Implementation of real time on-board navigator of the GNSS receiver for LEO satellite

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Abstract—Navigation information required by low earth orbit satellites is based on GPS. An on-board navigator is required because GPS cannot navigate if less than 4 visible satellites are received due to the nature of fast moving LEO (Low Earth Orbit) satellites. An orbital decision algorithm is required for this, and the EKF (Extended Kalman Filter) is used to estimate orbital elements using measured orbital information. The integrator is constructed using Runge-Kutta 4th method, which is commonly used. The purpose of this paper is to verify the performance of an on-board navigator on a real-time GNSS receiver. A simplified force model is applied and implemented in C language. The implemented results are also validated against MATLAB simulations and an analysis is performed on the error-generating elements. Algorithms implemented in C are transplanted into the GNSS receiver. Functional and real-time operational tests are carried out using a receiver to verify the behavior. Even if number of visible satellites required for initial position estimation falls to three, it track orbit well. As the horizontal error is less than 10 m, a study is needed to improve the accuracy. Thus it is considered that this on-board navigator have enough performance if there are minor accuracy improvement.

Keywords—orbit determination; on-board navigator; real-time; extended kalman filter

III. INTRODUCTION

Analysis and support on the orbit accuracy is essential to the operation of LEO satellites. Orbit determination is the use of orbit dynamic models and observational data to find the best estimate. Orbit prediction refers to the task of calculating the orbit at a specific point in a numerical or analytical way using results of orbit determination. The orbit information of the satellite calculated through the process is directly utilized for the satellite mission planning, the operation of the ground station antenna, and the calculation of the communication plan between the satellite and the terrestrial globe. Therefore, securing the accuracy of orbit determination is one of the most important factors in the management of satellite operations. Observatories used in orbit determination of LEO satellites include GPS receivers and ground tracking data. GPS receiver data include GPS navigation solution, GPS primitive data (pseudo range, carrier phase), and ground tracking data, including azimuth, elevation, and range. To improve accuracy in orbit determination, very precise
dynamics models have to be used. However, the use of simplified dynamics models and EKF was applied to apply on-board navigator in this paper. Further, it compares the results implemented in C and MATLAB and confirms the errors between navigation solution and estimation value.

II. Orbit Determination

A. Dynamic Models

The orbital motion of the satellite can be expressed in the following manner by Newton’s second law.

\[
\frac{d^2r}{dt^2} = -\frac{\mu}{r^3} + \alpha
\]  

(1)

In (1), \( \vec{r} \) is the position vector from earth center to satellite, \( r \) is the distance from earth center to the satellite, \( \mu \) and \( \alpha \) are the gravitational constant and acceleration of perturbation by outer space, respectively. Orbit propagation model applied only asymmetric gravitational model is considered in this paper. It is a reasonable assumption on this point. The asymmetric gravitational model is comparatively large relative to other perturbing force. The orbit propagation model is simple, but it is capable of obtaining proper results without a large error. Considering the asymmetric gravitational model \( J_2 \), the equation of motion can be rearranged into the following equation

\[
\begin{align*}
\dot{x} &= -\mu \frac{x}{r^3} \left[ 1 + \frac{3}{2} \frac{r_e^2}{r^2} \left( 1 - \frac{5z^2}{r^2} \right) \right] \\
\dot{y} &= -\mu \frac{y}{r^3} \left[ 1 + \frac{3}{2} \frac{r_e^2}{r^2} \left( 1 - \frac{5z^2}{r^2} \right) \right] \\
\dot{z} &= -\mu \frac{z}{r^3} \left[ 1 + \frac{3}{2} \frac{r_e^2}{r^2} \left( 3 - \frac{5z^2}{r^2} \right) \right]
\end{align*}
\]  

(2)

In (2), \( r_e \) is the radius of the earth, \( J_2 \) is a parameter for applying the asymmetric gravitational model.

B. Extended Kalman Filter

Orbit propagation is the calculation of future orbits using the orbit elements, whereas the calculation of the orbit elements using the measured orbital information is called orbit determination. EKF is applied to carry out the orbit determination. EKF is appropriate for nonlinear problems. EKF is appropriate for nonlinear problems. The optimal solution of the non-linear problem is determined to know precisely the condition probability density function of the condition. For this purpose, however, we have to find an infinite number of moments. This is physically impossible, so it embodies a simple form of non-linear filter under approximate assumptions. EKF is called the first order filter because it considers only the first order partial differential term of Taylor expansion for the linearization of the non-linear issue. In order to reduce a linear error, utilize a method for replace an optimal estimation orbit which obtained at each observation point with a nominal orbit. Since the actual state of the nonlinear system cannot be accurately recognized, the optimal value is estimated by utilizing the observation value. The simulation is performed using EKF that applies the basic gravitational model, Fig.1 shows the Kalman filter calculation procedure.

Fig 1 Kalman filter algorithm
iii. Tests and Results

E. Orbit Determination Program

Two types of programs are configured; m - file of MATLAB and C. A program consisting of MATLAB is a Fig.2, which has a simple and easy to confirm as a result of the addition, modification and simulation of the perturbation model. Fig.3 is a result of running a orbit determination program consisting of MATLAB.

![Fig 2 The structure of the orbit determination in MATLAB](image1)

Commonly used. Use a integral equation of higher degree to obtain accurate results. As a result of comparing the values calculated through each integral equation, it is judged that the error is small and reliability is sufficiently reliable. Fig.4 shows the behavior sequence of orbit determination algorithms embodied in C.

![Fig 4 The sequence of the orbit determination in C](image2)

A. Test Environment

Fig.5 shows the functional test environment for checking operation of the orbit determination algorithm. Using CCS (Code Composition Studio) v3.3, the orbit determination algorithm is transplanted to a receiver. A GPS signal is reproduced by utilizing a simulator, and the RF signal is transmitted to a receiver. The actual position and speed information of the receiver can be outputted by utilizing the SecureCRT program.

![Fig 5 Test environment](image3)
An input code is created for orbit determination data (pseudo range, position, velocity), and DSP code is applied to a GNSS receiver then the real time process code of orbit determination is implemented.

Fig 6 Real-time code application results

Test Results

Fig. 7 shows that graph that compares the results from orbit determination programs of MATLAB, C, and a GNSS receiver for 120 seconds. And position errors are the result value of the GPS satellite, which is subtracted estimation value from the navigation solution (value). The orbit determination algorithm has a positional error of 1 cm or less. Furthermore, the more satellites using orbit determination, the less position error.

<table>
<thead>
<tr>
<th>Axis</th>
<th>Matlab (m)</th>
<th>C (m)</th>
<th>Max. error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>5.1277506 -03</td>
<td>5.0004672 -03</td>
<td>7.5031243 -04</td>
</tr>
<tr>
<td>Y</td>
<td>5.1616741 -03</td>
<td>4.4929774 -03</td>
<td>1.7303277 -03</td>
</tr>
<tr>
<td>Z</td>
<td>9.6277008 -03</td>
<td>9.3175985 -03</td>
<td>3.0798947 -03</td>
</tr>
</tbody>
</table>

Even if number of visible satellites required for initial position estimation falls to three, it track orbit well. As the horizontal error is less than 10 m, a study is needed to improve the accuracy.
CONCLUSION

Implement an orbit determination program with C language applicable to the actual satellite. The results of the program, which converts MATLAB’s sources into C, do not match perfectly. However, since the error of the maximum 3.07E-3m is provided at the time of comparing the positional error, it can be judged that has the same performance with the MATLAB. An orbit determination algorithm implemented with C was ported into the receiver and operational experiments were performed. An input code of orbit determination data and real time process code of orbit determination was implemented. Real-time testing has shown that the orbit determination algorithm closely follows GPS. The horizontal error is less than 10 m, and additional studies are needed to improve the accuracy. In addition, to check the robustness of the algorithms, we decreased the number of satellites used for estimating the initial location, and up to three worked normally. The orbit determination algorithms studied in this paper are expected to be used to develop the GNSS receiver for satellite applications.

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