MULTI-SENSOR DATA PROCESSING FOR AIR TRAFFIC CONTROL SYSTEM

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ABSTRACT
Multi-sensor data processing (MSDP) software is developed as a core module of the surveillance data processing system (SDPS) for air traffic control. MSDP processes not only radar input but also data from ADS-B and multilateration (MLAT), allowing it to produce system tracks for other applications in the air traffic control system. The multiple plot variable update (MPVU) and the interacting multiple model (IMM) are adopted in the MSDP in order to process data from multiple sensors and to support multiple flight modes. Tracking performance test results based on EUROCONTROL surveillance standards indicate that the MSDP meets EUROCONTROL requirements.

KEY WORDS
Tracking, surveillance, radar, ADS-B, MLAT, interacting multiple model, air traffic control

1. Introduction
The surveillance data processing system (SDPS) is a subsystem of the air traffic control system that is currently being developed in Korea. The SDPS has two main features: multi-sensor data processing (MSDP) and safety nets (SNET). The purpose of MSDP is to process data from various sensors such as radar, ADS-B, and multilateration (MLAT) and to provide system tracks to air traffic controllers. SNET provides the controllers with safety warnings and alerts. It includes short term conflict alert (STCA), minimum safe altitude warning (MSAW), area proximity warning (APW), and approach path monitoring (APM).

The purpose of this paper is to present the algorithms implemented in the MSDP of SDPS and to show the results of the tracking performance assessment. The air traffic control systems which have been operated in Korea do not process surveillance sensors other than radar. The multi-radar tracking methods currently implemented are based on either the track switching [1] or the track average [1], both of which require mono-radar tracking before multi-radar tracking can be attempted. The filters used for state estimation are single-model-based Kalman filters [2] or alpha-beta filters [2]. The SDPS, which has been under development for 5 years in Korea, is designed to process data from heterogeneous multiple sensors and to support multiple flight modes. In order to meet EUROCONTROL requirements, the MSDP software described in this paper has adopted the multi-sensor multi-model tracking algorithms such as multiple plot variable update (MPVU) [1] and the interacting multiple model (IMM) [2-3]. In addition, MSDP uses 3-dimensional earth-centered earth-fixed coordinates (ECEF) during pre-processing and filtering. This minimizes the errors caused by stereographic projections [4-5] to the local sensor plane, which are typically utilized by legacy target tracking software.

This paper is organized as follows: Algorithms implemented in MSDP are presented in section 2. The tracking performance test results are presented in section 3, and concluding remarks are given in section 4.

2. Multi-Sensor Data Processing Algorithms
MSDP receives target reports from numerous sensors, including radars, ADS-B, and MLAT, and sends the processed tracks to SNET and other applications.

![Fig. 1. Block Diagram of Multi-Sensor Data Processing](image-url)
Fig. 1 shows the block diagram of MSDP. MSDP has the following functional components: 1) coordinate transformation of measurements from the sensors, 2) measurement covariance updates based on common coordinates, 3) associations between sensor data and their corresponding tracks, 4) track management, including track initiation, confirmation, and deletion, 5) filtering, and 6) bias estimation and correction. The detailed algorithms for each component are described in the following subsections.

2.1 Coordinate Transformation
For the state vector and system model, this study adopts ECEF-based 3-dimensional Cartesian coordinates instead of local coordinates based on a stereographic projection. This minimizes possible tracking errors due to projections. Thus, the sensor reports received from radar, ADS-B, and MLAT are all converted into ECEF X,Y,Z coordinates, which allow for tracking in the same coordinate system.

In the case of radar, the slant range (r) from the radar site to the target, azimuth (θ), and altitude (H) are typically obtained. The ECEF-based position X,Y,Z expressed in Eq. (1) can be calculated from those measurements in radar-centered polar coordinates and the location of the radar site.

\[ z_{radar} = [X \ Y \ Z]^T \]  

(1)

In the case of ADS-B, not only latitude, longitude, and altitude, but also aircraft-derived data such as ground speed (\( V_G \)), ground track (ψ), and altitude rate (\( \dot{H} \)) can be used. Thus the measurement vector \( z_{ads} \) is defined as:

\[ z_{ads} = [X \ Y \ Z \ V_X \ V_Y \ V_Z]^T \]  

(2)

where ECEF coordinates X,Y,Z are calculated using latitude, longitude, and altitude from ADS-B target reports. The formula for transforming coordinates from geodetic to ECEF, which was presented in [6], is used for the calculation. The velocity vector \([V_X \ V_Y \ V_Z]^T\) is calculated from local ENU (east-north-up) coordinate-based velocity \([V_e \ V_n \ V_u]^T\) with a coordinate transformation matrix \(U\), which converts the coordinates from ECEF to local ENU coordinate as follows:

\[
\begin{bmatrix}
V_X \\
V_Y \\
V_Z 
\end{bmatrix} = U^T \begin{bmatrix}
V_e \\
V_n \\
V_u 
\end{bmatrix} = U^T \begin{bmatrix}
V_G \cos\psi \\
V_G \sin\psi \\
\dot{h}
\end{bmatrix} .
\]  

(3)

\( U \) is calculated after calculating \( \vec{e}_X, \vec{e}_Y, \) and \( \vec{e}_Z \), which form the basis of the tangent plane at the target position (X,Y,Z) as:

\[ U = \begin{bmatrix}
\vec{e}_X & \vec{e}_Y & \vec{e}_Z \\
\vec{e}_n & \vec{e}_u & \vec{e}_v \\
\vec{e}_x & \vec{e}_y & \vec{e}_z 
\end{bmatrix} .
\]  

(4)

In the case of MLAT, the measurement vector \( z_{mlat} = [X \ Y \ Z]^T \) is set according to latitude, longitude, and altitude data obtained from the sensor.

2.2 Measurement Covariance Update
Since the measurement vector has been transformed, the measurement covariance needs to be updated based on the ECEF coordinates. Covariance of the radar measurement error in ENU coordinates is expressed as Eq. (5). Here, the error variances of range, azimuth, and altitude in local radar coordinates are \( \sigma_r, \sigma_\theta, \) and \( \sigma_h \) respectively, and the measurements of range and azimuth are \( r_m \) and \( \theta_m \).

\[
R_{radar, enu} = \begin{bmatrix}
\sigma_{r_m}^2 & \text{cov}(e,n) & 0 \\
\text{cov}(e,n) & \sigma_{\theta_m}^2 & 0 \\
0 & 0 & \sigma_{h_m}^2 
\end{bmatrix}
\]  

(5)

where

\[
\sigma_{r_m}^2 = (e^{\sigma_h^2} - 2)r_m^2 \cos^2\theta_m + \frac{1}{2}(r_m^2 + \sigma_r^2)(1 + e^{-2\sigma_h^2}) \sin 2\theta_m 
\]  

(6a)

\[
\sigma_{\theta_m}^2 = (e^{\sigma_h^2} - 2)r_m^2 \sin^2\theta_m + \frac{1}{2}(r_m^2 + \sigma_r^2)(1 - e^{-2\sigma_h^2}) \sin 2\theta_m 
\]  

(6b)

\[
\sigma_{h_m}^2 = \sigma_h^2 
\]  

(6c)

\[
\text{cov}(e,n) = \frac{1}{2}e^{\sigma_h^2}r_m^2 + \frac{1}{2}(r_m^2 + \sigma_r^2)e^{-2\sigma_h^2} - r_m^2 \sin 2\theta_m. 
\]  

(6d)

The measurement error covariance matrix in ECEF coordinates is calculated using \( U \), defined in Eq. (4) as:

\[
R_{radar} = U^T R_{radar, enu} U 
\]  

(7)

In the case of ADS-B, the covariance matrix is defined as Eq. (8) under the assumption that the state variables in ENU coordinates are independent of each other.

\[
R_{ads} = U^T \begin{bmatrix}
\sigma_e^2 & 0 & 0 & 0 & 0 & 0 \\
0 & \sigma_n^2 & 0 & 0 & 0 & 0 \\
0 & 0 & \sigma_u^2 & 0 & 0 & 0 \\
0 & 0 & 0 & \sigma_n^2 & 0 & 0 \\
0 & 0 & 0 & 0 & \sigma_u^2 & 0 \\
0 & 0 & 0 & 0 & 0 & \sigma_h^2 
\end{bmatrix} U 
\]  

(8)

MLAT has a 3 × 3 matrix for measurement covariance, which is shown in Eq. (9). This allows it to account for latitude, longitude, and altitude measurements.

\[
R_{mlat} = U^T \begin{bmatrix}
\sigma_e^2 & \text{cov}(e,n) & 0 \\
\text{cov}(e,n) & \sigma_n^2 & 0 \\
0 & 0 & \sigma_u^2 
\end{bmatrix} U 
\]  

(9)

2.3 Association between Sensor Data and Track

The global nearest neighbour (GNN) algorithm is used for the association between sensor data and its corresponding track. Likelihood functions for all the sensor reports associated with tracks are calculated in order to compute the cost of matching between each sensor report and track. Moreover, the cost is updated with appropriate factors according to whether the Mode 3/A, ICAO address, and other identification data are in agreement or not.

2.4 Track Management

Tracks are updated with sensor data so that track associations are kept up-to-date. If there is sensor data that is not associated with a currently maintained track, a new track is registered based on that sensor data and the weight of the track is initialized. On the contrary, if there is no plot that can be associated with a certain track, the weight of the track is decreased. To accomplish this, the weight of each track is computed using Eq. (10), which takes into account whether data associated with the track is detected by the sensors.

\[ P_{k+1} = \frac{P_k X_D}{P_k X_D + (1-P_k) X_F} \]  

(10)

\( P_k \) is the track weight at step \( k \). \( X_D \) and \( X_F \) are computed using detection probability \( P_D \) and false alarm probability \( P_F \), as follows:

\[ X_D = P_D, \quad X_F = P_F \quad \text{if detected} \]  

(11a)

\[ X_D = 1-P_D, \quad X_D = 1-P_F \quad \text{if NOT detected} \]  

(11b)

The track is updated if track weight exceeds the predefined threshold. If not, the track is deleted.

2.5 Filtering

The MPVU and IMM technologies are adopted for filtering the tracks. The pre-processing for coordinate transformation and covariance updates is performed when sensor measurement data such as radar, ADS-B, and MLAT are received. As shown in Fig. 2, the pre-processed measurement data are sent to each filter component of the IMM filter. In this study, sensor target reports are used rather than mono sensor tracks because, unlike track switching or track averaging methods, the MPVU method does not require mono sensor tracks. State and state covariance estimated from multiple filters for various flight modes are combined with mode probabilities based on the calculated likelihood functions. In this study, the IMM consists of three models: constant velocity (CV) [2,12], constant turn (CT) [2,12], and constant acceleration (CA) [2,12]. The state vector of each model is given in Eq. (12), and state equations are given in Eq. (13).

2.6 Bias Estimation and Correction

The biases for each radar are estimated via the Kalman filter based on the differences between tracks and sensor target reports. The biases estimated in this study are limited to range gain \( (G_r) \), range offset \( (O_r) \) and azimuth offset \( (O_\theta) \) of the radars.

First, the range and azimuth of a track \( (r_{track} \) and \( \theta_{track} \) are computed from the 3-dimensional ECEF based position of the track. Then, the differences in range and azimuth \( (\Delta r \) and \( \Delta \theta \) ) are calculated with them and the data of the radar plot \( (r_{plot} \) and \( \theta_{plot} \) ). The azimuth offset, \( O_\theta \), is estimated using a 1-dimensional Kalman filter with measurement \( \Delta \theta \). The range gain, \( G_r \), and range offset, \( O_r \), are estimated using a 2-dimensional Kalman filter, of which the state vector is \( [O_r \ G_r]^T \), the measurement matrix is \( [1 \ r_{track}] \), and measurement is \( \Delta r \). The estimated bias is used for the bias correction shown in Fig. 1.
3. Test and Evaluation Results

Tests and evaluations are performed to determine the tracking accuracy of MSDP. "EUROCONTROL Standard Document for Radar Surveillance in En-Route Airspace and Major Terminal Areas", SURETI.S T01.1000-STD-01-01[13] is used as a reference document for the requirements. The tracking results are shown in Table 1. More detailed information on the tests, including the scenarios, environments and procedures used, are documented in [14].

Table 1. Test Results of Tracking Accuracy

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Position</th>
<th>Ground Speed</th>
<th>Course</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Along Trajectory Position RMS Error</td>
<td>Across Trajectory Position RMS Error</td>
<td>Ground Speed RMS Error</td>
</tr>
<tr>
<td></td>
<td>Test Result</td>
<td>Req’t</td>
<td>Test Result</td>
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<tr>
<td>PSR Only</td>
<td>Uniform Motion</td>
<td>35m</td>
<td>85m</td>
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<tr>
<td></td>
<td>Uniform Speed Change</td>
<td>105m</td>
<td>250m</td>
</tr>
<tr>
<td>One SSR</td>
<td>Standard Turn</td>
<td>142m</td>
<td>150m</td>
</tr>
<tr>
<td></td>
<td>Uniform Motion</td>
<td>33m</td>
<td>60m</td>
</tr>
<tr>
<td></td>
<td>Uniform Speed Change</td>
<td>61m</td>
<td>180m</td>
</tr>
<tr>
<td>Two SSRs</td>
<td>Standard Turn</td>
<td>66m</td>
<td>100m</td>
</tr>
<tr>
<td></td>
<td>Uniform Motion</td>
<td>33m</td>
<td>50m</td>
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<tr>
<td></td>
<td>Uniform Speed Change</td>
<td>77m</td>
<td>125m</td>
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<tr>
<td>One SSR</td>
<td>Standard Turn</td>
<td>37m</td>
<td>70m</td>
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<td></td>
<td>Uniform Motion</td>
<td>107m</td>
<td>170m</td>
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<td>100m</td>
<td>400m</td>
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<td>Standard Turn</td>
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<td>285m</td>
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<tr>
<td></td>
<td>Standard Turn</td>
<td>153m</td>
<td>180m</td>
</tr>
</tbody>
</table>
4. Conclusion

In this study, MSDP software is developed for use in the SDPS for air traffic control. MPVU and IMM methods are adopted in order to process data from multiple sensors including radar, ADS-B, and MLAT and to support multiple flight modes. Moreover, an ECEF coordinate-based 3-dimensional tracking algorithm is used to minimize tracking error due to the stereographic projection that is widely used in legacy air traffic surveillance systems. Simulation results based on EUROCONTROL surveillance standards indicate that this MSDP software meets specified tracking accuracy requirements.

Acknowledgement

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References