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Position Estimation Scheme for Lunar Rover Based on Integration of the Sun and the Earth Observation and Dead Reckoning

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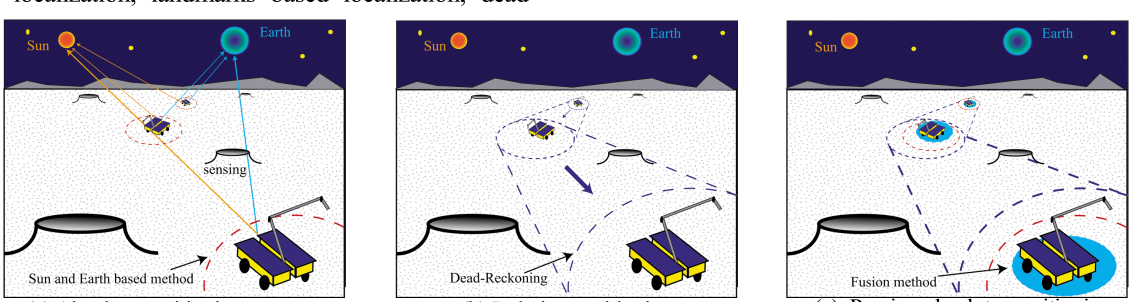
Abstract

This paper proposes a localization method to estimate position and azimuth of a lunar rover. In the proposed method, the position is precisely estimated by integration of an absolute and a relative position. The absolute position is measured by observing the Sun and the Earth, and the relative position is determined by the dead reckoning. Effectiveness is confirmed by the results of experiments and simulations.

1. Introduction

Recently, lunar or planetary rover missions have received a lot of attention, because rovers can explore widely on the surface in detail [1]. It is important for a rover to know its position on the surface by itself so as to reach a destination point. Some methods to identify the position have been developed in the filed of mobile robots on the Earth, e.g., GPS (Global Positioning System), map based localization, landmarks based localization, dead reckoning, etc. No methods are good enough for using on the Moon or the other planets, because of the following reasons. GPS is not available because it needs at least four satellites in orbit. Detailed maps are not usually measured beforehand, therefore, map based localization can not be used. In order to use landmarks based localization, we have to deploy plenty of landmarks on the surface of the Moon or the other planets. Dead reckoning is not accurate enough when a robot moves for a long range, because of accumulating the integration errors [2-4].

This paper proposes a localization method to estimate the position and azimuth of a lunar rover. In the method, precise positioning information is obtained by a sensor fusion technique that is an integration of the absolute position and the relative position [5,6]. The absolute position is calculated by observing the Sun and the Earth [7-10], and the relative position is measured by the dead reckoning. The effectiveness of the proposed method is confirmed by some numerical simulations and field experiments.



(a) Absolute positioning by observing the Sun and the Earth

(b) Relative positioning by dead reckoning

(c) Precise absolute positioning by integrating (a) and (b).

Figure 1: Proposed Localization Method for Lunar Rover

2. Coordinates Systems

In order to calculate the position of the rover on the Moon by observing the Sun and the Earth, the following four coordinate systems are used for.

CS1. Equatorial coordinate system at center of the Earth

z-axis: north celestial pole
x-axis: vernal equinox direction
y-axis: right-hand system of x-z
origin: the Earth

The positions of the Sun and the Moon are defined by this coordinates system.

CS2. Equatorial coordinate system at center of the Moon

z-axis: north celestial pole
x-axis: vernal equinox direction
y-axis: right-hand system of x-z
origin: the Moon

We can calculate the position of the Sun by transforming the coordinate system CS1 to CS2.

CS3. The Moon fixed coordinate system

z-axis: north pole of moon
x-axis: meridian of the Moon
y-axis: right-hand system of x-z
origin: the Moon

This coordinates system is changed into the coordinate which take the Moon rotation into account from the inertia space fixed coordinate system CS2.

CS4. Horizontal coordinates system of the Moon

z-axis: zenith
x-axis: south
y-axis: east
origin: center of the rover

This is the horizontal coordinates system which the rover uses on the Moon, though the coordinates systems of CS1-CS3 are based on the celestial bodies.

The values directly observed by the Sun and the Earth sensor are described by direction cosine. But, CS4 is rectangular coordinate system. Thus, CS4 is redefined as the direction cosine indication. The altitudes of the Sun and the Earth are defined as h_s and h_e, and their azimuths are represented by A_{zs} and A_{ze}. Then, the positions of the Sun and the Earth are described as follows:

$$\begin{pmatrix} \cos(h_s)\cos(2\pi - A_{zs}) \\ \cos(h_s)\sin(2\pi - A_{zs}) \\ \sin(h_s) \end{pmatrix} = \begin{pmatrix} x_s(t) \\ y_s(t) \\ z_s(t) \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} \cos(h_e)\cos(2\pi - A_{ze}) \\ \cos(h_e)\sin(2\pi - A_{ze}) \\ \sin(h_e) \end{pmatrix} = \begin{pmatrix} x_e(t) \\ y_e(t) \\ z_e(t) \end{pmatrix}. \tag{2}$$

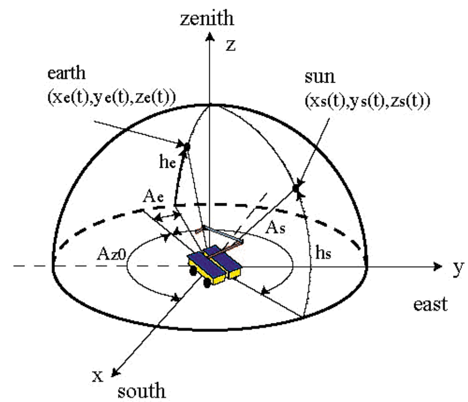


Figure 2: Horizontal Coordinates System

3. Self-Position Estimation

3.1 The Sun and the Earth Observation

The rover finds its absolute position on the Moon by observing the Sun and the Earth. Here the rover is supposed to have inclinometers and a precise time clock. The rover is also supposed to have lunar orbital information.

Altitudes of the Sun and the Earth are obtained from a Sun sensor and the Earth sensor on the rover, respectively. Two of three attitude angles of the rover, roll and pitch, are obtained by inclinometers. On the other hand, the yaw angle of the rover cannot be directly measured because, a magnetic sensor is not available on the Moon. Therefore, not only the position but also the yaw angle must be estimated by using the other angles, altitudes and azimuths of the Sun and the Earth.

Thus, unknown state is $x = (\lambda, \phi, A_{z0})$. Where λ and ϕ represent longitude and latitude of the Moon. A_{z0} represent the azimuth of the rover. By redefining A_{zs} and A_{ze} as $A_{zs} = A_{z0} + A_s$ and $A_{ze} = A_{z0} + A_e$ respectively, equation (1) and (2) can be rewritten as follows.

$$\begin{pmatrix} \cos(h_s)\cos(A_{z0}+A_s) \\ -\cos(h_s)\sin(A_{z0}+A_s) \\ \sin(h_s) \end{pmatrix} = \begin{pmatrix} x_s(t) \\ y_s(t) \\ z_s(t) \end{pmatrix} \tag{3}$$

$$\begin{pmatrix} \cos(h_e)\cos(A_{z0}+A_e) \\ -\cos(h_e)\sin(A_{z0}+A_e) \\ \sin(h_s) \end{pmatrix} = \begin{pmatrix} x_e(t) \\ y_e(t) \\ z_e(t) \end{pmatrix} \tag{4}$$

When the observation by each sensor is performed N times in $t = t_0, t_1, ..., t_{N-1}$, observed values are:

$$\begin{pmatrix} h_{s0} \\ A_{s0} \\ h_{e0} \\ A_{e0} \end{pmatrix} \begin{pmatrix} h_{s1} \\ A_{s1} \\ h_{e1} \\ A_{e1} \end{pmatrix} \cdots \begin{pmatrix} h_{sN-1} \\ A_{sN-1} \\ h_{eN-1} \\ A_{eN-1} \end{pmatrix} = y_0, y_1, \cdots y_{N-1} . \tag{5}$$

And, a state that should be estimated is:

$$\hat{x} = \left(\hat{\lambda}, \hat{\phi}, \hat{A}_{z0}\right). \tag{6}$$

$\hat{x}$ is estimated from the observed values $\{y_0, y_1, \cdots, y_{N-1}\}$ by the least square method. If the true values of y were defined as:

$$\bar{y} = \left(\bar{h}_s, \bar{A}_s, \bar{h}_e, \bar{A}_e\right), \tag{7}$$

evaluation function J described by the following least square equation is introduced to find an optimal y.

$$\begin{aligned} J &= \sum_{i=0}^{N-1} \left\{h_{si} - \bar{h}_{si}(\lambda, \phi, A_{z0}, t_i)\right\}^2 \\ &+ B_1 \sum_{i=0}^{N-1} \left\{A_{si} - \bar{A}_{si}(\lambda, \phi, A_{z0}, t_i)\right\}^2 \\ &+ B_2 \sum_{i=0}^{N-1} \left\{h_{ei} - \bar{h}_{ei}(\lambda, \phi, A_{z0}, t_i)\right\}^2 \\ &+ B_3 \sum_{i=0}^{N-1} \left\{A_{ei} - \bar{A}_{ei}(\lambda, \phi, A_{z0}, t_i)\right\}^2 \end{aligned} \tag{8}$$

$$\frac{\partial J}{\partial x} = 0 \tag{9}$$

In order to solve the equation, we use the Newton -Raphson method.

3.2 Simulation Study

The rover position (λ, ϕ, A_{z0}) is estimated from the observed value y, which contains a measurement error by the Sun sensor and the Earth sensor. The pattern of the measurement error is supposed to be normal distribution, therefore, some of errors as follows are added to the observed value. In this simulation, position is supposed to be in a central hill of the crater "Aristarchus", where a candidate in the future Moon missions.

The accuracy of the Sun sensor:
$0.01°$, $0.1°$, $1°$ (3σ)

The accuracy of the Earth sensor:
$0.1°$, $0.5°$, $2.5°$ (3σ)

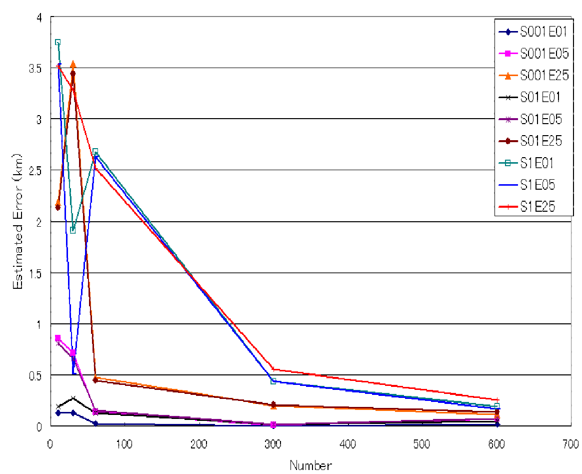
Date: August 20, 2002.

The lunar equator radius: $1738[km]$

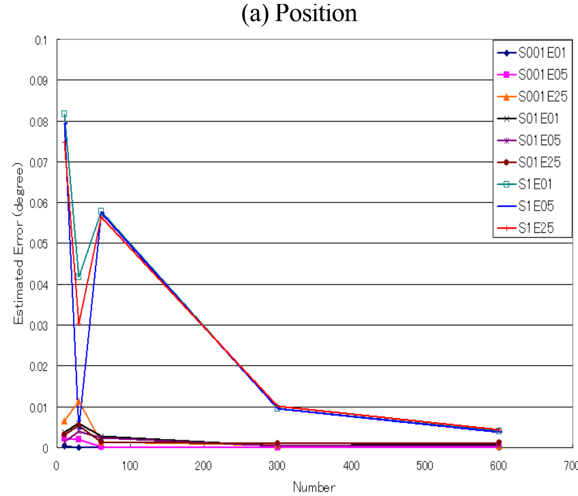
Longitude λ**:** $23.7N°$

Latitude ϕ**:** $47.4W°$

The result of simulation is shown in Figure 3. The position estimation is saturated when the observation of about 300 times. The estimated error is 500 meters or less. The position of less than 300 meters can be estimated with 600 times of observations. Furthermore, azimuth is estimated with accuracy of approximately 0.01°.



(a) Position



(b) Azimuth

Figure 3: Estimation Results

4. Accurate Self-Positioning Strategy

To reduce the position error estimated by the Sun and the Earth observation method, it is proposed that an integrated localization method with dead reckoning. Dead reckoning is effective when a robot moves in a short distance, however, position error accumulates as a robot moves further and further. Therefore, the sensor fusion techniques are introduced to obtain the precise positioning information.

4.1 Integration Algorithm

At first, rover's position is estimated by observing the Sun and the Earth on the point m. The estimated position is defined as an expectation of the position $\bar{x}_s$, and existence probability around the estimated position $\bar{x}_s$ is supposed to be a normal distribution with dispersion σ_s as:

$$S_k(x) \mid x-3\sigma_s \le x \le x+3\sigma_s \quad (k=m) \qquad (10)$$

where subscript of k (=1,2,...m,...) represents position number of the rover.

Next, relative position estimation from m to $m+1$ is carried out by dead reckoning at all times, the estimated movement is represented as d_m. Existence probability after the movement d_m is supposed to be a normal distribution with dispersion σ_d as:

$$D_k^j(d_k) \mid d_k-3\sigma_d \le d_k \le d_k+3\sigma_s \quad (k=m) \qquad (11)$$

where subscript of j (=1,2,...) represents update number.

The movement from m to $m+1$ is estimated by dead reckoning, however, the start point is unknown in existence range $S_m(x)$ of the point m. Assuming that the start point is in all of the range $x-3\sigma_s \le x \le x+3\sigma_s$, existence probability at position m+1 is shown as:

$$D_k^j(x+d_k) \quad (x-3\sigma_s \le x \le x+3\sigma_s) \quad (k=m) \qquad (12)$$

Weight $W_m^j(x)$ is calculated using both $D_k^j(x+d_k)$ and the estimated position $S_{m+1}(x)$ on the point $m+1$ as:

$$W_k^j(x) = P\left(D_k^j(x+d_k) \cap S_{k+1}(x)\right) \quad (k=m, j=1) \qquad (13)$$

where $P(*)$ represents probability. Existence probability $S_m(x)$ of the point m is updated by being multiplied the weight $W_m^j(x)$ as:

$$L_k^j(x) = C\left(W_k^j(x) \times S_k(x)\right) \quad (k=m) \qquad (14)$$

where C is a coefficient for regularization. After that, weight is defined as:

$$W_k^j(x) = P\left(D_k^j(x+d_k) \cap L_{k+1}^j(x)\right)$$
$$(k=m-1, m-2, \ldots, j=2,3,\ldots) \qquad (15)$$

According the above equations, the positions estimated previously are updated backward, so we call the fusion method "back propagation". The image of the proposed algorithm is shown in Figure 4.

The back propagation can only improve the precision of estimation of past position, however, the proposed algorithm can be applicable for the present position to change some subscripts:

$$W_{k+1}^j(x) = P\left(D_k^j(x+d_k) \cap S_k(x)\right) \quad (k=m, j=1) \qquad (16)$$

$$L_{k+1}^j(x) = C\left(W_{k+1}^j(x) \times S_{k+1}(x)\right) \quad (k=m) \qquad (17)$$

$$W_{k+1}^j(x) = P\left(D_k^j(x+d_k) \cap L_k^j(x)\right) \quad (k=m, j=2,3,\ldots) \qquad (18)$$

We call this operation "forward propagation", because it updates the estimation one after another with past data.

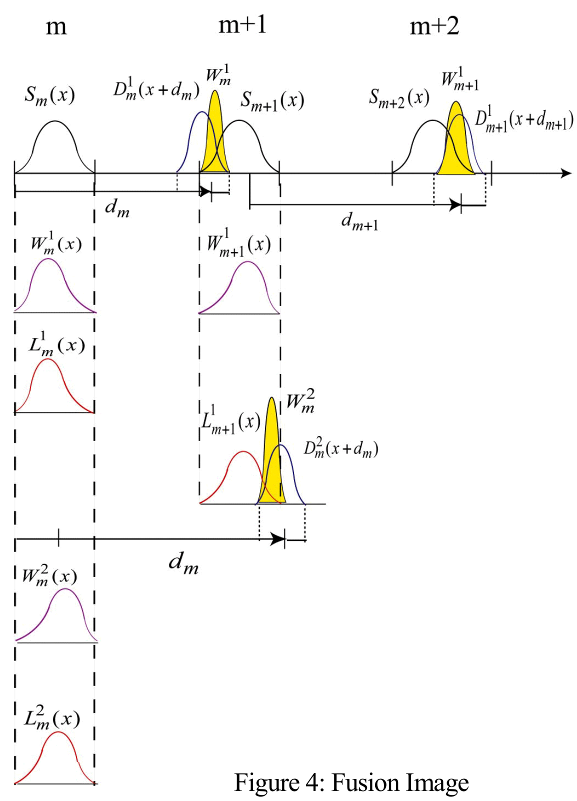


Figure 4: Fusion Image
(Back propagation)

4.2 Simulation Study

To investigate the effectiveness of the proposed integration method, computer simulations are performed. Parameters in this simulation are set as follows.

True position interval:

$300, 600, 900, 1200, 1500, 1800\,[m]$

The accuracy of the Sun & the Earth observation:

$150\,[m]\quad(3\sigma)$

The accuracy of dead reckoning:

10% of movement distance

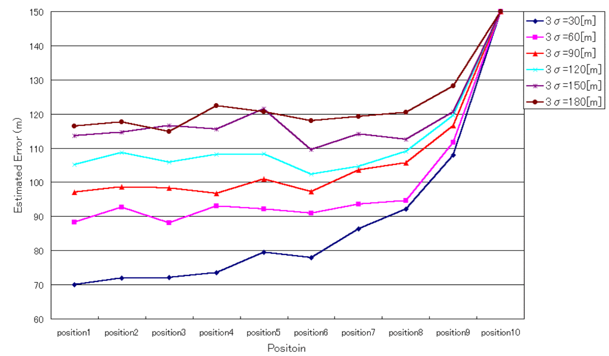
$30, 60, 90, 120, 150, 180\,[m]\quad(3\sigma)$

The normal distribution errors were added to the observation values.

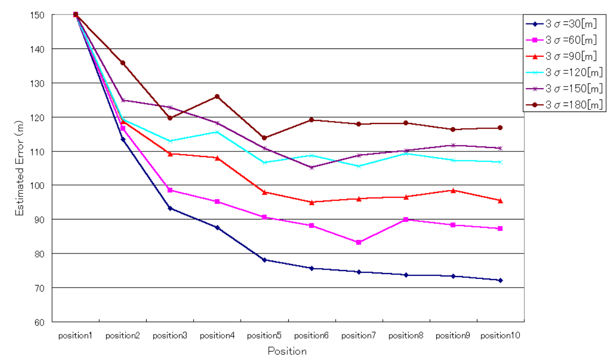
Monte Carlo simulation (300 times) was performed in order to confirm the statistical validity of an estimated value. The back propagation result is shown in Figure 5-(a), the forward propagation result is shown in Figure 5-(b), and combination result of the forward and the backward propagation is shown in Figure 5-(c). Then, the simulation results of integration updates in case of 300 meters interval are shown in Figure 6. This is shown that estimation accuracy is improved as back propagation and forward propagation are carried out.

5. Field Experiment

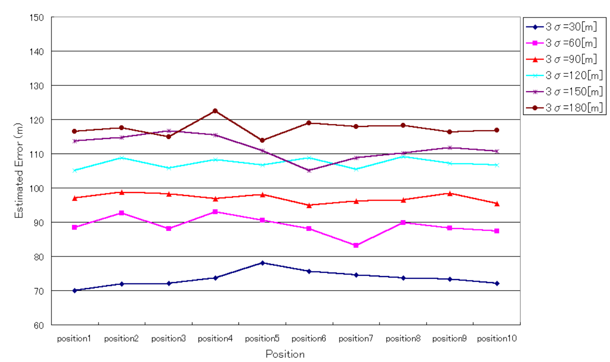
Some field experiments to examine the effectiveness of the proposed method were carried out. In order to emulate the Moon environment on the ground, D-GPS was substituted for the Sun and the Earth sensor to estimate absolute position, and odometry using wheel encoder was adopted for dead reckoning to estimate relative position.



(a) Back Propagation

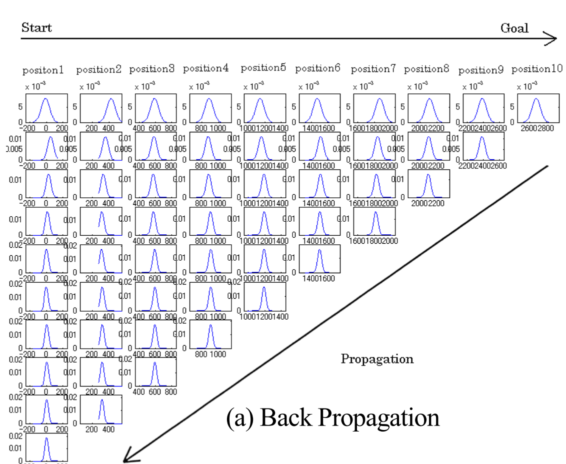


(b) Forward Propagation

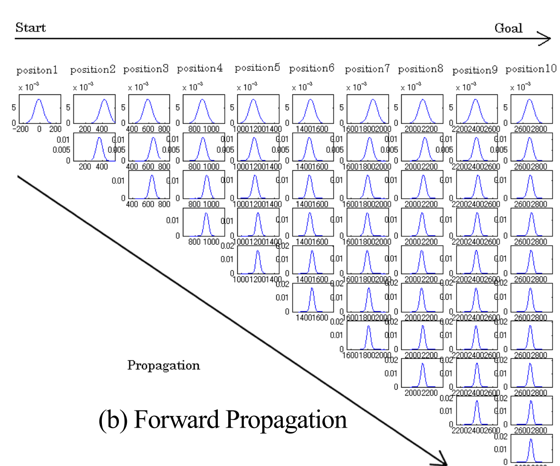


(c) Combination (Back & Forward Propagation)

Figure 5: Monte Carlo Simulation Results



(a) Back Propagation



(b) Forward Propagation

Figure 6: Simulation Results of Integration Updates

5.1 Preliminary Experiment

A preliminary experiment was carried out to decide noise pattern and extent of dispersion. The fixed point observation by D-GPS (10 sets, 300 acquisitions / set) was performed in the test field. As the result of the field test, we supposed incidental noise pattern of D-GPS as gaussian in this paper. The estimated error (3σ) was approximately 0.49 meters.

The ratio of the estimated error of the Sun and the Earth sensor ($3\sigma = 150$ [m]) to that of D-GPS ($3\sigma = 0.487$ [m]) is approximately 300:1. Therefore, the scale of the experiment is equivalent as 1/300 of the practical problem. Conditions of the simulation and the experiment are shown as follows.

The accuracy of absolute position estimation:

The Sun & the Earth sensor;

$3\sigma = 150$ [m] (Result of simulation)

D-GPS;

$3\sigma = 0.487$ [m] (Result of experiment)

Ratio; $308:1$

Distance of integration by relative position estimation:

The Sun & the Earth sensor;

$300, 600, 900, 1200, 1500$[$m$] interval

D-GPS;

$1, 2, 3, 4, 5$ [m] interval

Ratio; $300:1$

In order to decide degree of the estimation error of odometry in the test field, preliminary experiment of relative position estimation was carried out using the test bed "Onion" (Figure 7). At this time, tuning of parameters was also carried out so as to calculate odometry precisely.

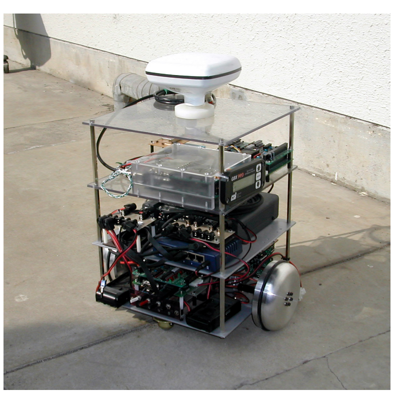


Figure 7: Test bed "Onion" is especially designed for sensing and navigation experiment.

30 times of estimations were performed at each position with distance from 1 to 5 meters. As the result of the preliminary experiment, the pattern of the error was supposed to be a normal distribution, and the size of 3σ was approximately 0.85% of distance of integration. Since the test field was pavement, the odometry was very precise.

5.2 The verification of the proposed method

To examine the effectiveness of the proposed integration method, the following experiment was carried out. In the experiment, 8 absolute positions where were set in a series of each distance interval measured by the D-GPS. And relative positions were measured by the odometry.

Absolute position estimation by the proposed integration method was performed using extent of distributions which were obtained from preliminary experiment. The results of integration in case of 1 meter interval are shown in Figure 8. As the experimental results, the accuracy of estimation is improved to approximately one third by carrying out the back propagation and the forward propagation as well as the simulation. The experimental results show more accurate than those of simulations of Section 4.2, because the accuracy of odometry in this test field is more precise than that of simulation. The estimation errors when the position estimation is saturated by the proposed method are shown in Table 1.

The 3σ accuracy of the D-GPS was 0.487 [m] by the result of the preliminary experiment, however, the accuracy of the estimation by the proposed integration method was improved to approximately 0.160-0.171 [m]. Thus, the accuracy on the Moon would correspond to be 49.2-52.6 [m] as shown in Table 1. As the result of the experiment, the proposed integration method could be estimate absolute positions three times as precise as using the method of only observing the Sun and the Earth on the Moon.

Table 1: 3σ Accuracy of Estimation

Measurement Interval [m]	1/300 Experiment	Equivalent to Moon Measurement
1	0.1596	49.16
2	0.1611	49.62
3	0.1635	50.36
4	0.1668	51.37
5	0.1708	52.61

Table 2: Result of Slip Simulation

Slip Ratio	Accuracy of Estimation [m]	Rate of Accuracy Improvement [%]
0.1	0.3232	39.23
0.3	0.3564	26.26
0.5	0.3857	11.66

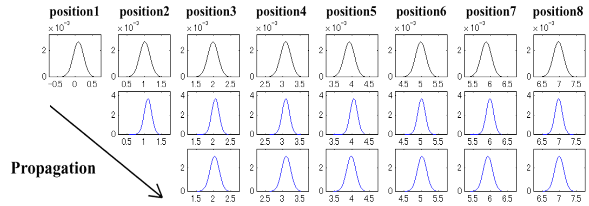
6. Slippage Simulation added DC

Odometry is accurate enough to estimate position on the pavement, because slippage of tire is small. But, for the rover application, the slippage on the Moon surface covered with sand is supposed so large. It is afraid that odometry is not good enough to use for the estimation because of large slip ratio. Therefore simulations supposed on the sand environment (forward propagation) were carried out. The error with none-zero mean is represented to "DC", here after. Three types of DC were given as below, so as to make the slip ratio $\lambda = 0.1$, 0.3, and 0.5.

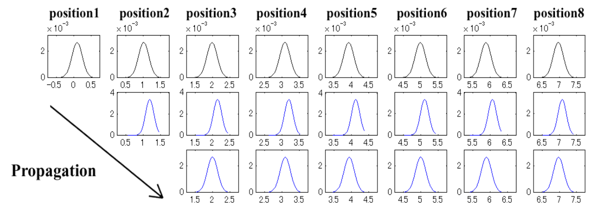
DC added to the measurement value:

11.0% of movement distance ($\lambda = 0.1$)
42.9% of movement distance ($\lambda = 0.3$)
100% of movement distance ($\lambda = 0.5$)

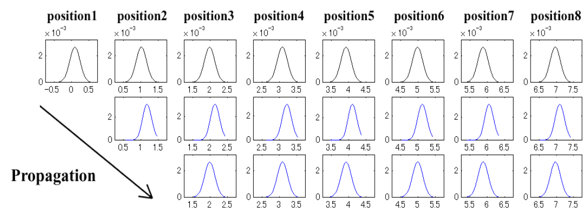
Integration results are shown in Figure 9. Under all conditions, accuracy is not improved after the second update. It is the reason why the estimated error of the odometry is larger than that of the D-GPS by error accumulation. Therefore, integration after the third update is omitted. Accuracy of the position estimation after one update is shown in Table 2. Though only one update is effectual, accuracy of estimation can be improved to 66.4-79.2% by the integration method.



(a) $\lambda = 0.1$

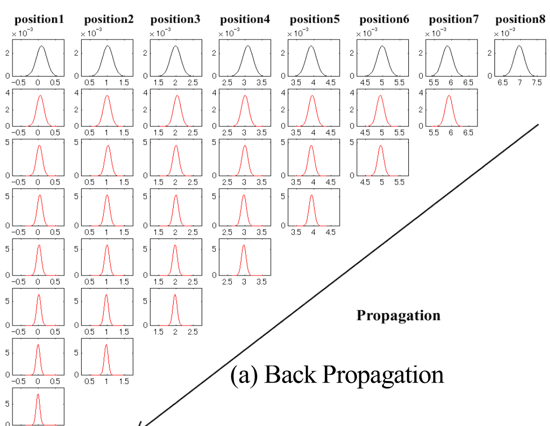


(b) $\lambda = 0.3$

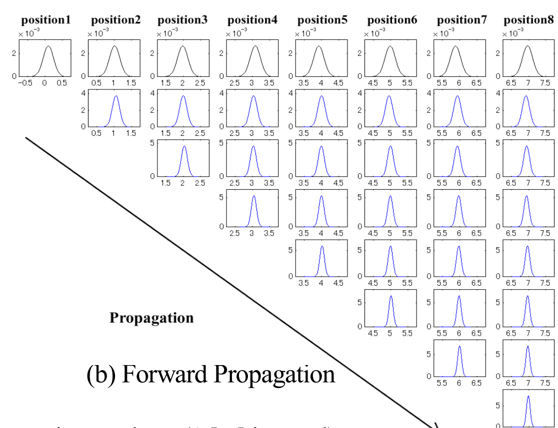


(c) $\lambda = 0.5$

Figure 9: Slip Simulation Results



(a) Back Propagation



(b) Forward Propagation

Figure 8: Experiment Results of Integration Updates (1 [m] interval)

7. Conclusions

This paper presented a method to estimate absolute position of a lunar rover by using the Sun sensor and the Earth sensor. This paper also proposed an accurate localization scheme to integrate the Sun and the Earth observation and the dead reckoning. The effectiveness of the proposed method was confirmed by field experiments and some computer simulations.

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