Localization of Hopping Rover Using Round-Trip Propagation Delay with Multiple Motion Models

Sayaka KANATA,† Yuta UEZONO, and Takashi SHIMOMURA

Aerospace Engineering, Osaka Prefecture University, Sakai, Osaka 599–8531, Japan

A method to localize a space rover on a planetary body using round-trip propagation delay between the rover and its mother spacecraft has previously been proposed. The approach can provide localization with meter-order accuracy. However, the method is based on the assumption that the rover is stationary on the surface of the asteroid during the localization. In this study, this method is expanded for application to the rover’s hopping motion. The proposed method is based on the use of the extended Kalman filter (EKF). Multiple motions of the rover are modeled for the time-update steps in the EKF. The localization accuracy is demonstrated through numerical simulations that assume a hopping rover on a small planetary body with the size of the asteroid Itokawa.

Key Words: Localization, Hopping Rovers on Small Planetary Body, Two-Way Range Measurement

1. Introduction

Investigations of small planetary bodies such as asteroids and comets have attracted increasing attention recently. The spacecraft Hayabusa succeeded in landing on the asteroid Itokawa before returning to Earth with asteroidal material samples in 2010. The ESA’s Rosetta mission soft-landed its Philae probe on a comet in November 2014. Further, the spacecraft Hayabusa-2 was launched loaded with three hopping rovers, collectively called MINERVA-2. One of the purposes of MINERVA-2 is the direct investigation of its hopping motion. This method is attractive because it provides the position and attitude of the rover in real-time with only the use of cameras. However, the estimated position and attitude depend on the local frame (i.e., the planetary-body-fixed surface frame). Therefore, it is necessary to transform these estimations into a planetary-body-centered inertial frame.

Fiorini et al. proposed a self-localization method for a hopping rover. It provides a posteriori localization of the landing point using dynamic sensors such as accelerometers, gyros, and contact sensors. They also proposed a stereo vision system using an omni-directional lens. In the missions of the Mars Exploration Rovers, it was demonstrated that the stereo vision system performs well on Mars. However, on the surface of a small asteroid, it is uncertain whether enough landmarks exist within the small range of view of the rover. The range of view depends on the height of the rover. A smooth region covered by sand makes it difficult to perform vision-based localization. The limited resolution of the camera is also of concern.

In this context, we have proposed a method of localization for a rover based on radio-waves. The method uses measurements of the round-trip propagation delay between the rover and its mother spacecraft. The approach is based on the use of the extended Kalman filter (EKF) and provides real-time localization with meter-order accuracy for a rover located on the surface of an Itokawa-sized asteroid.

2. Localization Method for a Hopping Rover

2.1. Coordinate definition

The inertial-fixed coordinate frame is used in our approach. The frame’s origin is fixed to the center of mass of a small planetary body. We define the z axis as being parallel to the direction of the rotation axis of the small planetary body. The x axis coincides with the longitude of the ascending node of the spacecraft’s orbit. The y axis is defined such...
that the coordinate system is a right-handed system. This coordinate system is illustrated in Fig. 1, where $x$ denotes the position of the rover, $X$ the position of the mother spacecraft, $\sigma$ the direction of the rotational axis of the small planetary body, and $\omega$ the angular velocity of rotation.

### 2.2. EKF-based localization with multiple motion models\(^{(15)}\)

We consider $N$ motion models in our EKF-based approach. We define $s$ as the state vector, and the estimated state generated by the motion model $f_a$ at $t_i$ is defined as $s_a(t_i)$ and its covariance matrix as $P_a(t_i)$, where $a = 1, 2, \cdots, N$. We next define the estimated state generated by the motion model $f_b$ at $t_{i-1}$ and a motion model $f_a$ at $t_i$, and its covariance matrix as $P_{ab}(t_i)$, where $b = 1, 2, \cdots, N$. The following description focuses on the time instant $t_i$ that $(t_i)$ is omitted in the following equations; for example, $s_a(t_i)$ is simply denoted as $s_a$.

The time-update step of the EKF is given by

\[
\begin{align*}
\delta s_{ab} &= f_a(s_a) \quad \delta s_{ab} = \begin{bmatrix} s_{a1} - s_{ab} \\ \vdots \\ s_{aN} - s_{ab} \end{bmatrix}, \\
P_{ab} &= \begin{bmatrix} P_{a1} + K_{a1} \\ \vdots \\ K_{aN} \end{bmatrix} + Q_a,
\end{align*}
\]

where $\hat{a}$ denotes the prediction, $\bar{a}$ the measurement updated value, $Q_a$ the covariance matrix of the process noise of model $f_a$, and

\[
F_a = \frac{\partial f_a}{\partial s} \bigg|_{s_a}.
\]

The measurement update is given as

\[
\begin{align*}
\delta s_{ab} &= \delta s_{ab} + K_{ab} (z - \bar{z}_{ab}), \\
\hat{P}_{ab} &= \hat{P}_{ab} - K_{ab} H_a \hat{P}_{ab},
\end{align*}
\]

where $z$ represents the measurement, $K_{ab} = \hat{P}_{ab} H_a^T (H_a \hat{P}_{ab} H_a^T + R_a)^{-1}$, and $H_a = \frac{\partial f_a}{\partial s} \bigg|_{s_a}.$

\[
\begin{align*}
H_a &= \frac{\partial f_a}{\partial s} \bigg|_{s_a}.
\end{align*}
\]

Here, $h_a$ represents the measurement equation in the case of the motion of $f_a$, $R_a$ represents the covariance of the measurement noise of model $f_a$.

The integrated state vectors are defined as

\[
\delta s = \sum_{b=1}^{N} [Pr]_{ab} \delta s_{ab},
\]

\[
P_a = \sum_{b=1}^{N} [Pr]_{ab} \hat{P}_{ab} + (\delta s_{ab} - \delta s)(\delta s_{ab} - \delta s)^T,
\]

where

\[
[Pr]_{ab} = \frac{N_{ab} [Pr]_{ab} \beta_{ab}}{N},
\]

Here, $N_{ab}$ is equal to

\[
N_{ab} = \frac{1}{\sqrt{2\pi S_{ab}}} \exp \left\{ -\frac{1}{2} \frac{(z - \bar{z}_{ab})^2}{S_{ab}} \right\}.
\]

The term $[Pr]_{ab}$ denotes the probability that a motion model transfers from $f_b$ to $f_a$, while $N_{ab}$ denotes the probability density function that reflects the error between the actual measurement $z$ and the estimated value $\bar{z}_{ab}$. Further, $\beta_{ab}$ denotes the probability that the state vector based on the model $f_a$ is correct, and it is defined as

\[
\beta_{ab}(t_i) = \frac{\sum_{b=1}^{N} N_{ab} [Pr]_{ab} \beta_{ab}(t_{i-1})}{\sum_{a=1}^{N} \sum_{b=1}^{N} N_{ab} [Pr]_{ab} \beta_{ab}(t_{i-1})}.
\]

where the initial belief $\beta_{ab}(0)$ and the transfer probability $[Pr]_{ab}$ are chosen arbitrarily. The system outputs the state $s_i$, which has the highest probability, $\beta_{aa}$.

In our problem, the state vector is defined as a set of the position and velocity of the rover as

\[
s = \begin{bmatrix} x \\ v \end{bmatrix}.
\]

Three motion models are considered in this study. The first model $f_1$, corresponds to the case that the rover is stationary on the surface. The second model $f_2$, corresponds to the case that the rover moves using gravitational force (i.e., the motion of freefall). The last model $f_3$, considers the case of a bounding motion. Rolling motion is ignored in our model because it depends on the shape of the rover and a terrain that is difficult to model.

### 2.3. Model $f_1$: Stationary on surface

The motion of the rover only depends on the rotational motion of the small planetary body. Assuming that the planetary body’s angular velocity, $\omega$, and the direction of the rotational axis, $\sigma$, are constant, the rover’s motion can be described by the equation

\[
s(t_{i+1}) = f_1(s(t_i)),
\]

where $f_1$ is equal to

\[
f_1(s(t_i)) = \begin{bmatrix} R(\sigma, \omega \Delta T) & 0_3 \\ 0_3 & R(\sigma, \omega \Delta T) \end{bmatrix} s(t_i),
\]

where $\sigma$, $\omega$, and $\Delta T$ denote the direction of the rotational axis, the angular velocity of rotation, and the time increment, respectively.
\(0_n\) denotes the zero matrix of \(n\) dimension, and \(R(\sigma, b)\) represents the rotation matrix:

\[
R(\sigma, b) = I + \sin b[\sigma^T] + (1 - \cos b)[\sigma^T]^2.
\]

(17)

Here \(I\) denotes the identity matrix, and \([a^T]\) a skew-symmetric matrix describing the cross-product of vector \(a\).

2.4. Model \(f_2\): Freefall

The surface of the small planetary body is assumed to be exposed to a vacuum; air friction does not exist. The only force acting on the rover is gravitational force. Consequently, we have

\[
m\ddot{x} = -G \frac{Mmx}{|x|^3},
\]

(18)

where \(m\) is the mass of the rover, \(G\) the gravitational constant, \(M\) the mass of the planetary body, and \(|a|\) the norm of vector \(a\). Thus, the rover motion is described by the expression

\[
\frac{d}{dr} s = \begin{bmatrix} v \\ GMx \\ |x|^3 \end{bmatrix} = f_{2c}(s).
\]

(19)

The motion model for freefall, \(f_2\), is obtained by transferring the continuous function \(f_{2c}\) into a discrete system.

2.5. Model \(f_3\): Bounding motion

The bounding motion occurring when the rover contacts the surface is modeled as

\[
v_A = v_B - (1 + \alpha)(v_e^T) e,
\]

(20)

where \(v_B\) and \(v_A\) denote the velocities of the rover before and after the bound, respectively. Vector \(e\) represents a unit normal vector of the position at which the rover bounds. Our bounding motion model is illustrated in Fig. 2. The equation of the rover’s motion is given as

\[
s_{i+1} = f_2 \left[ \begin{bmatrix} x_i \\ v_{iA} \end{bmatrix} \right] = f_3(s_i).
\]

(21)

2.6. Measurement equation

The round-trip propagation delay between the spacecraft and rover is measured every \(\Delta T\). The measurement, \(z = \tau\), satisfies

\[
\tau = h(x_e)
\]

(22)

where \(c\) denotes the speed of light, \(t_e\) the emission time, \(t_r\) the receiving time, and \(t_{ref}\) the reflection time at the rover. These parameters are related as

\[
x(t_{ref}) = x(t_e + \tau_d),
\]

(24)

\[
X(t_f) = X(t_e + \tau_d + \tau_u),
\]

(25)

where \(\tau_d\) denotes the downward propagation delay (from the spacecraft to the rover) and \(\tau_u\) the upward propagation delay (from the rover to the spacecraft), and \(\tau = \tau_d + \tau_u\).

The downward propagation time, \(\tau_d\), is given as

\[
\tau_d = \frac{1}{c} |X(t_e) - x(t_{ref})|,
\]

(26)

and the upward propagation delay, \(\tau_u\), satisfies

\[
\tau_u = \frac{1}{c} |X(t_e + \tau_d + \tau_u) - x(t_{ref})|.
\]

(27)

3. Simulation Results

3.1. Parameter settings

The localization error is estimated through numerical simulations assuming a rover on a fictional planetary body dimensionally resembling the asteroid Itokawa. The parameters for the planetary body and spacecraft are summarized in Table 1. In our study, the orbit parameters were defined so that the rover and spacecraft were able to communicate and localize with high sensitivity. The proposed method has sensitivity in line-of-sight direction between the rover and spacecraft. The measurement interval, \(\Delta T\), was 10 s. The measurement noise was assumed as white Gaussian with a covariance of \(10^{-10}\) s², which takes into account the performance of the communication devices loaded on a given mother spacecraft at the present time.

The actual state, \(s^*_v\), was set an error of 10 m in each direction and 10 degrees of error in the hopping direction; that is,

\[
s^*(0) = \begin{bmatrix} x^*(0) \\ v^*(0) \end{bmatrix}^T,
\]

(28)

where

\[
x^*(0) = \dot{x}(0) + \begin{bmatrix} 10 & 10 & 10 \end{bmatrix}^T
\]

(29)
and
\[ \mathbf{v}^*(0) = R \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}^\top \frac{\pi}{18} \mathbf{\hat{v}}(0). \]

The initial covariance matrix \( P_0 \) was set as
\[ P_0 = \begin{bmatrix} 10^4 \mathbf{I} & 0 \\ 0 & 10^{-4} \mathbf{I} \end{bmatrix}. \]  

These values reflect the following conditions: The previous study\(^{13}\) estimated the initial position of the rover with an error of less than 10 m. The maximum hopping velocity of the rover MINERVA was 0.1 m/s,\(^{4} \) which was designed so that the rover does not overshoot the escape velocity on asteroid Itokawa.

The transition probability, \([\mathbf{P}_{tr}]_{lab}\), was set as
\[ ([\mathbf{P}_{tr}]_{lab}) = \begin{bmatrix} 1 - 2\delta & \epsilon & \epsilon \\ \delta & 1 - 2\epsilon & \epsilon \\ \delta & \epsilon & 1 - 2\epsilon \end{bmatrix}, \]  

where \( \delta = 10^{-6} \) and \( \epsilon = 10^{-2} \) in this simulation. These values reflect the case that the motion \( f_1 \) (stationary on the surface) mostly does not transfer to \( f_2 \) (freefall) or \( f_3 \) (bounding). The transition probability from \( f_2 \) to \( f_1 \) or \( f_3 \) is relatively greater than that of the transition from \( f_1 \) to \( f_2 \) or \( f_3 \). The initial belief values, \( \beta_i(0) \) were set as
\[ \beta_1(0) = \delta, \]
\[ \beta_2(0) = 1 - 2\delta, \]
\[ \beta_3(0) = \delta, \]

reflective of the rover’s motion being modeled as \( f_2 \) (freefall) immediately after the hopping command is set.

The continuous Eq. (19) was calculated using the Runge-Kutta method. The localization results were calculated using Monte Carlo analysis, wherein 100 noise patterns were applied.

### 3.2. Contact detection

The asteroid was assumed to have an ellipsoid shape. For determining the rover having contact with the surface during hopping, we defined
\[ J(x, y, z) = \frac{x^2}{r_x^2} + \frac{y^2}{r_y^2} + \frac{z^2}{r_z^2} - 1. \]

When \( J(x, y, z) \leq 0 \), it was judged that the rover contacted the surface. Here, the normal vector to the tangent plane is given as
\[ \frac{\partial J}{\partial \mathbf{x}} = \begin{bmatrix} \frac{2x}{r_x^2} \\ \frac{2y}{r_y^2} \\ \frac{2z}{r_z^2} \end{bmatrix}. \]

The unit normal vector of the function \( J \) is given as
\[ \mathbf{e}(x) = \frac{\partial J}{\partial \mathbf{x}} \begin{bmatrix} \partial J \\ \partial \mathbf{x} \end{bmatrix}. \]

### 3.3. Rover at pole

The rover is considered to be at the asteroid’s pole at a point where the radius of the asteroid is minimum and the rover can hop at maximum velocity. The initial state for estimation in this case was set as
\[ \mathbf{\hat{s}}(0) = \begin{bmatrix} \mathbf{\hat{x}}(0) \\ \mathbf{\hat{v}}(0) \end{bmatrix}, \]

where
\[ \mathbf{\hat{x}}(0) = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \]
\[ \mathbf{\hat{v}}(0) = \frac{0.1}{\sqrt{2}} \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}. \]

The actual motion of the rover is plotted in Fig. 3. The rover was observed to touch the surface five times at observation times of 1,350, 1,910, 2,160, 2,280, and 2,350 s, which time intervals are denoted by vertical lines in all of the following figures. At 2,350 s, the rover did not bound and was stationary on the surface of the asteroid: the \( z \) component was constant while the \( x \) and \( y \) components varied sinusoidally.

Figure 4 plots the time-scale error of localization calculated by the conventional method.\(^{12}\) The average of 100 noise patterns is plotted in the figure. Because the conventional method of localization assumes that the rover is stationary on the surface, the localization error increased during the hopping motion from 0 to 2,350 s of measurement time. In the time interval after 2,350 s, the localization error in-
creased once and gradually decreased when the motion model coincided with the actual motion. After 3 h of observation, the localization error was 4.78 m.

Figure 4 also plots the results obtained via the proposed method with multiple models for the rover’s motion. The mean value of 100 noise patterns is plotted. Upon comparing our results with those of the conventional method, we observed that the proposed method exhibits smaller error; the maximum error was 22.5 m at 2,410 s. After 3 h of observation, the localization error was 1.34 m.

Figure 5 plots the maximum, mean, and standard deviation of the localization error of 100 noise patterns as obtained by the proposed method of multiple motion models. Figure 6 plots motion models with the highest probability \( P_{a}(t) \). At the beginning of the observation, the system modeled the rover’s motion as freefall. After 1,970 s of observation, the rover was modeled as stationary on the surface. The motion prediction does not coincide with the actual motion; the repeating bounds at 1,910, 2,160, 2,280 and 2,350 s were modeled as the rover being stationary on the surface, which increases the maximum localization error to 22.5 m at 2,410 s.

Figure 7 plots the probability \( P_{a}(t) \) of each motion model from 0 to 3,600 s of observation time. The probability of the bounding motion increased when the actual bound occurred, as indicated by the arrows in the figure. Just after the first bound at 1,350 s, the system modeled the rover’s first motion as bounding motion for a couple of minutes. Then, the probability of freefall motion was as high as that of the bounding motion. Next, the probability of freefall motion increased. Lastly, before the second bound at 1,910 s, the system modeled the rover’s motion as freefall. Bounding happens in a moment instead of continuously, but the system estimated that the rover is in bounding motion continuously. This comes from the transition probability \( P_{r} \). In the simulations, the transition probability was simply defined as Eq. (32): Only the motion model of \( f_1 \) (stationary on the surface) had different transition probability, where the models of \( f_2 \) (freefall) and \( f_3 \) (bounding) had the same transition probability. The transition probability from the bound-to-bound motions were set as (1 - \( 2e \)), which brought the system to judge the bounding motion continues.

3.4. Rover on equator

In order to validate our choice of the arbitrarily selected parameters, that is, initial belief \( P_{a}(0) \) and transfer probability \( P_{r} \), we performed another simulation. Only the initial state for the rover was changed. The rover was set be on the equator when the radius of the asteroid is maximum. The initial state for estimation was

\[
\hat{x}(0) = \begin{bmatrix} r_x & 0 & 0 \end{bmatrix}^T
\]

and

\[
\hat{v}(0) = \frac{0.04}{\sqrt{2}} \begin{bmatrix} 1 & 0 & 1 \end{bmatrix}^T,
\]

where the escape velocity was about 0.07 m/s. The actual motion of the rover in plotted in Fig. 8. The rover touched the surface eight times at observation times of 4,330, 5,570, 6,030, 6,260, 6,380, 6,440, 6,470 and 6,540 s. At 6,540 s, the rover did not bound and was stationary on the surface of the asteroid.

Figure 9 plots the time-scale error of the localization as calculated by the conventional method along with the corresponding results as obtained by the proposed method of multiple motion models. The average of 100 noise patterns is plotted.

Similar to the cases of the rover at the pole, the localization error, as obtained using the proposed method, was considerably smaller than that obtained using the conventional meth-
The proposed method exhibited an error of 1.14 m after 6 h of observation while the conventional method yielded an error of 188 m.

Figure 10 plots the maximum, mean, and standard deviation of the localization error of 100 noise patterns. Figure 11 plots the motion model with the highest probability. Similar to the case of the rover at the pole, the system’s motion model does not match the rover’s actual motion. However, the system detected bounds with a slight delay, and repeated bounds were modeled as the rover in stationary mode. From Fig. 9, we observe that the mismatch between the motion models and the actual repeated bounds increased the maximum error to 66.8 m at 664 s.

3.5. Summary

The proposed method of rover localization with multiple motion models yielded a localization error of less than 70 m while the conventional method exhibited a localization error of 1,000 m. The transition probability \( \operatorname{Pr}_{\text{lab}} \) directly affects the estimated model. Although \( \operatorname{Pr}_{\text{lab}} \) was defined simply in Eq. (32), we confirmed that our choice of \( \operatorname{Pr}_{\text{lab}} \) in Eq. (32) and initial belief \( \beta_f(0) \) of Eq. (35) were appropriate for two different initial states. The method proposed using multiple motion models worked well for localization of the hopping rover.

4. Conclusion

In this study, we described a method to localize a hopping rover on the surface of a small planetary body. The conventional methods of localization assume that the rover is stationary on the surface, wherein the state vector is used to map the position of the rover. In order to localize the hopping motion, the state vector defined here consists of both the position and velocity of the rover. Three motion models for the hopping rover were considered: the model for the rover being stationary on the surface of the asteroid, the freefall model, and the model for bounding. Through numerical simulations with a fictional planetary body the size of the asteroid Itokawa, we demonstrated the applicability of the proposed method. The localization error obtained with the proposed method was 10 times smaller than that obtained by the conventional method.

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