INTEGRATION OF NAVIGATION SATELLITE SYSTEM AND VISION SYSTEM FOR PRECISE POSITIONING

Chi-Ho Park, Nam-Hyeok Kim
Daegu Gyeongbuk Institute of Science & Technology
50-1, Sang-ri, Hyeonpung-myeon, Dalseong-gun, Daegu, 711-873, Korea
chpark@dgist.ac.kr, nhkim@dgist.ac.kr

ABSTRACT
In this paper, we propose a reliable and stable precise positioning technique for solving common problems, such as a navigation satellite's signal occlusion in an urban canyon and increasing positioning error due to a limited number of available navigation satellites. This is a fusion system of the navigation satellites system and a vision system. Generally, the navigation satellite positioning system has a fatal weakness in that it cannot calculate a position coordinate when its signal is occluded by some obstacle. For this reason, positioning by the navigation satellites system cannot be used for a variety of applications. Therefore, we propose as a solution, a fusion system of the navigation satellites system and a vision system. Some target objects that have accurate position coordinates, for example, in an outdoor shaded area like an urban canyon, are installed into the vision system. When the vision system recognizes a target object, it loads the accurate coordinate of that target object. Then, it measures the distance by using the disparity from the camera sensor to the target object. These distance and object coordinate data are used for positioning with the navigation satellites system's data. This fusion system can be a solution for the outdoor shaded areas, which now accounts for 47% of the earth. And, it can reduce position errors that result from the lack of the number of available satellites, and the multipath effect. This paper shows that the fusion system can calculate a position coordinate by adding the vision system to the navigation satellites system even though the number of available satellites are less than 4. And, it is more reliable and stable because the vision system's distance error is less than the navigation satellites system's error. Therefore it can be used for precise positioning. It can also compensate for the weakness of the navigation satellites system in an environment like an urban canyon. Therefore it can be a stable and reliable positioning method not affected by environmental influences, and it can be used for a variety of applications, such as kinematic positioning, precise positioning and so forth.

KEY WORDS
Satellite Navigation System, Vision System, GNSS.

1. Introduction
The Global Positioning System (GPS) was made in the United States for military purposes. However, in the 1990s, after being opened to the private sector, it has become widely used for vehicle navigation, aircraft, communications, science, agriculture, and exploration. In addition, the Soviet Union's navigation satellite system GLONASS was also opened to the private sector and this has allowed the utilization of the Global Navigation Satellite System (GNSS)[3-6] to be more multipurpose. Recently, there have been a lot of studies involving GNSS applications. An increase in the satellites and multifrequency have solved problems, like poor accuracy and continuity, however rapidly developing industrialization has increased many of these problems. In particular, increased position error due to cycle slip and multipath exacerbates these problems. Further, 47% of the earth outdoors is still in a GPS shadow. These factors are a main cause of decreased reliability and continuity [1-2]. Today's navigation satellite system provides location information services within around 100 m(drms) accuracy at any time, regardless of the number of users. The system calculates a three-dimensional position by using triangulation, so it can be operated whenever the receiver can take signals from more than 4 satellites. However, city or mountainous areas cannot always receive the satellite signals because of high buildings or mountains. In such cases, the position error will be bigger or shaded areas will occur. Consequently, many researchers have proposed techniques using the navigation satellite system and other applications, to solve these problems. Due to rapid industrialization, the areas and environments where the navigation satellite system can be used is being reduced by the increasing growth of urban canyons. Figure 1 shows a typical situation for navigation satellite system signal reception in an urban canyon.

Figure 1. The situation for signal reception from the navigation satellite in an urban canyon.

Recently, a vision system has been studied which is associated in some part with obstacle recognition and
detection. In particular, one team reported that they had used only a vision system for detection and recognition, at a DARPA unmanned vehicle conference in the United States. But the vision system had some constraints, such as a real time processing problem due to the large amounts of data, and a recognition error due to external lighting changes.

A stereo vision system that can solve many of the problems of a monocular vision system uses a stereo matching algorithm for extracting a depth map, and an obstacle detection algorithm based on this depth map. Therefore, in this paper, we solve the problems that result from shadow areas caused by obstacles, the shortage of the number of available satellites, and the increasing position error due to the multipath effect. This proposed system can be more stable and reliable for high precision positioning for navigation, because the vision based system has fewer error elements than the navigation satellites system. To the author's knowledge, there has been no previous trial to check a high precision system that integrates a vision system and the navigation satellite system.


2.1 The Determination of a Positioning Algorithm

Figure 2 shows the measurement equation of navigation satellite systems that receive signals[8].

\[ \sqrt{(x_1 - x_i)^2 + (y_1 - y_i)^2 + (z_1 - z_i)^2} = \rho_1 + CB \]

where, \( \rho \) is the pseudorange, \((x_i, y_i, z_i)\) is the satellite position, \((x_1, y_1, z_1)\) is the receiver position, Clock Bias (CB) is the time error.

Equation 1 can be obtained in Figure 2[8].

\[ \sqrt{(x_2 - x_i)^2 + (y_2 - y_i)^2 + (z_2 - z_i)^2} = \rho_2 + CB \]
\[ \sqrt{(x_3 - x_i)^2 + (y_3 - y_i)^2 + (z_3 - z_i)^2} = \rho_3 + CB \]
\[ \sqrt{(x_4 - x_i)^2 + (y_4 - y_i)^2 + (z_4 - z_i)^2} = \rho_4 + CB \]

Figure 3 shows the situation when the fusion sensor receives the signal from satellites and the target object. For the convergence of the navigation satellite system and vision system, Equation (1) has to be modified to Equation (3). Equation (2) is the measurement equation in the case that the number of satellites is three.

\[ \sqrt{(x_1 - x_o)^2 + (y_1 - y_o)^2 + (z_1 - z_o)^2} = \rho_1 + CB \]
\[ \sqrt{(x_2 - x_o)^2 + (y_2 - y_o)^2 + (z_2 - z_o)^2} = \rho_2 + CB \]
\[ \sqrt{(x_3 - x_o)^2 + (y_3 - y_o)^2 + (z_3 - z_o)^2} = \rho_3 + CB \]

Equation (3) is obtained from the vision system, which calculates the accurate distance from the camera to the target object. Since the vision system can recognize 3 target objects, it can be used for, multiple targets. In other words, the vision system can calculate three distance values \( (\rho_2, \rho_3, \rho_4) \) from three target objects at a time.

\[ \sqrt{(x_4 - x_o)^2 + (y_4 - y_o)^2 + (z_4 - z_o)^2} = \rho_4 \]

The vision system does not take Clock Bias (CB) into calculation.

(3)

Equation (3) has the advantage of being accurate and invariable because of the value obtained by the vision system from an object with an exact location.

2.2 Positioning Equations using a Navigation Satellite System

The following equation calculates location coordinates by using the navigation satellites system. The position calculation uses the point positioning method by using a receiver chip that is mounted on the vehicle and receives L1 C/A (Coarse/Acquisition) code from the navigation satellites. The C/A code observation equation of the navigation satellites system is given as follows [7].

\[ \rho^k_{i,3} = \rho^k_i + T^k_i + \frac{L^k_i}{R^k_i} + c(\Delta t_i - \Delta t^k_i) + b_{i,2} + e^k_{i,1} \]
\[ \rho^k_i = \sqrt{(x^k - x_i)^2 + (y^k - y_i)^2 + (z^k - z_i)^2} \]

where, \( i \) is the receiver, \( k \) is the satellite and each factor is as follows:

\[ \rho^k_{i,3} : \text{L1 C/A code pseudorange between the receiver and the satellite (m)}; \]
\( \rho^k \): Actual geometric distance between receiver and satellite (m);
\( T^k \): Tropospheric delay error (m);
\( \frac{l^k}{l^k} \): Ionospheric delay error (m);
\( C \): Speed of light (m/s);
\( dt_k \): Receiver clock error (sec);
\( dt^k \): Satellite clock error (sec);
\( e_{e1}^k \): Observation random error;
\( i \): Specific object,
\( N \): Design matrix
\( d \): Distance estimated by the Vision system from the specific object.

We denote by \( P_G \) in the left side of Equation (5) and linearize Equation (5) because it is non-linear equation. After that, the Gauss-Markov Model (GMM) is applied. The result is Equation (6). The satellites’ position coordinates are determined by using the navigation message. Unknown factors are the 3-dimensional position and receiver clock error.

\[
y = \hat{A}x + \epsilon, \quad \epsilon \sim (0, \sigma_{\epsilon}^2 I)
\]

Each item is shown below, \( \hat{\rho} \) is calculated by the receiver's initial position \((\hat{x}_i, \hat{y}_i, \hat{z}_i)\).

\[
y = \begin{bmatrix}
\rho^k_{i,0} - \hat{\rho}^k \\
\rho^k_{i,1} - \hat{\rho}^k \\
\vdots \\
\rho^k_{i,N} - \hat{\rho}^k
\end{bmatrix} : \text{observation matrix}
\]

\[
A = \begin{bmatrix}
-\frac{x^e - \hat{x}_i}{\hat{\rho}^k} & -\frac{y^e - \hat{y}_i}{\hat{\rho}^k} & -\frac{z^e - \hat{z}_i}{\hat{\rho}^k} & c \\
-\frac{x^e - \hat{x}_i}{\hat{\rho}_i} & -\frac{y^e - \hat{y}_i}{\hat{\rho}_i} & -\frac{z^e - \hat{z}_i}{\hat{\rho}_i} & c \\
-\frac{x^e - \hat{x}_i}{\hat{\rho}^a} & -\frac{y^e - \hat{y}_i}{\hat{\rho}^a} & -\frac{z^e - \hat{z}_i}{\hat{\rho}^a} & c
\end{bmatrix} : \text{Design matrix}
\]

\[
\epsilon = \begin{bmatrix}
\Delta x_i \\
\Delta y_i \\
\Delta z_i \\
\epsilon_k
\end{bmatrix} : \text{Unknown matrix}
\]

\[
\epsilon = \begin{bmatrix}
e^k_x \\
e^k_y \\
e^k_z \\
\vdots \\
e^k_{\rho^k}
\end{bmatrix} : \text{Random error matrix}
\]

The coefficient of \( A \) has to be more than 4 because the number of the unknown is 4. For this reason, we can calculate the receiver's position and clock error in the case that the available satellites are more than 4.

The unknown that is calculated in Equation (6) is the increment for initial position.

\[
\epsilon = \frac{C N P^{-1} \hat{P}^{-1} \epsilon}{\hat{N}}
\]

The increment from Equation (7) is added to the receiver's initial position and then the receiver's position is updated. This process is iterated until the increment is under the particular threshold value. After this process, the receiver's position is determined.

\[
\begin{bmatrix}
x_i \\
y_i \\
z_i
\end{bmatrix}_{\text{update}} = \begin{bmatrix}
x_i \\
y_i \\
z_i
\end{bmatrix}_{\text{initial}} + \Delta \begin{bmatrix}
x_i \\
y_i \\
z_i
\end{bmatrix}
\]

At this point, the variance component is Equation (9) and the variance-covariance matrix is Equation (10).

\[
\sigma^2_0 = \frac{\bar{\epsilon}^T \bar{\epsilon}}{N - r \hat{N}}
\]

where, \( \bar{\epsilon} = \epsilon - A \hat{\epsilon} \), \( N \) is the observed number of navigation satellites.

\[
D(\hat{\epsilon}) = \sigma^2_0 N^{-1}
\]

2.3 Fusion Positioning Equations by Navigation Satellite System and Vision System

The vision system obtains observation values by recognizing objects. The number of matrix increases in the case that a multiple observation is given. And, the mathematical calculation method is the same as the method described below. The distance from the receiver to the target object can be calculated by using the vision system. The observation equation by the vision system is as follows.

\[
PV_i = \rho^a + \epsilon_i
\]

where, \( a \) is the specific object, \( i \) is a receiver, and each of the items are as follows.

\[
PV_i : \text{Distance estimated by the Vision system from the specific object to the receiver (m)}
\]

\[
\rho^a : \text{Actual distance from the Specific object to the receiver}.
\]

\[
x^a, y^a, z^a : \text{Three-dimensional position of a specific object}.
\]

\[
x_i, y_i, z_i : \text{Three-dimensional position of the receiver}.
\]

Equation (12) is when nonlinear Equation (11) is linearized.

\[
Z_o = KZ_e + \epsilon_o, \quad \epsilon_o \sim (\sigma_0^{-1} \epsilon_0^{-1})
\]

\[
Z_o = \left[ PV_i - \rho^a \right] : \text{Observation matrix}
\]

\[
A = \begin{bmatrix}
-\frac{x^a - x_i}{\rho_i} & -\frac{y^a - y_i}{\rho_i} & -\frac{z^a - z_i}{\rho_i} & 0
\end{bmatrix} : \text{Design matrix}
\]

\[
\epsilon = \begin{bmatrix}
\Delta x_i \\
\Delta y_i \\
\Delta z_i \\
\epsilon_k
\end{bmatrix} : \text{Unknown matrix}
\]

\[
\epsilon = \begin{bmatrix}
e^k_x \\
e^k_y \\
e^k_z \\
\epsilon_k
\end{bmatrix} : \text{Random error matrix}
\]
The equation to solve the unknown matrix by using the Gauss-Markov Model with Stochastic Constraints Model is Equation (13). However, \( rK(A^T, K^T) \geq 4 \) should be more than 4.

\[
\hat{\epsilon} = (\nu + K^T P_0 K)^{-1}(C + K^T P_0 Z_0)
\]

(13)

The residual of the distance estimated by the vision system is \( \hat{z}_0 = Z_0 - K \hat{\epsilon} \) and the estimated variance component is Equation (14).

\[
\hat{\sigma}_0^2 = \frac{\hat{z}_0^T P \hat{z}_0 + \hat{\epsilon}_0^T P_0 \hat{z}_0}{n - m + l}
\]

(14)

Here, \( n \) is the observed number of navigation satellites, \( m \) is the 4 unknown factors (coordinates 3, receiver's clock error 1), \( l \) is the number of the distance estimated by the vision system. The unknown's variance-covariance matrix, using the navigation satellite system and vision system is shown in Equation (15).

\[
D\{\hat{\epsilon}\} = \hat{\sigma}_0^2 (N + K^T P_0 K)^{-1}
\]

(15)

Above, the position of the receiver is determined by the navigation satellites system and the vision system. Even though the number of the available satellites is less than 4, this system can calculate its current position by the vision system.

3. Test

Figure 4 shows the North Position Error when the available satellites were three and the number of target objects for the vision system was one, two, three. (In the figures, \( G \) means the number of available navigation satellites and \( V \) means the number of target objects for the vision system. For example, \( G3V1 \) means that the navigation satellites are 3 and vision's target object is one.)

![Figure 4. North Position Error.](image)

Figure 5 shows the East Position Error when the available satellites are three and the number of target objects for the vision system is one, two, three.

![Figure 5. East Position Error.](image)

Figure 6 shows the Down Position Error when the available satellites are three and the number of target objects for the vision system is one, two, three.

![Figure 6. Down Position Error.](image)

Figure 7 shows the Horizontal Position Error when the available satellites are three and the number of target objects for the vision system is one, two, three.

![Figure 7. Horizontal Position Error.](image)

Figure 8 shows the North Position Error when the available satellites are four and the number of target objects for the vision system is zero, one, two, three.

![Figure 8. North Position Error.](image)

Figure 9 shows the East Position Error when the available satellites are four and the number of target objects for the vision system is zero, one, two, three.

![Figure 9. East Position Error.](image)

Figure 10 shows the Down Position Error when the available satellites are four and the number of target objects for the vision system is zero, one, two, three.

![Figure 10. Down Position Error.](image)
Figure 10. Down Position Error.

Figure 11 shows the Horizontal Position Error when the available satellites are four and the number of target objects for the vision system is zero, one, two, three.

Figure 11. Horizontal Position Error.

Figure 12 shows the North Position Error when the available satellites are five and the number of target objects for the vision system is zero, one, two, three.

Figure 12. North Position Error.

Figure 13 shows the East Position Error when the available satellites are five and the number of target objects for the vision system is zero, one, two, three.

Figure 13. East Position Error.

Figure 14 shows the Down Position Error when the available satellites are five and the number of target objects for the vision system is zero, one, two, three.

Figure 14. Down Position Error.

Figure 15 shows the Horizontal Position Error when the available satellites are five and the number of target objects for the vision system is zero, one, two, three.

Figure 15. Horizontal Position Error.

Figure 16 shows the North Position Error when the available satellites are six and the number of target objects for the vision system is zero, one, two, three.

Figure 16. North Position Error.

Figure 17 shows the East Position Error when the available satellites are six and the number of target objects for the vision system is zero, one, two, three.

Figure 17. East Position Error.

Figure 18 shows the Down Position Error when the available satellites are six and the number of target objects for the vision system is zero, one, two, three.

Figure 18. Down Position Error.

Figure 19 shows the Horizontal Position Error when the available satellites are six and the number of target objects for the vision system is zero, one, two, three.
4. Conclusion

In this paper, we proposed a technique for solving problems such as signal occlusion by obstacles and increasing position error due to the lack of available satellites. The proposed technique could be a reliable and stable high-precision positioning method for navigation satellite system and vision system convergence. In the experimental results shown in Figure 4-7, even though the available navigation satellites are less than four, we could calculate the position with the added vision system. Our positioning error is around 10m when there are 3 available navigation satellites and one target object is added for the vision system. And the position error can be reduced to 2 – 3m when two vision system target objects are added. Through these results, we can confirm that positioning problems due to outdoor shaded areas can be solved, and reliability and stability are guaranteed, by using the convergence system. Comparing Figure 4-7 with Figure 8-11, we can confirm that the results using 3 available satellites with 1 visual target object are better than using 4 available satellites without the vision system. The RMS (Root Mean Square) value of North Position Error was reduced from 28.28m to 11.77m, and the RMS value of East Position Error was reduced from 11.52m to 7.09m, and the RMS value of Down Position Error was reduced from 11.46m to 9.73m, and the RMS value of Horizontal Position Error was reduced from 30.53m to 13.74m. Comparing Figure 4-7 with Figure 12-15, we can confirm that the results by using 3 available satellites with 2 visual target objects are better than using 5 available satellites without the vision system. The RMS value of North Position Error was reduced from 8.48m to 2.10m, and the RMS value of East Position Error was reduced from 3.92m to 1.78m, and the RMS value of Down Position Error was reduced from 8.54m to 6.17m, and the RMS value of Horizontal Position Error was reduced from 9.34m to 2.75m. Comparing Figure 4-7 with Figure 16-19, we can confirm that the results by using 3 available satellites with 3 visual target objects are better than using 6 available satellites without the vision system. The RMS value of North Position Error was reduced from 4.34m to 1.35m, and the RMS value of East Position Error was reduced from 2.27m to 1.04m, and the RMS value of Down Position Error was reduced from 8.95m to 4.41m, and the RMS value of Horizontal Position Error was reduced from 4.90m to 1.70m. This improvement is produced by the vision system's error: because the vision system's error is small, the positioning error is reduced by increasing the number of vision target objects. Even though we used a high performance navigation satellite system - not cheap commercial GPS - the positioning results are improved. So we can confirm that adding the vision system is a good method for improving positioning accuracy. We can overcome the limit of the positioning accuracy of the navigation satellites with our fusion system. As can be seen in the research results, the problem of outdoor shaded areas are solved by the fusion system, and in addition, reliability and stability are improved. We expect the vision system to assist the navigation satellites system in a wide variety of applications.

Acknowledgement

This work was supported by the DGIST R&D Program of the Ministry of Science, ICT & Future Planning of Korea(13-IT-02)

References