradient, and L_{ri} the range of repulsive potential in which the variable as $\hat{z}_{t1}$.

The sigmoid function converges to $f(\hat{z}_{t1}) = 1$ when the rough terrain parameter changes suddenly, i.e., the position of the repulsive potential closes to the space rover that detects the rough terrain area. Therefore, the space rover can avoid the area by the designed potential field.

C. EKF-SLAM

1) EKF

Discrete-time state equation of space rover is expressed by the following equation.

$$\mathbf{X}(k+1) = \mathbf{f}\big(\mathbf{X}(k), V(k), \omega(k)\big) + \mathbf{v}(k) \tag{37}$$

$$\mathbf{f}\big(\mathbf{X}(k), V(k), \omega(k)\big) = \begin{bmatrix} x(k) + TV(k)\cos\psi(k) \\ y(k) + TV(k)\sin\psi(k) \\ \psi(k) + T\omega(k) \end{bmatrix} \tag{38}$$

Here $\mathbf{X}(k) \in \mathrm{R}^{\mathbf{3}}$ shows the state vector of a space rover, $x(k)$ the X coordinate, $y(k)$ the Y coordinate, $\psi(k)$ the attitude angle, $V(k)$ the velocity, $\omega(k)$ the angular velocity, $\mathbf{v}(k) \in \mathrm{R}^{\mathbf{3}}$ the system noise of covariance matrix $\mathbf{R}$, and T the sampling period. The noise $\mathbf{v}(k)$ is defined as white noise.

Fig. 3 shows the definition of the coordinate system and variable. The observation equation is expressed by the following equation.

$$\mathbf{z}(k) = \begin{bmatrix} \sqrt{dx_j{}^2 + dy_j{}^2} \\ \tan^{-1}\left(\dfrac{dy_j}{dx_j}\right) - \psi(k) \end{bmatrix} + \mathbf{w}(k) \tag{39}$$

$$dx_j = x_j(k) - x(k), dy_j = y_j(k) - y(k) \tag{40}$$

where x_j is the position of the j-th obstacle in the X coordinate, y_j the position of the j-th obstacle in the Y coordinate, $\mathbf{w}(k) \in \mathrm{R}^{\mathbf{2}}$ the observation noise of covariance matrix $\mathbf{Q}$. The system noise $\mathbf{w}(k)$ is set on the assumption that it depends on white noise.

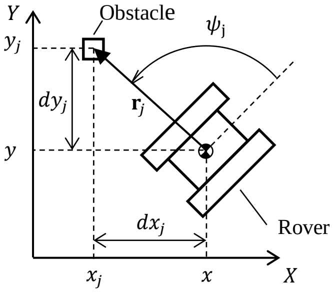


Figure 3. Relative position between rover and obstacles

Relationship of the covariance $\mathbf{R}$ and $\mathbf{Q}$ is set on the assumption that the following equation.

$$E\left\{\begin{bmatrix} \mathbf{v}(k) \\ \mathbf{w}(k) \end{bmatrix} \begin{bmatrix} \mathbf{v}^{\boldsymbol{T}}(k) & \mathbf{w}^{\boldsymbol{T}}(k) \end{bmatrix}\right\} = \begin{bmatrix} \mathbf{Q} & 0 \\ 0 & \mathbf{R} \end{bmatrix} \tag{41}$$

$$E(\mathbf{v}(k)\mathbf{X}(0)), E(\mathbf{w}(k)\mathbf{X}(0)) = 0 \tag{42}$$

2) SLAM

SLAM is the method that a space rover is capable of building a map of an unknown environment on the basis of information obtained from its various sensor and estimates its location at the same time [5]. This method is realized by a spreading system which is expressed as the following equation.

$$\begin{bmatrix} \mathbf{X}(k+1) \\ \mathbf{L}_j \end{bmatrix} = \begin{bmatrix} \mathbf{f}\big(\mathbf{X}(k), V(k), \omega(k)\big) \\ \mathbf{L}_j \end{bmatrix} + \begin{bmatrix} \mathbf{v}(k) \\ 0 \end{bmatrix} \tag{43}$$

where $\mathbf{L}_j$ is the position vector of the j-th obstacle.

IV. NUMERICAL SIMULATION

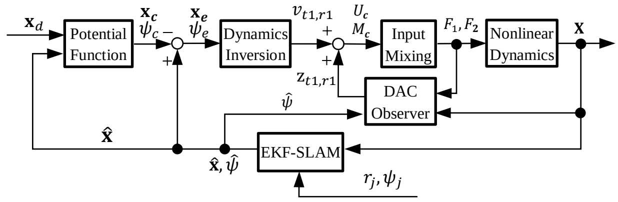


Figure 4. Block diagram of proposed control system

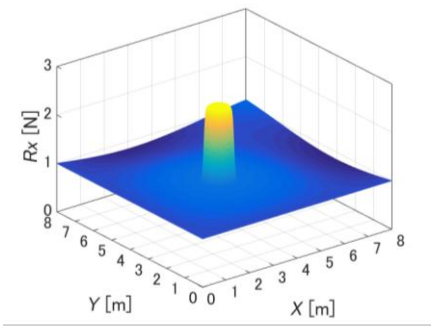
Fig. 4 shows the block diagram of the proposed control system. The parameter $\mathbf{x}_d$ used in the figure is the destination, r_i the relative distance, and φ_i the relative angle of an obstacle measured by a distance sensor mounted on the space rover. $\hat{\mathbf{x}}^-$ and $\hat{\psi}^-$are state variables that are estimated by using the revolution number of the crawler belt.

It is assumed in the numerical simulation that the rough terrain area is considered as a high resistance area. Resistance force acting on the space rover is expressed by the following equation [1].

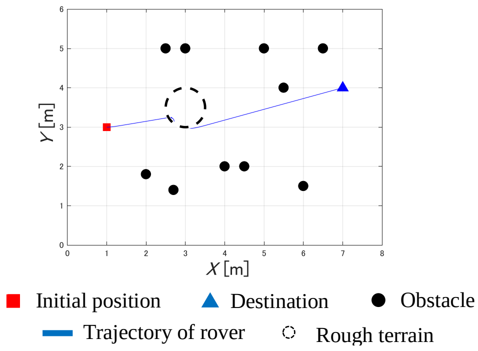
$$R_x = \left(1 + \frac{\sin^2 0.5x}{2} + \frac{C_c}{1 + \exp(L_c\sqrt{\rho - 0.5})}\right) R_{x0} \tag{44}$$

$$\rho = \sqrt{(x - x_l)^2 + (y - y_l)^2} \tag{45}$$

where C_c is the strength of rough terrain, L_c the range of rough terrain, x_l and y_l the center of rough terrain. These parameters values used in the numerical simulation are shown in Tables 1 to 5.



(a) Distribution of running resistance



(b) Trajectory of rover

Figure 5. Avoidance of rough terrain region

Fig.5(a) shows the function that expresses shows the rough terrain area used in the numerical simulation. It is shown from Fig.5(b) that the space rover reaches the desired position by avoiding the rough terrain area. Time responses of state variables of the space rover are shown in Fig.6. Fig. 6(c) shows that it takes about 15 seconds to avoid the rough area. It is clear from Fig.7 that the space rover detected the rough area as the change of nonlinear term z_{t1} at 15 [s] from the beginning of the numerical simulation. The control input changed suddenly when avoiding the rough area as shown in Fig.8.

TABLE I. SPECIFICATION OF ROVER

Mass m [kg]	0.480
Moment of inertia J [kg・m]	0.00594
Length of rover $2l$ [m]	0.150
Width $2b$ [rad/s]	0.110

TABLE II. CONDITIONS OF NUMERICAL SIMULATION

Sampling time [s]	0.09
Rover position $\mathbf{x}_0$[m]	[1 3]
Desired position $\mathbf{x}_d$ [m]	[7 4]
Steering potential function C_s, L_s[-]	[0.06 0.3]
Repulsive potential function C_r, L_r[-]	[0.0001 0.5]
Rough terrain function C_c, L_c[-]	[1.5 40]
Parameter of LQR $\mathbf{Q}$ [-]	diag[100 100]
Parameter of LQR R [-]	1

TABLE III. CHARACTERISTICS OF SYSTEM NOISE

System noise of variance $\mathbf{Q}$[-]	diag[0.01^2 0.01^2 $(\pi/180)^2$]
Observation noise of variance $\mathbf{R}$[-]	diag[0.01^2 0.01^2 $(\pi/180)^2$]

TABLE IV. PARAMETER VALUES OF OBSERVER AND CONTROLLER

Initial state $\hat{\mathbf{z}}_{t,r}(0)$[-]	[0 0 0]
Parameter of LQR $\mathbf{Q}, R$ [-]	diag[1 100 1], 1

TABLE V. PARAMETER VALUES OF POTENTIAL FUNCTION

Initial position of potential function[m]	[100 100]
Sigmoid gradient rate α [-]	2.5
Sigmoid potential function C_r, L_r[-]	[0.3 0.6]
Sigmoid threshold $\bar{z}_{t1}$[-]	0.4

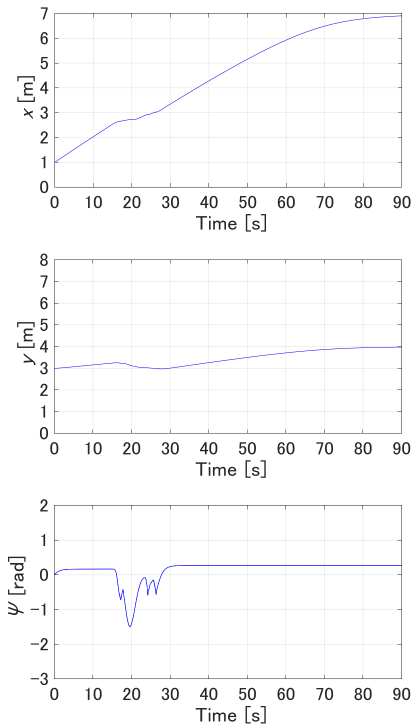


Figure 6. Time histories of state of the rover

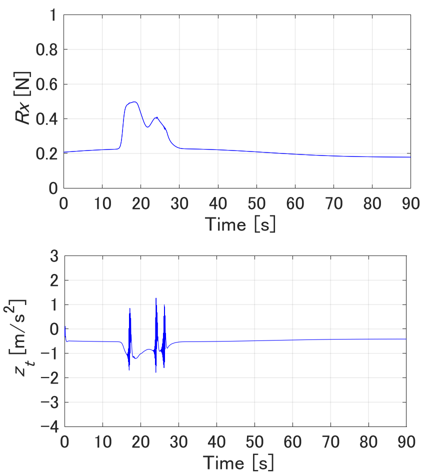


Figure 7. Time histories of rough terrain parameter

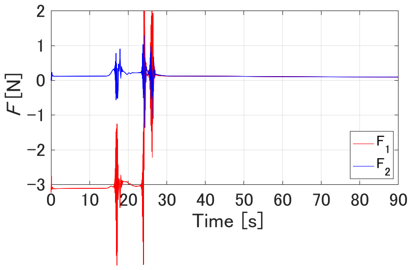


Figure 8. Control input

V. CONCLUSION

We proposed the novel method that uses the observer based on DAC method and the moving repulsive potential for detection and avoidance of a rough terrain without the use of camera images. The numerical simulation results showed that the space rover succeeded in detection and avoidance of the rough terrain smoothly while estimating its own position under a non-GPS environment. It was clear from the numerical simulation that the proposed method is useful for an exploration of the unknown planet that includes the rough terrain of high resistance area. We will confirm the proposed system by experiment and verify for planetary exploration.

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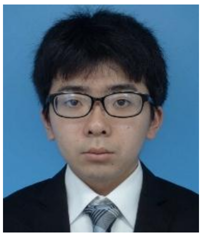

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