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Navigation Performance Analysis Method for Integrated Navigation System of Small Unmanned Aerial Vehicles

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Abstract

Currently, the operation of unmanned aerial vehicle (UAV) is regulated to be able to fly only within the visible range, but in recent years, the needs for operation in the invisible area, in the urban area and at night have increased. In order to operate UAVs in the invisible area, at night, and in the urban area, a flight path for UAVs must be prepared like those operated by manned aircraft, and for this, it is necessary to establish an unmanned aircraft system traffic management (UTM). In order to establish the UTM, information on the minimum separation distance to prevent collisions with UAVs and buildings is required, and accordingly, information on the navigation performance of UAVs is required. In order to analyze the navigation performance of an UAV, total system error (TSE), which is the difference between the planned flight path and the actual location of the UAV, is required. If the collected data are insufficient and classification according to integrity, independence, and direction is not performed, accurate navigation performance is not derived. In this paper, propose a navigation performance analysis method of UAV that is derived TSE using flight data and modeled with normal distribution, analyze performance.

Keywords: *"UTM(Unmanned Aircraft System Traffic Management)", "UAV(Unmanned Aerial Vehicle)", "TSE(Total System Error)", "Navigation Performance"*

1. Introduction

In the case of manned aircraft, it has been standardized for a long time to establish an air traffic management (ATM) system. Likewise, in order to ensure stable operation of UAV, attempts are being made to establish

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legal regulations and certification systems worldwide [1]. To this end, the problem of the navigation performance of the UAV is becoming important, and until recently, researches such as a method of fusing various sensors and a Terrain Reference Navigation have been conducted in order to increase the navigation accuracy of the UAV. However, in order to determine the flight path in which the UAV will be operated, an analysis of the navigation performance of the UAV is required, but relevant research is still insufficient. In order to analyze the navigation performance of an UAV, TSE, which is the difference between the desired path and the actual location, is required. And the TSE is caused by being influenced by various factors such as the reception sensitivity of satellite signals, the control performance of the flight control computer, the performance of the navigation system. In addition, since UAVs are operated at low altitude and are equipped with low-cost sensors, are susceptible to disturbances, and are used for various purposes compared to manned aircraft, navigation performance should be analyzed from a variety of perspectives than the conventional method for manned aircraft. However, currently, research on the navigation performance analysis of UAVs is insufficient. Therefore, this paper proposes a method for analyzing the navigation performance of an UAV and the navigation performance is analyzed by deriving TSE of the data collected through experiments.

2. Proposed Method

If the collected data are not post-processed, navigation results with low accuracy due to satellite signal conditions, ionospheric delay, and ground effects are reflected in the results of the navigation performance analysis as they are, reducing the reliability of the analysis results. In addition, data must be synchronized based on UTC time for analyze in the same timestamp. In order to determine the flight path of the UAV, performance analysis for the horizontal and vertical directions should be performed by considering the linear distance error in two dimensions, not simply calculating the linear distance error. In this paper, we would like to post-process the collected data in the order shown in Figure 1 for data classification. The first classification step in Figure 1 is classification of the flight data are based on the type, velocity, and altitude of the UAV. In the second classification step is consistency check, the classification criteria are the navigation solution status of the precision positioning device and the integrated navigation solution status. The third to fifth classification steps ensure data synchronization and data independence. Then derive the vertical and horizontal TSEs and model in the form of a normal distribution.

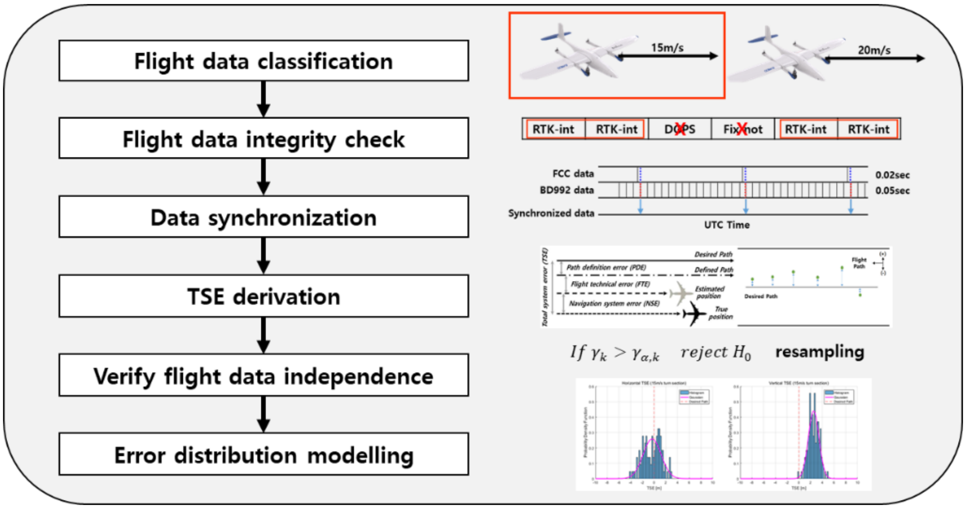


Figure 1. Data analysis sequence

2.1 Integrity Check

Poor data logging, poor global navigation satellite system (GNSS) reception, or unexpected situations during flight can result in unreliable flight data being collected, which degrades the reliability of the UAV's navigation performance analysis. Therefore, in this study, data integrity check was performed to accurately analyze the navigation performance of UAV. Through the integrity test, the condition of the precision positioning equipment navigation solution, the condition of the GNSS navigation solution mounted on the UAV, and the presence or absence of deviation due to an accident or unexpected situation were checked and excluded. Integrity check items are shown in Table 1.

Table 1. Integrity check

Step	Description
Step 1	**Check BD992 navigation solution is RTK-int**
Step 2	**Check the integrated navigation solution is 3D-fix or DGPS**
Step 3	**Check failsafe during flight and whether the flight path is deviated due to accidents**

2.2 Data Synchronization

Post-processing is required because the navigation solution of the precision positioning device mounted on the UAV and the integrated navigation solution have different logging cycles. Therefore, using the logging time of the integrated navigation solution and the logging time of the navigation solution of the precision positioning device, the time synchronization of the data was performed using linear interpolation based on UTC time. As you can see in Figure 2, the logging cycle of FCC is 50Hz, and the logging cycle of the precision positioning device (BD992) is 20Hz. [2].

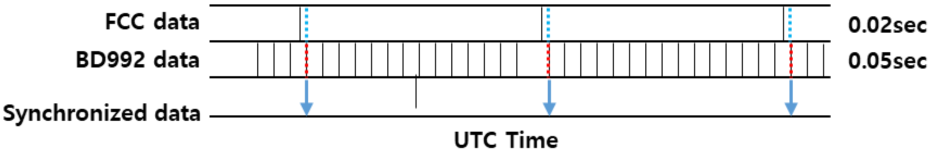


Figure 2. Data synchronization example

2.3 TSE Derivation

As you can see in the left side of Figure 3, TSE is an error that describes the degree to which an aircraft deviates from its planned flight path (desired path) consisting of the path definition error (PDE), flight technical error (FTE), and navigation system error (NSE) [3].

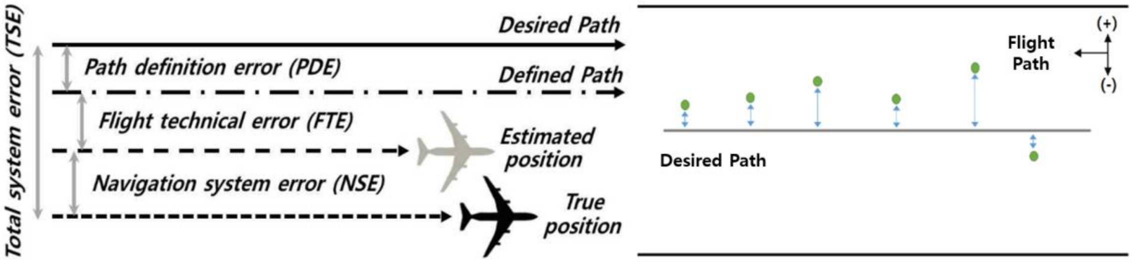
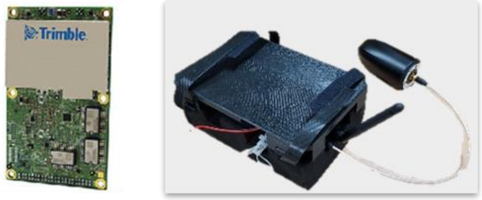


Figure 3. TSE definition & sign direction

PDE, FTE and NSE have a direct impact on integrated navigation performance. Recently, it has been treated as PDE-free due to its accurate maps and improved computer performance. As you can see in the right side of Figure 3, the sign of the error is defined as a positive value when UAV is above the Desired path. This document assumes that Trimble's BD992 is mounted on a UAV and that Trimble's BD992's navigation solution is in a real location. Table 2 shows the performance specification of the precision positioning device (BD992) [4].

Table 2. BD992 specification

Position(m)	0.008(H), 0.015(V)	
Heading(°)	0.09	

There are methods to derive TSE through methods such as scalar quantity summation method (SQSM), root sum square method (RSSM), and line tangent ellipse method (LTEM) using NSE and FTE [5, 6]. However, this study assumes a simple separation distance between the UAV's actual location and the desired path as TSE. We also calculated the TSE by converting the saved latitude and longitude into a UTM coordinate system for intuitive analysis.

$$TSE_{horizontal} = P_{true} - P_{path} \tag{1}$$

In equation (1) P_{true}, P_{path} is the horizontal value of the actual location and desired path measured in BD992.

$$TSE_{vertical} = H_{true} - H_{path} \tag{2}$$

In equation (2) H_{true}, H_{path} is value of the actual altitude and desired altitude. As a result, in this paper, we try to derive the horizontal TSE and the vertical TSE.

2.4 Verify Data Independence

In the case of deriving the TSE of the UAV using time series data, since the previous error affects the subsequent error, independence between the error samples must be guaranteed [7-9]. To this end, the null hypothesis is assumed and the size of the threshold value for the autocorrelation coefficient and the Type 1 Error significance Level is compared to determine whether to reject the null hypothesis. If the null hypothesis is rejected, the above process is repeated until the null hypothesis is adopted, increasing the data sampling lag value.

Formula for deriving the autocorrelation coefficient

$$\gamma_k = \frac{1}{\sqrt{\sum_{i=1}^{n-k} x_i^2 - \frac{1}{n-k}\left(\sum_{i=1}^{n-k} x_i\right)^2}} \times \frac{\sum_{i=1}^{n-k} x_i x_{i+k} - \frac{1}{n-k}\sum_{i=1}^{n-k} x_i \sum_{i=k+1}^{n} x_i}{\sqrt{\sum_{i=k+1}^{n} x_i^2 - \frac{1}{n-k}\left(\sum_{i=k+1}^{n} x_i\right)^2}} \tag{3}$$

In equation (3) γ_k is an autocorrelation coefficient, x_i is a sample of the i-th TSE, and k is a time delay(lag) between series of data samples.

Formula for deriving the Critical value

$$\gamma_{\alpha,k} = N^{-1}(\alpha,0,1)\sqrt{\frac{1}{n}(1+\sum_{i=1}^{k}\gamma_i^2} \tag{4}$$

In equation (4) $\gamma_{\alpha,k}$ is the critical value, $N^{-1}(\alpha,0,1)$ is the inverse function of the standard normal cumulative distribution, α is Type I Error Significance Level.

Formula to the Check whether to reject the null hypothesis

$$If\ \ \gamma_k > \gamma_{\alpha,k} \qquad reject\ \ H_0 \tag{5}$$

2.5 TSE Modeling

In the case of manned aircraft, modeling is performed with a zero mean Gaussian, but the normal distribution is used instead of the zero mean Gaussian with a mean of 0, because there is no standardization for UAV’s navigation performance analysis. Therefore, when a TSE sample with guaranteed independence is secured, modeling is performed with a normal distribution, and the validity of the model can be determined through comparison with the histogram of the sample.

$$y = f(x|\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}}e^{\frac{1(x-\mu)^2}{2\sigma^2}} \tag{6}$$

In equation (6) μ,σ means the mean and standard deviation. x means TSE data with guaranteed independence.

3. Experiments Result

3.1 Flight Test & Flight Path

Table 3 shows the specifications of the UAV used to collect TSE analysis data. The flight path was flown in a trajectory as shown in Figure 5, and the turning part of the trajectory consists of a radius corresponding to 30 seconds turn and a one minutes turn, which are manned aircraft maneuvering. In addition, since the TSE with a different sign depending on the turning direction was derived, the UAV flew the right turn and left turn to offset the turning effect.

Table 3. Flight test information

Flight area	Buk-myeon, Uichang-gu, Changwon-si, Gyeongsangnam-do
Type	VTOL
MTOW	4.3 kg
Wingspan	2.2 m
FCC	Self-development
Flight speed	15 m/s

Figure 4. Test UAV

3.2 Data Analysis Result

As a result of sampling by checking the independence of the collected flight data, 0.59% data were extracted. Figure 5 shows flight trajectory and sampled data on 3D-space and 2D-plane. This result shows that the independence of the collected flight data is very low.

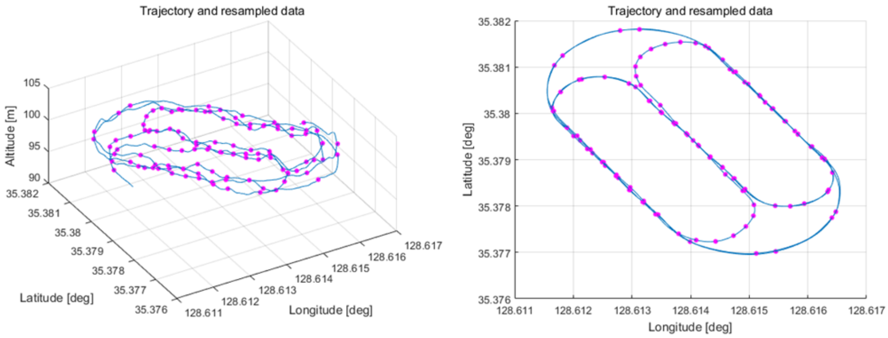


Figure 5. Trajectory of racetrack flight (3D & 2D)

The following navigation performance analysis was derived using sampling TSE data. As you can see in Figure 6, it is shown that the TSE corresponding to the horizontal direction shows path tracking performance with an average of close to 0, and it can be modeled as a zero mean gaussian if more data are collected and analyzed. The vertical direction has a smaller deviation than the horizontal direction and seems to follow the flight control command well, but referring to Table 4, there is a bias of about 2.5m. It seems to have a large effect of the integrated navigation sensor. It can be seen that the GNSS integrated navigation performance in the horizontal direction is lower than the GNSS integrated navigation performance in the vertical direction when considering the analysis result that the TSE deviation in the horizontal direction is larger.

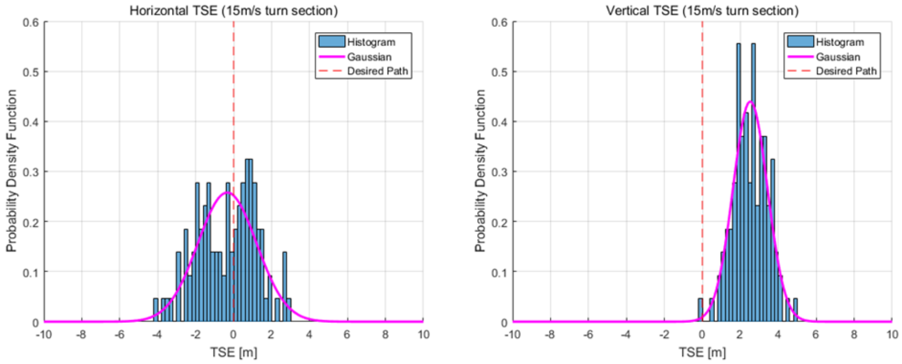


Figure 6. TSE histogram (horizontal & vertical)

Table 4. Integrated navigation performance

	Horizontal error	Vertical error
Mean (μ)	-0.3377 m	2.5223 m
Standard deviation(σ)	1.5474 m	0.9071 m

4. Conclusion

In this study, the TSE required to determine the flight path of an UAV was derived, and a method of analysis the integrated navigation performance through error distribution modeling was proposed and analyzed. We planned the flight path for analysis and performed a flight test. In addition, we got 0.59% sample data with integrity and independence was guaranteed through post-processing of the collected data. Analyzing the derived results, it can be seen that the horizontal direction performance of integrated navigation system is low and the vertical direction TSE is biased. We thought that the horizontal performance can be modeled with zero mean gaussian. In the future, additional flight data will be collected to increase the reliability of the analysis results, and NSE and FTE will be derived respectively, and TSE will be derived using various methods. Finally, we intend to propose a flight path for UAVs to be used in the UTM system, taking into account the probability of path deviation, safety, etc.

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