３．SWIMのコンセプトによる監視情報ドメイン構築に関する検討

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1. INTRODUCTION

With the rapid increase in local and global air traffic, the system-wide operational information exchange and life-cycle management technologies are required to improve the capacity, safety and efficiency of Air Traffic Management (ATM). However, today's ATM system comprises a wide variety of applications with their own communication protocols, interfaces and self-contained information systems. Therefore, this point-to-point communication is difficult to upgrade with new technologies, information exchange is not globally harmonized, and information security is poor.

The System Wide Information Management (SWIM) concept is to change the conventional ATM information architecture from point-to-point data exchanges to system-wide interoperability, and to achieve life-cycle management of data, information, and service. The SWIM concept provide not only system architecture for the delivery of information services to support meeting the expectations of the ATM community in different key performance areas, but also a common understanding of different information domains. Therefore, implementation of the SWIM concept must address the challenge of creating an interoperability environment which allows the SWIM IT systems to cope with the full complexity of operational information exchanges [1][2].

The research and development of SWIM concepts and solutions has been undertaken in different countries. ATM modernization programs such as Next Generation Air Transportation System (NextGen) [3][4] in the United States and Single European Sky ATM Research (SESAR) [5][6] in Europe both consider the implementation of SWIM as a fundamental element for future ATM systems. Moreover, the International Civil Aviation Organization (ICAO) has made efforts to promote the SWIM concept and establish the communication and information standards.

The main objective of SWIM is not only to achieve seamless integration among geographically distributed and heterogeneous systems in the air transportation field but also to enable seamless information sharing among the multiple stakeholders in the ATM domain. Therefore, how to use the information from different domains systematically and efficiently to improve the performance of current systems should be considered.

The most traditional aircraft surveillance systems are operated independently and it is difficult to get the flight and flow information previously. Therefore, the tracking model does not perform well during the flight mode changes dynamically. Recently, the Required Navigation Performance (RNP) has been implemented in many airports in Japan to optimize the air route configuration and to enable a smaller midair separation standard to safely accommodate high-density air traffic. Moreover, the Flight Plan with 4 Dimension Trajectory (4DT) information will be applied from 2020 according to the operational concepts outlined in Flight and Flow Information for a Collaborative Environment (FF-ICE) [7]. In this paper, to improve aircraft tracking accuracy, the SWIM concept based surveillance information domain construction is discussed. By incorporating the air routes, waypoints and other related information into the aircraft model, the method to describe the aircraft with changing flight modes and model the flight mode switches accurately is proposed. And the performance of the proposed method is evaluated with real air traffic data.

This paper is structured as follows. The next section describes the relationship between information exchange services, information exchange models and information domains in SWIM. In section 3, the SWIM concept based surveillance information domain construction to improve aircraft tracking accuracy is presented. The results of computer simulations are shown and discussed in section 4, and the paper is concluded in section 5.

2. SWIM AND INFORMATION DOMAINS

SWIM consists of standards, infrastructure and governance enabling the management of ATM related information and its exchange between qualified parties via interoperable services. The scope of SWIM includes information exchange services, information exchange models and the infrastructure required to exchange information between SWIM-enabled applications [2].

2.1 Information Exchange Models

Information exchange models are desirable when information is provided by a large number of different participants and made available to a wide range of ATM information consumers. To permit interoperability, the information needs to be clearly and unambiguously defined and well understood. In other words, there is a need for semantic interoperability. This requires a detailed definition of the information both at the conceptual level and at the level of the data that is exchanged between systems.
Several exchange modes have been defined for the following domains of ATM operations: meteorological information (WXXM), aeronautical information (AIXM), flight and flow information (FIXM), and surveillance information (ASTERIX). In addition, it is possible for other communities of interest to develop exchange models such as is the case for the industry requirements for aerodrome mapping, terrain and obstacle information involving organizations such as RTCA (Radio Technical Commission for Aeronautics), EUROCAE (European Organization for Civil Aviation Equipment) and ARINC (Aeronautical Radio, Incorporated).

2.2 Information Domains

An information domain is focused on identifying,

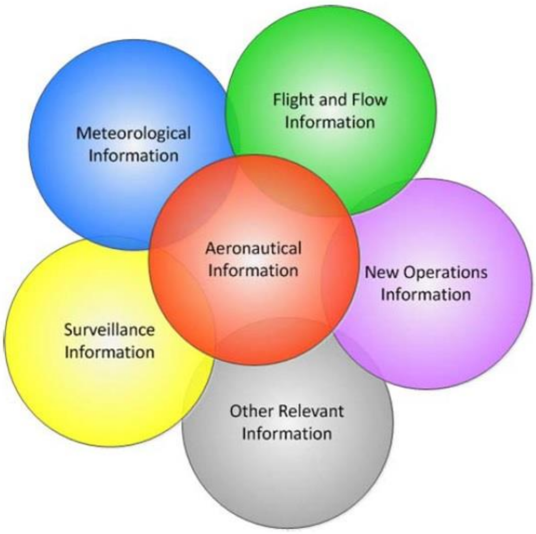


Figure 1: ICAO identified Information Domains

defining, and satisfying the information needs of the set of business activities associated with a specific area. The concept of information domains can be used to manage the definition of exchange models as smaller and more manageable units. The initial information domains were identified informally based on the major service exchanges that were already in use (pre-SWIM). In Figure 1, several ICAO identified information domains are shown. Individual States or organizations may choose to define other domains for their own region.

Current information domains are related to the current subdivision of identified activities. Users however see the information in a more interrelated way than it is in its current information domain state. Hence, within each solution space there is a tendency for users to expect seamless and interoperable information which can be fused. The concept of progressively achieving a seamless information space, supported by exchange models related to information domains within each user context, is realized by SWIM-enabled applications. This means that applications which consume and provide information services may relate to one or more domains, to one or more stakeholders, and to one or more points on the strategic-tactical time axis.

3. INFORMATION SHARING FOR AIRCRAFT SURVEILLANCE

In a traditional aircraft surveillance system, the tracking model does not perform well when the aircraft changes its mode unexpectedly. This difficulty arises because the model on which the filter is based does not accurately represent the behavior of the aircraft over all of its flight regime. The flight mode changes in an aircraft depend on the determined air route in the flight plan that is usually unknown to the surveillance system. The lack of knowledge of the flight information makes the flight-mode changes of an aircraft nondeterministic because they cannot be determined a priori.

The FF-ICE concept has been developed by ICAO to illustrate information for flow management, flight planning, and trajectory management associated with ATM operational components [7]. The flight plan with gate-to-gate 4DT information will be applied and shared among related systems. A gate-to-gate trajectory includes the departure aerodrome, a departure surface segment, an airborne segment, and an arrival surface segment at a destination aerodrome. As shown in Figure 2, the airborne segment is described in terms of airborne elements. Each airborne element describes a path from the last airborne element to the "to-point 4D". This point is expressed using 3D location and time. The airborne element includes airspeed at a change point and the type of change point described by the "to-point". The type of change point (e.g. top-of-climb, speed change) is also described. Constraints can be specified for the airborne element and are applicable at the "to-point". These can be altitude, time, speed, or lateral constraints. An airborne element may require a turn descriptor; in this case, additional information is included to describe the turn, together with a "reference point" describing the point traditionally associated with the route. If the flight is to follow a sequence of airborne elements that are part of a defined route, the "constituent route" will also be included. This can be useful if the route has performance requirements associated with it.

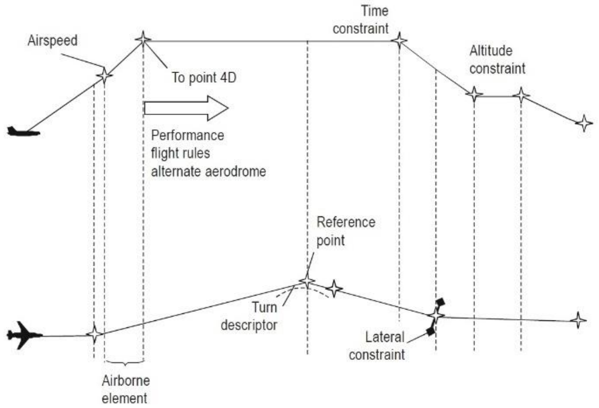


Figure 2: Airborne Segment of 4DT

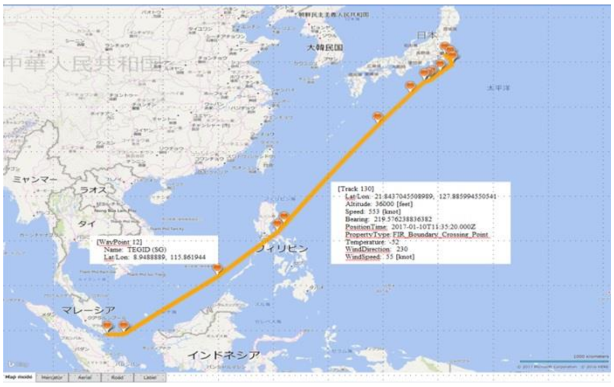


Figure 3: 4D Trajectory

Currently, aircrafts usually follow air routes and change their flight modes to maneuver at waypoints or 4D points whose locations can be extracted from the flight plan and incorporated into the tracking system. According to the information sharing between surveillance information domain and flight and flow information domain, the air routes and waypoints can be extracted from the flight plan and 4D trajectory can be generated by data fusion (Figure 3). In this section, the aircraft models and a method to describe an aircraft's dynamics with changing flight modes are presented.

3.1 Flight Models

The aircraft's state is defined as:

$$\mathrm{x} = [\mathrm{x}\ \dot{\mathrm{x}}\ y\ \dot{y}\ z\ \dot{z}]^T$$

At each time k the aircraft's continuous-state dynamics are described by a difference equation defined in the discrete time:

$$\mathrm{x(k+1) = Fx(k) + Gv(k)}$$

where v is a zero-mean Gaussian white noise used to model accelerations with an appropriate covariance Q, F and G are system metrics with appropriate dimensions, corresponding to each flight mode.

We consider an aircraft whose dynamics can switch between three flight modes: constant velocity (CV), constant descent (CD), and coordinated turn (CT).

(1) CV mode

The discrete-time state equation of constant velocity model is given by:

$$x(k+1) = \begin{bmatrix} 1 & T & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & T & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} x(k) + \begin{bmatrix} \frac{T^2}{2} & 0 & 0 \\ T & 0 & 0 \\ 0 & \frac{T^2}{2} & 0 \\ 0 & T & 0 \\ 0 & 0 & T \\ 0 & 0 & 0 \end{bmatrix} v(k)$$

where T is the sampling interval.

(2) CD mode

The discrete-time state equation of constant descent model is given by:

$$\mathrm{x(k+1)} = \begin{bmatrix} 1 & T & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & T & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & T \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} x(k) + \begin{bmatrix} \frac{T^2}{2} & 0 & 0 \\ T & 0 & 0 \\ 0 & \frac{T^2}{2} & 0 \\ 0 & T & 0 \\ 0 & 0 & \frac{T^2}{2} \\ 0 & 0 & T \end{bmatrix} v(k)$$

(3) CT mode

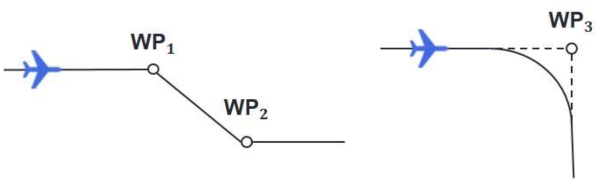
The discrete-time state equation of constant turn model is given by:

$$\mathrm{x(k+1)} = \begin{bmatrix} 1 & \frac{\sin(\omega T)}{\omega} & 0 & -\frac{1-\cos(\omega T)}{\omega} & 0 & 0 \\ 0 & \cos(\omega T) & 0 & -\sin(\omega T) & 0 & 0 \\ 0 & \frac{1-\cos(\omega T)}{\omega} & 1 & \frac{\sin(\omega T)}{\omega} & 0 & 0 \\ 0 & \sin(\omega T) & 0 & \cos(\omega T) & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} x(k) + \begin{bmatrix} \frac{T^2}{2} & 0 & 0 \\ T & 0 & 0 \\ 0 & \frac{T^2}{2} & 0 \\ 0 & T & 0 \\ 0 & 0 & T \\ 0 & 0 & 0 \end{bmatrix} v(k)$$

where ω is the tum rate.

3.2 State Transition Model

Since an aircraft is usually required to follow air



(a) Fly-over mode (b) Fly-by mode

Figure 4: Transition Modes

routes and take maneuvers at given waypoints or 4D points to enter a new segment of the air routes. If an aircraft's flight mode changes to mode j from mode i when it crosses a certain waypoint (denoted by WP_n, n =1,…,N), the flight mode transitions can be described as: (WP_n, M_{ij}). In this paper, we consider two kinds of waypoints, fly-over waypoints and fly-by waypoints (Figure 4).

(1) Fly-over waypoints

Consider a landing aircraft in the local navigation frame. The aircraft flies through a series of fly-over waypoints, and its flight mode switches between the CV and CD modes when it crosses the fly-over waypoints. Let mode 1 be the CV mode and mode 2 be the CD mode. As shown in Figure 4 (a), the transition from mode 1 to mode 2 at WP_1 can be written as: (WP_1, M_{12}).

(2) Fly-by waypoints

Consider a fly-by waypoint connecting two segments of an air route. The aircraft usually enter

CT flight mode before they reach the fly-by waypoint, then enter the CV flight mode when their headings are aligned with the direction of the next segment of the route. Let mode 1 be the CV mode and mode 3 be the CT mode. As shown in Figure 4 (b), the transition from mode 1 to mode 3 at WP_3 can be written as: (WP_3, M_{13}).

3.3. Hybrid Estimation

The proposed method is inspired by the Interacting Multiple Model (IMM) estimator, which is a suboptimal hybrid filter [8, 9]. However, unlike the IMM algorithm which assumes that the discrete transitions are governed by a time-homogeneous Markov chain, the proposed method uses the state transition model to compute the transition probabilities, which integrate the prior information about the state transition model to hybrid estimation.

If at time k, an aircraft's flight mode changes from mode i to mode j (i, j=1, 2, 3) at WP_n, the mode transition probabilities can be computed as:

$$if\ (|x(k) - WP_n| < e_n\ \&\ i \neq j), then$$
$$if\ j = 1, then\ \mu_1(k+1) = P_1 P P_1^T$$
$$if\ j = 2, then\ \mu_2(k+1) = P_2 P P_2^T$$
$$if\ j = 3, then\ \mu_3(k+1) = P_3 P P_3^T$$

where $x(k)$ is measurement position at time k, e_n is uncertainty error at waypoint n, $\mu_1(k+1)$, $\mu_2(k+1)$ and $\mu_3(k+1)$ are mode probabilities for CV model, CD model and CT model at time $k+1$ respectively. P is the mode transition probability matrix, and P_1, P_2 and P_3 are the transition matrixes for CV model, CD model and CT model, given by:

$$P_1 = [1 \quad 0 \quad 0], P_2 = [0 \quad 1 \quad 0], P_3 = [0 \quad 0 \quad 1]$$

Due to various uncertainties, the flight mode changes usually happen around but not exactly at the waypoints. The uncertainty error at a given waypoint can be parameterized based on two kinds of air traffic data: past trajectory records around a given point or the required navigation performance (RNP) of a given aircraft. Which kind of data should be used depends on the natures of available data.

4. EVALUATION

In this section, the proposed method is tested through a 3-dimensional landing aircraft tracking scenario. The aircraft has three flight modes: CV, mode 1; CD, mode 2; and CT, mode 3. The aircraft is initially in the CV mode and crosses one waypoint and switches its flight mode to CT. Then it crosses another waypoint and switches its flight mode to CD successively. The aircraft dynamics corresponding to the three flight modes. With the information about the waypoints, the proposed method is used to describe the flight mode transitions of the aircraft.

Figure 5 shows simulated aircraft trajectories. The simulated trajectories are generated based on the real flight trajectories and measurement data.

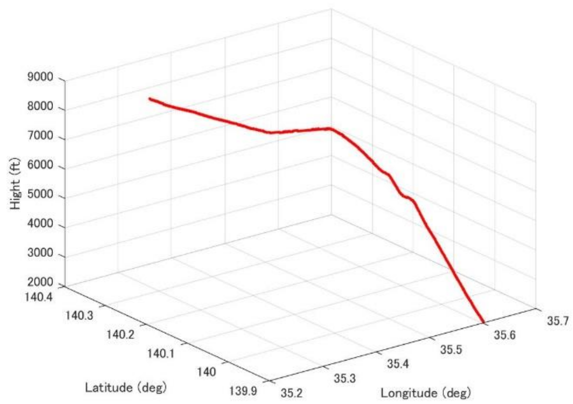


Figure 5: Simulated Aircraft Trajectory

Table 1. Parameters

Model	Process Noise	Measurement Noise (m)
Constant velocity	0.01g	30
Constant descent	g	30
Coordinated turn	0.1g	30

4.1 Parameters

The performance of proposed method is compared with conventional IMM estimator on the real ADS-B (Automatic Dependent Surveillance - Broadcast) measurement data. To obtain the best possible results, the system has to be properly designed to meet the special requirements of the particular sensor. Based on the preliminary study, the design parameters are given in Table 1.

The model transition probabilities for IMM filter is designed as follows [10]:

$$P = \begin{bmatrix} 0.95 & 0.025 & 0.025 \\ 0.025 & 0.95 & 0.025 \\ 0.025 & 0.025 & 0.95 \end{bmatrix}$$

4.2 Results

The performance of the proposed algorithm is compared with the standard IMM estimator through a Monte Carlo simulation. Since the proposed method can use flight information to accurately estimate the current flight mode, it provides better state estimates

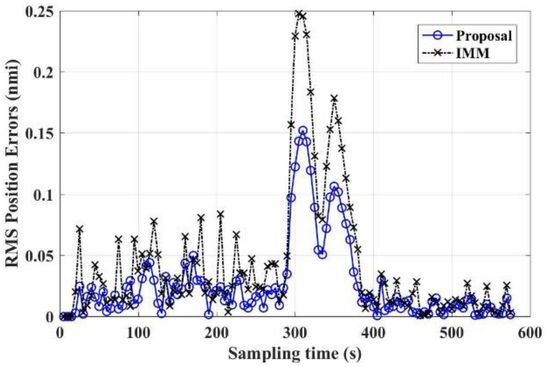


Figure 6. RMS Prediction Errors

than the IMM algorithm which cannot incorporate the prior information of flight mode transitions. The results shown in Figure 6 reveal that the proposed system permits to significantly leverage prediction errors through maneuvers during the turn mode. The average improvement of the prediction error is about 40% compared with the standard IMM estimator.

5. CONCLUSIONS

The SWIM concept is not only to achieve seamless integration among geographically distributed and heterogeneous systems in the air transportation field but also to enable seamless information sharing among the multiple systems in different information domains. In this paper, the relationship between information exchange models and information domains are described. Moreover, the SWIM concept based surveillance information domain construction to improve aircraft tracking accuracy is discussed. By incorporating the flight information into the aircraft model, the method to describe the flight mode transitions of the aircraft is proposed. From the obtained results, the performance of proposed method is confirmed and the effectiveness for tracking system is shown. Compared with the standard IMM estimator, the proposed method significantly reduces the prediction error through maneuvers. For satisfying the desired level of accuracy, the further analysis of uncertainty error under the dynamic changing situation is required.

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