MANAGEMENT OF RADAR TRACKING SYSTEMS FOR AIR TRAFFIC CONTROL

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ABSTRACT

This paper describes a novel methodology for the adaptive management of radar systems or radar networks used for air traffic control. It is based on linking radar tracking system overall resources consumption with air traffic control operational requirements. The method is exemplified with the design of a tracking function for a multifunction ESA radar. Some simulation results for this system are provided, showing the interest of such a concept, in terms of lowering of resources consumption and fulfillment of operational requirements.

1. INTRODUCTION

Current Air Traffic Control (ATC) systems rely heavily on the use of a network of sensors to perform accurate aircraft tracking. These sensors are usually primary and secondary radar systems, providing measurements with a predefined (almost constant) data rate and measurement accuracy. Therefore, the only way to adapt the surveillance system to ATC operational needs is selecting the most adequate set of radars and their placements, so that the overall tracking system is capable of handling the worst case scenario in the interest airspace. As a result, both ATC oriented radars and tracking systems are designed thinking on worst case scenario, not on the actual changing scenario, with changing operational demands due to the increasing (in the long term) air traffic demands. The methods used to enhance the surveillance system, mainly based on incorporating new radars to the existing ones, or replacing a whole generation of radars by a new one, are not adaptive. It leads to an excessive consumption of resources (in terms of deployed radars, communication demands, and data processing cost), because of the need to perform a worst case design. In other words, the current designs of ATC tracking systems lead to an accuracy much better than needed for most aircraft during most of the duration of each flight, specially in en-route airspace, but spending much more resources than needed to guarantee aircraft safety.

This contribution proposes an adaptive methodology to manage a radar or radar network, communication systems and data-fusion systems to lower overall resources consumption, but ensuring the flight safety is guaranteed (at least to the current safety levels). Depending on the availability of methods to control radar measurement process, communication subsystems and data fusion systems, the proposed methodology would lead to reductions of resources consumption on each of the parts of the system. To do so, we will need to encompass the cost (in terms of processing and communication resources) induced by this management function. The proposed methodology would lead to a more adaptive system, capable of increasing responsiveness to real problems by reducing the load induced by non-problematic situations.

2. ADAPTIVE ATC TRACKING SYSTEM

The proposed overall architecture of an adaptive tracking system for ATC applications is sketched in figure 1.

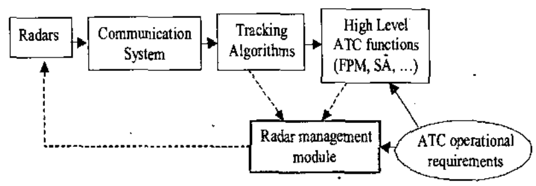

Figure 1: Adaptive tracking system architecture

Under this architecture, the radar or radar network providing observability of aircraft trajectories are controlled adaptively by the radar management module, on the basis of a continuos monitoring of the high level ATC functions results, and taking into account ATC operational requirements (also potentially changing in time) and resources consumption. In this ideal framework, the radars are controllable: we may change the track update rate, the signal to noise ratio, ... to attain a predefined tracking system accuracy.

In this contribution we will mainly address Flight Plan Monitoring (FPM in figure 1), among all high level ATC functions. Similar ideas to those described in this paper might be used to control the sensor network additionally enabling a robust aircraft Separation Assurance (SA in figure 1) function, or for other functions. However they will not be addressed in this paper due to the lack of space. It should be noted under this architecture there is a prerequisite to perform adequate ATC, which is having robust tracking. Therefore, in addition to high level ATC functions, the resources control subsystem will have to take into account track continuity constraints.

These ideas will be exemplified with some simulation results from a hypothetical stand-alone ESA radar for ATC (similar to the one described in Rogers (1)), including a Mode S compatible secondary mode. This example has been selected because the existence of such a radar would allow a much finer control than that allowed by current sensors. Current TWS Mode S radars could also be controlled (using efficiently selective addressing characteristics to tune the track update period) although the potential update rates to be used will be discretised due to the constant antenna rotating period, which reduces the controllability of the system.

Primary and conventional SSR radar systems used for ATC usually are not controllable. Therefore, the ideas introduced in this paper would not apply directly to this kind of tracking systems. Nevertheless, some reduction of the overall resources spent may be attained by either controlling the communications subsystem (not sending unnecessary plots to be processed) or the tracking system (avoiding processing all received plots).

3. RADAR MANAGEMENT MODULE

This module is in charge of continuously adapting the use of tracking system resources to the operational needs. To do so, it is important to have a rigorous characterisation of the impact of the controllable radar parameters over the high level ATC functions.

Radar tracks accuracy clearly impacts on the quality of these high level functions. Higher accuracy implies more responsive flight plan monitoring tests, more accurate aircraft separation measurements, better extrapolations, etc. Therefore, if we are able to characterise both the relation between radar control parameters and tracking accuracy, and the relation between tracking accuracy and high level functions quality, restrictions (taken from operational requirements) over high level functions lead to restrictions over tracking accuracy, and in turn, over potential radar control parameters. As a conclusion, the radar control parameters are the ones minimising radar (or radar network) resources consumption, restricted to values not compromising operational requirements.

Mathematically, we will define:

- **C** as the vector of radar control parameters.
- **S** as the vector of track accuracy interest statistics. It depends on the radar control parameters. For tracking function management, it is necessary to define a model of this dependence, of the form **S**=**S**(**C**).
- $\mathbf{Q}_i$ as the i-th high level ATC function quality. Note it is a function of track accuracy statistics. We will model this function mathematically, having a dependence of the form $\mathbf{Q}_i = \mathbf{Q}_i(\mathbf{S})$.
- R as the resources consumption figure of merit to be optimised. We should also define a model relating resources consumption with the control parameters vector, of the form R=R(**C**).

Therefore, to find the optimal set of radar control parameters we would need to solve the following (usually non-linear) minimisation problem:

$$C^* = \min_{\substack{Q_1(S(C)) \leq Q_{DESIRED,1} \\ Q_2(S(C)) \leq Q_{DESIRED,2} \\ \vdots \\ Q_N(S(C)) \leq Q_{DESIRED,N}}} R(C) \tag{1}$$

where we assume the operational requirements could be translated to constraints over quality measurements, which we will call $\mathbf{Q}_{DESIRED,i}$. It is important to note that sometimes it is impossible to find a set of control parameters accomplishing all requirements with the available resources, and therefore a means to gracefully relax those constraints should be included in this module. This method should take into account potential hierarchies between different operational constraints (for instance, we could assume separation assurance is more important than flight plan monitoring).

Examples of radar tracking systems control parameters could be:

- Measurement period: Track accuracy (especially during manoeuvres) depends clearly of this parameter.
- Sensor or group of sensors allocated to take measures of each target: A general optimisation process could decide to use worse sensors for certain not too problematic targets, freeing resources from better sensors for other target in a more problematic situation.
- Signal to noise ratio.

Typical accuracy statistics are RMSE (root mean square error), bias, standard deviation, or error distribution percentiles. **S**(**C**) function is very dependent on the overall tracking architecture, and usually should be estimated through an interpolation of the results of Monte Carlo estimates or semianalytical predictions of the overall performance on a grid of parameter samples. Meanwhile, $\mathbf{Q}_i(\mathbf{S})$ would be defined in a different way for each high level function, taking into account the kind of measures (distance to flight plan predicted position, distance between aircraft, ...) monitored in this function and the relation between this monitoring and the tracking errors, as well as the statistical nature of this errors and the permissible risk level. In figure 2 it can be seen how the desired behaviour of the different high level ATC functions drive the resources allocation.

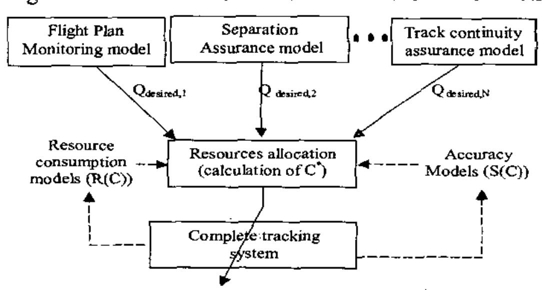

Figure 2: Resources control concept for ATC.

This methodology works on a per-target basis: in order to avoid compromising any flight, the quality required for each high level function for each aircraft must be taken into account. The amount of parameters to be controlled could be very high (period for each target and sensor), ... But simplifications finding suboptimal control parameters could be employed. Usually, the accuracy does only depend on the own target history. Additionally, most of the operational requirements only depend on the aircraft behaviour or may be decomposed as requirements over each aircraft behaviour. In addition, the resources consumed to track each aircraft are independent of those used to track the rest of the aircraft, if we are not in overload situation. Therefore, in most situations, equation (1) may be decomposed as a set of minimisation problems, one for each aircraft, and all of them with the same form described in equation (1).

4. DESIGN EXAMPLE

Using previous ideas, we have defined a tracking mode for an ATC oriented ESA multifunction radar for Terminal Area surveillance. We will assume a non-rotating antenna, and an addressable secondary mode (Mode S based). This kind of sensor would allow for a very fine control of the measurement process through the change in time of the track update period for each target. If the aircraft is appropriately equipped, the radar may obtain cinematic information (groundspeed, heading and rate of turn) from it, using Mode S data-link and DAP registers. We will assume we may not change individual measurement quality, but only control measurement periods. We use an IMM filter similar to that described in Wang et al (2) for tracking aircraft not providing cinematic data and a cinematic measurements-based extrapolation technique, similar to that in Leffas (3) for those providing this information.

The resources allocation subsystem searches a minimum for resources consumption. In this example the resources taken into account are the time spent by the tracking function (taking into account any potential reacquisition process, as described in section 4.4). As described in section 3, the overall optimisation problem may be decomposed as a set of much simpler optimisation problems, one for each aircraft. Our problem for each aircraft is to minimise the time spent on it. In this example the only two functions which will be taken into account are Flight Plan Monitoring and Track Continuity. In our design, we have translated the requirements from both functions into a range of usable track update periods for each aircraft, of the form [T_{min}, T_{max}] as will be shown in subsections 4.2 and 4.3, using the accuracy models derived as described in section 4.1.

The example system architecture may be seen in figure 3, where index j is the index of the aircraft.

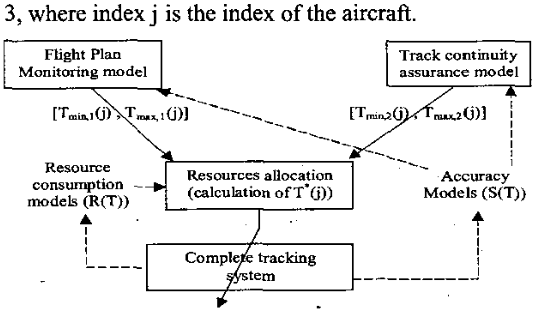

Figure 3: Resources control for example system

Next we will detail the accuracy models, FPM and continuity models and resource consumption models.

4.1. Accuracy models

They were calculated using a conservative upper bound of the results obtained interpolating the results from different Monte Carlo simulations in different situations. We assessed two quantities for each output of the tracking function (position and velocity filtered estimates): bias and standard deviation of the error. The reason is the rest of the models in this example design used only those statistics.

The tracking error depends on the exact trajectory of the aircraft (history of the track), and principally on distance to radar, and the current mode of flight. It also depends on some other non controllable parameters, such as the availability of cinematic parameters.

4.2. Flight Plan Monitoring Model

We will assume 4D flight plan monitoring: the 3D position is monitored for all times. In this paper we would describe the idea restricted to the horizontal plane. So what this function will be monitoring is the horizontal distance between the desired position of the aircraft and the position it should be following according to the approved flight plan. We should be aware the monitoring can be only performed over estimated positions, which have an error with an statistical distribution. The flight monitoring requisites should take into account the existence of this error, and therefore the probability to measure excursions larger than the real one (potentially inducing false alarms of non-compliance with flight plan), or smaller (making the probability of detection of actual dangerous excursions lower than one). Additionally, it should be taken into account that aircraft do not exactly follow the flight plan, but there are some assumable excursions due to the positioning error of the navigation system or to the lack of responsiveness of the flight control system.

In figure 4 the requisites and the actual filtered situation, as seen by the controller, are represented, together with the flight plan desired position (in the centre).

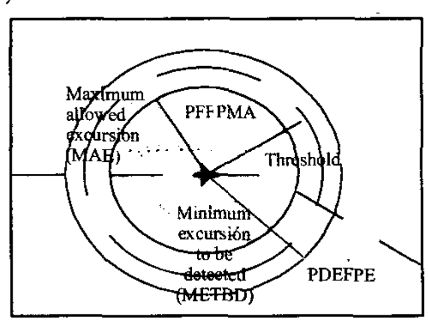

Figure 4: High level FPM requisites

If the interest aircraft is within the dark grey circle of radius MAE, almost no false alarms of flight plan breaking should appear (there is an assumable Probability of False Flight Plan Monitoring Alarm, PFFPMA, related with high level ATC design). Meanwhile, if the distance to the desired position is higher than the METBD, it should be detected with very high probability (higher than a predefined Probability of Detecting an Excessive Flight Plan Excursion PDEFPE value), to ensure aircraft safety.

This is assumed to be attained by measuring the distance between the flight plan derived aircraft and the filtered estimates after each measurement, and comparing it with a threshold (adaptively calculated to fulfil the high level ATC requirements).

The method for deriving the interval of track update periods which may allow to accomplish these requirements is summarised next:

- For each T, and depending on other non controlable parameters (for instance the position or the availability of cinematic measurements) we summarise in a vector (we will call this vector **P**), we may predict the accuracy of the track using the functions described in section 4.1, obtaining **S**(T,**P**).
- Using this accuracy prediction we may model statistically the error in each instant, and therefore we may define a threshold ensuring probability of false alarm equal to PFFPMA when the aircraft is exactly at a distance to the desired position equal to the MAE. In other words, the threshold dependencies may be summarised in the form:

$\alpha=\alpha(\mathbf{S},\mathrm{PFFPMA},\mathrm{MAE})$ (2)

- Using this threshold, the statistical model of the error, and a model of the potential divergences from the approved flight plan (summarised in the form of a maximum possible divergence velocity V_{DIV}), we may calculate the probability (P) to detect an excursion equal to the METBD, using a model of the form:

$P=P(\mathbf{S}, \alpha,\mathrm{METBD},V_{DIV})$ (3)

All previous dependencies may be summarised as:

$P=P(\text{operational requirements}, \mathbf{P}, T)$ (4)

If P is higher than PDEFPE, using a period equal to T the FPM function would be able to fulfil its operational requirements. Otherwise, T should not be used.

In our example, using this concepts, with MAE equal to 1 NM, METBD equal to 1.3 NM, a false alarm rate per aircraft lower than one false alarm per 500 hours, and a PDEFPE equal to 99,99%, we arrived to the time intervals shown in figure 5.

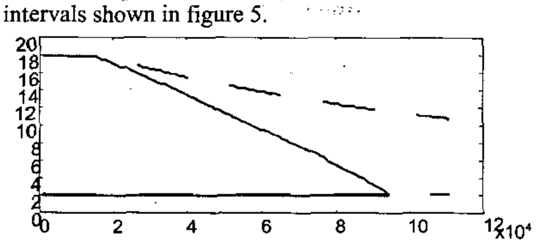

Figure 5: Maximum and minimum periods for FPM (seconds) depending on distance to radar.

In this figure we show the maximum and minimum periods (truncated over 18 s for Mode S continuity, an below 2 to ensure low resources consumption) for aircraft sending cinematic information (discontinuous line) and those not sending it (continuos line). Different limiting values would appear for different airspace areas with different excursion demands, potentially changing in time.

4.3. Continuity Model

This model, for our example, takes into account two effects potentially leading to the loss of tracks:

- Radar detection probability (PD) is lower than 1. This model should take into account the need of reacquisition looks, which reduces the importance of this effect.
- Due to the error in the predicted position, we might be pointing in a slightly wrong direction, being the desired aircraft outside the radar beam. To overcome this problem, the reacquisition loop could be extended to look (maybe repeatedly, to overcome detection misses) towards adjacent directions. An important parameter here is the radar beamwidth B (assumed not controllable).

We may summarise both effects by a model relating the probability of loosing a track (PTL) with both the PD and the accuracy statistics of the form:

$\mathrm{PTL}=\mathrm{PTL}(\mathrm{PD},\mathbf{S}(T,\mathbf{P}),B)$ (5)

Additionally, the mean time between track losses (MTBTL) may be calculated as:

$\mathrm{MTBTL}=T/\mathrm{PTL}$ (6)

and therefore there is a clear relation between the MTBTL and the track update period T. Then, imposing an operational requirement over the allowed values of the MTBTL lead to a margin of usable period.

4.4. Resources consumption model

For this example, the resources-consumption figure of merit to be minimised is the percentage of time spent on each target. In our radar system, the time spent on each look (τ) depends on the distance (R) between the radar and the target (no interleaving of tracking looks is assumed). The dependence is of the form:

$\tau=2R/c+\Delta\tau$ (7)

where $\Delta\tau$ is the time interval devoted to signal transmission plus the delay introduced in aircraft transponder. If all tracking looks were successful, the percentage of time spent (U_{ideal}) for this aircraft might be calculated as:

$U_{ideal}= 100 \times \tau/T$ (8)

But, as introduced in point 4.3, the radar looks are not successful with a certain frequency, and there is need for performing reacquisition looks. This frequency may be modelled, as described in section 4.3, in terms of PD, B, and **S**(T,**P**). Then, the actual percentage of time consumed (U) can be modelled as:

$U= 100 \times \tau/T_{eq}$ (9)

where T_{eq} is an equivalent update period. It may be modeled, summarizing previous models, in a form:

$T_{eq}=T_{eq}(\mathrm{PD},B,\mathbf{P},T,\text{reacq. procedure})$ (10)

in which we also take into account the potential impact of the reacquisition procedure (number of looks in predicted direction and in other contiguous beams, and the order in which they are performed). Minimizing consumed resources is equivalent to maximizing T_{eq}. In our radar, we may only control the track update period. In figure 6 we make a contour plot of the value of T_{eq} versus both the distance to the radar (X axis, in meters) and the track update period (Y axis, in seconds). It is provided for tracks of aircraft providing cinematic data. The allowed MTBTL is 500 hours, having an assumed PD equal to 0.98 and a beamwidth of 2°.

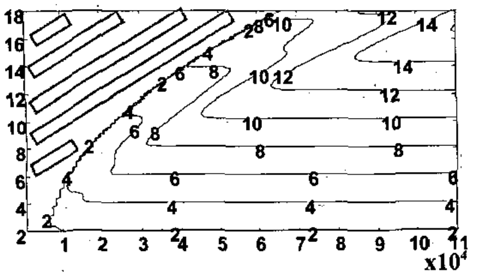

Figure 6: T_{eq} versus distance and track update period.

The gray lines zone in the upper left corner corresponds to update periods not fulfilling continuity requirements. The most problematic areas are the close distance ones, in which the beamwidth corresponds to a very small linear distance, and therefore unexpected maneuvers may easily produce tracks losses. The method to be used by the resources management module would be calculating the maximum of T_{eq} for the predicted track distance to radar.

5. RESULTS AND CONCLUSION

In this section we are providing some results from simulations of the example MFAR.

First, in figure 7 we show the track update period for an aircraft at constant velocity entering the coverage, passing at a distance of 20 km from the radar, and leaving the coverage.

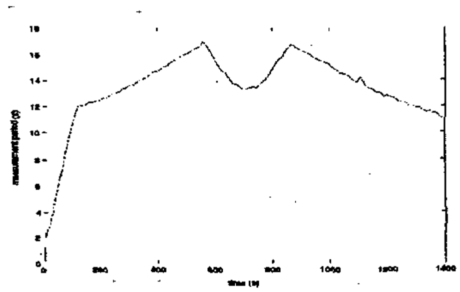

Figure 7: Track update period.

It may be seen how, for long distance, the FPM function limits the track update period, while for lower distances, this period is provided, approximately, by the maximum of T_{eq} . The system adapts the measurement period according to our models.

To assess if this methodology is able to guarantee the correct behaviour of ATC high level functions we have conducted several experiments:

- We have simulated more than 5000 hours (10 times the mean time between track loss allowed) of random flights in the radar coverage, having no track loss at all. This is because all our models have been derived using quite conservative assumptions.
- We have performed a Monte Carlo simulation (with 100 experiments) to analyse the real distance at which a flight plan excursion is detected. In this simulation we had an aircraft diverging from its flight plan at the maximum assumed velocity. The results are provided in figure 7, where we draw the probability of detecting an excursion from flight plan as a function of the actual distance between aircraft and desired flight plan position (expressed in NM), for different distances to radar and headings: R-25 line corresponds a trajectory quasi radial staring diverging at 25 NM of the radar, R-65 to a radial trajectory at 65 NM, T-65 to a tangential trajectory at 65 NM, and T-25 to a tangential trajectory at a distance of 25 NM.

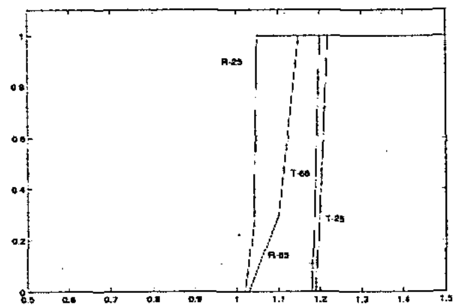

Figure 8: probability of detecting an excursion from flight plan versus actual excursion in NM.

We may see how the system, independently of the trajectory, is able to ensure the desired performance for the defined high level parameters (Maximum Allowed Excursion equal to 1 NM, Minimum Excursion to be detected equal to 1.3 NM).

As a conclusion, we may say the proposed methodology is able to adapt system parameters to ensure high level ATC requirements are fulfilled, potentially reducing the total tracking system resources consumption of current systems.

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BIBLIOGRAPHY

1. Rogers J, 1995, "Terminal Area Suveillance System", IEEE International Radar Conference
2.Wang H, Kirubarajan T, Bar Shalom Y, 1999, "Precision Large Scale Air Traffic Surveillance Using IMM/Asignment estimatos". IEEE Trans. on Airspace and Electronic Systems, Vol AES-35, No 1
3. Leffas C, 1991, "Improved tracking with Mode-S data linked velocity measurements", IEEE Trans. on Airspace and Electronic Systems, Vol AES-27, No 4