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7 Development of complementary technologies for RTK-GNSS and IMU

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Abstract

Due to serious labor shortages in the agriculture and construction industry, so-called smart agriculture and i-Construction based on policies promising to utilize ICT have been gradually progressing. For the automation of agricultural and construction machinery which are important factors for those policies, high accuracy measurement for the vehicle's position is required. In high accuracy measurements, RTK positioning uses GNSS with cm-level accuracy is a key technology. However, in an obstacle environment, GNSS decreases positioning accuracy due to reflection of satellite signals by obstacles. Therefore, we have been developing a technology to maintain accuracy by mutual complement with IMU even in an obstacle environment. This paper reports the usefulness of this development and an experiment to evaluate for positioning in an obstacle environment.

1. Introduction

Japan has one of the most extremely aging populations in the world, and, among various industries, the problem of an aging labor force is especially deep in agriculture and construction work. In the agricultural field in particular, revolutionary improvements in production are needed because of projected deterioration of the food production environment due to increased world population and climate change.[1)] In order to handle these increasing uncertainties in our social situations, so-called smart agriculture and i-Construction based on policies promising to utilize robots and ICT, are being advanced through collaborations between industry, academia, and government. The automation of agricultural and construction machinery, which is a critical element in these policies, requires high-accuracy measurement of vehicle position. RTK (Real-Time Kinematic) positioning, which allows for positioning with centimeter-level accuracy, is a key technology for achieving high-accuracy positioning. RTK positioning is a technology for measuring position using a GNSS (Global Navigation Satellite System). However, in environments with obstructions like windbreaks and slopes where agricultural and construction machinery travel, the accuracy of positioning through positioning technology that uses GNSS decreases because of the reflection of signals from the satellites. Without the possibility of automated travel with high-accuracy positioning even in environments with obstructions, the revolutionary improvements in production discussed above will not be reached.

Therefore, we have been developing a technology that makes high-accuracy positioning possible even in environments with obstructions by using IMU (Inertial Measurement Unit), which apply inertial navigation technology developed in the defense and space fields, and RTK positioning to mutually complement one another. When the accuracy of RTK positioning decreases, accuracy is maintained by having the IMU, the accuracy of which is not affected by the measurement environment, perform positioning alone. In this paper, we will introduce the technique of mutual complementation of RTK positioning and IMU and report on the results of evaluation of positioning in environments with obstructions.

2. RTK positioning and GNSS information

2.1. Overview of RTK positioning

RTK positioning is a positioning method that uses a combination of information on a carrier phase received by a user (rover station) and a carrier phase observed by a base station that has an accurately measured position (Figure 1). The most frequently used independent positioning in GNSS is positioning using a code signal referred to as “C/A” that is superimposed on an L1 carrier wave (1.57542 GHz). The resolution of this is approximately 19 cm, the wavelength of a single L1 carrier wave, but if carrier phases are used, the resolution can be raised to around 1/100 of the wavelength of a single carrier wave.

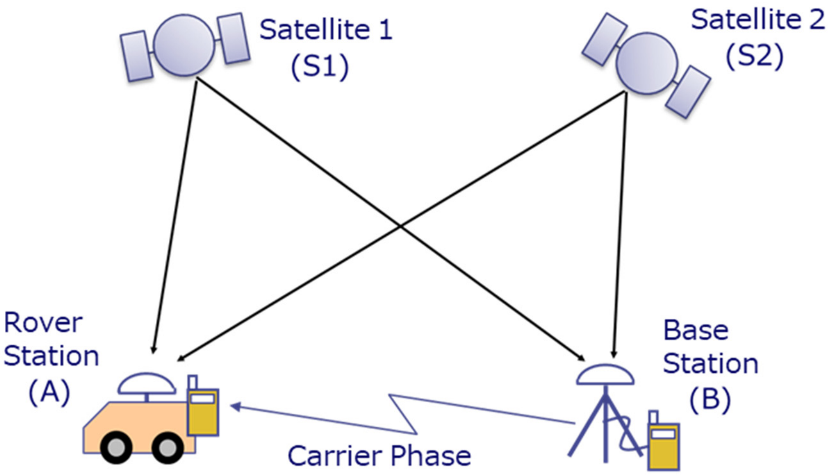

Figure 1. Rover station and base station

Error factors that arise in GNSS positioning include ionospheric delay and tropospheric delay of carrier waves, satellite clock error, receiver clock error, multi-pass effects, and noise within receivers. Also, the carrier waves captured by receivers consists of an equivalent to the true distance with a contribution due to error added in. In RTK positioning, an observation value referred to as a double difference is used, which utilizes carrier phases sent from two satellites to two receivers (Eq.1).

$$\Phi_{A\_B}^{S1\_S2} = (\Phi_A^{S1} - \Phi_B^{S1}) - (\Phi_A^{S2} - \Phi_B^{S2}) \qquad \text{Eq. 1}$$

$\Phi_{A\_B}^{S1\_S2}$ represents the double difference of the carrier phase at the rover station and base station from the satellite 1 and satellite 2, and Φ_A^{S1} represents the carrier phase received by the rover station (A) from the satellite 1 (S1). If the terms in Eq.1 are written out, the ionospheric delay, tropospheric delay, satellite clock error, and receiver clock error terms disappear, leaving only the true distance equivalent term, the multi-pass term, and the noise term. The use of this observation value called the double difference is a major feature of RTK positioning. The true distance equivalent of the carrier phase includes an integer multiple of the carrier wave and a portion after the decimal point. This integer multiple portion includes some remaining ambiguity. This ambiguity is called integer ambiguity. High-accuracy positioning can be achieved if this ambiguity is resolved by the LAMBDA method (Least-squares AMBiguity Decorrelation Adjustment method) or the like.[2, 3]

2.2. Example of RTK positioning and GNSS information

Positioning results with the integer ambiguity resolved are called FIX solutions, and they have positional accuracy at the centimeter scale. The positioning results with the ambiguity undetermined are called FLOAT solutions. Examples of RTK positioning FIX solutions are shown in Figure 2. The receiver used is a low-cost dual-frequency receiver. The observation data is for approximately ten minutes in a resting state with open sky.

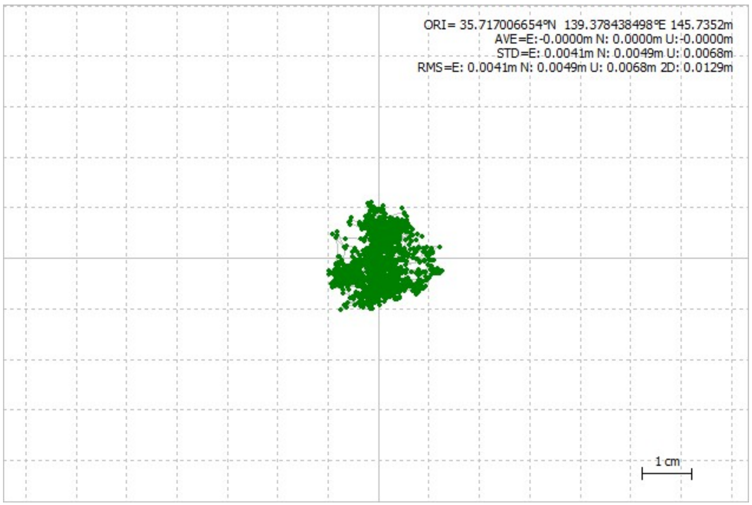

Figure 2. Example of RTK positioning results in a resting state

Next, we will present an example of positioning while in motion. Figure 3 shows an example in which the target moves from a location with a somewhat reliable ratio of openness of sky to an obstructed location blocked by a roof.

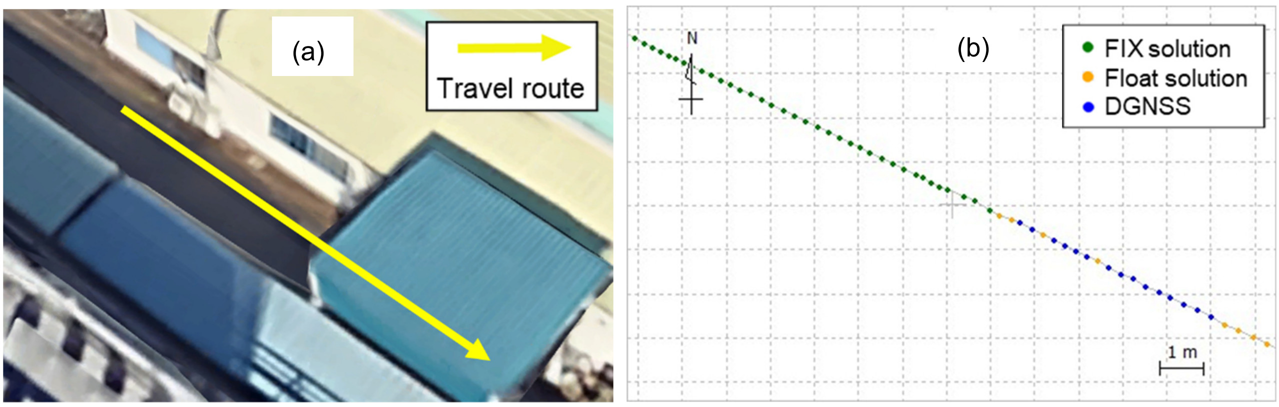

Figure 3. Example of positioning while passing through an environment with obstructions.
(a) travel route, (b) RTK positioning results

The positioning results when the position indicated by the arrow in Figure 3(a) moved at a speed of around 5 km/h are shown in Figure 3(b). The green dots in this figure represent FIX solutions, the yellow dots indicate FLOAT solutions, and the blue dots represent differential positioning (DGNSS). The information output by the GNSS receiver includes, in addition to position and speed, positioning quality (types such as FIX solutions, FLOAT solutions, and DGNSS), number of observed satellites, DOP (Dilution of Precision: rate of decrease in accuracy due to satellite distribution), etc.

Examples of the GNSS information output from the GNSS receiver during the positioning shown in Figure 3 are shown in Figure 4. In Figure 4, the number of observed satellites decreases due to the effect of roofs starting at around four seconds, and there is a shift from FIX solutions to FLOAT solutions and DGNSS after seven seconds, so the positioning quality has decreased. Also, it can be seen that the number of observed satellites and HDOP also change together.

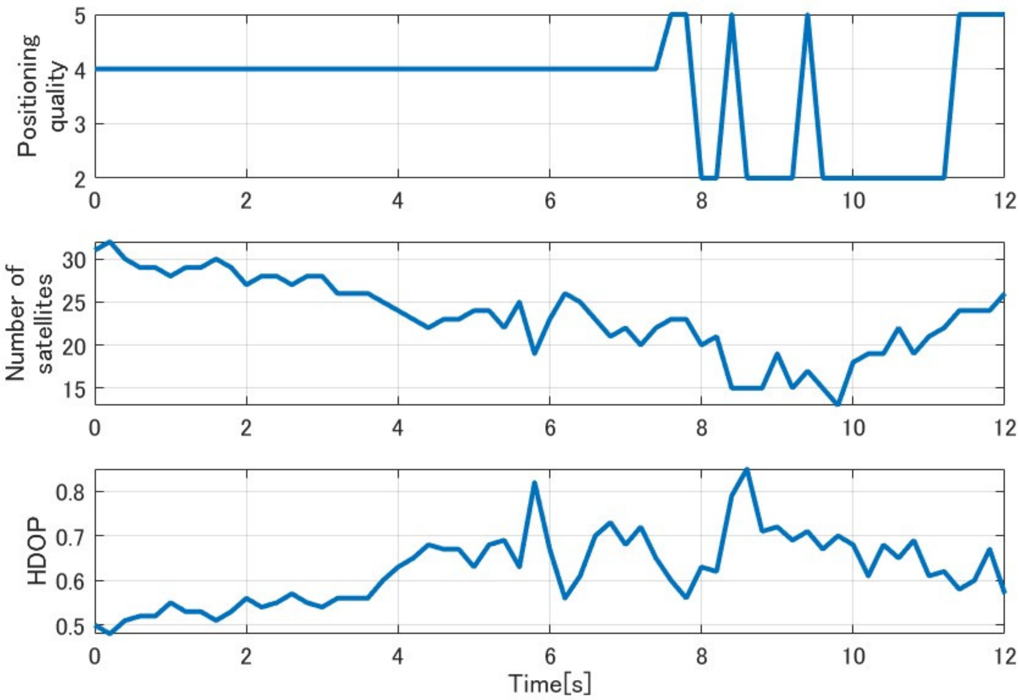

Figure 4. GNSS information

Positioning quality is 5: FLOAT solution, 4: FIX solution, 2: DGNSS

HDOP is the horizontal component of DOP

3. Complementary technologies for RTK and IMU

3.1. Subjects of complementation

The kinds of RTK positioning and IMU information that are mutually complementary are shown in Table 1. The IMU is an IMU that utilizes a low-cost MEMS (Micro Electro Mechanical Systems) sensor, and RTK positioning represents a case in which a low-cost dual-frequency receiver is used. This is intended to allow popularization in agricultural and construction work by keeping costs low. The IMU has a high refresh rate, and its accuracy with regard to position, speed, and heading angle do not vary with the measurement environment. However, because position it is calculated by integration of acceleration and angular rate, error increases and accuracy decreases over time. On the other hand, RTK positioning has extremely high accuracy of position, at the centimeter scale, and its accuracy does not decrease over time. However, it has a low refresh rate, and its accuracy decreases due to obstructions such as windbreaks. We have developed an algorithm to mutually complement the shortcomings of each.

Table 1. Complementary parameters of IMU and RTK positioning

	MEMS IMU	**RTK-GNSS positioning (low-cost receiver)**
Positional accuracy	× Accuracy decreases over time	○ Extremely high (cm-level accuracy), accuracy does not decrease over time
Measurement refresh rate	○ High (At least 50 Hz)	× Low (~5 Hz)
Dependency on measurement environment	○ Accuracy does not vary with measurement environment	× Accuracy decreases due to obstructions

3.2. Mutual complementation method

In order to achieve high-accuracy positioning in obstructed environments, a closed-loop method needs to be used for mutual complementation of RTK positioning and the IMU. There are two types of mutual complementation methods, closed-loop and open-loop. [4)] Simple computation block diagrams for these methods are shown in Figure 5. The Kalman filter shown in the diagrams represents computation to statistically estimate error in inertial navigation using observation values from RTK positioning and output values from inertial navigation. In the open-loop method, the difference between the output value from inertial navigation and the estimated value for error is determined and output. Development is easy, but if the accuracy of RTK positioning has decreased, mutual complementation becomes ineffective because of increasing error in inertial navigation. On the other hand, in the closed-loop method, the estimated error is fed back into the inertial navigation. Development is more difficult, but the increasing error in inertial navigation is constantly eliminated by feedback, so even if the accuracy of RTK positioning has decreased, high-accuracy position can be maintained over short periods.

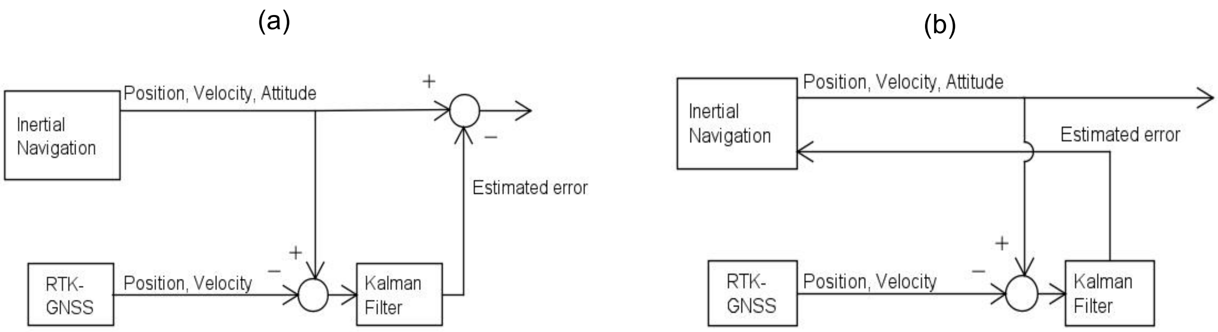

Figure 5. Overview block diagrams of open-loop and closed-loop methods
(a) open-loop, (b) closed-loop

3.3. GNSS error determination

In order to achieve high-accuracy positioning in obstructed environments, GNSS error determination is necessary. If the error has been determined to be large, high accuracy is maintained by positioning with the IMU alone, since its accuracy does not vary by measurement environment. Figure 6 shows a mutual complementation block diagram that includes this determination processing.

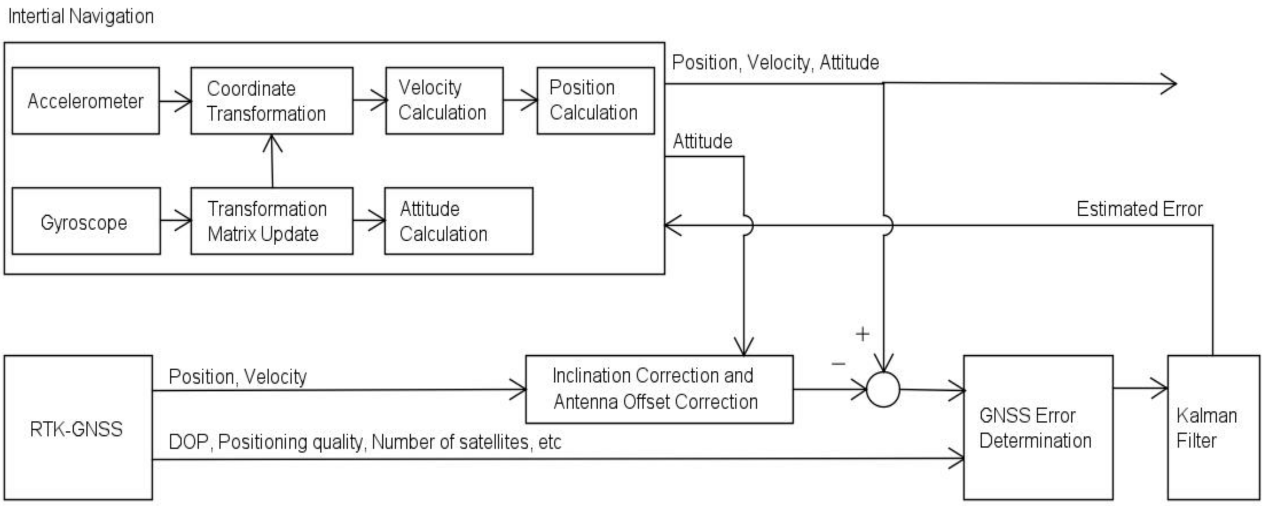

Figure 6. Block diagram of mutual complementation of RTK positioning and IMU

A method in which DOP is used for GNSS error determination has already been proposed. [5] In order to improve the accuracy of determination still further, we have constructed a determination equation that incorporates, in addition to DOP, information on positioning quality, such as FIX solutions and FLOAT solutions, the number of satellites, and the like. Even if a FIX solution showing accuracy on the order of 1 cm has been obtained, error determination is performed without exception, since there are cases in which Miss-FIX solutions are produced. Miss-FIX solutions are FIX solutions in which the integer ambiguity has been incorrectly resolved.

The accuracy of error determination is also improved by incorporating information such as position, speed, and heading angle obtained from inertial navigation into the aforementioned determination equation. By making determinations that incorporate information from both GNSS and the IMU, it is determined whether or not to use positioning points obtained by RTK positioning.

4. Results of positioning in obstructed environments

In order to prove the usefulness of the mutual complementation technique we developed, we performed a positioning evaluation experiment in an obstructed environment. The IMU used for evaluation is a MEMS IMU that is integrated with a low-cost dual-frequency GNSS receiver capable of RTK positioning, a prototype model (Figure 7) created by JAE. The built-in GNSS receiver can perform RTK positioning by receiving correction information by LTE communication. The output rates were set to 5 Hz for the built-in GNSS receiver and 50 Hz for the IMU mutually complementing the GNSS receiver. This IMU was installed in an automobile, which was driven at around 5 km/h within the grounds of JAE's Akishima Plant, and positioning was performed. The travel route within the grounds of JAE's Akishima Plant is shown in Figure 8. The red circle in Figure 8 indicates a roof with a length of 7 m and a height of around 2.5 m, an area where GNSS reception is unstable. Figure 9 shows the results of RTK positioning.

Figure 7. External view of RTK positioning–IMU prototype model

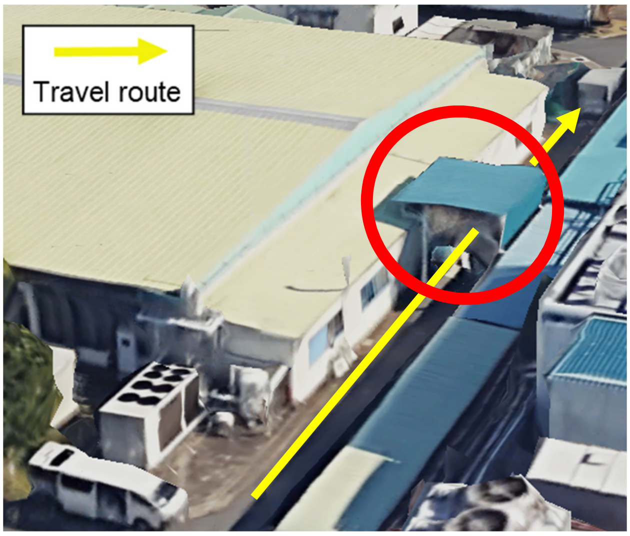

Figure 8. Travel route for evaluation experiment

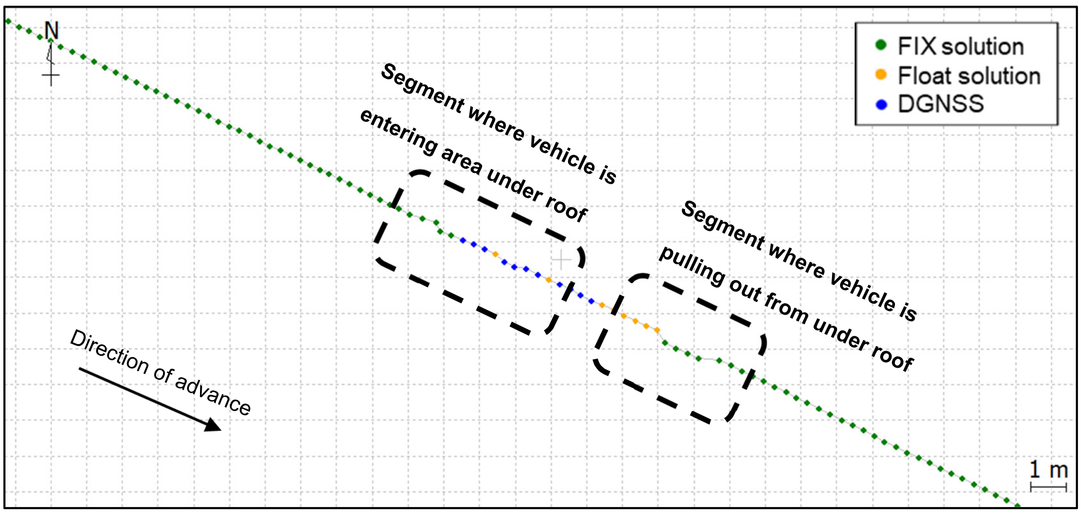

Figure 9. Results of RTK positioning

First, let us focus on the segment where the vehicle is entering the area under the roof. The results for RTK positioning for this segment and the results of positioning based on mutual complementation with the IMU are shown in Figure 10. In the results of RTK positioning in Figure 10(a), the positioning quality changes from FIX solutions to FLOAT solutions and DGNSS as the vehicle enters the area under the roof. Variation arises in the lateral direction of the vehicle in correspondence with this change. In this way, in response to this decrease in the accuracy of RTK positioning, the mutual complementation with the IMU shown in Figure 10(b) allows for positioning that suppresses the variation in the lateral direction of the vehicle.

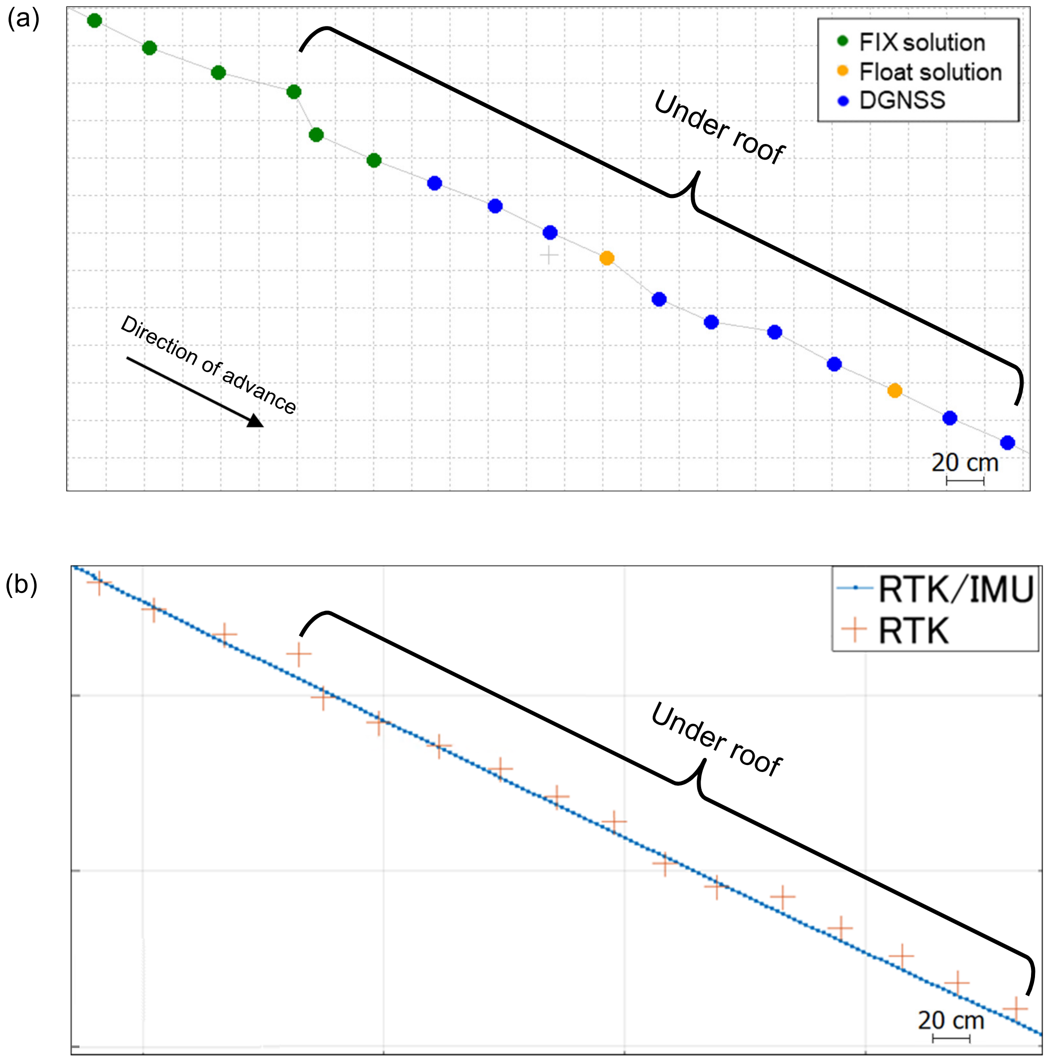

Figure 10. Results of positioning in segment where vehicle is entering area under roof

(a) results of RTK positioning, (b) results of positioning based on mutual complementation with IMU

Next, let us focus on the segment where the vehicle is pulling out from under the roof. The results for RTK positioning for this segment and the results of positioning based on mutual complementation with the IMU are shown in Figure 11. In the RTK positioning results in Figure 11(a), there are positioning points immediately after the vehicle pulled out from under the roof that deviate greatly in the latitude direction.

These results deviate in the latitude direction despite being FIX solutions, so they are presumed to be Miss-FIX solutions. In this way, in response to this decrease in the accuracy of RTK positioning, the mutual complementation with the IMU shown in Figure 11(b) allows for positioning that suppresses the influence of the Miss-FIX solutions.

These results showed that mutual complementation of RTK positioning and the IMU is a useful method for maintaining positioning accuracy in obstructed environments.

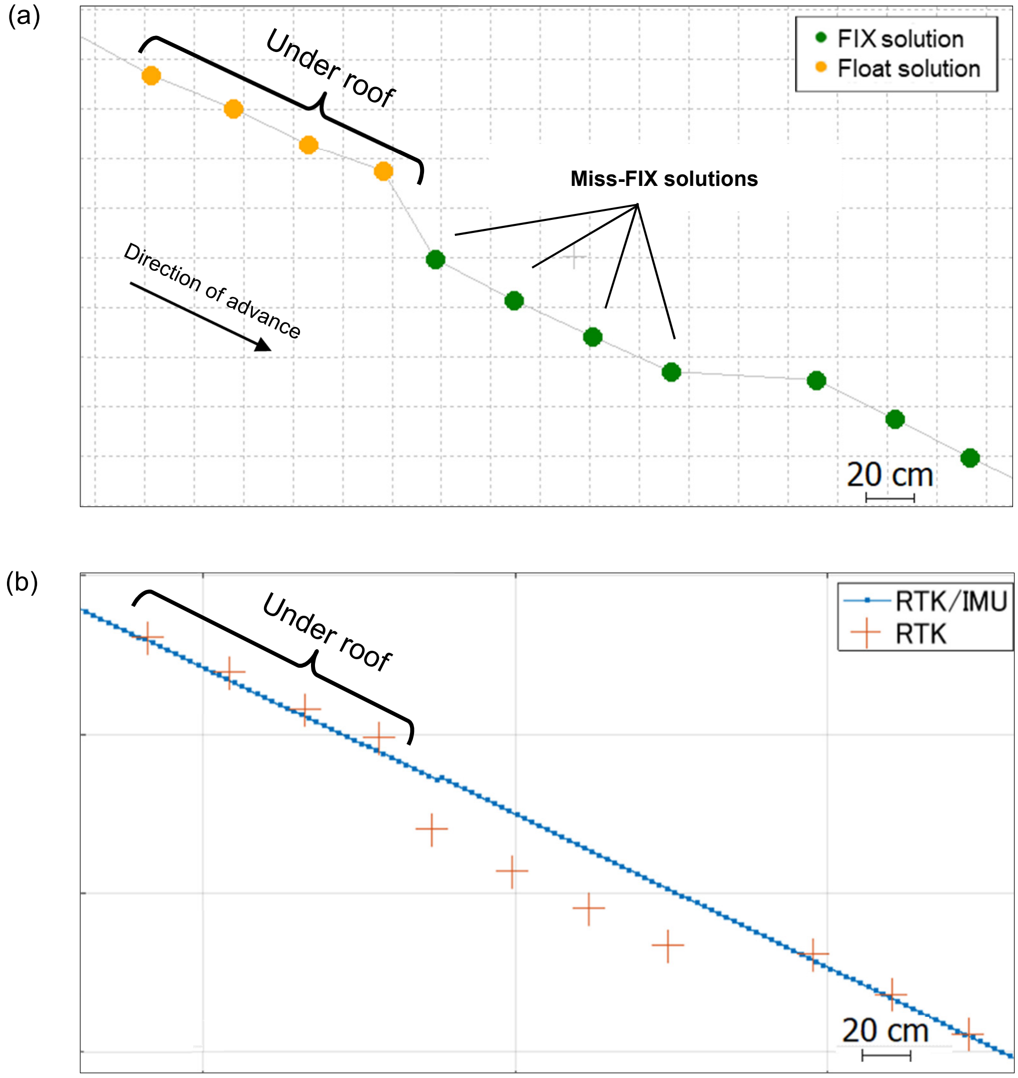

Figure 11. Results of positioning when vehicle is pulling out from under roof

(a) results of RTK positioning, (b) results of positioning based on mutual complementation with IMU

5. Summary and future work

We have reported here on the usefulness of the mutual complementation technique through a positioning evaluation experiment in an obstructed environment. We believe that this technique will be difficult to utilize in locations where GNSS reception is markedly unstable, such as urban areas lined with high-rise buildings, but will be useful in envisioned areas where there are windbreaks and slopes. We are also moving forward with research into improving accuracy of heading angles as well as position in order to allow agricultural and construction machinery to steer along programmed travel routes.

For future work, we are considering include improving accuracy through determination by neural networks to determine GNSS error. Because neural networks are particularly adept at classifying signals, they are suited for determining whether or not the accuracy of RTK positioning is decreasing.

With the initiatives reported above, we will contribute to agricultural and construction work from the aspect of achieving full automation of vehicles.

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