실시간 DGPS를 이용한 헬리콥터 착륙 시스템 개발

Flight Test of Helicopter Landing System Using Real-time DGPS

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요 약

최근 수년간, GPS와 관련된 연구들이 항공분야를 비롯한 다양한 분야에서 진행되었다. 특히, GPS를 항공기의 착륙 유도 시스템에 이용하려는 연구가 많이 이뤄지고 있다. 이러한 시도들은 GPS의 경제성, 신뢰성, 정확성 등의 장점들을 십분 활용하기 위한 것이라고 할 수 있다. 서울대학교 GPS 실험실에서도 이러한 경향에 보조를 맞추어, GPS를 기반으로 하는 항공기 착륙 시스템을 개발하고, 헬리콥터를 이용한 비행실험을 수행하고 있다. 그 동안 누적된 실시간 DGPS 시스템 개발기술들을 바탕으로 항공기 착륙 시스템을 확장, 보강하여 최근의 비행실험을 실시하였다. 본 논문에서는 새롭게 구성된 항공기 착륙 시스템을 소개하고 이를 이용한 비행실험 결과를 분석하였다.

기존의, 기본적인 실시간 DGPS 시스템에서 추가, 발전된 부분은 세 가지로 분류할 수 있다. 첫 번째는, 단일 GPS 안테나를 이용하여 항공기의 자세를 추정하는 부분이고, 두 번째는, 통합적인 cockpit display이다. 이 display는 가상현실을 이용하여 조종사에게 기존의 ILS 정보와 그 이외의 다양한 정보들을 보여준다. 마지막으로, 공항의 기상상태에 관계없이 조종사가 공항에 접근할 수 있도록, 전자지도를 삽입하여 안전한 착륙을 시도할 수 있도록 시스템을 구성하였다.

이렇게 새롭게 구성된 시스템을 이용하여 김해 국제 공항에서 비행실험을 수행하였다. 분석된 결과를 바탕으로, 이 시스템이 정확도 측면에서, CAT-I을 충분히 만족시킴을 확인하였으며, 신뢰도 높은 자세결정이 이뤄지고 있음을 확인하였다.

Abstract

In recent, there has been remarkable progress in the field of GPS applications. In a few years, an appreciable number of aircraft will adopt GPS as a landing guidance system because GPS is more economic, more reliable and more accurate than any other aviation systems. In this respect, we have performed several helicopter landing flight tests based on the real-time DGPS system made in SNUGL (Seoul National University GPS Laboratory). From the experimental results, we found several problems which should be fixed to adopt DGPS as a aircraft landing guidance system. In this paper, we will introduce the problems found in tests and also suggest modifications to solve the problems.

Our modifications can be classified into three parts. The first is about the attitude determination with single GPS antenna. The second deals with the cockpit display module. The display was devised to integrate the Instrument Landing System(ILS) with tunnel-in-the-sky using virtual reality. With the

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display, pilot can achieve more safe landings. The last part is the digital map. We inserted digital map into our system and put direction indicator on the map using position information from GPS. It is very useful for pilot to find airports even in bad weather.

Using the newly designed DGPS landing system, we conducted flight test at Kimhae International Airport, Pusan, Korea. It was successful! Our system can also satisfy Category-I criterion for aircraft landing approach and determine attitude angle with a high level of reliability. It is supported by video materials.

I. INTRODUCTION

Since the Global Positioning System(GPS) is open to the civil user community, many researches have been performed in a wide variety of applications. The basic GPS positioning algorithm provides the navigation service of about 100 meters accuracy. It is due to some error sources such as Selective Availability(SA), ionospheric delay, tropospheric delay, satellite ephemeris error, multipath, and so forth. This performance is not acceptable especially to precision landing guidance.

Yet, differential GPS(DGPS) can achieve the accuracy of 0.5 to 5 meters if the baseline between reference station and user is within about 100 km. In recent years, there have been extensive activities to apply DGPS to aircraft navigation. Why are they trying to use DGPS especially in landing system instead of the current ILS system that can meet Category-III requirements?

First of all, we need to consider the characteristics of existing ILS landing system. In particular, we intend to mention its main problems compared with GPS-based navigation or landing system [7]:

1) Curved approach is impossible.
2) Display only 2D information.
3) Cause interference due to weather condition or local terrain
4) Insufficient to frequency bandwidth available in region where airports are densely located.

GPS can solve all the above problems. In addition, GPS can improve the safety of aircraft users and simplify the complex avionics equipments by replacing the sensors used in each navigation stage with GPS.

Under these situations, it is necessary to substitute GPS-based landing system for existing ILS. That is the basic motivation of our flight test. We select helicopter as an object of flight tests. Our choice is intended to construct the future system that can realize Instrument Flight Rules (IFR) of helicopter with GPS.

There are some items to be implemented in flight tests. Reference station system includes the RTCM SC-104 DGPS correction message generator that has better positioning accuracy than 4.1 m (2DRMS, 95%) in vertical. In user system, there are attitude determination and cockpit display. The former is to determine aircraft attitude with single GPS antenna using velocity measurements and the latter is to show both the improved 3D ILS display with tunnel-in-the-sky and the 2D digital map to help pilot approach airport.

II. SYSTEM STRUCTURE

In this section, we will show reference station segment and user segment in our GPS-based aircraft landing system. Particularly, attitude determination part will be described separately.

2-1 Reference Station Segment

Reference station segment consists of four parts as shown in Figure 1:

1) Parse GPS data and other information reported by GPS receiver.
2) Process L1 pseudorange measurements and ephemeris data.
3) Generate RTCM SC-104 correction message.
4) Display the status of reference station and user.

Reference receiver can provide reference PC with various information. This information is logged in reference PC for post-processing. Out of the delivered information, pseudorange measurements and ephemeris information are used to find the position of reference antenna. Another information plays a key role in monitoring its status. With raw and processed information, RTCM SC-104[9] correction message is generated and transmitted to user segment via wireless modem.

On the other hand, reference station monitors the uplinked position of user by displaying it on digital map. For example, a controller at control tower can observe the position and other status of aircraft using our landing system. It is similar to the role of commercial radar system.

2-2 User Segment

User segment consists of three parts as shown in Figure 2:

1) Parse GPS data and other information reported by GPS receiver.
2) Process velocity measurements and determine vehicles attitude.
3) Display 3D ILS and 2D digital map.

The first part is the same as the information parsing of reference station segment. But the processing data are different. Our 3D ILS display requires the attitude and position information with

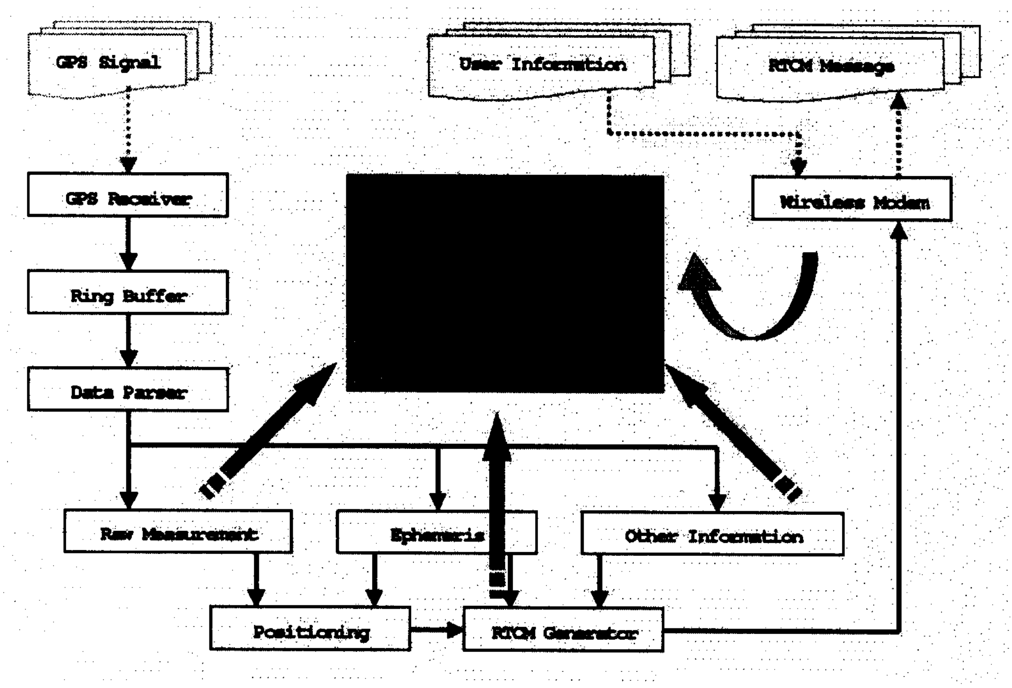

Fig. 1. Block diagram of reference station.
그림 1. 기준국의 Block diagram

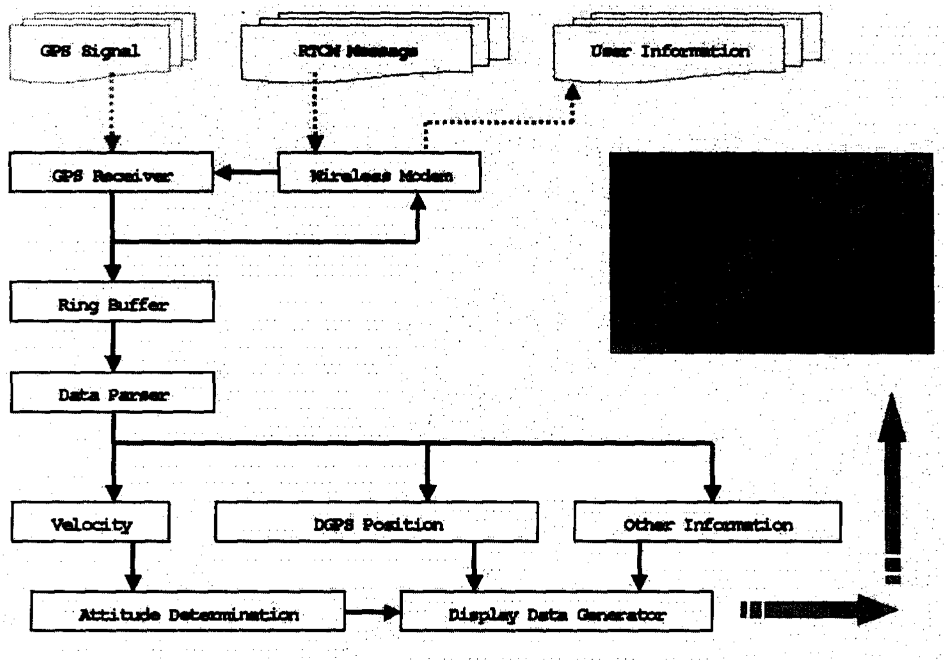

Fig. 2. Block diagram of user system.
그림 2. 사용자 시스템의 block diagram

the update rate of 5 Hz. If user PC is responsible for attitude determination and positioning, it may experience too high computational loads to show the 3D graphics.

In an attempt to avoid high processing load, user segment takes advantage of the reliable position-filtering method and the rapid data update rate that are applicable to GPS receiver: i.e., positions are given from GPS receiver and attitude is processed in user PC. Using this information, user PC shows 3D ILS display and 2D digital map to help pilot approach and land on. This task allocation will eventually increase the system capability and reliability.

2-3 Attitude Determination

Our attitude determination algorithm is based on that of Kornfeld [6]. This algorithm estimates attitude angle from the aircraft trajectory measured by a single GPS receiver. Assuming that aircraft is a point mass model under coordinated flight, pitch (pseudo-pitch: pitch that the angle of attack is not removed) and yaw angles are calculated from filtered velocity and roll angle is computed from estimated acceleration, by-product of velocity filter.

Filtered velocity and acceleration are severely affected by filter gain because measured velocity contains a significant level of noise component. It means that the attitude angles calculated from them are very sensitive to filter gain. To search reasonable filter gain is more important issue than to calculate roll, pitch and yaw.

Figure 3 describes the block diagram of attitude determination module with our modified filter.

The modified part is measurement modeling. In general, GPS positioning accuracy has the different error level along the direction because of the satellite geometry in space. This is so-called Dilution Of Precision(DOP).

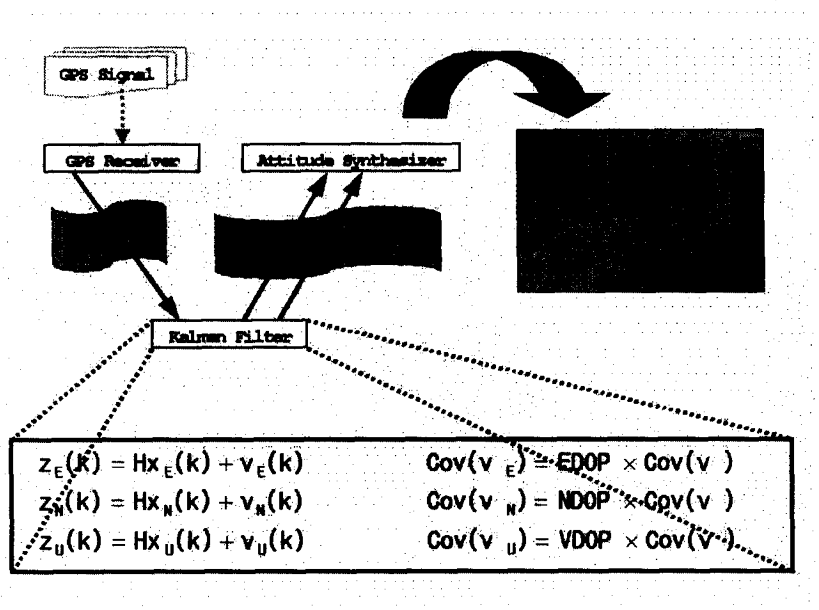

Fig. 3. Attitude determination part.
그림 3. 자세 결정 부분

Here we considered this actual phenomenon. Let be the noise of original source from that velocity is measured. Then noise covariance of velocity component in each direction is the covariance of times each DOP value. With this modification, we implemented attitude determination algorithm.

Ⅲ. PERFORMANCE ASSESSMENT

Zero-baseline test and static survey test were performed to assess the reliability and performance of our DGPS landing system.

3-1 Zero-baseline Test

Zero-baseline test was performed in the building 301, Seoul National University. It has excellent positioning accuracy because even uncommon error sources such as multipath are removed. The test results are showed in Figure 4 and 5. According to statistical data manipulation, horizontal error is 0.32 m(2DRMS,95%) and vertical error is 0.48m (2DRMS, 95%).

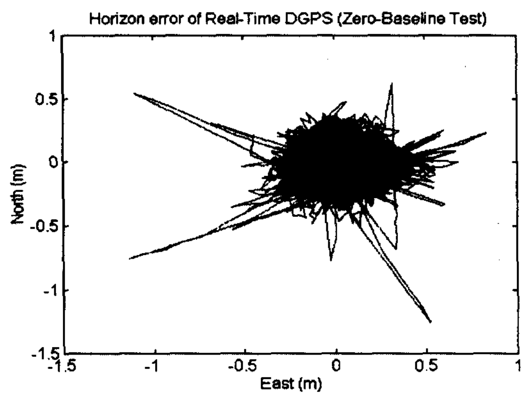

Fig. 4. Zero baseline test : horizontal error.
그림 4. 영 기저선 실험 : 수평 오차

3-2 Static Test

Static test was conducted to anticipate the real performance of our aircraft landing system in building 301 and 44, Seoul National University. In

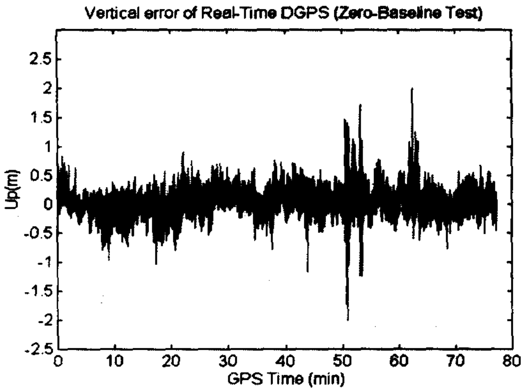

Fig. 5. Zero baseline test : vertical error.
그림 5. 영 기저선 실험 : 수직 오차

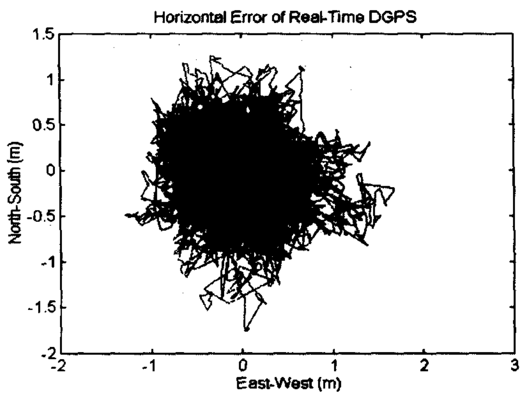

Fig. 6. Static test : horizontal error.
그림 6. 정적 실험 : 수평 오차

this test, uncommon error sources affect user position, which is contrary to zero-baseline test.

Figure 6 and 7 show the static test results. According to statistical data manipulation, horizontal error is 0.88 m(2DRMS, 95%) and vertical error is 2.43 m(2DRMS, 95%).

Ⅳ. FLIGHT TEST

Flight Test was performed on July 2425, 1999 at Kimhae International Airport, Pusan, Korea. This airport is in heavy traffic and has only one ILS. Thus, the number of flight experiment is insufficient to analyze the full operational capability.

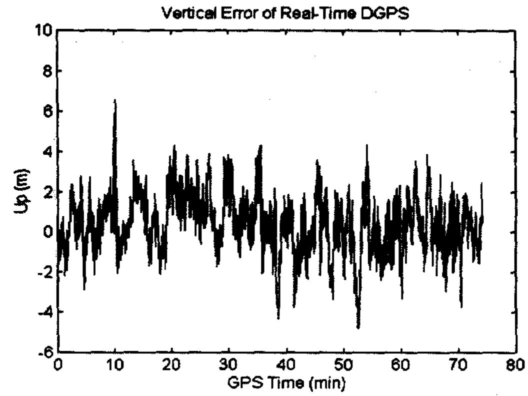

Fig. 7. Static test : vertical error.
그림 7. 정적 실험 : 수직 오차

Fig. 8. Aircraft used in test : UH-60P.
그림 8. 실험에 사용된 항공기 : UH-60P

Aircraft used in test is military helicopter, UH-60P in Figure 8.

4-1 Overall System Equipments

4-1-1 Reference Station Equipments

Reference station equipment consists of NovAtel 3151R receiver, wireless modem, reference station PC, and Trimble 4000ssi receiver. NovAtel 3151R is for real-time DGPS. Reference PC processes the data that NovAtel 3151R receiver reports, generates RTCM SC-104 correction message, and transfers this message to user via wireless modem. Trimble 4000ssi is available to survey the precise

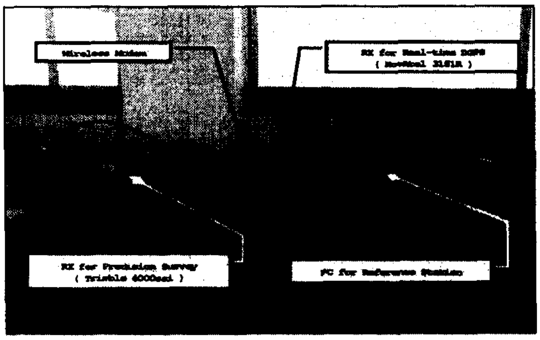

Fig. 9. Reference station equipment.
그림 9. 기준국 장비

position of reference station to mm-level accuracy.

Figure 9 depicts the reference station equipments used in our experiments.

4-1-2 User Equipments

We installed equipment box and user PC inside of helicopter. In particular, equipment box contained NovAtel 3151R, wireless modem, and battery. Camera was set in the cockpit window.

NovAtel 3151R receiver seeks the position of user GPS antenna with correction message transmitted through wireless modem. Battery provides receiver and modem with power supply. Camera takes the pictures of the front view of helicopter.

Figure 10 shows the user equipments used in our flight test.

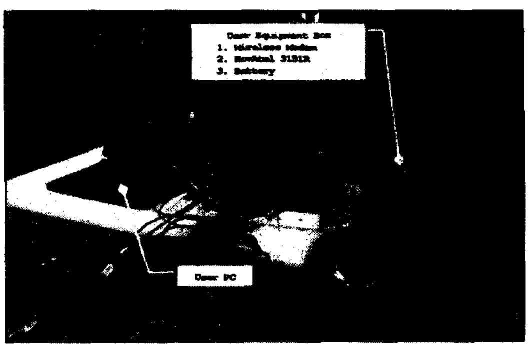

Fig. 10. User equipment.
그림 10. 사용자 장비

Table 1. Positioning Accuracy of Reference Survey.
표 1. 기준국 측위 정확도

Direction	Standard deviation(mm)
X	6.951
Y	8.100
Z	7.781

4-2 Procedure

4-2-1 Reference Station Survey

Before flight tests, it is necessary to survey the precise position of reference station. To achieve the mm-level of accuracy, GPS signal was simultaneously received through Trimble 4000ssi in both Kimhae airport and Seoul National University for 1 hour. The baseline between two sites is about 309 km. The logged data are processed using GP-Survey software made in Trimble. The positioning accuracy is shown in Table 1.

4-2-2 Runway Survey

User position in Earth Centered Earth Fixed (ECEF) coordinates must be transformed into the local coordinates about runway for 3D ILS display. Therefore we surveyed the touch-down point and end point of runway. We selected our touch-down point as the point from which the radio wave of the installed ILS is radiated. Helicopter stays at each point and takes DGPS position output with NovAtel 3151R receiver. The test duration is about 5 minutes per point. We selected the mean value of DGPS position as reference point of runway.

Using these results, the helicopter positions in ECEF coordinates were transformed into the positions in local XYZ coordinates about runway touch-down point to display the ILS. This local XYZ coordinates have the origin on the touch-down

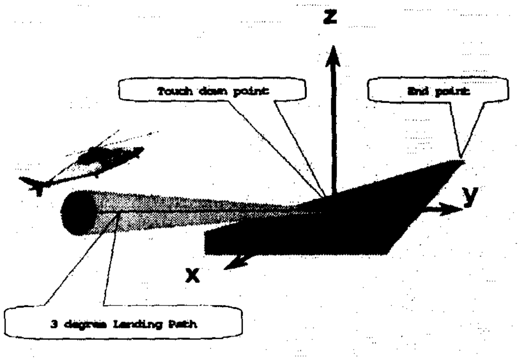

Fig. 11. Helicopter landing path.
그림 11. 헬기의 착륙 궤적

point and its axes were set as shown in Figure 11.

4-2-3 Landing

After above prerequisite works were done, helicopter landing tests were performed. Helicopter takes off, revolves the area of 1020 km radius with 2D digital map, and tries to land on with 3D ILS display.

The 3D ILS display is shown in Figure 12. It shows the tunnel-in-the-sky, attitude, and other useful information.

Fig. 12. Digital map and 3D ILS display.
그림 12. 전자지도와 3D ILS 화면

V. RESULT

We only conducted 10 landing trials because of the bad airport condition. For error analysis, it is required that we measure the true landing path for each trial. Any sensor was not equipped to obtain the information about the true path. But it is reasonable to take the carrier-DGPS solution as true landing path because carrier-DGPS has cm-level of accuracy.

In the process of carrier-DGPS technique, there are some difficult problems. Tropospheric delay is not fully removed by modeling because the difference between reference station and user is over 100 m in height. Due to this mismodeling error, we have trouble in solving cycle ambiguity accurately. Out of 10 landing trials, we obtain only 4 true landing path.

We intend to compare real-time DGPS results with carrier-DGPS solution.

There are some portions that hop between DGPS mode and stand-alone mode in real-time landing path because of data link failure. In error analysis, stand-alone modes were not considered for such interval.

Figure 13 shows the total flight path with respect to the local ENU(East, North, Up) coordinates and Figure 14 provides a landing path out of 4 landing trials. This landing path of real-time DGPS is compared with stand-alone and CDGPS results. The positioning errors in horizontal and

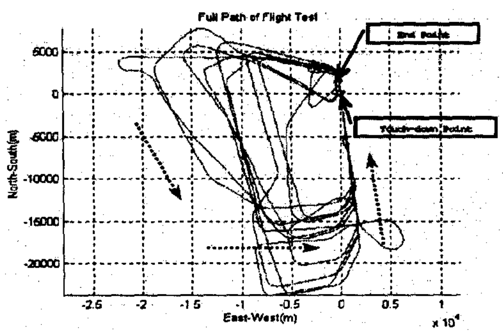

Fig. 13. Total flight path.
그림 13. 전체 비행 궤적

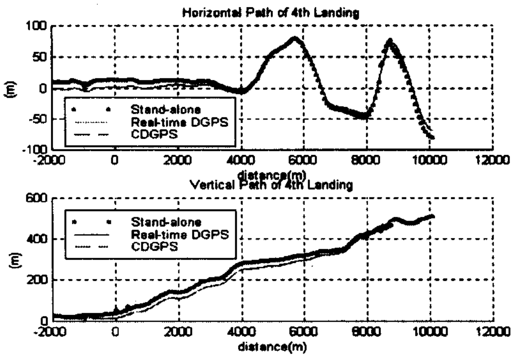

Fig. 14. Landing path of 4th trial.
그림 14. 4번째 착륙 궤적

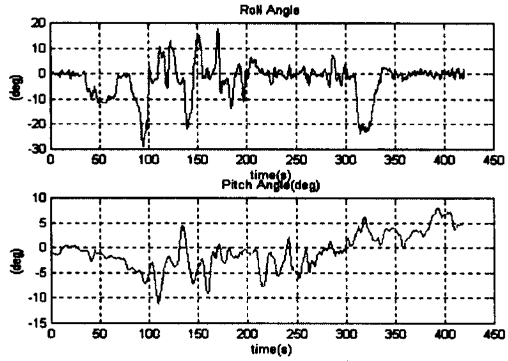

Fig. 16. Roll and pitch angle.
그림 16. 롤 피치각

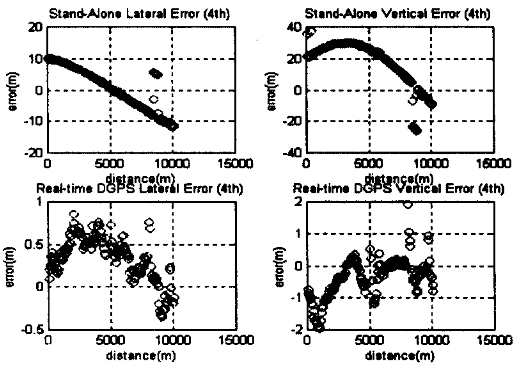

Fig. 15. Error in 4th landing path.
그림 15. 4번째 착륙 궤적의 오차

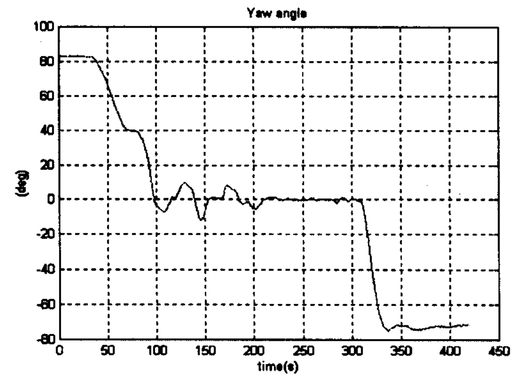

Fig. 17. Yaw angle.
그림 17. 요각

vertical directions are given in Figure 15.

The error analysis for 4 landing trials is summarized in Table 2. According to this table, our real-time DGPS landing system can satisfy the Category-I requirements in an aspect of accuracy.

Attitude angles vs. time are shown in Figure 16

Table 2. Error analysis of 4 landing trial.
표 2. 착륙 궤적의 오차 분석 결과

Mode / Landing No.	Stand-alone 2DRMS (m)		Real-time DGPS 2DRMS (m)	
	Horizontal	Vertical	Horizontal	Vertical
4-th	15.53	45.27	1.21	1.51
5-th	51.07	48.67	1.28	1.77
6-th	49.78	1.33	0.88	2.35
9-th	35.40	34.67	1.41	1.51
Total	40.56	37.49	1.22	1.82

and 17. During our flight test, we cannot obtain true information about the attitude of helicopter. But we can ascertain the reliability of estimated attitude angle by comparing the 3D ILS display with the front view of helicopter. It is supported by our video materials.

Ⅵ. CONCLUSIONS

In this paper, we tried to evaluate the performance of real-time DGPS landing system developed by SNUGL. Through helicopter flight test, we can successfully implement attitude determination, 2D digital map, and 3D ILS display.

Two types of test were conducted before flight test. Zero-baseline test gives us the accuracy of 0.32 m(2DRMS, 95%) in horizontal and 0.48 m (2DRMS, 95%) in vertical. In addition, static test gives us the accuracy of 0.91 m (2DRMS, 95%) in horizontal and 2.45 m(2DRMS, 95%) in vertical.

We takes carrier-DGPS position as the true path for error analysis. This acceptance is reasonable because CDGPS has the accuracy of cm-level. Therefore we can conclude that our real-time DGPS has the accuracy of 1.22 m(2DRMS, 95%) in horizontal and 1.82 m(2DRMS, 95%) in vertical. This positioning performance has sufficient redundancy to satisfy Category-I landing requirements.

Several topics for further study still remains unsolved to our team: i.e., the characteristics of latency along data link equipment, the estimation technique of pseudorange and range rate correction, and the development of precision landing guidance algorithm based on carrier phase measurements. These works are currently in progress and the advanced aircraft landing system will be designed and tested in next flight test.

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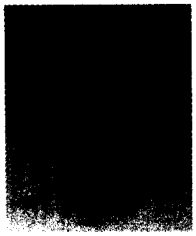
장 재 규(張載圭)



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관심분야 : 광역 보정 위성 항법 시스템, 지역 보정 위성 항법 시스템, 반송파 보정 위성 항법 시스템, GPS를 이용한 항체의 자세 결정, 한국형 전리층 지연 모델 개발

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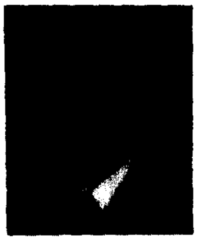

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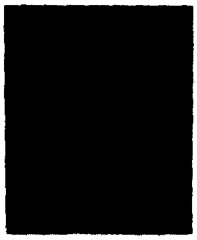

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