Radar / ADS-B data fusion architecture for experimentation purpose

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Abstract – This paper describes data fusion architecture for air traffic control applications based on radar plots and ADS-B reports. ADS-B reports help to enhance accuracy of system tracks and radar plots provide track continuity over mixed ADS-B and radar coverage area. The chosen architecture makes use of all available measurements (radar data being synchronized according to revolution time period, while ADS data are taken into account in an asynchronous way) to produce an unique track for each aircraft, making global optimal data association and correcting sensor biases. The proposed architecture has been designed for experimentation purpose: it aims to prepare a mature model based on operational feedback. Simulations are conducted on live recording and highlight the benefits of the architecture over wide area.

Keywords: Radar, ADS-B, multi sensor surveillance, air traffic control, tracking, data fusion.

1 Introduction

In the past decade, Thales has developed a multi radar tracking system (MRTS) for air traffic control (ATC) applications. This system incorporates Thales’ extensive ATC experience, its commitment to international standards, its innovative use of state-of-the-art technology and, above all, the recognition of safety as the most important design criteria.

MRTS system is continuously upgraded through the operational feed back from the delivered programs. Due to recent advances in navigation and data communication technologies, a data link between aircraft and control centres is now available. It is known as Automatic Dependant Surveillance-Broadcast (ADS-B). In order to take into account ADS-B sources, the MRTS has been enhanced to Multi Sensor Tracking System (MSTS). The MSTS fuses the data from the various radar sources and ADS-B stations to create a unified, and accurate surveillance picture [1]. ADS-B data can be used to increase coverage when some areas are not covered by radars. ADS-B also allows to complement the coverage for the areas already covered by radar.

2 Data fusion architecture

2.1 MRTS Processing

As entry data, the multi radar tracking function has at its disposal several UTC time stamped plots (e.g. EUROCONTROL ASTERIX standard Category 001 message [4]). Measurements from different radars are then allocated so as to update radar tracks (e.g. EUROCONTROL ASTERIX standard Category 030 message [4]).

Figure 1 shows Multi Radar Tracking System synoptic.

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- Handling of sector N-1 tentative tracks using sectors N-1 and N-2 plots by activating in the same way:
  - Correlation, association, track management, track update,
  - Creation of new tracks with remaining sector N-2 plots,
  - Output of sector N-2 plots updating confirmed tracks,
  - Output of updated confirmed tracks.

**Pre-correlation step**
This step concerns the selection of possible plot-track pairs based on coarse sieve and gate computation. This one consists in computing the possible area volume around the last updated position of a track in which the plot detections could be found in a probabilistic way. This volume is the superimposition of 3 polar windows:
- Kinematics window: due to possible target manoeuvre,
- Extrapolated error window: from filter uncertainties,
- Measurement error window: from radar measurement noises.

**Correlation:**
It constitutes the best plot-track pairs among all pre-correlated pairs, based on a likelihood value.
Three levels of processing are performed:
- Track prediction at each pre-correlated plot time,
- Plot-track pair likelihood computation depending on normalised distance (based on Kalman filter) and bonus terms (based on Mode 3A or aircraft address matching, …),
- Plot classification through the ranking of plot-track pairs according to their likelihood.

**Association:**
Association function is based on a Global Nearest Neighbour approach: it solves correlation conflicts and searches among correlated measurements for the one, which corresponds best to the aircraft detection. At the end of the association process, a track has at most one associated plot.

**Track management process performs:**
- Track update based on auto adaptive extended Kalman filter and/or IMM filter for tracks which are associated to a plot,
- Track extrapolation for non-associated tracks.
It also manages:
- Forking logic for possible manoeuvre (MHT),
- Track identification,
- Track drop in particular on position, speed or age bounds,
- Track general information update,
- Output of tracks.

**Filtering:**
This function updates track kinematics on the basis of, on the one hand, a three-dimensional Kalman filter for horizontal tracking:
- Order 2 filter: position / speed state vector expressed in System Cartesian coordinates,
- Target behaviour model is considered as uniform motion,
- Adaptation of dynamic noise covariance matrix according to target manoeuvres,
- Measurement vector is expressed in spherical coordinates with range, azimuth and elevation,
- Update realized with either 1D, 2D or 3D measurements,
and on the other hand, a one-dimensional Kalman filter for flight level tracking.

An Interacting Multiple Model based on uniform motion, accelerated motion and coordinated-turn model can be activated by software configuration parameter.

Plot-track couples, with a distant plot for straight-line trajectory (plot which does not belong to the correlation volume but to an extended possible manoeuvre volume), are processed using a specific manoeuvring components management function acting as a multi hypothesis tracking. This case can correspond to either a strong manoeuvre or a false plot. Two components are subsequently generated for the track: a main component (CP) not taking the plot into account (false plot hypothesis) or a manoeuvring component (CM) using the plot to update the Kalman filter (manoeuvre hypothesis). While the two hypotheses co-exist, only one component is displayed.

**Initialisation:**
The automatic initialisation function aims to generate new tracks when aircraft appears in the system domain of interest. Initialisation can be secondary mono radar, primary mono radar, or multi radar. The confirmation of tentative tracks is based on a Bayesian approach to avoid false track creation.

**Systematic Radar Error Assessment (SREA):**
Assessment of Bias (also called systematic measurement errors) is performed through defining a common spatial reference system for the multi radar configuration, applying to all radars to have an accurate state vector for all tracks.

The SREA principle deals with the continuous estimation of bias values for each radar. The purpose is to minimize the tracking errors to remove them from plots before updating tracks.

Only some “selected” system tracks are chosen as reference to improve the accuracy of the bias assessment.

A Kalman filter is used to assess systematic errors along range and azimuth axis.

**2.2 MSTS Processing**
As can be seen in the figure 2, the synoptic of the MSTS is quite similar to MRTS one (most of radar tracking functionalities have been kept.).
Initialisation, track management and filtering have been upgraded so as to accept ADS-B reports and manage Multi Sensor Track (MST). This design reduces the risk of regression on the multi radar capabilities.

**ADS branch:**
The ADS branch takes ADS-B reports (e.g. EUROCONTROL ASTERIX standard Category 021 [4]) as inputs. Pre-correlation and correlation phases determine the reports, which correlate to a MST track (track which has filtered at least one ADS-B reports and/or one radar plot). This step is based on kinematics window and aircraft address matching (in a predominant way). The association process provides the best pairs report-track to the track management process.

In ADS-B reports, aircraft position is provided in geodesic frame. All processing are done in System Cartesian frame in which WGS84 position is converted.

**Common branch:**
The common branch principles remain close to MRTS one. Initialisation process has been modified to allow the creation of tracks with ADS-B reports. For the track management, capability has been extended to manage multi sensor track life.

Filtering process has been enhanced to manage one more kind of measurement: ADS-B report (see [2],[3]).

MST filtering being done in Cartesian frame, state equation is not changed as it uses in MRTS (state vector, transition matrix and state noise covariance matrix remain the same).

**State equation:**
For both type of sensors, state vector used is:

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

**Transition matrix is:**
\[
\Phi_k = \begin{bmatrix}
1 & 0 & 0 & \Delta t_k & 0 & 0 \\
0 & 1 & 0 & 0 & \Delta t_k & 0 \\
0 & 0 & 1 & 0 & 0 & \Delta t_k \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
\end{bmatrix}
\]  

where \(\Delta t_k\) is the delta of time between time \(k\) and time \(k-1\).

**Kalman adaptation:**
The automatic adaptation of the Kalman filter is made with an adaptation of the state noise covariance matrix \(Q_k\) before computing successively the estimated covariance matrix, the gain matrix and the estimated state vector (see [3]). Noise covariance is given by:

\[
Q_k = \begin{bmatrix}
\Delta t_k^2 & \Delta t_k^3 & 0 \\
\Delta t_k^3 & \Delta t_k^2 & 0 \\
0 & 0 & \sigma_{q_{kxy}}^2 \\
0 & 0 & \sigma_{q_{kz}}^2 \\
\end{bmatrix}
\]

where \(\sigma_{q_{kxy}}^2\) is the variance of ground acceleration (XY plan).
where \(\sigma_{q_{kz}}^2\) is the variance of vertical acceleration (z plan).

Thus the Kalman filter can be adapted according to the target behaviour:

- For the XY plan evolution: \(\sigma_{q_{kxy}}^2\).
- For the vertical plan evolution: \(\sigma_{q_{kz}}^2\).

The Kalman filtering technique ensures that the normalized innovation squared is distributed according to a \(\chi^2\) distribution under the assumption that the model is adapted to the observed process. This means that if the normalized innovation squared is not distributed according to its \(\chi^2\) distribution, the current model must be adapted to follow the new target behaviour (manoeuvring behaviour).

Radar and ADS-B data sources have to be considered for measurement vector and observation matrix determination.

**Observation equation:**
Observation vector is similar to \(Z_k = [R \ Az \ El]^T\) in radar case and to \(Z_k = [x \ y \ z]^T\) in ADS-B case.
This leads to a non-linear observation equation in radar case with following observation matrix:

$$H_k = \begin{bmatrix}
\frac{\partial R}{\partial x} & \frac{\partial R}{\partial y} & \frac{\partial R}{\partial z} & 0 & 0 & 0 \\
\frac{\partial \Delta z}{\partial x} & \frac{\partial \Delta z}{\partial y} & \frac{\partial \Delta z}{\partial z} & 0 & 0 & 0 \\
\frac{\partial \Delta z}{\partial x} & \frac{\partial \Delta z}{\partial y} & \frac{\partial \Delta z}{\partial z} & 0 & 0 & 0 \\
\frac{\partial E_l}{\partial x} & \frac{\partial E_l}{\partial y} & \frac{\partial E_l}{\partial z} & 0 & 0 & 0 \\
\frac{\partial E_l}{\partial x} & \frac{\partial E_l}{\partial y} & \frac{\partial E_l}{\partial z} & 0 & 0 & 0 \\
\frac{\partial E_l}{\partial x} & \frac{\partial E_l}{\partial y} & \frac{\partial E_l}{\partial z} & 0 & 0 & 0
\end{bmatrix}$$

Observation equation in ADS-B case is linear and observation matrix is similar to:

$$H_k = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0
\end{bmatrix}$$

Radar branch:
Bias assessment processing is based on selection of some system track reference. The design does not need to be upgraded in the scope of MSTS. The benefit is obtained through a better accuracy of selected tracks related to ADS-B report updates.

2.3 Tracking features

As mentioned before, radar plots are buffered in azimuth sectors, which introduces an acquisition delay proportional to the radar-scanning period. On contrary, ADS-B reports are processed straight away, which does not introduce any acquisition delay. A limitation of backtracking filter update is then necessary to avoid degrading the tracking accuracy.

Backtracking processing, also called late plot update, is useful in a multi radar configuration to increase the track observability. Nevertheless, it does not improve the tracking accuracy as soon as the system track is updated by ADS-B reports. Indeed, previous ones have a better positional accuracy and a better refresh rate than radar plots and are not subject to high blunder and outlier. In such a case, plots do not contribute to track updates but correlate to the system tracks which reinforces the tracking integrity regarding to pure ADS-B system tracks.

This tracking architecture guarantees also the tracking continuity in case of ADS-B misses, by processing radar plots, which are no more in such a case in a backtracking situation.

The radar plot correlation can also be monitored to detect any degradation from ADS-B position reports due to any onboard failure. Thus, in case of discrepancy between ADS-B reports and radar plots, the system track can only be updated by radar plots, which seem to be more reliable than ADS-B reports. This statement will be checked during experimentation phase.

Otherwise, the ADS-B branch correlation function allows detecting and filtering out any aberrant ADS-B reports regarding to the filter model.

3 Simulations

Tracker was evaluated with live data for radar and ADS-B to assess the global behaviour of the tracking system in an operational context.

Two representative experimentations were conducted: In the first one, the performance of Radar / GPS data fusion processing and multi-sensor coverage was evaluated on calibration flight. In the second one, a statistical analysis was realized on ADS-B reports and ADS-B only tracks were finely analyzed.

3.1 Scenario

**Calibration flight**

Two SSR radars (revolution period equal to 4s) and a hand-held on-board GPS receiver was used to make up the scenario.

**Live recording**

One ADS-B station and 2 radars (1 PSR / 1 SSR) were used.

3.2 Statistical analysis

During calibration flight, hand-held on-board GPS receiver always gives the latitude, longitude and altitude parameters at a mean refresh rate equal to 1.5s.

Live recording contains ADS-B reports in EUROCONTROL ASTERIX standard format. A statistical analysis on the percentage of fields’ presence in ASTERIX Category 021 messages gives following results:

![Figure 3: Statistics on ADS-B fields’ presence](image)

According to the previous figure, we can see that the time of detection, target position, aircraft address and Figure Of Merit (FOM; target accuracy level) are always present in ASTERIX messages contrary to the flight level or ground vector for example. These mentioned fields and flight level (90 % of presence) have been considered as mandatory in the scope of this study.

Comment: As can be seen, geometric vertical rate is more often present than geometric altitude. Generally speaking, all data are available but are not transmitted in ADS-B report: this depends on ADS-B avionics used, and performance currently required for these systems.
3.3 Results

Shown results have been obtained by replay of scenario on a testbed version of MSTS architecture. Firstly, multi sensor tracking performance on calibration flight is shown. Secondly, radar-only coverage phase is emphasized and last results deal with ADS-B-only coverage on live recording.

On the first three following pictures, MST tracks and radar-only tracks have been superimposed:
- MST tracks are in red,
- Radar-only track are in grey.

Further hypothesis:

Simulations are realized with a standard Kalman filter (the IMM filter is not activated).

On live recording, tracking performance is evaluated by considering an en-route track with flight level available.

Track initialisation:

Due to the great refresh rate and to the low transmission delay, track initialisation for the MST track is quicker than for a radar-only track. Track confirmation and reporting follow this logic.

Tracking performance in turn:

Due to the great refresh rate of the GPS, the effect of a delay between the time when a manoeuvre begins and when it is detected is minimised.

Multi sensor coverage:

Radar / ADS-B coverage

Figure 6: Tracking performance comparison

Figure 6 shows that the transition between multi sensor coverage area to radar-only coverage area goes off smoothly. Due to the refresh rate, MST track gets mainly ADS-B reports in multi-sensor coverage (MST track are close to ADS-B only track), while it is similar to multi-radar track on radar-only coverage area. Current architecture then provides a continuity of track over different types of coverage area.

ADS-B only tracking performance:

Figure 7: ADS-B only track ground speed evolution

Figure 7 shows the stability of ADS-B only track ground speed over 30 minutes, while figure 8 shows its heading evolution.
In the scope of the study, presence of ground speed vector in ADS-B report is not compulsory. Thus it is necessary to elaborate a speed vector with the Kalman filter: it is used for track prediction (alert server) and controller display. It also constitutes a less cooperative mean to detect ADS-B erroneous reports in the correlation function. According to figure 7, the ground speed vector is quite stable and conforms to accuracy model. The question is then opened on the use of ground speed vector, when available, as measurement input in the Kalman filter.

3.4 Architecture performance evaluation

The advantages of the chosen architecture are listed below:
- System track accuracy improvement:
  - High rate of track refresh,
  - ADS-B processing does not introduce any buffering delay: acquisition time delay is quite low,
  - Use of variable update technique: does not introduce any delay on the use of radar plots in case of track exit from ADS-D area of interest, which is not the case of plot averaging technique.
- Enhanced reliability by the correlation with previous reports and crude plots,
- Continuity of tracking in multi sensor coverage areas,
- Safety improvement by mixing of cooperative (ADS-B, SSR) and non-cooperative (PSR) data sources (cooperative data are checked by non-cooperative ones) => tracking supervision.

This architecture has been built for experimentation phase and is not mature enough. It needs some enhancements such as:
- Robustness improvement according to ADS-B data source degradation,
- Synchronization of multi-sensor data sources,
- Tracking supervision enhancements.

4 Conclusions

In this study a Multi Sensor Tracking System architecture has been proposed for ADS-B integration in ATC centres. Evaluation, based on live recording shows that fusing ADS-B reports with radar plots seems to improve the quality of tracking. This architecture is now suitable to conduct additional experimentation phases (performance and stress tests will be then realized). Future enhancements will concern the introduction of a data-driven processing in order to increase robustness to any ADS-B report parameters unavailability. Future line of research will include its extension to other data sources such as Enhanced Surveillance (S Mode) and Wide Area Multilateration (WAM).

References