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Influencing factors of low-altitude unmanned aircraft navigation using AHP

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Abstract

This study examines whether unmanned aircraft systems (UAS) operated in the context of UAS traffic management (UTM) can be properly operated in its flight environment. In detail, this study examines the influencing navigation factors affecting UASs during flight and examines factors affecting the navigation of UASs under UTM. After deriving various factors affecting navigation, their importance are determined by applying the analytic hierarchy process technique, and the important influencing factors are examined. For low-altitude UAS navigation, errors are classified into navigation-system and flight-technical errors, and a hierarchy is constructed for their sub-factors affecting the influencers. Through this, influencing factors for precise navigation of low-altitude UAS are analyzed, and high importance items are identified

Keywords: *UTM, UAS, AHP, Navigation system error, Flight technical error*

1. Introduction

An unmanned aircraft is a flying system that flies without a human pilot onboard. The number of such aircraft has increased rapidly because of the massive supply of a small multi-blade copter aircraft, often called "drones." Unmanned aircraft systems (UAS) have been the subject of vast research for a variety of airborne services. Currently, UASs are mainly used for aerial photography. However, research has been conducted to increase their application scope to include small-cargo transportation. At present, most countries allow private UAS flights as long as they fly within the visible range of the remote operator. The governments and industries of developed countries have applied UAS services beyond the line of sight, and UAS traffic-management (UTM) systems have therefore become very important. In Korea, UTM research has focused on safety, and collaborative studies have been sponsored among various governmental and industrial agents.

This study examines the proper flight capabilities of UASs in UTM environments. The influencing factors of navigation affecting UAS operation and navigation are focused. For navigation, operators must know the position, distance, direction, and speed of the UAS at all times. These four factors are commonly ascribed "the four factors of navigation." UAS operators conduct flight operations using visual capabilities or dedicated instruments that operate via radio frequencies (RF). Sophisticated sensors are required to be equipped on UASs, including cameras and Global Positioning System locators.

Navigation tools have varying accuracies, depending on several factors that affect position measurement and aircraft control. In the case of a UAS flying at low altitude, navigation accuracy can vary according to external factors, such as topography, altitudinal winds, RF obstacles, and other disturbances. This study

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examines those factors. The structure of this paper is as follows. Section 2 discusses the navigational factors of UASs and UTMs. Section 3 discusses the analytic hierarchy process (AHP) used for analysis. Chapter 4 applies AHP to the navigational influencing factors, and Chapter 5 concludes the paper.

2. UAS and UTM

UASs have been heavily used for military purposes, but they are being used increasingly in industrial fields. The term "drone" was historically applied to UASs used for target practice. However, the term is now applied ubiquitously to UASs of all purposes. Markets have spawned and grown as a result of the increasing scope of UAS applications (e.g., reconnaissance, farming, and fun). The Korean government has unsurprisingly taken a keen interest in UAS markets.

According to the Korean Aviation Safety and Security Act, aircraft of a designated small size is classified as "ultralight." Aircraft less than 22 kg do not require governmental certification or authorization. However, there are restrictions on the long-distance operation of UASs. Currently, UASs can be operated below a 150 m altitude under visual line-of-sight control during the daytime. A certified UTM is required to operate a UAS beyond the line of site. UTMs provide effective UAS traffic control and are used commonly in the U.S., Europe, Singapore, and Japan. In South Korea, studies have been conducted related to UTMs to promote the safe operation and utilization of UASs.

3. AHP

3.1 Method

The multitude of factors influencing navigation create a complex relationship of influential items. Thus, it is important to apply appropriate decision-making techniques to the management system. The AHP, which is easy to apply, calculates relationship importance by comparing multiple evaluation items. It can easily handle complex objects having multiple evaluation items. It considers the effects of interactions between items, links evaluation criteria to evaluation objectives, and checks for consistency. This makes it possible to subjectively quantify judgment by avoiding simple evaluations of decision factors and qualitative factors.

AHP analyzes the entire process of decision making via relative comparisons between each item divided by stages, because the human brain uses a step-by-step hierarchical analytical procedure. This method is designed for multi-faceted evaluation criteria and decision making by evaluating multiple actors for a large number of items. Simultaneously, quantitative and qualitative factors are considered to influence rational or irrational judgments. This method is based on multi-criteria decision making, which is analyzed by designing or selecting the most suitable item from among various conflicting criteria, analyzed by designing or selecting the most suitable item. It is a process of selecting the most appropriate item based on the relative importance of the elements.

AHP applies the conditions of four steps. First, the evaluator must be able to pair and compare two factors in the same hierarchy and express their importance. The expression of importance must satisfy the reciprocal condition that B is 1/x times as important as A if A is x-times more important than B. Second, a set of comparison matrices creates a pairwise comparison of the importance of homogeneity. Third, the intrinsic numerical and relative weights are computed for each item's dependency, requiring an associative relationship between lower and upper hierarchies by class. Fourth, the analysis of each step of the hierarchy structure includes all matters about the purpose of decision-making. This process results in poor matrix accuracy if the responder fails to respond consistently to the relative importance of each item in paired comparison matrices that assess relative importance. Consistency is examined using the consistency index and consistency ratio to determine accuracy. The higher the consistency, the closer the value is to zero. At 0.1 or lower, the consistency of evaluation is considered consistent.

3.2 Influencing factor classification of navigation

Positional accuracy related to aircraft navigation can be affected by lateral and longitudinal errors. Longitudinal errors are excluded from the influencing factors of navigation in this study, because safety can be ensured via the separation of the forward and rear aircraft (temporal or spatial).

Lateral errors can be classified into total system errors (TSE), flight technical errors (FTE), and navigation system errors (NSE). FTEs are caused by an aircraft's flight characteristics. It can be changed according to the characteristics of flight. To clarify this, it is necessary to identify factors that can affect aircraft performance. In the case of UASs, the error contains information on the time characteristics required for the pilot to view, judge, and operate aircraft according to the pilot's intention. Not only the time required for the aircraft to react to the pilot's command, but also control errors are included in the influencing factors. NSE values are provided for aircraft navigation, and it includes location, position, or hardware errors. These data all pertain to direct factors of navigation and not external factors.

TSE is a method of expressing overall positional accuracy, including navigation system and FTEs. Positional information measured during flight includes navigation and flight system errors and may require separate identification and application of measurement methods. Table 1 shows general and technical factors affecting final results and navigation error factors, which can apply medium levels of AHP.

Table 1. General and technical parameters

Final result	**Navigation error factors**	Influencing factor
TSE	NSE	Atmospheric environment
		Wave propagation environment
		Product differences of control equipment / sensor
		Integration method for navigation systems
		Flight state and flight mode
	FTE	Atmospheric environment
		NSE effects
		Flight state and flight mode

The sub-indicators of this study are applied as a result of the application of universal items affecting the navigation and maneuvering of aircraft. They include temperature, humidity, atmospheric pressure, atmospheric environments, including wind direction/wind speed, the wave propagation of satellite signals, characteristics and differences of sensor products and data integration method for navigation, measured for general or universal effects.

The atmospheric environment, temperature, humidity, pressure, wind speed, and wind direction serve as influencing factors, and, for the wave propagation environment, the availability of satellite signals, influencing factors for environmental wave propagation, and satellite-signal disturbance can be influential factors. Flight state and mode may be influenced by speed, altitude, information about circulation, ascent/descent, takeoff/landing, and loading, and product differences between flight-control equipment/sensors can be influencing factors. Finally, if the navigation system uses only satellite navigation systems, integrated navigation systems with satellite navigation, instruments, optical sensors, etc., are integrated, it could affect accuracy of navigation. In case of FTEs, whether it has NSE values in advance or not might serve as an influencing factor.

3.3 Hierarchy construction for analysis

Table 2 presents a hierarchy for analysis. Influencing factors on TSEs were set to layer 1 as the goal of the AHP, and layer 2 is divided into navigation system and FTEs. Level 3 is classified into atmospheric environment, wave propagation environment, product differences of control equipment/sensor, navigation system integration method, flight state, flight mode, and prior or real-time calculation of NSE values connecting them to level 2. Depending on its influencing factor, repeated application was necessary. Level 4 is a sub-factor of level 3, and atmospheric environment includes temperature, humidity, atmospheric pressure, wind speed, and wind direction, and wave propagation environment includes satellite signal availability, environmental influencing factors, and satellite signal disturbances. For differences in control equipment and sensor products, flight control equipment and position sensor differences are included, and navigation system integration includes single-satellite navigation and multiple-satellite navigation. Flight state and flight modes include flight speed, flight altitude, course alteration information, ascend/descend, take off/landing, and baggage load. With NSE effects, whether NSE value is derived in advance or predicted in real-time is included.

Table 2. Influencing factor hierarchy

layer 1	layer 2	layer 3	layer 4
TSE	NSE	Atmospheric environment	Temperature
			Humidity
			Atmospheric pressure
			Wind speed
			Wind direction
		Wave propagation environment	Satellite signal availability
			Environmental propagation influencing factor
			Satellite signal disturbance
		Product differences of control equipment / sensor	Flight control equipment
			Position sensor
		Navigation system integration method	Single satellite navigation
			Multiple integration navigation
		Flight state and flight mode	Flight speed
			Flight altitude
			Course alteration information
			Ascend/descend
			Take off/landing
			Baggage load
	FTE	Atmospheric environment	Temperature
			Humidity
			Atmospheric pressure
			Wind speed
			Wind direction
		NSE effects	NSE value pre derivation/assumption
			NSE value real-time prediction/comparison
		Flight state and flight mode	Flight speed
			Flight altitude
			Course alteration information
			Ascend/descend
			Take off/landing
			Baggage load

4. Empirical Analysis of Navigation Influencing Factor

4.1 Analysis overview and top hierarchy (level 2) analysis

A Delphi survey was conducted after reviewing the preliminary questionnaire items in the related field of the classification of the navigation influencing factor. The survey was conducted on a limited sample of experts having experience in relevant studies. For the AHP questionnaire, the weights were derived by comparing the questions, and when the AHP questionnaire lacked a clear understanding of the detailed relationship of the question items, the consistency became low. Therefore, limiting the questionnaire to respondents with experience was done to derive appropriate results.

Questionnaire participants were limited to those having more than 3-years' experience in the relevant field. A total of 20 questionnaires were collected and analyzed. We used the Expert Choice 11.5 program, and the consistency index for risk-factor analysis was 0.07, suggesting that there was little logical contradiction in the judgment of the evaluators who participated in the AHP.

As a result of the analysis, the navigation system and FTEs, which were the high hierarchical evaluation factors of the low altitude UAS navigation error, were evaluated, and the results showed that a NSE showed a value of 0.393 and a FTE of 0.607, indicating FTE was more influential. This implies that various environments and flight conditions affecting real-time flight affect the navigation more than NSEs. See Table 3 for details.

Table 3. Importance of navigation influencing factor

Category	NSE	FTE
weight	0.393	0.607

4.2 Middle hierarchy (level 3) analysis

The importance evaluation of the detailed classification hierarchy of NSEs was derived using values of atmospheric environment, 0.108, wave propagation environment, 0.283, equipment manufacturer difference, 0.127, navigation system integration method, 0.298, flight state and flight mode, 0.184. The importance of the navigation system integration method and propagation environment was analyzed to be higher than other factors. This means that securing the variety of information measured by sensors and ensuring the smooth information measurement had higher importance than other factors. See Table 4.

Table 4. Importance of NSE influencing factors

Category	Atmospheric environment	Wave propagation environment	Equipment manufacturer difference	Navigation system integration method	Flight state and flight mode
weight	0.108	0.283	0.127	0.298	0.184

The results of the importance evaluation for the middle hierarchy of FTE were analyzed to be atmospheric environment, 0.270, NSE effects, 0.245 and flight state and flight mode, 0.485, indicating the higher importance of flight state and flight mode. This means that conditions such as flight speed, flight altitude, course alteration, ascend/descend, takeoff/landing, and baggage load had a high influence that could cause FTEs. See Table 5.

Table 5. Importance of FTE influencing factors

Category	Atmospheric environment	NSE effects	Flight state and flight mode
weight	0.270	0.245	0.485

4.3 NSE low hierarchy (level 4) analysis

The results of the importance evaluation for the low hierarchy of NSE were analyzed. For atmospheric environment factors, temperature was 0.149, humidity was 0.208, atmospheric pressure was 0.218, wind speed was 0.249, and wind direction was 0.177, indicating smaller deviation compared to the importance difference of higher hierarchy. This means that the sub-items of atmospheric environment factors had a relatively uniform effect on the NSEs. See Table 6.

Table 6. Importance of atmospheric environment sub-influencing factors

Category	Temperature	Humidity	Atmospheric pressure	Wind speed	Wind direction
weight	0.149	0.208	0.218	0.249	0.177

The results of the importance evaluation for the sub-hierarchy of NSE for wave propagation environment factors were as follows. The number of available satellites was 0.206, the surrounding wave influence (e.g., high voltage line) was 0.338, and satellite signal disturbance was 0.457, indicating that smooth radio-wave receipt for position information calculation has a large effect on NSE. See Table 7.

Table 7. Importance of wave propagation environment sub-influencing factors

Category	Number of available satellites	Surrounding wave influence such as high voltage line	Satellite signal disturbance
weight	0.206	0.338	0.457

For the equipment manufacturer difference factor, which is the lower hierarchy of the navigation system-error factor, the results of the importance evaluation showed that the difference of flight control equipment manufacturer was 0.306, and the position sensor manufacturer difference was 0.694. This analysis, in conjunction with the results of the influencing factor of the wave propagation environment, indicates that, for the error in the navigation system, ensuring proper reception of satellite navigation signals from the outside is important in reducing errors. See Table 8.

Table 8. Importance of wave propagation environment sub-influencing factors

Category	Flight control equipment manufacturer difference	Position sensor manufacturer
weight	0.306	0.694

For the navigation system integration method factor, which is the lower hierarchy of the NSE factor, the results of the importance evaluation showed that single satellite navigation was 0.209, and integration of satellites and other sensors was 0.792, indicating that receiving information by combining various sensors was influential in obtaining better accuracy. In the case of UASs at low altitudes, the results indicate that, where possible, it is better to perform navigation with data from various measurement sensors rather than from a single source. See Table 9.

Table 9. Importance of wave propagation environment sub-influencing factors

Category	Single satellite navigation	Integration of satellites and other sensors
weight	0.208	0.792

For the flight state and flight mode factor, which is the lower hierarchy of the NSE factor, the results of the importance evaluation showed that flight speed was 0.200, flight altitude was 0.166, course alteration information was 0.246, ascend/descend speed was 0.151, take off/landing mode was 0.112, and baggage-load status was 0.126, indicating less deviation compared to the importance difference in the higher hierarchy. However, in the case of course alteration, in which the aircraft changes its direction of flight, the result indicate that the NSE may be larger than straight-line flight or the ascend/descend flight. See Table 10.

Table 10. Importance of atmospheric environment sub-influencing factors

Category	Flight speed	Flight altitude	Course alteration information	Ascend/descend speed	Take off/landing mode	Baggage loading status
weight	0.200	0.166	0.246	0.151	0.112	0.126

4.4 FTE low hierarchy (level 4) analysis

The results of the importance evaluation for the sub-hierarchy of FTE for atmospheric environment factors were as follows. Temperature was 0.128, humidity was 0.192, atmospheric pressure was 0.167, wind speed was 0.295, and wind direction was 0.219, indicating a larger difference in importance between sub-items compared to the case of NSE. In particular, wind speed showed the highest importance, indicating that in case of strong winds, FTEs may become large. See Table 11.

Table 11. Importance of atmospheric environment sub-influencing factors

Category	Temperature	Humidity	Atmospheric pressure	Wind speed	Wind direction
weight	0.128	0.192	0.167	0.295	0.219

Regarding the NSE effects, which is a sub-hierarchy of FTE, for the case of obtaining NSE values in advance, the value was 0.423, and the case of obtaining NSE value in real-time was 0.577, showing larger but similar importance for real-time error-value acquisition. This means that in case of NSE values, data can be corrected or post-processed by prior or post measurement.

Table 12. Importance of wave propagation environment sub-influencing factors

Category	NSE value pre derivation/assumption	NSE value real-time prediction/comparison
weight	0.423	0.577

For flight state and flight modes, the sub-hierarchy of FTE factors importance results were flight speed, 0.236, flight altitude, 0.129, course alteration information, 0.237, ascend/descend speed, 0.119, take off/landing mode, 0.114, and baggage load state, 0.165. The results indicate that flight speed and course alteration information importance were larger than other items, indicating that the error may increase when aircraft flies at high speed and when it changes course. This is similar to the results of NSE, which showed that the error may increase when the aircraft changes its course.

Table 13. Importance of atmospheric environment sub-influencing factors

Category	Flight speed	Flight altitude	Course alteration information	Ascend/descend speed	Take off/landing mode	Baggage loading status
weight	0.200	0.166	0.246	0.151	0.112	0.126

5. Conclusion

This study examined factors that affect the navigation of UASs operating in a UTM system. Several factors that affect navigation were drawn, and the AHP method was applied according to importance, and the study looked into the important influencing factors.

Regarding the navigation of the low-altitude UASs, errors were classified into navigation system and FTEs, and the analysis was conducted by forming a hierarchy of sub-factors and factors that may affect them. Through this process, influencing factors for precise navigation for actual low-altitude UASs were reviewed, and analysis of items having high effect sizes was conducted.

For the aviation sector, many factors often comprehensively work together compared to other traffic systems because of the specific operational environments. For this reason, unpredictable risk factors exist, and they may have the potential to cause accidents. Furthermore, for low-altitude UTMs, owing to limitations of the conceptual and early stages of the industry, research and development is conducted without examining the detailed influencing factors. It is thus to examine whether the proper environment in the actual operation can be guaranteed.

Navigational influencing factors of low-altitude UASs were examined in this study. Factors of high importance among the detailed factors need to be examined to ensure that the UAS can safely fly or that it can operate with proper performance. Therefore, such factors might need further examination and verification during prototype reviews and operational tests.

Notably, this study did not consider test methods that can effectively verify these influencing factors. Therefore, actual testing will be necessary, if possible, to see if the study results have practicality, and further study is needed to find alternative datasets from test levels that reflects real environments.

Navigation performance affects the identification of the precise location, resulting in differences in accuracy, depending on numerous factors that affect location measurements and aircraft control. In particular, for small UASs operating at low altitudes, and navigation accuracy may vary, depending on external factors, such as topography, low altitudinal winds, wave propagation interference, or jamming caused by obstacles. This factors are essential and affect not only the possibility of flight but also safe operation.

This study examined factors that affecting the navigation of unmanned aircraft which operate in a UTM system. Several factors that might affect navigation were drawn, the AHP method was applied according to their importance, and the study looked into the important influencing factors.

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