Precise UAV Position and Attitude Estimation by Multiple GNSS Receivers for 3D Mapping

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BIOGRAPHIES

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ABSTRACT

Recently, small unmanned aerial vehicles (UAVs) have been widely investigated for a variety of applications, including remote sensing and aerial surveying. For such applications, current small UAV platforms use a camera to generate a 3D map from aerial images obtained by the UAV. To generate a 3D map, accurate position and attitude data of the UAV is necessary. However, the typical positioning accuracy of a single frequency global navigation satellite system (GNSS) receiver is 1–3 m, and the attitude accuracy obtained from a low-cost micro electro mechanical system (MEMS) sensor is limited to approximately 1–3°. This accuracy is not sufficiently high for accurate 3D mapping.

The goal of this study is establish an accurate position and attitude determination technique by using low-cost GNSS receivers for small UAVs. The key idea behind the proposed method is using multiple low-cost and single-frequency GNSS antennas/receivers to accurately estimate the position and attitude of a UAV. Using the “redundancy” of multiple GNSS receivers, we improve the performance of Real-time kinematic (RTK)-GNSS by using the single-frequency GNSS receivers. This method consists of two approaches: hybrid GNSS fix solutions and consistency check of the GNSS signal strength. In multipath environments, the carrier-phase multipath affects the ambiguity resolution of RTK-GNSS. Different GNSS signal propagation paths are caused at each GNSS antenna. As a result, different multipath errors are caused in each GNSS receiver. It can be used to detect the multipath signals. With this method, we can enhance the availability of carrier-phase ambiguity solutions by using a single-frequency GNSS receiver. Furthermore, we propose a direct attitude estimation technique for a small UAV by using the multiple GNSS receivers. To estimate the absolute attitude of the UAV, we used relative GNSS antenna positions determined by GNSS carrier-phase measurements. It is difficult to resolve the ambiguity for a low-cost single-frequency receiver. In this paper, baseline length constraints can be applied between the GNSS antennas to estimate a reliable ambiguity.

To evaluate the proposed method, we conducted a static test in a narrow-sky environment. First, we determined the attitude by using the proposed technique. Using the proposed method, we could almost perfectly solve the GNSS carrier-phase ambiguity by using low-cost single-frequency GNSS receivers in multipath environments. Next, we evaluated the position determination by using the proposed technique. The fix rates are improved in every GNSS antenna by using the proposed multipath elimination technique. Finally, the fix rate reaches 99.9 %, and it can be concluded that the proposed technique offers increased positioning accuracy in urban environments.

INTRODUCTION

As the use of aerial remote sensing with satellites and manned aircrafts has become increasingly widespread, aerial laser surveys with laser scanners installed on aircrafts are commonly used for applications such as landslide measurements in natural disasters, quality work analysis in civil engineering, and river and levee management in flood control. Although laser surveys by manned aircrafts are suitable for measuring broad terrain

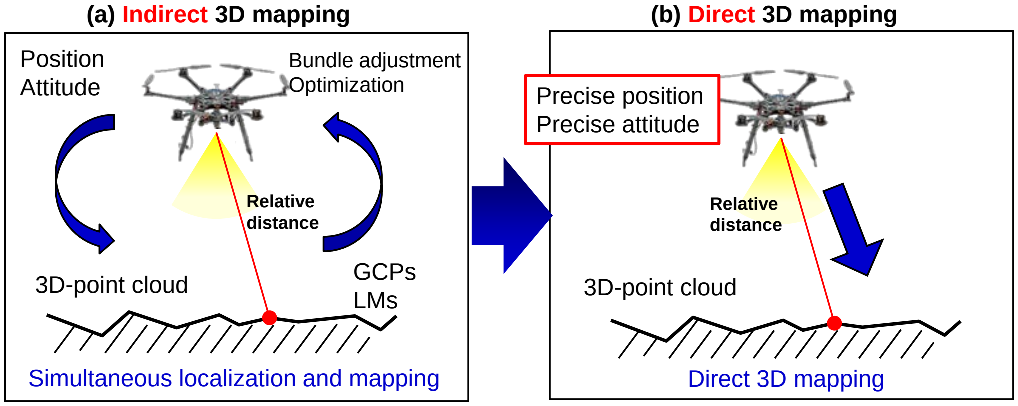

Fig.1 Differences between indirect and direct 3D mapping approaches using UAVs.

ranges, their operation is so costly and the relevant flight procedures are so time-consuming that they are not convenient for measuring terrains that require frequent observations. In this context, remote sensing with small unmanned aerial vehicles (UAVs) has attracted considerable attention in recent researches [1].

Small UAVs are more inexpensive and easier to operate than manned aircrafts and fly at low altitudes when acquiring high-resolution data. However, three-dimensional (3D) mapping with small UAVs has problems. The strictly limited weight of small UAVs imposes restrictions on the size and weight of on-board equipment, such as sensors. This limits the on-board installation of instruments, such as laser scanners used in aerial surveys and precise position and attitude estimation systems that are based on a dual-frequency global navigation satellite system (GNSS) and a high-grade inertial measurement unit (IMU). Owing to the above restrictions that prevent the use of high-precision UAV position and attitude sensors, it is difficult to estimate the accurate position and attitude of small UAVs, which is essential for 3D mapping.

Two approaches exist for constructing 3D maps: indirect and direct 3D mapping. Fig. 1 shows the difference between these two methods. In both cases, 3D map generation requires the accurate position and attitude data of the UAV to transform the coordinates of the relative sensor data obtained from the UAV. In indirect 3D mapping, a camera is typically used for constructing the 3D map and the position and attitude data are estimated by an indirect approach, such as the bundle adjustment technique [2] or optimization-based techniques [3]. In this case, the position and attitude of the UAV are estimated from sequential images or video recordings obtained by a camera installed on the UAV; thus, the precise position and attitude data are not needed for 3D mapping. Several software tools developed for the construction of 3D UAV maps from aerial images [4] have already been used in industry and science applications [5-7]. The disadvantage of indirect 3D mapping is that it requires field surveys to include geographical information (such as latitude, longitude, and altitude) in the generated 3D-point clouds. To analyze the generated 3D maps, a high-quality georeferencing performance is required. The observation of ground control points (GCPs) or natural landmarks (LMs) from images is essential for georeferencing in indirect 3D mapping. In addition, the accurate GCP or LM locations must be predetermined by the field survey. Thus, the indirect approach is difficult to use in disaster environments that are inaccessible to people.

In contrast, in the case of direct mapping, accurate position and attitude information must be directly measured by on-board sensors in real time. In this case, a laser scanner is required for generating the 3D map instead of a camera because a monocular camera cannot directly measure the relative distance and can only measure the direction. If the precise position and attitude of the UAV during flight can be measured by on-board sensors, the 3D-point clouds are automatically generated from the laser scanning data based on the position and attitude of the UAV. The main advantage of direct 3D mapping during flight is that no field surveys are required to determine GCPs for georeferencing. In other words, a direct 3D mapping system can be used in unknown environments, such as a disaster environments or places inaccessible to people.

Current UAVs typically use low-cost single-frequency GNSS receivers and micro electro mechanical system (MEMS) gyroscopes, accelerometers, and magnetometers to estimate the position and attitude of the UAV. The typical positioning accuracy of a single-frequency GNSS receiver is 1–3 m and the attitude accuracy obtained from a low-cost MEMS sensor is limited to approximately 1–3°. This accuracy is not sufficiently high for direct 3D mapping [11,12]. Real-time kinematic (RTK)-GNSS positioning technology can be used to estimate the UAV position with centimeter-level accuracy. In general, a dual-frequency GNSS receiver is used for RTK-GNSSs.

Some studies have employed a dual-frequency GNSS receiver to estimate the UAV position and a high-grade gyroscope, such as a fiber optic gyroscope or a ring laser gyroscope, to estimate the attitude of the UAV [8-10]. However, these sensors are not practical when considering their cost and total weight and size, which can easily surpass the payload limitation of a small UAV.

On the other hand, RTK-GNSSs using low-cost and light-weight single-frequency GNSS receivers and antennas are currently attracting significant attention in many applications. In recent years, many GNSSs have been launched in several countries and the number of positioning satellites has increased rapidly. This increase has enabled the implementation of single-frequency RTK-GNSSs. However, the use of low-cost single-frequency GNSS receivers in the single-frequency RTK-GNSS technique results in greater degradation of the carrier-phase ambiguity resolution compared to that obtained with dual-frequency GNSS receivers. In particular, the performance of RTK-GNSSs is considerably degraded in urban environments that are surrounded by buildings because of reflection and diffraction signals (also known as multipath signals).

The goal of this study is to establish an accurate position and attitude determination technique for small UAVs by using low-cost GNSS receivers. The key concept behind the proposed method is the utilization of multiple low-cost single-frequency GNSS antennas/receivers to accurately estimate the position and attitude of a UAV. Thus, the performance of the RTK-GNSS is enhanced by using the "redundancy" of multiple GNSS receivers. Furthermore, we propose a technique to directly estimate the attitude of a small UAV by using multiple GNSS receivers.

PRPOSED SYSTEM

We developed a unique multicopter equipped with multiple single-frequency GNSS antennas/receivers to estimate the precise position and attitude of the UAV. Fig. 2 shows the prototype multicopter that consisted of three GNSS antennas and receivers. The GNSS antennas were installed on the exterior of the propellers. Fig.3 displays the prototype multiple-GNSS data logging system and Table 1 shows its specifications. We used u-blox M8T GNSS receivers and Tallysman TW2710 GNSS antennas. The total weight of the multiple GNSS antenna system was 749 g and the system can be used in many small UAV systems.

The key idea of this study is the use of multiple GNSS receivers/antennas to improve the accuracy of the position and attitude estimation. In general, one GNSS receiver is sufficient for estimating the UAV position and a single-frequency GNSS receiver is typically used in many UAVs

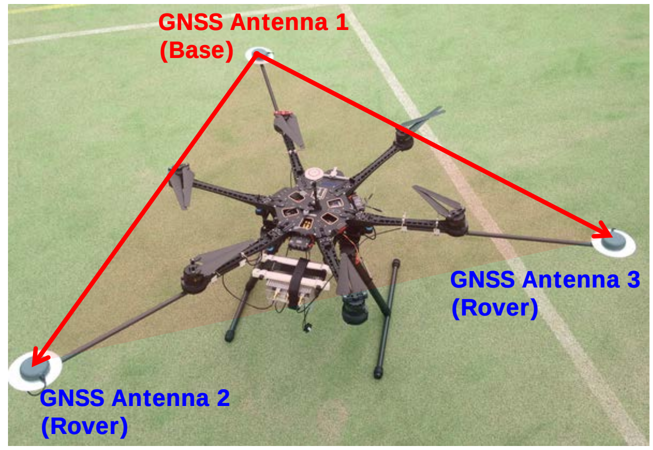

Fig. 2 Prototype multicopter using three GNSS antennas and receivers.

Fig. 3 Prototype multiple-GNSS data logging system.

Table 1 Specifications of prototype GNSS data logging system.

Item	Specification	Weight
GNSS receivers × 3	u-blox NEO M8T	164 g
GNSS antennas × 3	Tallysman TW2710	360 g
Battery	ZIPPY 350mAh 2S	21 g
Others		204 g
		Total 749 g

for navigation purposes. Here, we employed multiple single-frequency GNSS receivers to estimate the UAV position. By using the "redundancy" of multiple GNSS receivers, we developed a technique that can improve the positioning accuracy in multipath environments, such as those located near buildings. Furthermore, our system used multiple GNSS receivers instead of IMUs to estimate the 3D attitude of the UAV. By using an RTK-GNSS consisting of multiple GNSS antennas, the 3D plane can be determined from baseline vectors between the base and rover GNSS antennas (shown in Fig. 2). In other words, the absolute attitude of the UAV can be estimated based on the geometry of the multiple GNSS antennas.

The remainder of this paper describes the details of the attitude and position estimation methods applied on the multiple GNSS receivers. Additionally, we evaluate the precision of our proposed method by estimating the position and attitude of the UAV in actual urban environments.

ATTITUDE ESTIMATION USING MULTIPLE GNSS ANTENNAS

To estimate the absolute attitude of the UAV, we used relative GNSS antenna positions determined by GNSS carrier-phase measurements. If the GNSS carrier-phase ambiguity can be solved in the RTK-GNSS, the baseline vector between the multiple GNSS antennas can be determined with millimeter-level accuracy. The absolute 3D attitude of the UAV can be computed from two baseline vectors, i.e., three GNSS receivers/antennas are necessary for the 3D attitude determination. Here, this accuracy depends on the baseline length between the GNSS antennas. Fig. 4 shows the baseline length versus the estimated yaw angle accuracy, which was simulated from the analysis of the actual GNSS positioning error. The blue line in Fig. 4 indicates the standard deviation of the angle error. According to our simulation, if the distance between the GNSS antennas is greater than 1.5 m, the absolute attitude of the UAV can be estimated with an accuracy of 0.1º. The target accuracy of the attitude estimation was selected as 0.1º because it is sufficient for directly generating a 3D map based on the position and attitude of the UAV. Thus, the baseline length of our UAV shown in Fig.2 was designed to be 1.8 m.

Fig. 5 illustrates the attitude calculation for the three-GNSS-antenna system. The baseline vectors (b_1 and b_2 in Fig. 5) are estimated by the carrier-phase difference technique. To resolve the GNSS carrier-phase integer ambiguity, a reliable ambiguity search was performed with a constraint for the baseline vector. Unlike the case of high-performance dual-frequency GNSS receivers, it is difficult to resolve the ambiguity for a low-cost single-frequency receiver. In this case, baseline length constraints can be applied between the GNSS antennas to estimate a reliable ambiguity.

In the proposed technique, we used the following two constraints:

1. The baseline lengths are known.

$$|\mathbf{b}_j| = B_j \tag{1}$$

2. The angle θ between the baselines is known.

$$\cos\theta_{12} = \frac{\mathbf{b}_1 \mathbf{b}_2}{|\mathbf{b}_1||\mathbf{b}_2|} \tag{2}$$

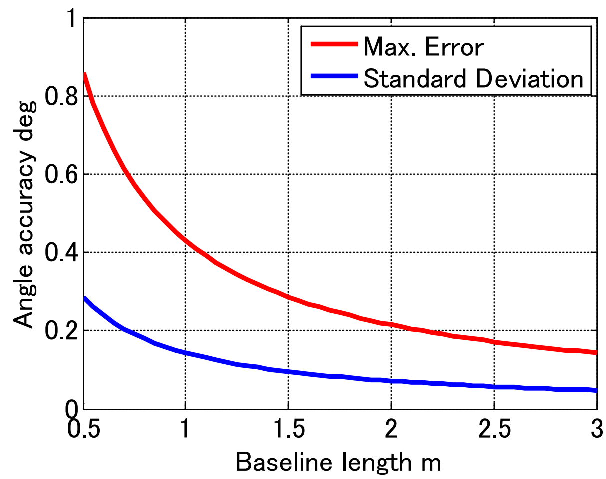

Fig. 4 Procedure of ambiguity resolution using the baseline constraint.

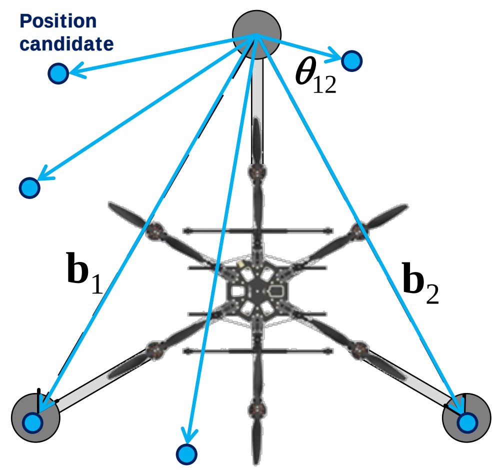

Fig. 5 Ambiguity resolution using baseline constraints.

We implemented the above constraints into the LAMBDA method [13,14], which is widely used to resolve the GNSS carrier-phase integer ambiguity. Specifically, we employed the proposed constrained-LAMBDA(C-LAMDA) [15] technique, which uses the baseline length constraint for the LAMDA method, and implemented it into RTKLIB [16,17], an open-source software package written in C for GNSS data analysis that is distributed under a BSD 2-Clause license. RTKLIB provides many powerful functions that are needed in GNSS data analysis, including position computation based on RTK-GNSS. In addition, we validated the computed baseline vectors based on the angle between the baselines in Eq. (2). With the proposed method, the precise attitude of the UAV was directly estimated using only low-cost single-frequency GNSS receivers. Fig. 6 shows a flowchart describing the attitude determination process in the proposed method. Our algorithm was executed as follows.

(1) GNSS carrier-phase and pseudorange measurements were obtained by multiple GNSS receivers at a rate of 10 Hz. Here, we used a multi-GNSS constellation

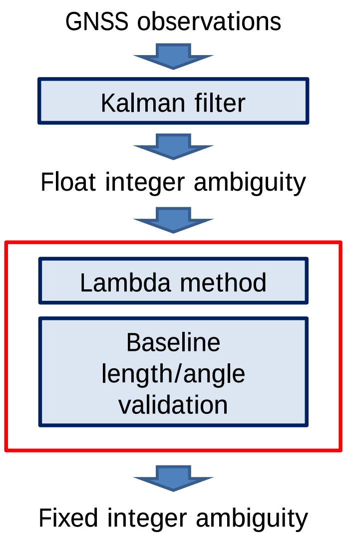

Fig. 6 Flowchart of ambiguity resolution using baseline constraints.

(GPS, BeiDou, and QZSS) to improve the single-frequency RTK-GNSS performance. Note that the receiver clocks of the multiple GNSS receivers were not synchronized in this study. The observed GNSS data were interpolated and synchronized during post-processing.

(2) Double-differenced GNSS measurements were computed from the base- and rover-GNSS measurements. An extended Kalman filter was used to estimate the float ambiguities in the double-differenced carrier-phase measurements.

(3) The carrier-phase ambiguities were estimated by the C-LAMBDA method and validated using the baseline length constraint. Two baseline vectors were estimated and the baseline vectors were subsequently validated using the angle constraint between the baseline vectors.

(4) The fixed integer ambiguity was determined. The 3D attitude (roll, pitch, and yaw angle) of the UAV was computed from the baseline vectors.

Using the proposed method, the carrier-phase ambiguity can be easily resolved even when using low-cost single-frequency GNSS antennas/receivers. The proposed method does not require a gyroscope to estimate the attitude of the UAV. Compared with the conventional method, the proposed attitude determination approach can directly estimate the absolute attitude during a hover. The output of a gyroscope (angular rate) is integrated to determine the orientation angle; however, orientation angle errors increase linearly with time because of the constant bias error of the output of gyroscope. In contrast, the proposed method does not involve drift errors and can determine the absolute 3D attitude with 0.1° accuracy.

POSITION ESTIMATION USING MULTIPLE GNSS ANTENNAS

GNSS is commonly used for UAV navigation in outdoor environments. UAVs are commonly used to inspect bridges with high piers and monitor the construction of buildings and other structures. In these situations, UAVs must hover near structures where the GNSS satellites are blocked by obstacles. However, significant improvements in the availability of GNSS positioning systems are expected because of the increase in the number of positioning satellites launched by various countries. GNSS positioning is problematic in areas that have many buildings. In GNSS positioning, invisible satellites (those that are obstructed by buildings) emit multipath signals called non-line-of-sight (NLOS) signals, which cause major positioning errors [18]. Various practical signal correlation techniques are widely used to mitigate theses multipath errors [19, 20]. However, if an antenna cannot receive a direct signal, these techniques do not provide satisfactory results because they assume that the antenna primarily receives direct signals. Urban areas include many locations in which GNSS antennas receive NLOS multipath signals; thus, it is important to develop a positioning technique that can achieve accurate positioning in multipath environments.

To improve the positioning accuracy of the UAV, we use a RTK-GNSS technique with single-frequency GNSS receivers. As mentioned, the performance of RTK-GNSSs is greatly degraded in urban environments because of multipath signals. In multipath environments, a robust and precise positioning technique is required to estimate precise positions for 3D mapping. We propose a novel robust multipath mitigation and positioning technique that uses the redundancy of multiple GNSS receivers. This method consists of two approaches: hybrid GNSS fix solutions and consistency check of the GNSS signal strength. Fig. 7 shows a flowchart describing the proposed positioning method.

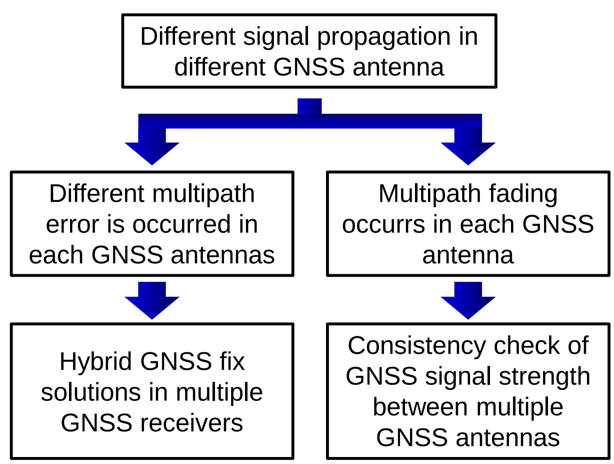

Fig. 7 Flowchart of ambiguity resolution using the baseline constraint.

A. Hybrid GNSS fix solutions

The first approach combines GNSS fix solutions of multiple GNSS antennas to improve the fix rate of the GNSS carrier-phase ambiguities. This concept is very simple but also very effective in improving positioning availability and accuracy. In multipath environments, the carrier-phase multipath affects the ambiguity resolution of the GNSS. Fig. 8 illustrates GNSS multipath signals for multiple GNSS antennas. Because each GNSS antenna involves different GNSS signal propagation paths, each GNSS receiver exhibits different multipath errors. In general, only one GNSS receiver is used to estimate the UAV position. If a multipath error occurs and the carrier-phase ambiguities cannot be solved in the RTK-GNSS, no accurate UAV position can be determined. In contrast, the use of multiple GNSS receivers can improve the probability of obtaining a GNSS fix solution because the UAV position can be determined from the fix solution of at least one GNSS receiver. Note that we assume that the 3D attitude of the UAV is determined when the UAV position is estimated from the fix solution of at least one GNSS receiver. To transform the coordinates of the fix solution, the UAV attitude is necessary to calculate the UAV position. The UAV attitude is estimated from the GNSS receivers as described in Section 3. Our algorithm is executed as follows.

(1) Each antenna position is computed using the RTK-GNSS technique. Here, we use a ground RTK base station or network RTK correction data for the RTK-GNSS.
(2) We assess whether the carrier-phase ambiguity is resolved in each GNSS receiver. If at least one GNSS fix solution can be computed, the UAV position can be estimated.
(3) The 3D attitude of the UAV is used to transform the antenna position to the UAV position. The UAV position is computed based on the coordinate transform of the GNSS antenna position, which is calculated from the RTK-GNSS fix solution.

With this method, we can enhance the availability of carrier-phase ambiguity resolutions by using a single-frequency GNSS receiver. Thus, the availability and accuracy of the positioning solutions can also be improved in multipath environments. In this study, we combine the RTK-GNSS fix solutions of three GNSS receivers to improve the fix rate. By employing more GNSS receivers, we expect the accuracy and availability of the UAV position to be further improved.

B. Multipath Detection

The second approach involves detecting and eliminating multipath signals by using the observations of multiple GNSS receivers. If a GNSS antenna receives a multipath signal from a satellite, the carrier-phase ambiguity can sometimes not be resolved because of the multipath error. It is therefore essential to establish a positioning technique that identifies and selects only satellites that provide the lowest multipath error.

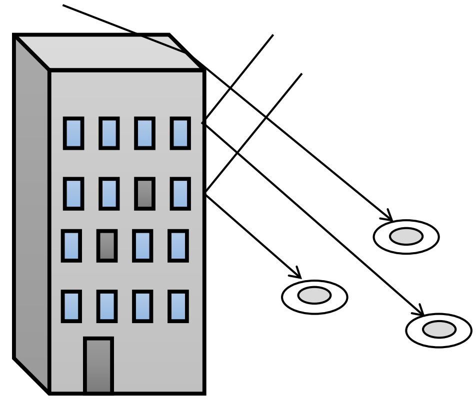

Fig. 8 Multipath signals in multiple GNSS antennas near buildings.

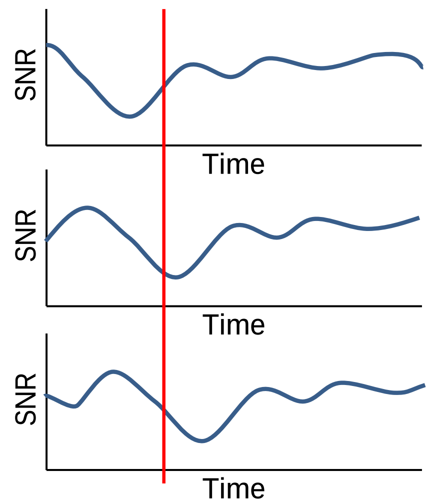

Fig. 9 SNRs in multiple GNSS antennas in multipath environments.

We focus on the signal-to-noise ratio (SNR) of the multipath signal. The phase of a reflected signal with respect to its directly received counterpart depends on the wavelength; thus, by comparing the difference of the measured SNRs between two frequencies, strong multipath interferences may be detected [21]. The signal phase also depends on the distance of the propagation path. Fig. 9 shows the SNRs of multiple GNSS receivers of the same satellite in a multipath environment. Because different GNSS antennas involve different signal propagations, multipath fading occurs at different times in each antenna. To examine the consistency between the SNRs of multiple GNSS receivers, the multipath signal is first determined. If all antennas are in an open-sky environment, the same SNR is expected to be observed in each GNSS antenna. If an antenna receives multipath signals, different SNRs are observed in each GNSS antenna; a simple threshold test can be used to detect the multipath signal. Then, the multipath signals are excluded from the RTK-GNSS computations to improve the performance of the carrier-phase ambiguity resolution. Our algorithm is executed as follows.

(1) For each GNSS satellite, the SNR is obtained from the GNSS receivers and the SNR variance is computed.
(2) A large SNR variance indicates a high possibility of multipath signals. Therefore, GNSS satellites with large SNR variances are eliminated by a simple threshold test. Here, we used the threshold $\sigma = 4$ dB-Hz.
(3) The RTK-GNSS fix solutions are computed without the eliminated GNSS satellites. Then, the fix solutions are combined by the method described in the previous section.

Using this method, the fix rate of the RTK-GNSS is decreased because the number of satellites is reduced by the satellite selection process. However, new fix solutions can be generated by eliminating multipath signals. We combined multiple fix solutions to improve the positioning availability, as described in Section 4.2. The total fix rate is improved by satellite selection using the proposed method.

EXPERIMENTS

To evaluate the proposed method, we conducted a static test in a narrow-sky environment surrounded by obstacles, shown in Fig. 10. A fish-eye image captured at the GNSS antenna location is shown in Fig. 11. We used GPS, BeiDou, and QZSS to estimate the position and attitude of the UAV. The satellite geometry during the test is shown in Fig. 12, where “G”, “C”, “J” indicate the GPS, BeiDou, and QZSS, respectively. The GNSS data were collected and analyzed during post-processing.

A. Attitude Estimation

First, we determined the attitude by using the proposed technique. Table 2 shows the fix rate of the RTK-GNSS, which is 68.1 % when using the normal LAMBDA method and is improved to 99.6 % by the proposed method. With the proposed method, we could almost perfectly resolve the GNSS carrier-phase ambiguity by using low-cost single-frequency GNSS receivers in multipath environments. Fig. 13 shows the result of the attitude estimation. The standard deviation of the estimated roll, pitch, and yaw angle errors are 0.30º, 0.23º, and 0.07º, respectively. We can therefore conclude that the proposed technique can improve the accuracy of the attitude estimation for the small UAV.

Fig. 10 Test environment for position and attitude determination in the static test.

Fig. 11 Fish-eye image captured during the static test.

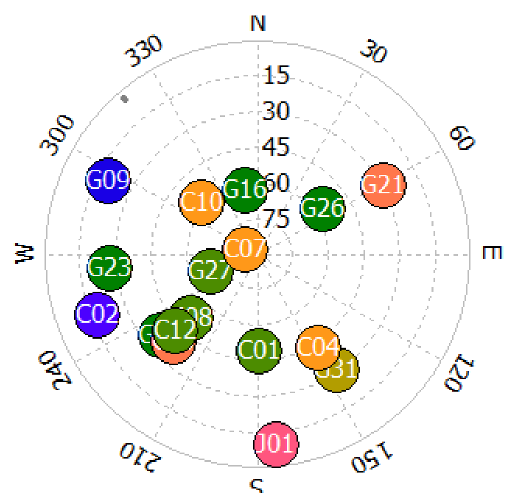

Fig. 12 GNSS satellite geometry during the static test.

Table 2 Fix rate for attitude estimation.

Method	Fix rate %
Normal LAMBDA	68.1
Proposed method	99.6

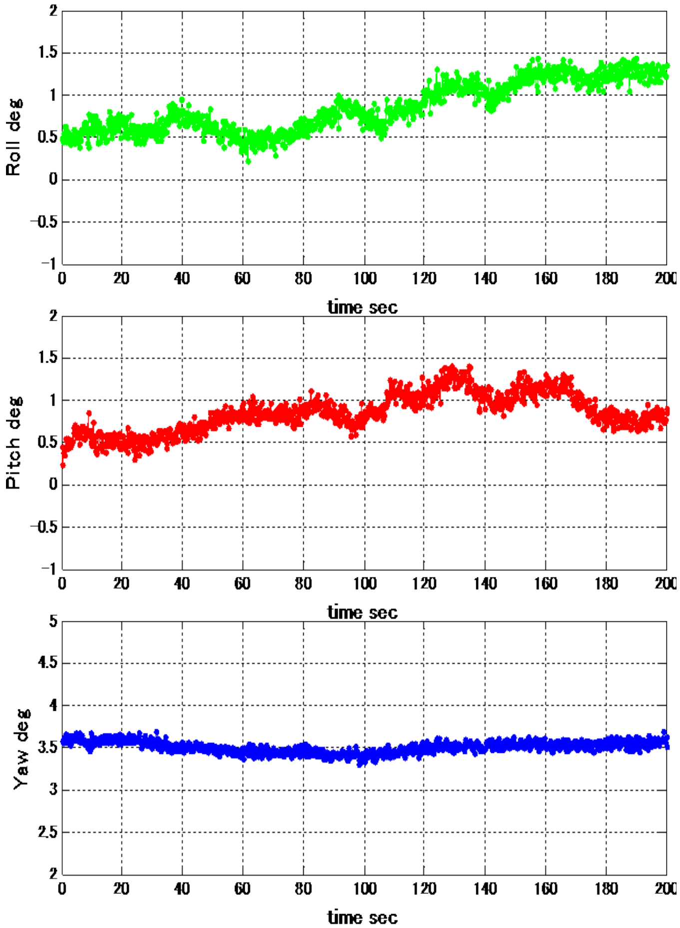

Fig. 13 Results of attitude determination in the static test.

B. Position Estimation

Next, we evaluated the position estimation by the proposed technique. Fig. 14 shows the change of the fix rate in each GNSS antenna before and after multipath rejection. The blue dots indicate that the carrier-phase ambiguity can be resolved. Before multipath rejection, it is evident that fix solutions are not frequently obtained. After multipath rejection, a fix solution can be obtained even in cases when this is not possible without multipath rejection. Note that some fix solutions change to float solutions because of the satellite selection. However, it is more important that the many float solutions are modified to fix solutions by the proposed method. Because we used a hybrid method to combine all the fix solutions, the float solutions do not pose a significant problem. Table 3 shows the fix rate of each GNSS antenna for the normal and proposed multipath mitigation methods; the latter obtained improved fix rates in every GNSS antenna. Finally, in the hybrid method, the fix rate reached 99.9 %; consequently, the proposed technique offers increased positioning accuracy in urban environments.

Table 3 Fix rates for position estimation.

Method	GNSS1 Fix rate %	GNSS2 Fix rate %	GNSS3 Fix rate %
Normal	67.2	82.4	60.1
Multipath mitigation	81.9	84.7	73.5
Hybrid positioning		99.9	

CONCLUSION

Direct 3D mapping using a small UAV equipped with a laser scanner is required for many remote sensing applications. In direct 3D mapping, the precise position and attitude of the UAV are necessary to construct 3D maps. A small UAV has a payload limitation, thus dual-frequency GNSS receivers and high-grade IMUs are difficult to implement for 3D mapping. In this paper, we propose a precise position and attitude determination technique that employs multiple low-cost and light-weight GNSS antennas and receivers for small UAVs. Using the “redundancy” of multiple GNSS receivers, we can improve the positioning accuracy in multipath environments, such as those located near buildings. Furthermore, we propose a direct attitude estimation technique using the multiple GNSS receivers.

We developed a prototype UAV equipped with three GNSS antennas and receivers. From the test results, we conclude that the proposed technique can improve the accuracy of the position and attitude estimation. In the future, we will perform a flight test to evaluate the proposed technique in a dynamic environment. We will also evaluate the accuracy of a 3D map generated from laser scanning data.

ACKNOWLEDGMENT

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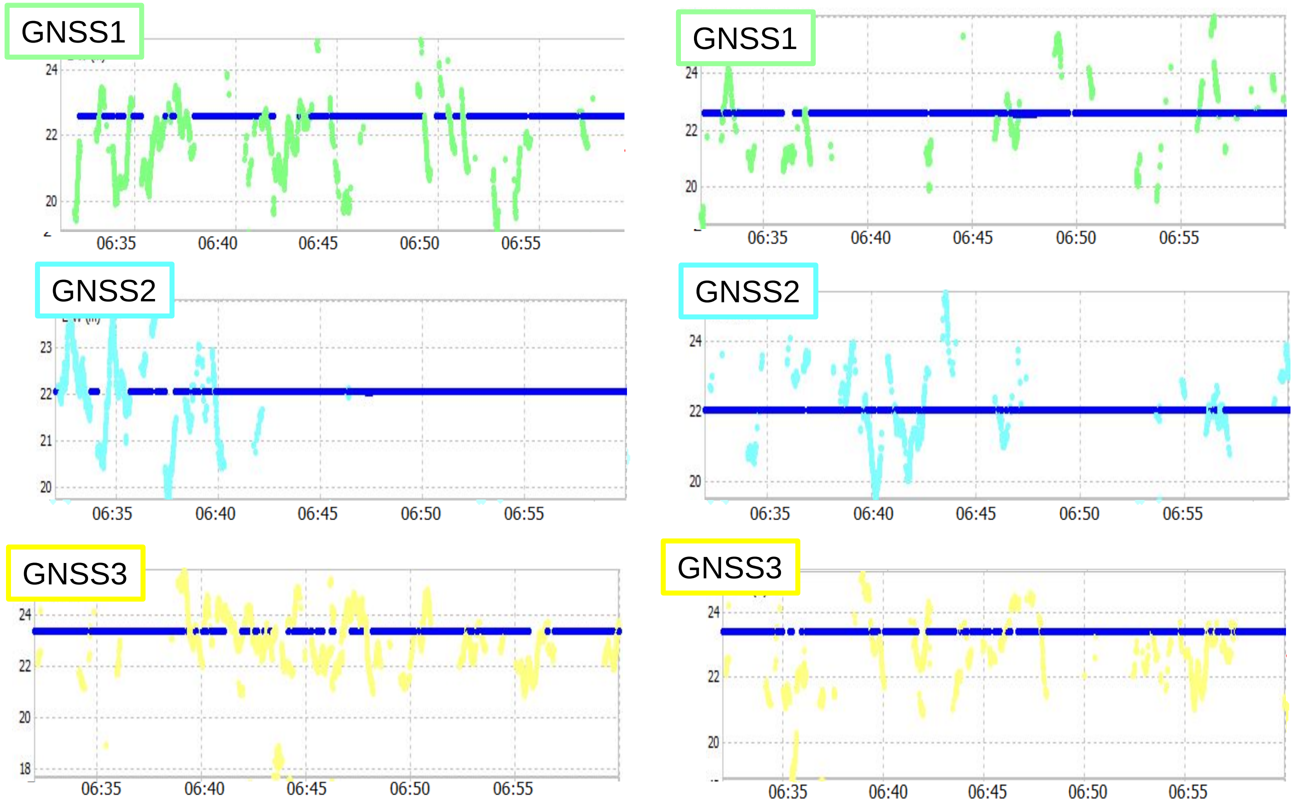

(a) Before multipath rejection (b) After multipath rejection

Fig. 14 Fix rates obtained during the static test for position estimation.

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