３．DAPs を用いた高精度追尾技術に関する研究

監視通信領域　※呂　暁東，古賀　禎

1. INTRODUCTION

In response to the rapid increase in air traffic demands, the more accurate and reliable tracking systems for aircraft surveillance are required to improve the capacity, safety and efficiency of air traffic control (ATC) services. With the advancement of the sensor and communication technologies, the extensive deployment of air-to-ground data links leads to the emergence of complementary means for the aircraft tracking system.

As a considered part of the basis of the surveillance infrastructure, Secondary Surveillance Radar (SSR) Mode S has been widely utilized. There are two possible configurations for the Mode S radar, the first one is called the Mode S Elementary Surveillance (ELS) and the other one is the Mode S Enhanced Surveillance (EHS) [1]. Each aircraft is assigned one unique ICAO 24-bit address by the State Registration Authority [2]. This address is the one used for selective interrogation, which permits the obtaining of the flight ID and the altitude in 25 feet steps. The Mode S EHS consists of ELS supplemented by the extraction of downlink aircraft parameters (DAPs) which can be used to improve the performance of current tracking systems. In [3], Roll-Angle is used to assist trackers during maneuvers to improve accuracies during straight-line flight. And in [4], the DAPs information is applied to calculate the control noise of the Kalman filter.

The Interacting Multiple Model (IMM) estimator is a suboptimal hybrid filter that was shown to achieve an excellent compromise between performance and complexity [5, 6]. However, it is difficult to estimate precisely the aircraft state when the target has the maneuvering motion since the detection of maneuvers is often delayed by the response of Kalman filters. In this paper, to improve the accuracy, the DAPs based IMM tracking system is proposed. The system consists of an IMM filter with 3 different models and a maneuver detector which is able to dynamically revise the mode probabilities in real time according to the different motions of aircrafts by using DAPs information. Moreover, as the availability and certification of DAPs cannot be guaranteed, the system with two tracking functions, the EHS based one and the usual one, is also implemented.

The paper is structured as follows. In the next section, the Mode S and DAPs concept are described. In section 3, the DAPs based IMM tracking system is presented. The results of computer simulations and practical experiments are shown and discussed in section 4, and the paper is concluded in section 5.

2. MODE S EHS

The SSR Mode S includes two elements: an interrogative ground station (GS) and a transponder on board of the aircraft. Each GS has its own interrogation code which permits the configuration of the target answers, as they know who is interrogating them. Currently, most of Mode S radars are using the multisite surveillance protocol [7].

The Mode S radar has the elementary surveillance and the enhanced surveillance modes. The differences between them fall on uplink and also downlink data transmissions. The data items sent by a Mode S ELS are the following ones:

- ICAO 24-bit address
- Data-link capability reporting
- Common usage airborne parameter register capability reporting
- Aircraft identification reporting

Table 1. Characteristics of DAPs

DAPs	Units	Update Rate	Precision	Range
Roll Angle	degrees	1s	45/256	[-90, +90]
True Track Angle	degrees	90/512	1s	[-180, +180]
Ground Speed	knots	1s	2	[0, 2046]
Track Angle Rate	degrees	1s	8/256	[-16, +16]
True Air Speed	knots	1s	32	[0, 2046]
Barometric Altitude Rate	feet/min	1s	32	[-16384, +16352]

- Mode 3/A code reporting
- Mode S pressure altitude reporting
- Special position identification reporting/Flight status reporting

From a tracking point of view, the most important aspect of ELS is the height measurement improvement (measured in 25 feet steps), which allows a better vertical tracking.

Mode S EHS delivers further information. Thus, an aircraft can send to the ground station several aircraft registers or BDS with flight information. The decision of what BDSs are sent depends on the local configuration and also on the ATC Authority. The ones that seem to be more useful from an Air Traffic Control point of view are:

BDS 4.0:
- Selected Altitude

BDS 5.0:
- Roll Angle
- Track Angle Rate (or True Airspeed)
- True Track Angle
- Ground Speed

BDS 6.0:
- Magnetic Heading
- Indicated Airspeed or Mach Number
- Vertical Rate
- True Airspeed (if Track Angle Rate is not available)

For the tracking function, the useful parameters are the vector state DAPs, which tell the ground station what movement the aircraft is performing in that moment. Even though, not all of them are useful for the tracking function. As our task is to track aircraft in a ground-fixed coordinate system, the most suitable DAPs are the ones referred to the ground system (BDS 5.0). Four parameters are directly related to the ground based tracking system: Track Angle Rate, True Track Angle, Ground Speed and Roll Angle

The characteristics of the DAPs considered for the tracking function are given in Table 1. The update rate in Table 1 is the refresh time of DAPs data in the aircraft registers. Regarding error analysis, it has been found two main error sources: one related to the quantification performed before sending the chosen DAPs through the Mode S downlink and the other to a delay due to update rates [8].

3. DAPS BASED IMM TRACKING SYSTEM

Safe and effective operation of the ATC relies on accurate and timely airspace situational awareness supported by surveillance systems. However, there are at least two problems that should be considered for designing the DAPs based tracking system. One is that DAPs are not always available, even if the aircraft has the ability to send them. This depends on the channel congestion and on the ATC Authority. Thus, it is difficult to guarantee that the DAPs data can be continuously processed. The other problem is the reception of corrupted or erroneous DAPs, which is even more dangerous than the former. Since, it can easily lead to wrong predictions and consequently to wrong estimates. Therefore, one appropriate approach is to construct a tracking system taking ELS data as primary, and EHS data as complementary.

3.1 Motion Models

The models in the horizontal and vertical are treated separately, due to the fact that the target motions in horizontal plane and vertical plane are comparatively independent. The motion models used in the IMM filter are defined in this section. The uniform motion can be described by a second-order kinematic (constant velocity) model. The maneuver motion can be described by a third-order kinematic (constant acceleration) model and a coordinated turn model.

3.1.1 Constant Velocity Model

The state vector corresponding to the constant velocity model is defined as:

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

with x and y denoting the orthogonal coordinates of the horizontal plane. And the discrete-time state equation is given by:

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

where T is the sampling interval, and ν is a zero-mean Gaussian white noise used to model accelerations with an appropriate covariance Q, which is a design parameter.

3.1.2 Constant Acceleration Model

The state vector corresponding to the constant acceleration model is defined as:

$$x = [x\, \dot{x}\, \ddot{x}\, y\, \dot{y}\, \ddot{y}]^T$$

The state equation is given by:

$$x(k) = Fx(k-1) + Gv(k-1)$$

where

$$F = \begin{bmatrix} 1 & T & 0 & 0 & \frac{T^2}{2} & 0 \\ 0 & 1 & 0 & 0 & T & 0 \\ 0 & 0 & 1 & T & 0 & \frac{T^2}{2} \\ 0 & 0 & 0 & 1 & 0 & T \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad G = \begin{bmatrix} \frac{T^2}{4} & 0 \\ \frac{T}{2} & 0 \\ 0 & \frac{T^2}{4} \\ 0 & \frac{T}{2} \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$$

3.1.3 Coordinated Turn Model

A coordinated turn is a turn with a constant turn rate (rate of angle change) and a constant speed. Although the actual turning of a civilian aircraft is not exactly coordinated since the ground speed is the airspeed plus the wind speed, the kinematic behavior of the aircraft during the turn is suitably described by the coordinated turn model plus a fairly small noise representing the modeling error. This will be referred to as the nearly coordinated turn model in the sequel. Such a model is necessarily a nonlinear one if the turn rate is not a known constant. The state vector corresponding to this model is

$$x = [x\, \dot{x}\, y\, \dot{y}\, \omega]^T$$

where ω is the tum rate. The coordinated tum model is then given by:

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

Note that the process noise ν has in general different noise statistics to reflect different modeling errors.

3.2 System Architecture

(1) Data Field

Figure 1 represents the adaptive tracking system architecture which consists of Mode S Radar, Tracker, DAPs Monitor and Position Monitor. The nodes in the system are connected through Data Field (DF) that serves as a communication medium of coordination between the nodes. It can be a Local Area Network (LAN) or LANs connected by Wide Area Network (WAN). All necessary data is broadcast into the DF, where the data logically circulates in the DF.

(2) Radar and Monitors

Mode S Radar gets targets' information from its own surveillance area. Then it sends the target report message which contains the position, identification number, time and DAPs information to the DF.

DAPs Monitor stores the DAPs information of each aircraft, and shows the values of each parameters of the selected aircraft in the figures. Position Monitor displays and updates the measurement, smoothing and predicted positions of each aircraft.

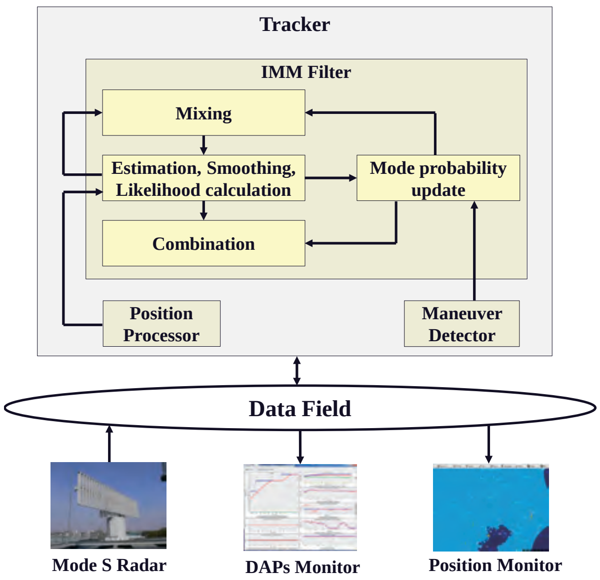

Figure 1: System Architecture

(3) Tracker

Tracker is composed of Position Processor, Maneuver Detector and IMM Filter. Position Processor is in charge of storing and updating the position information of aircrafts. After receiving a target report message, the processor extracts the aircraft position information, and converts it from local radar coordinates (Rang, Azimuth and Flight Level) to geodetic coordinates (Latitude, Longitude and Altitude).

Maneuver Detector is responsible for extracting and storing DAPs information from the target report message. And based on this information, it detects the motion model changes of aircraft. The equations of detection are as follow:

$$C_v = V_{gs}(k) - V_{gs}(k-1)$$

$$C_a = R(k-1) \cdot W(k-1)$$

where $V_{gs}(k)$ is ground speed at time k, $R(k\text{-}1)$ is roll angle at time $k\text{-}1$, and $W(k\text{-}1)$ is track angle rate at time $k\text{-}1$. If the Track Angle Rate is not available, we can calculate the angular velocity which is related to the Roll Angle and True Air Speed by following expression:

$$W(k-1) = g \cdot \frac{\tan(R(k-1))}{V_{tas}(k-1)}$$

where g is the acceleration due to gravity and $V_{tas}(k\text{-}1)$ is true airspeed at time $k\text{-}1$.

One computational cycle of IMM filter consists of four major steps: interaction (mixing), filtering, probability update, and combination. At each time, the initial condition for the filter matched to a certain mode is obtained by mixing the state estimates of all filters at the previous time under the assumption that this particular mode is in effect at the current time. This is followed by a regular filtering (prediction and update) step, performed in parallel for each mode. Then, the mixing and model probabilities are updated by using the likelihood function. Finally a combination (weighted sum) of the updated state estimates of all filters yields the state estimate. The probability of a mode being in effect plays a key role in the weighting of the mixing and the combination of states and covariances.

In the standard IMM filter, the default mode probabilities are used for initialization since it is difficult to predict the motion model of aircraft at the beginning. Therefore, if the default mode probabilities do not match the motion model or the motion model changes during the initial tracking period, the prediction accuracy is degraded. Moreover, during the later tracking period, each mode probability becomes uniform since the difference of residual vectors between modes decreased through mixing process. As a result, if motion model changes during the later tracking period, the prediction error

Table 3. RMS Prediction Errors in Horizontal

Sampling time (sec)	Measurement points	RMS error (nmi)		%Reduction
		Proposal	IMM	
[0, 100)	62	0.0442	0.1006	56.06
[100, 200)	51	0.0657	0.1022	35.69
[200, 300)	49	0.0433	0.1022	57.63
[300, 400)	37	0.0673	0.1331	49.41
[400, 500)	44	0.0432	0.1111	61.09
[500, 600)	48	0.0427	0.0807	47.16
[600, 700)	64	0.0311	0.05	37.73
[700, 800]	57	0.0317	0.0601	47.33

increases because the response of filters is often delayed. To solve this problem, based on the DAPs information, the predictions of each mode probability during the initial tracking period are presented below:

if ($C_a \neq 0$), then

$$\mu_1(k) = \min\{\mu_1(k-1), \mu_2(k-1), \mu_3(k-1)\}$$
$$\mu_2(k) = \mathrm{mid}\{\mu_1(k-1), \mu_2(k-1), \mu_3(k-1)\}$$
$$\mu_3(k) = \max\{\mu_1(k-1), \mu_2(k-1), \mu_3(k-1)\}$$

if ($C_a = 0 \,\&\, C_v \neq 0$), then

$$\mu_1(k) = \mathrm{mid}\{\mu_1(k-1), \mu_2(k-1), \mu_3(k-1)\}$$
$$\mu_2(k) = \max\{\mu_1(k-1), \mu_2(k-1), \mu_3(k-1)\}$$
$$\mu_3(k) = \min\{\mu_1(k-1), \mu_2(k-1), \mu_3(k-1)\}$$

where $\mu_1(k\text{-}1)$, $\mu_2(k\text{-}1)$ and $\mu_3(k\text{-}1)$ are mode probabilities for constant velocity model, constant acceleration model and coordinated turn model at time *k-1* respectively.

In addition, during later tracking period, since each mode probability becomes uniform they can be revised as follows:

if ($C_a \neq 0 \,\&\, \mu_3(k-1) < 0.5$), then

$$\mu_1(k) = \min\{e_1(k-1), e_2(k-1), e_3(k-1)\} - 0.2$$
$$\mu_2(k) = \mathrm{mid}\{e_1(k-1), e_2(k-1), e_3(k-1)\} - 0.1$$
$$\mu_3(k) = \max\{e_1(k-1), e_2(k-1), e_3(k-1)\} + 0.3$$

if ($C_a = 0 \,\&\, C_v \neq 0 \,\&\, \mu_2(k-1) < 0.5$), then

$$\mu_1(k) = \mathrm{mid}\{e_1(k-1), e_2(k-1), e_3(k-1)\} - 0.1$$
$$\mu_2(k) = \max\{e_1(k-1), e_2(k-1), e_3(k-1)\} + 0.3$$
$$\mu_3(k) = \min\{e_1(k-1), e_2(k-1), e_3(k-1)\} - 0.2$$

where $e_1(k\text{-}1)$, $e_2(k\text{-}1)$, and $e_3(k\text{-}1)$ are prediction error rate in latitude and longitude at time k-1 of each model, which are defined as:

$$\varepsilon_i(k-1) = |x_m(k) - x_p(k-1)| + |y_m(k) - y_p(k-1)|$$

$$e_i(k-1) = \frac{\varepsilon_i(k-1)}{\sum_{i=1} \varepsilon_i(k-1)}$$

where $x_m(k)$ and $y_m(k)$ are measurement position in latitude and longitude at time *k*, and $x_p(k\text{-}1)$ and $y_p(k\text{-}1)$ are prediction position in latitude and longitude at time *k-1*.

4. EVALUATION

4.1 Parameters

The performance of proposed DAPs based IMM tracking system is compared with conventional IMM filter on the real-time radar 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 2.

Table 2. Parameters

Model	Process Noise	Measurement Noise (m)
Constant velocity	0.01g	60
Constant acceleration	g	60
Coordinated turn	0.1g	60

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

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

4.2 Results

The evaluation results are based on the real-time Mode S radar data that span a time interval about 800 seconds. The aircrafts with DAPs information during the maneuvering periods are selected for comparison. The actual prediction errors obtained using these two methods are tabulated. These results not only demonstrate the error reduction obtained with the DAPs based estimator, but also indicate the magnitude of the actual errors in a typical ATC scenario. The RMS prediction errors in the horizontal aircrafts based on the measurements of maneuvering periods are given in Table 3. The results indicate approximately 50% RMS prediction error reduction in the critical maneuvering periods for the proposal over the standard IMM estimator. During the non-maneuvering periods, these two methods have identical performance. The performance comparison of RMS on horizontal accuracy is shown in Figure 2. We see that during the maneuvering periods the proposed system consistently yields lower error and gets much improvement over the standard IMM estimator. As shown in Figure 2, the average reduction in RMS prediction error of the proposed system is 50.11%.

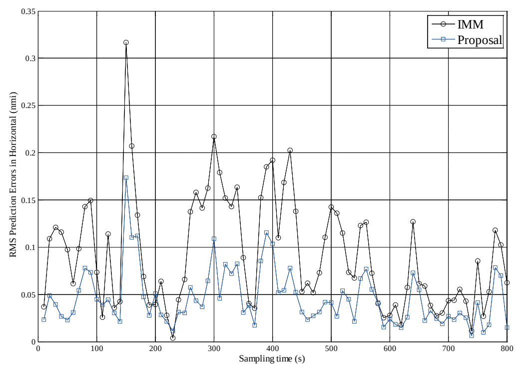

Figure 2. RMS Prediction Errors

5. CONCLUSION

In this paper, the development and practical experiments of DAPs based IMM tracking system for aircraft surveillance are proposed. From the obtained results, the performance of proposed system is confirmed and the effectiveness for real application is shown. Compared with the standard IMM filter, the proposed system significantly reduces the prediction error through maneuvers not only during the initial tracking period but also during later tracking period. For satisfying the desired level of accuracy, it is required to assure the quality of DAPs data and improve the performance during the dynamic changing environment.

REFERENCES

[1] Principles of Mode S Operation and Interrogator Codes, 2nd ed., EUROCONTROL, March 2003.

[2] Manual of SSR systems, 2nd ed., ICAO, July 1998.

[3] C. C. Lefas, “Using roll-angle measurements to track aircraft maneuvers,” IEEE Trans. on Aerospace and Electronic Systems (AES), vol. 20, no. 6, pp. 672-681, 1984.

[4] A. Soto, G. de Miguel, J. Besada, and J. Garcia, “Robust tracking architecture for mode-s enhanced surveillance,” in IEEE Proc. of 9th International Conference on Information Fusion, pp. 1-8, July 2006.

[5] X. R. Li and Y. Bar-Shalom, “Design of an interacting multiple model algorithm for air traffic control tracking,” IEEE Transactions on Control Systems Technology, vol. 1, no. 3, pp. 186-194, 1993.

[6] X. Lu and T. Koga, “Preliminary study on tracking technologies for hybrid aircraft surveillance,” in IEICE Technical Report SANE2012-142. IEICE, pp. 55-60, January 2013.

[7] Aeronautical Telecommunications annex10 vol. IV, 4th ed., ICAO, July 2007.

[8] DAP Technical Characteristics for Mode S Enhanced Surveillance, 1st ed., EUROCONTROL, June 1999.