LRF Based Autonomous Navigation System Measuring on Moving Rover

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ABSTRACT

This study deals with an autonomous navigation system combining a scanning LRF with attitude sensors. The system extends the rover's travel distance and also reduces the risk of stuck in loose soil. This paper shows that terrain surface can be reconstructed from scanned LRF data which are obtained by a moving rover. Furthermore, by using a scanned line data, it is shown that rover's position and its slip rate can be estimated in a high frequency.

1 INTRODUCTION

Planet exploration missions based on unmanned rovers are attracting attention in recent years. Due to the limited launch capability of rockets, rover's size/weight and available energy are strictly restricted. Thus usually, the mission period of small rovers becomes short and its moving speed is slow. Therefore, during the limited mission period, how to enhance rover's travel distance has become an important issue, because it is sometimes said that the amount of scientific achievements of exploration missions is proportional to the travel distance of rovers. For exploration missions on a celestial body far from Earth, remote control from Earth is not realistic because communication latency becomes extremely long. Therefore, an autonomous navigation system which can be implemented in a relatively low-performance onboard computer is desirable for planetary exploration missions.

Navigation based on stereoscopic camera is most frequently used for exploration rovers [1]-[3]. However, terrain mapping in each image is a time-consuming task for onboard computers to extract feature points and find corresponding points. Therefore, usually stereo camera images are transmitted to Earth and processed with a high-performance computer. This compels rovers to wait without moving until commands arrive from Earth. On the other hand, Laser-Range-Finder (LRF) can obtain distance data easily based on a time-of-flight principle of the laser beam [4]-[8]. However, to reconstruct three-dimensional terrain surface, the laser beam of a LRF must be scanned in two directions, and it takes several seconds for scanning. Thus usually, during the scanning process, rovers must be in standstill to avoid the deviation of its laser beam direction due to terrain slope or bumps.

This study deals with an autonomous navigation system combining a scanning type LRF with attitude sensors. This system enables exploration rovers to continue moving during their laser scanning. Since the attitude sensors compensate the direction of the beam deviation due to rough terrain, the terrain surface reconstruction becomes possible even for LRF data obtained from moving rovers. Furthermore, this system is useful to reduce the fatal risk of "complete stuck" in loose soil. With the proposed navigation system, the rovers can identify their positions in a short time interval through matching a scanned line-shaped terrain data obtained at certain instant with a reconstructed map. Thus the rovers can detect the change of the slip rate and change the moving direction before it is completely trapped in loose soil.

2 LRF BASED NAVIGATION

2.1 Travel distance of exploration rovers

In space exploration missions on near celestial bodies, remote operation is possible because signal's transmission delay is short (typically several seconds for Moon rovers), and because the communication speed is relatively high. However, on celestial bodies like Mars, the transmission delay of signals becomes at least several minutes for one way, and the transmission rate is quite slow. Thus, autonomous navigation is necessary for deep space missions.

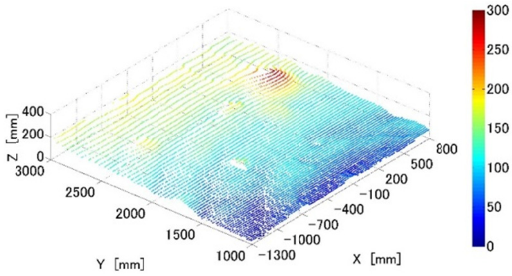
For autonomous navigation, camera systems are most frequently used. However, due to the reason described in Sec. 1, exploration rovers with such navigation systems must wait the command from Earth without moving. For Mars rovers, the waiting time occasionally becomes nearly one hour. Moreover, due to available communication period between the rovers and ground stations on Earth, the rovers' travel distance is very restricted, typically less than 50 [m] per day. Contrary to camera based navigation, the concept of LRF

Fig. 1 Manufactured experimental testbed rover

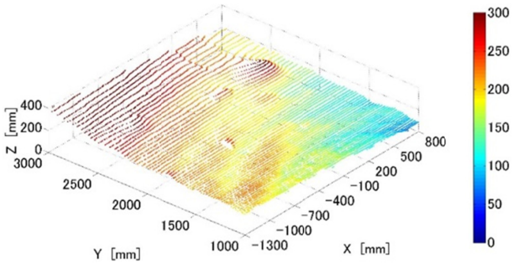
Table 1 Specifications of the LRF scanning system

[Scanning for the pan directional rotation]	
scan range	190 [deg]
resolution	0.25 [deg]
scan time for a rotation in pan direction	50 [ms]
[Scanning for the tilt directional rotation]	
scan range	20~90 [deg]
resolution	0.35 [deg]
scan time for the full range in tilt direction	10 [s]
Mounted height of LRF from ground	1.48 [m]

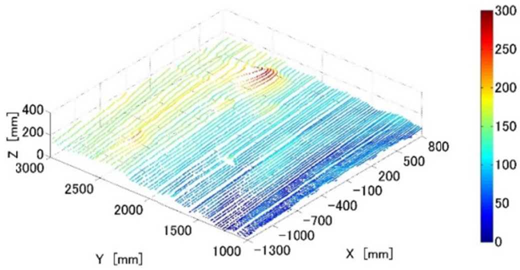
(a) Test environment used in experiments



(b) Reconstructed terrain obtained on a static rover



(c) Reconstructed terrain without compensation



(d) Reconstructed terrain with compensation

Fig.2 Comparison of reconstructed terrains in an experiment

based terrain reconstruction is quite simple and does not require high-performance processors. Thus it has possibility to make the travel distance several times of camera based navigation. Let us assume rover's speed is 2 [cm/s] as a typical value. Then if the rover continues to move, the travel distance becomes 72 [m] for one hour. This, under an assumption of three-hour movement per day, implies that 20 [km] travel can be achieved in three months; this distance is almost equivalent to three times of the distance Spirit traversed during six years.

In the LRF based navigation, one of the most essential problems is that it takes at least several seconds to scan the beam in two-dimension to obtain one "image" data. Thus, to avoid the laser beam deflection, rovers stop during the scanning interval in a standard LRF navigation. Contrary, this study discusses terrain reconstruction from distance data which are obtained on a moving rover. In the proposed system, the deviated laser beam direction due to surface slope or bumps is compensated with attitude sensors mounted on the rover. Furthermore, it should be noted that the proposed method can reduce the rover's risk of complete stuck in loose soil, which is explained in Sec. 3.

2.2 Experimental verification of the proposed reconstruction method

To verify the usefulness of the proposed reconstruction method under practical condition including sensor noises and environmental effect (e.g. external light, object material, etc.), a rover shown in Fig. 1 has been manufactured with using Hokuyo's UXM-30LX-EW LRF. Table 1 shows the specification of the LRF scanning system. In this system, the LRF rotates on its pan axis with 20 cycles per second, and irradiates the laser beam in every 0.25 [deg]. Simultaneously, the tilt

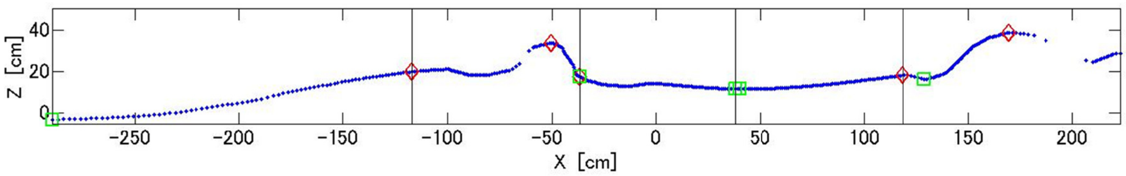


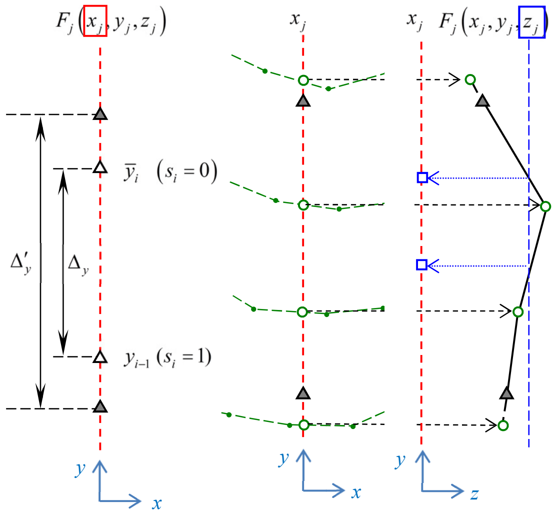
Fig.3 Feature points extracted from the divided scanned line

angle of the LRF changes with a constant angular rate, which is specified in its program. Note a slower tilt angular rate can generate high resolution surface, but the scanning time becomes longer: e.g., for 3.5 [deg/s] tilt rate, 10 [s] is required to obtain one "image" with 70 [deg] range in the vertical direction, and the resolution of the reconstructed surface data is 0.25×0.35 [deg]. To compensate the attitude change, a three-axis attitude sensor AMU-3002B Lite is placed on the rover. This sensor can output attitude date with 50 [Hz], and the accuracy is ±1 [deg] according to the catalogue.

Figure 2 shows a typical result; (a) is a photo of the environment used in the experiments. Rover attached coordinate *O-xyz* is defined as follows: *O* is the projection of LRF position onto the virtual flat surface, *y*-axis is the rover's moving direction, *z*-axis the vertical direction, and *x*-axis composes of a right hand frame. Fig. 2 (b) is the terrain surface reconstructed from the data obtained by the LRF in standstill, and this indicates the best performance of the used LRF. In the verification experiments, the rover moves with a speed of 2 [cm/s] and its attitude changes during the movement roughly 0~5 [deg] in both its pitch and roll directions. Figure 2 (c) is a result reconstructed by a standard procedure, while (d) is a result by the proposed system. This result indicates that terrain reconstruction from the proposed system combined a scanning LRF and attitude sensors works well in practical conditions.

3 ESTIMATION OF SLIP RATE

Since the proposed system can reduce the waiting time to scan, it can expand its travel distance. Moreover, it should be noted that the system is effective to reduce a fatal problem of "complete stuck" in loose soil. In standard LRF based navigation, rovers are in standstill during LRF scanning and then move some specified distance (typically, several meters). In this moving process, however, the rover has a risk of "stuck" in loose soil. Unlike cameras, LRF cannot get texture information of surface, and thus LRF based navigation has larger risk to be stuck. In the proposed system, the rover identifies the position in every short time interval through matching a scanned line-shaped terrain data obtained at certain instant with a reconstructed map. Then, the rover



(a) Mapping region *(b) Mapping point*

Fig. 4 Mapping process from a featured points

can detect the change of the slip rate and change the moving direction before it is completely trapped in loose soil. For this process, a most essential problem is to identify the rover position precisely without complicated calculations. In below, two concepts are described.

3.1 Estimation from selected feature points

If a scanned line is identified in the reconstructed map (hereafter, referred to "reference map"), from the laser beam direction at the certain instant, the rover position can be theoretically specified. (In practical situations, the following factors make the position identification degrade: the attitude sensors have some range of errors, the reference map is composed of discrete point data, the direction of scanned planes depends on the rover's position and attitude, etc.)

In the first method, to reduce computational load, the scanned line is projected in the *x-z* plane and only selected feature points in the scanned line-shape data are used to identify the scanned line in the reference map. Figure 3 shows an example of a scanned line for an experimental environment shown in Fig. 2: blue dots are LRF data obtained every 0.25 [deg] in the pan direction, the pan direction is divided into five regions with a same number of data, red diamond and green square are

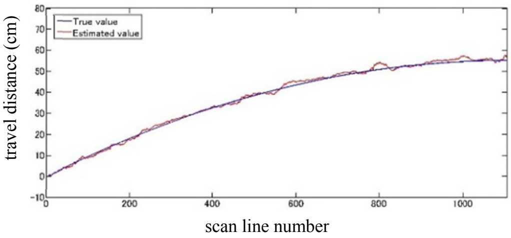


Fig. 5 Estimation of travel distance

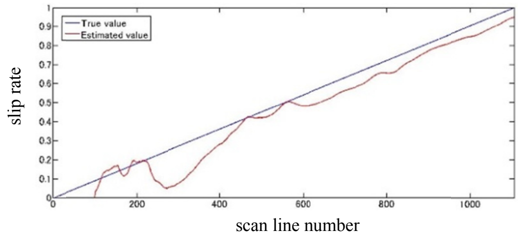


Fig. 6 Estimation of slip rate

the highest and lowest points in each region, respectively. Only these feature points are used to identify the scanned line in the reference map.

The position of the selected feature points can be expressed as $F_j(x_j, y_j, z_j)$ in the *O-xyz* coordinate. From the previous position identification, the rover should have moved forward. When the slip rate is zero ($s = 0$), the moving distance is calculated from multiplication of the designated speed and time. While, when the wheel slips completely ($s = 1$), the rover position is same as before. Thus, from the laser beam direction, the possible rover position at $t = t_i$ is restricted in Δ_y in Fig. 4(a). However, since the attitude sensors have some inaccuracy, the possible region is replaced with Δ'_y considering the maximum attitude error. Note that considering exploration rovers' speed is quite slow, and the position identification is repeated in a short time interval, the region Δ'_y is also small. The green dots in the left figure of Fig. 4(b) indicate the discrete points measured for the reference map, and the height at the points on $x = x_j$ is interpolated as shown in the right figure. Then, from z_j of the feature point, the candidate of the rover position is specified as blue squares in the figure. Finally, since these candidates are selected for each feature point, the rover position is specified so that the sum of the distance between the rover position and the feature candidates becomes minimal.

To examine the accuracy of the above estimation method, consider the following simulation: the experimental rover moves on the surface of Fig. 2 with 2 [cm/s] speed, but the slip ratio of the wheel increases linearly. The rover position is estimated for every scanned line data by applying the process explained above for 10 feature points, under the condition that the attitude sensors have random errors with its maximum value of ±1 [deg]. Furthermore, because in this simulation the position estimation is repeated quite small traveling distance and thus sensor errors easily mislead the rover's position, the following Kalman filter algorithm is also applied:

$$\hat{x}(k \mid k-1) = \hat{x}(k-1 \mid k-1) + u(k) \tag{1}$$

$$P(k \mid k-1) = P(k-1 \mid k-1) + Q \tag{2}$$

$$K(k) = P(k \mid k-1) / \left(P(k \mid k-1) + R\right) \tag{3}$$

$$\hat{x}(k \mid k) = \hat{x}(k \mid k-1) + K(k)\left(z(k) - \hat{x}(k \mid k-1)\right) \tag{4}$$

$$P(k \mid k) = \left(I - K(k)\right) P(k \mid k-1) \tag{5}$$

where $\hat{x}(k \mid k-1)$, $\hat{x}(k \mid k)$: a priori and posteriori estimates respectively; $P(k \mid k)$: error covariance; $K(k)$: Kalman gain; Q, R : system and measurement noises respectively, and $Q = 0.1$, $R = 1$; $z(k)$: measurement; and input $u(k)$ is defined as $v_c \cdot \Delta t$, where v_c is the commanded rover's speed.

Figure 5 shows a typical result of the estimated travel distance. Since the slip rate increases with time, the travel distance is gradually saturated. The slip rate is calculated from the ratio of true travel distance to commanded travel distance as follows:

$$s = 1 - \left(d_{true} / d_{command}\right) \tag{6}$$

Figure 6 shows the time history of the estimated slip rate for Fig. 5. As shown in the figure, the increase of slip rate is captured

3.2 Estimation from Fourier coefficients

As shown in Figs. 5 and 6, they are successful to estimate the rover position and the slip rate. However, there remains some amount of errors between the estimated and true values, and they cannot guarantee that the applied concept works well for other terrain. Especially, to reduce the computational load, this estimation method discards some information of the scanned data: *y*-component and other scanned position data except for the selected feature points.

Thus, to increase the adaptabilities to other terrain, this subsection introduces another estimation method which reduces discarding information but keeps small computational load. For this purpose, Fourier coefficients are evaluated for a pan region

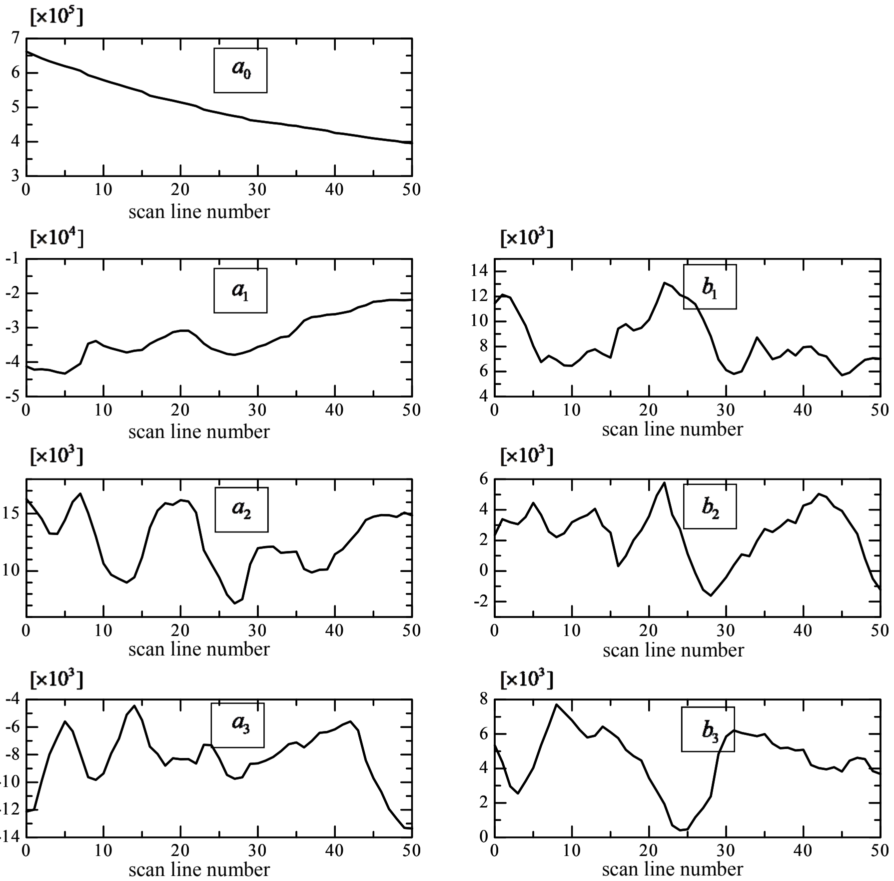


Fig. 7 Fourier coefficients for each scan line

of the scanned line as follows:

$$a_n = \frac{2}{\Delta\Phi}\int_{\phi_1}^{\phi_2} S(\phi)\cos\frac{2\pi n\phi}{\Delta\Phi}d\phi \quad (n = 0,1,2,\cdots) \quad (7)$$

$$b_n = \frac{2}{\Delta\Phi}\int_{\phi_1}^{\phi_2} S(\phi)\sin\frac{2\pi n\phi}{\Delta\Phi}d\phi \quad (n = 1,2,\cdots) \quad (8)$$

where $S(\phi)$ is the distance data in the plane scanned by the laser beam, and $\Delta\Phi = \phi_2 - \phi_1$. Note that $S(\phi)$, calculated from the time of flight principle, does not discard any distance data, and that the integration in Eqs. (7) and (8) utilizes all distance data in the pan region of $\phi_2 \sim \phi_1$. This implies that Fourier coefficients include more information than the previous feature point based estimation method. Furthermore, as seen in Fig. 3, the discrete distance data of $S(\phi)$ are sufficiently dense for the integration and have a same interval with respect to the pan angle ϕ, the integration (7) and (8) can be replaced with Riemann sum for the discrete data. Consequently, the computational load required to calculate Fourier coefficients is small.

To examine the possibility to identify a scanned line data from the reference map, Fourier coefficients have been calculated for the scanned lines in the tilt angles $\theta = 30 \sim 47.5$ [deg] for the experimental circumstances shown in Fig.2. Figure 7 indicates the result. This result indicates that the position of scanned line data can be identified in the reference map. Since the Fourier coefficients include more information than the previous method based on feature points, more accurate estimation is expected. (However, estimation accuracy of rover's positon and slip rate is strongly dependent to the estimation algorithm, and better algorithm is still under construction.)

4 CONCLUSION

This study deals with an autonomous navigation system of an exploration rover works on a planet far from Earth. By combining a scanning LRF with attitude sensors, the proposed system can extend the travel distance and reduce the risk of stuck in loose soil. This paper has indicated that terrain surface reconstruction is possible from

LRF data which are obtained by a moving rover. Furthermore, it is also shown that through the identification of rover's position, the variation of the slip rate can be captured every a short time interval.

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