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An Efficient Information Fusion Method for Air Surveillance Systems

조 태 환 · 오 세 명 · 이 길 영*
공군사관학교 전자통신공학과

Taehwan Cho · Semyoung Oh · Gil-Young Lee*
Department of Electronics Engineering, Republic of Korea Air Force Academy, Chungcheongbuk-do 26187, Korea

[요 약]

자동종속 감시 시스템 (ADS-B; automatic dependent surveillance - broadcast) 시스템과 다변측정 항공감시 시스템(MLAT, multilateration) 시스템은 통신/항행/감시 및 교통관리 (CNS/ATM; communications, navigation, and surveillance/air traffic management)의 다양한 분야 중에서 감시분야에 속한다. ADS-B와 MLAT는 위성 및 디지털 통신 기술을 기반으로 구현되어 레이더 보다 성능이 뛰어나지만, 여전히 오차는 가지고 있다. 우는 이러한 오차를 줄이기 위해 reweighted convex combination method를 제안한다. Reweighted convex combination method는 기존의 convex combination method를 개선한 정보융합 기법으로 시스템에 주어지는 가중치를 재조정하여 항공기 추적 성능을 향상시킨다. reweighted convex combination method을 ADS-B와 MLAT에 적용시켰을 때, 평균 51.51 %의 성능향상이 있었다.

[Abstract]

Among the various fields in the communications, navigation, and surveillance/air traffic management (CNS/ATM) scheme, the surveillance field, which includes an automatic dependent surveillance − broadcast (ADS-B) system and a multilateration (MLAT) system, is implemented using satellite and digital communications technology. These systems provide better performance than radar, but still incur position error. To reduce the error, we propose an efficient information fusion method called the reweighted convex combination method for ADS-B and MLAT systems. The reweighted convex combination method improves aircraft tracking performance compared to the original convex combination method by readjusting the weights given to these systems. In this paper, we prove that the reweighted convex combination method always provides better performance than the original convex combination method. Performance from the fusion of ADS-B and MLAT improves an average of 51.51% when compared to the original data.

Key word : Automatic dependent surveillance – broadcast, Mutilateration, Information fusion, Communications, navigation, and surveillance (CNS), Air traffic management.

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***Corresponding Author; Gil-Young Lee**

Tel: +82-32-860-7417
E-mail: gylee45@afa.ac.kr

Ⅰ. Introduction

The United States and the European nations which are countries with advanced aviation technologies have shown dedication to the improvement of aviation system for air traffic safety. In addition, research on navigation systems using the satellite technology has been promoted to improve the existing navigation systems. The International Civil Aviation Organization (ICAO) has been carrying out research on a new scheme for air traffic management, which is called communications, navigation, and surveillance/air traffic management (CNS/ATM).

The transition to CNS/ATM will have influences on the technical aspects, such as increasing airspace capacity and achieving aircraft position accuracy. ATM is used to control air traffic flow quickly and safely, and air traffic control (ATC) is the most important part of ATM that improves the efficiency of ATM. ATC is a service provided by ground-based controllers for directing the aircraft, and the purpose of ATC is to prevent the aircraft from collisions, to organize and control the flow of air traffic, and to provide traffic information to the pilots. Therefore, ATC is an essential and most important part of ATM and needs accurate aircraft position information in order to provide support for aircraft safety.

Among the various CNS/ATM fields, the surveillance field, which includes the automatic dependent surveillance – broadcast (ADS-B) system and the Multilateration (MLAT) system, is implemented using satellite and digital communications technology. These next-generation systems provide superior performance than conventional systems such as radar. However, they still incur position error.

The ADS-B system is designed to ease air traffic management (ATM), improving safety and increasing air traffic capacity [1]. In the air, the information provided by the ADS-B system enhances the pilots' situational awareness, allowing optimal flight levels and fuel savings [2]. The ADS-B system uses a combination of a global navigation satellite system (GNSS), transmitters, and receivers to provide both aircraft and ground controllers with very specific information about the position and speed of the aircraft. Unlike radar, the ADS-B system can be used at low altitudes and ground level in order to monitor ground vehicles, taxiways and runways. The ADS-B system is also effective in areas where there is no radar or where radar coverage is limited.

The MLAT system is a surveillance system using the signals transmitted by aircraft in order to calculate the position of the aircraft [3]. The MLAT system uses aircraft transmission systems such as Mode A/C/S, and thus, requires no additional equipment in the airborne infrastructure [4]. The basic principle of the MLAT system is time difference of arrival (TDOA) [5]. TDOA determines the aircraft's position from four receivers using received signals.

In this paper, we propose a novel information fusion method called the reweighted convex combination method, which is designed for next-generation systems such as ADS-B and MLAT. The convex combination method is widely used for information fusion. The reweighted convex combination method further improves aircraft tracking performance compared to the convex combination method by readjusting the weights given to each system.

The rest of this paper is organized as follows. Section 2 discusses background on ADS-B, MLAT, and multisensor fusion method. Section 3 introduces the reweighted convex combination method. Section 4 presents the performance analysis results of the proposed method. Finally, Section 5 discusses the results of this research and presents questions on further research.

Ⅱ. Air surveillance systems and fusion method

2-1 ADS-B

ADS-B is a replacement for traditional radar-based surveillance of aircraft. It has brought major change in surveillance systems, by which, instead of using ground-based radar for aircraft surveillance, the aircraft will detect its own position and automatically broadcast its position information. It is a function on the aircraft or a surface vehicle that periodically broadcasts its horizontal and vertical positions. It provides support for improved use of airspace, reduced visibility restrictions, improved surface surveillance, and enhanced safety such as collision management.

Under ADS-B, the aircraft periodically broadcasts its own position and other information without its knowledge and without expecting an acknowledgement or reply. ADS-B is automatic in the sense that no pilot or controller action is required for broadcasting the information. Therefore, it is surveillance dependent.

Eventually, ADS-B is a next-generation aircraft surveillance system that will supplant and complement the conventional radar, since conventional ATM such as radar systems will reach their limits soon owing to the increases in air traffic. According to recent studies, ADS-B achieves a position accuracy of 30~35 m [6]. Although ADS-B achieves aircraft position accuracy efficiently, it includes errors from the global navigation satellite system (GNSS) because the position information of the aircraft relies on the GNSS [7].

2-2 MLAT

Multilateration(MLAT) is a surveillance system that makes use of the signals transmitted by the aircraft to calculate its position [8]. It uses aircraft transmission systems such as Mode A, Mode C, and Mode S transponders, thus requiring no changes to the airborne infrastructure. MLAT is very useful when the installation of conventional radar is difficult or there are blind areas of aircraft surveillance.

The basic principle of MLAT is the use of a hyperbolic curve and determination of the hyperbolic position, as shown in Fig. 1. These measurements use the time difference of arrival (TDOA) of the received signals from the four receivers. [9]. The aircraft position error of MLAT is 6~10 m.

The distance between each receiver and the target aircraft is calculated as follows:

$$D_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} \tag{1}$$

where (x_i, y_i, z_i) denotes the location of each receiver; i is the number of receivers; and (x, y, z) is the position of the aircraft. If a particular receiver is set as the origin, the distance between that receiver and the aircraft is:

$$D_4 = \sqrt{x^2 + y^2 + z^2} \tag{2}$$

Thus, with four receivers, the three-dimensional coordinates (x, y, z) can be determined.

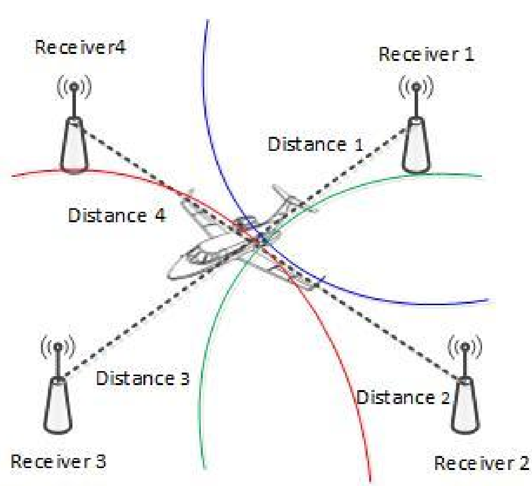

그림 1. MLAT의 거리 계산
Fig. 1. Distance calculation of MLAT.

MLAT is only used near airport due to its error. However, same techniques are being used for air-route. Such systems are wide-area multilateration (WAM) systems [10-11]. WAM installations provide superior range over secondary radar, more accurate tracking, significantly lower costs, and significantly earlier operational readiness following contract award. Some countries have chosen WAM as a replacement for their existing secondary radar because cost and performance analyses have shown clear advantages for WAM [12].

2-3 Multisensor fusion method

A Multisensor fusion method has been used in various fields [13]. An information fusion method is used for multisensor tracking of multiple targets [14]. The centralized information fusion method fuses measurements from all sensors in a central processor, but the decentralized information fusion method fuses only track estimates and covariance [15]. Therefore, the centralized information fusion method is more accurate and reliable than the decentralized information fusion method. However, the centralized information fusion method demands greater computational resources in the central processor than the decentralized information fusion method. Thus, although the centralized information fusion method has better performance, the decentralized information fusion method is widely used. The centralized information fusion method includes a measurement fusion method. Decentralized information fusion includes a convex combination and a Bar-shalom/Campo method.

Ⅲ. reweighted convex combination method

In this paper, we propose an information fusion method called the reweighted convex combination method, which is an improved version of the convex combination method.

First, we used is a Robust Interacting Multiple Model filter, called Robust IMM filter, that improves IMM filter as the subfilter [16]. The Robust IMM filter can not only improves the aircraft tracking performance but also track aircraft continually using estimates calculated from the filter when data losses occur. We created three models of aircraft movements to apply the Robust IMM filter to each sensor: uniform motion, accelerated motion, and rotational motion models. The first model assumes a constant speed, the second model, accelerated motion, and the third model, following a circle at a constant speed. These results are applied to the fusion filter.

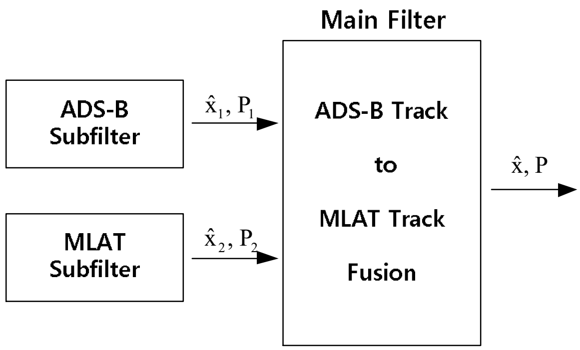

그림 2. 제안된 기법의 흐름도
Fig. 2. The flowchart of the proposed method.

The reweighted convex combination method for combining the ADS-B and MLAT data is proposed as the main filter. Both the conventional convex combination method and the reweighted convex combination method are decentralized information fusion methods and give weight to data from sensors, although the reweighted convex combination method gives more weight to more precise sensors. When a subfilter receives sensor readings, it calculates and passes an estimated value $\hat{x}_N$ and a covariance P_N to a main filter, as shown in Fig. 2. The main filter calculates the final estimated value and the covariance.

We can obtain the final results of the conventional convex combination method with equation (3) and equation (4). Since a small covariance value means that an estimated value is precise, multiplying the estimated value by a reciprocal of the covariance means that more weight is given to the more precise value.

$$\hat{x} = P[P_1^{-1}\hat{x}_1 + P_2^{-1}\hat{x}_2] \tag{3}$$

$$P = [P_1^{-1} + P_2^{-1}]^{-1} \tag{4}$$

However, we use equation (5) and equation (6) to obtain the final estimated value and the covariance of the reweighted convex combination method, since it gives more weight to more precise sensors.

$$\hat{x} = P[(w_1P_1)^{-1}\hat{x}_1 + (w_2P_2)^{-1}\hat{x}_2] \tag{5}$$

$$P = [(w_1P_1)^{-1} + (w_2P_2)^{-1}]^{-1} \tag{6}$$

Though ω_1 and ω_2 could be constants, adjusting ω_1 and ω_2 according to P_1 and P_2 could lead to more precise results. In this paper, we set ω_1 and ω_2 with equation (7) to achieve optimal fusion results.

$$w_1 = P_1P_2^{-1}, \quad w_2 = P_2P_1^{-1} \tag{7}$$

With the values from equation (7), we can enhance the performance of the system because it can maintain a small covariance. From the above, we have the following lemma.

LEMMA 1. Let $w_1 = P_1P_2^{-1}$, $w_2 = P_2P_1^{-1}$. Here, we always have $(P_1^{-1} + P_2^{-1})^{-1} > [(w_1P_1)^{-1} + (w_2P_2)^{-1}]^{-1}$. Since the covariance of the reweighted convex combination method is always smaller than the covariance of the convex combination method, the reweighted convex combination method provides better performance than the convex combination method.

PROOF. $(P_1^{-1} + P_2^{-1})^{-1} > [(w_1P_1)^{-1} + (w_2P_2)^{-1}]^{-1}$

$$\Rightarrow P_1^{-1} + P_2^{-1} < (w_1P_1)^{-1} + (w_2P_2)^{-1}$$

$$\Rightarrow P_1^{-1} + P_2^{-1} < (P_2^{-1}P_1P_1)^{-1} + (P_1^{-1}P_2P_2)^{-1}$$

$$\Rightarrow P_1^{-1} + P_2^{-1} < P_2(P_1^{-1})^2 + P_1(P_2^{-1})^2$$

$$\Rightarrow (P_1 + P_2)(P_1P_2)^{-1} < (P_1^3 + P_2^3)(P_1^{-1}P_2^{-1})^2$$

$$\Rightarrow (P_1 + P_2)(P_1P_2)^{-1} < (P_1 + P_2)(P_1^2 - P_1P_2 + P_2^2)(P_1^{-1}P_2^{-1})^2$$

$$\Rightarrow 1 < (P_1^2 - P_1P_2 + P_2^2)(P_1^{-1}P_2^{-1})$$

$$\Rightarrow P_1P_2 < P_1^2 - P_1P_2 + P_2^2$$

$$\Rightarrow P_1^2 - 2P_1P_2 + P_2^2 > 0$$

$$\Rightarrow (P_1 - P_2)^2 > 0, \quad P_1 \neq P_2$$

Thus, LEMMA 1 is always valid.

Ⅳ. Performance Evaluation

Performance evaluation was conducted by using MATLAB. The trajectories of the aircraft are virtual sensor data generated for aircraft maneuvers. We compare the final value, which is obtained by the reweighted convex combination method, with the original value of the ADS-B and MLAT systems. All the evaluations were conducted 1000 times using the Monte Carlo method.

The aircraft's true position, ADS-B data, MLAT data and fusion data are shown in Fig. 2. The trajectories consist of eight segments: acceleration motion with constant acceleration → deceleration motion with constant acceleration → left turn with constant velocity → uniform motion with constant velocity → right turn with constant velocity → acceleration motion with constant acceleration → deceleration motion with constant acceleration → uniform motion with constant velocity. Each segment lasts 10 s, and the position information of the aircraft is obtained every 1 s from ADS-B and MLAT.

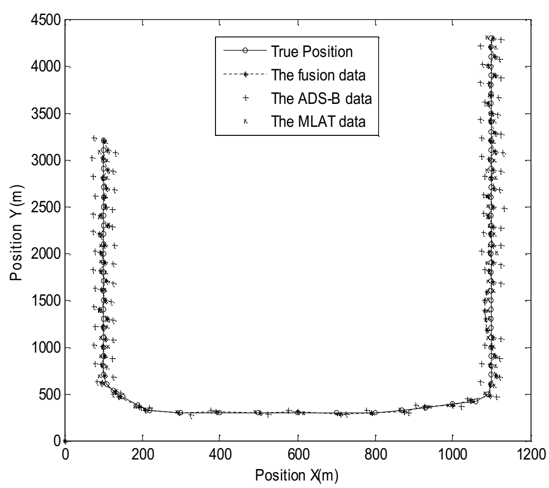

그림 3. ADS-B와 MLAT의 항공기 궤적
Fig. 3. The aircraft trajectories from ADS-B and MLAT.

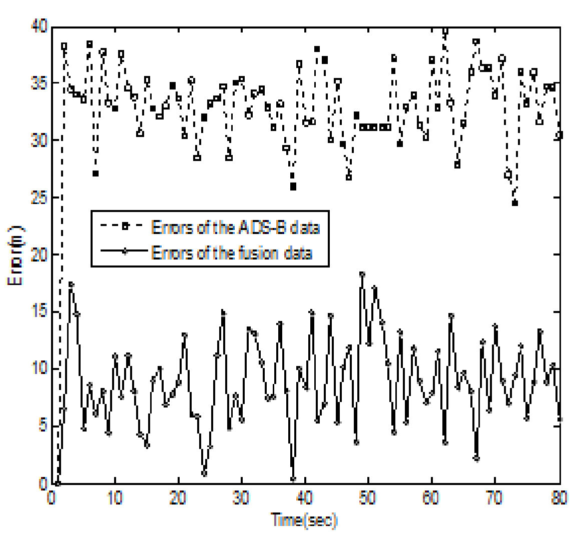

그림 4. ADS-B 데이터와 융합 데이터의 오차
Fig. 4. The error in ADS-B data and fusion data.

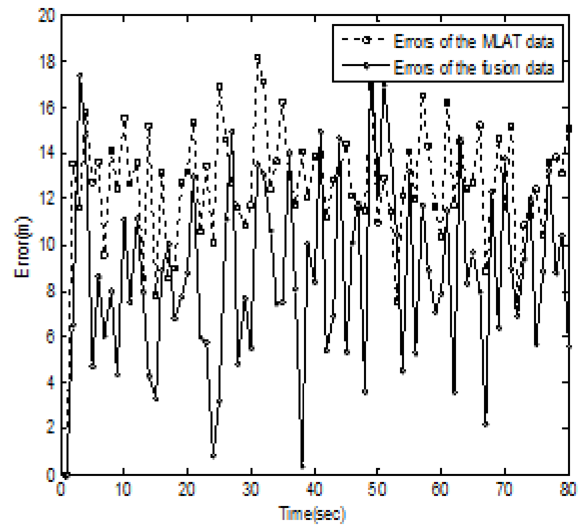

그림 5. MLAT 데이터와 융합 데이터의 오차
Fig. 5. The error in MLAT data and fusion data.

표 1. 시뮬레이션 결과 요약
Table 1. A summary of the simulation results.

-	Position error (m)
ADS-B	32.78
MLAT	12.65
Convex Combination	10.86
reweighted Convex Combination	8.85
-	Performance improvement (%)
ADS-B	73.00
MLAT	30.03
Convex Combination	18.50

Fig. 3 shows the error between the true position and that obtained from the ADS-B data. It also shows the error between the true position and that obtained from the proposed method. In addition, Fig. 4 shows the error between the true position and that obtained from MLAT data. As seen in the figures, the information fusion data using the reweighted convex combination method has less error than the original ADS-B data and MLAT data. Table 1 shows a summary of the simulation results.

Ⅴ. Conclusion

The ADS-B system and the MLAT system are implemented using satellite and digital communications technology. These systems provide better performance than radar, but still have error. To reduce the error, we suggest what we call the reweighted convex combination method, which improves the convex combination method for the ADS-B and MLAT systems. The reweighted convex combination method further improves aircraft tracking performance compared to the convex combination method by readjusting the weight given by each system. The performance from the fusion of ADS-B and MLAT is improved an average of 51.51 % when compared to the original data.

The proposed method can be very useful in CNS/ATM, since it can improve the aircraft tracking performance. And as a consequence, providing increased airspace efficiency and capacity with reduced separation distance, and enhancing safety by providing stabilized approach and departure path. Future research will focus on optimizing the proposed method to each system and expanding the research to actual ADS-B and MLAT data generated by airports that operate these systems.

Acknowledgments

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조 태 환(Taehwan Cho)
2001년 2월 : 인하대학교 항공우주공학과 (공학사)
2014년 2월 : 인하대학교 전자공학과 (공학박사)
2014년 12월 ~ 현재 : 공군사관학교 전자통신공학과 조교수
※ 관심분야 : 항공전자 시스템, 항공통신

오 세 명(Semyoung Oh)
2007년 3월 : 공군사관학교 전자공학과 (공학사)
2011년 5월 : 위스콘신대학교 전기공학과 (이학석사)
2016년 1월 ~ 현재 : 공군사관학교 전자통신공학과 조교수
※ 관심분야 : 무선통신, 안테나

이 길 영(Gil-Young Lee)
1997년 3월 : 공군사관학교 전자공학과 (공학사)
2004년 2월 : 서울대학교 전기컴퓨터공학부 (공학석사)
2012년 3월 : 미국 오하이오주립대학교 전기컴퓨터공학부 (공학박사)
2005년 2월 : 공군사관학교 전자통신공학과 전임강사
2007년 6월 ~ 현재 : 공군사관학교 전자통신공학과 교수
※ 관심분야 : 항공전자 시스템, 레이더 시스템, 전자전 시스템, 안테나 설계 및 측정, 전파환경 분석