Maneuvering Target Tracking in Wide Area Multilateration Radar System

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Abstract—**The Radar Research Group of the Budapest University of Technology and Economics has been developing a distributed passive radar system. Multilateration principle is used to locate aircraft in the zone defined by the location of the receivers. The measurement principle challenges the conventional tracking algorithms, therefore a new solution was developed.**

Index Terms—**passive radar; multilateration; tracking; unbiased FIR filter**

I. Introduction

Traditionally air traffic control utilizes primary and secondary radar systems. While primary radars can detect and locate aircrafts, they can not identify them. This gap ought to be filled by secondary radar systems. At the current levels of readily available technologies, ill-intentioned people and groups can spoof air traffic controller by generating ghost aircrafts, or falsify aircraft identification.

Wide area multilateration is an emerging technology, that can address this vulnerability in air traffic control. It makes this possible by integrating two separated function of primary and secondary radars into a single system, as it can locate and identify transponder signals. Transponder signals with embedded GPS coordinates can be easily altered, but the locator function of the multilateration system will reveal the real position of the signal source.

The wide area multilateration system developed by the Radar Research Group of the Budapest University of Technology and Economics - called WAMLAT - currently is in a demonstrator phase (http://radarlab.hvt.bme.hu/~wamlat), while covering the city of Budapest and its suburban areas. The multilateration capabilities of this system is already proven [1], but at that time it was able to measure only independent and instantaneous events. For practical application a tracking solution is needed, but the measurement principle requires a new solution.

II. Conventional Tracking Methods [2][3]

The conventional tracking methods were developed for primary radars, therefore they are only valid for simplified models.

The hypotheses

- uniform sampling
- quadratic measurement error surface
- Gaussian measurement noise distribution

allow the use of the Kalman filtering (also known as linear quadratic estimation). Usually the Kalman filtering is applied on the discrete time state space representation, described in equations (1) and (2).

$$\mathbf{x}_k = \mathbf{F}_k \mathbf{x}_{k-1} + \mathbf{w}_k \tag{1}$$

$$\mathbf{z}_k = \mathbf{H}_k \mathbf{x}_k + \mathbf{v}_k \tag{2}$$

The state transition and observation model are usually simplified to time invariant functions, represented as matrices **F** and **H**, respectively. The process noise represented by $\mathbf{w}_k$ contains all the unforeseen changes in the state, in this case the maneuvering of the observed target. The measurement results ($\mathbf{z}_k$) are disturbed by the observation noise, represented by $\mathbf{v}_k$.

The main challenge using Kalman filter is the required a priori knowledge of process and observation noise's covariances, $\mathbf{Q}_k$ and $\mathbf{R}_k$, respectively. In the case of maneuvering target, the covariance of the process noise is unknown (however there are methods for its estimation), therefore only suboptimal Kalman filter can be used. The measurement noise can be estimated with a quadratic algebraic form.

III. Unbiased FIR filtering[4][5]

In [4] a novel filtering method was proposed. Unlike the Kalman filter, which has infinite impulse response, the presented UFIR filter is unconditionally stable. While the UFIR filter's estimation capabilities are worse than the optimal Kalman filter, the latter is nearly impossible to realize in practical tracker application; the UFIR filter's estimation performance is independent of the noise statistic's predictions, shown in Fig. 1.

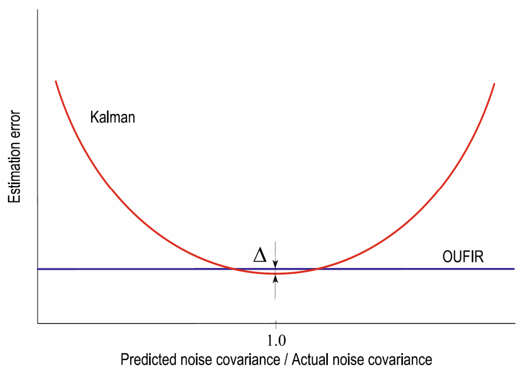

Figure 1. Estimation error comparison [5]

IV. Multilateration Measurement Properties

The multilateration position estimation method is based on measurements of time difference of arrivals, that is, solutions of nonlinear equation systems. The solution of these systems causes location dependent non quadratic error surface in the measurement accuracy. An example is shown in Fig. 2, where the red dots represent the locations of the receivers, the color gradient scale represents the geometric dilution of precision, referenced to the base error, derived from the timing uncertainties.

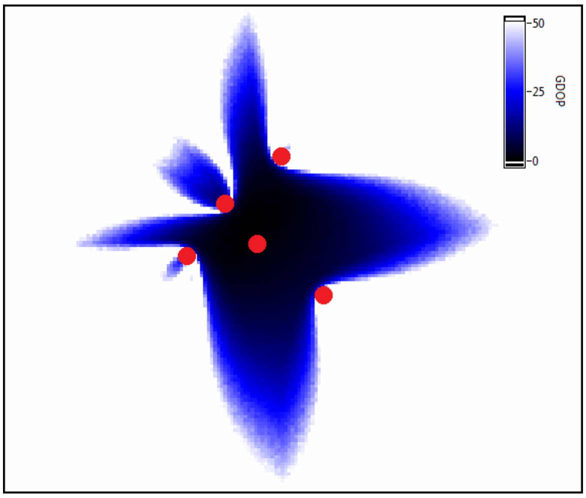

Figure 2. Location dependent position estimation error [1]

This phenomenon does not allow the efficient estimation of the noise statistics. As a result of this, the UFIR filter is a better choice than the Kalman filter.

Assuming an aircraft travelling in a straight line, but crossing singularity zone, the measurement errors are temporarily magnified. Therefore decision-making is recommended to exclude outlier results. Due to the infinite impulse response nature of the Kalman filter ill conditioned inputs can spoil the output of the filter in the long term. From this perspective, the UFIR filter also produces better results.

The constantly rotating primary radar antennas can provide a uniform sampling for the conventional tracking algorithms. Due to the passive nature of the multilaterational radar systems, the sampling time is unambiguously determined by the signal sources. Therefore the sampling is irregular. The Kalman filter, as the UFIR filter can be operated on irregularly sampled input data, but the complexity of the filter will be increased.

V. Target Discrimination

In [1] it was shown, that the Mode A and Mode C based multilateration produces unreliable results, as the false detection rate is very high; but Mode S based multilateration is viable. Our study found that, almost all the time the sources of the Mode S replies can be discriminated by the unique, ICAO issued 24 bit long identifiers, however our tracker method can ignore it, while producing similar discrimination performance (based on state space prediction) in most cases, but heavy air traffic.

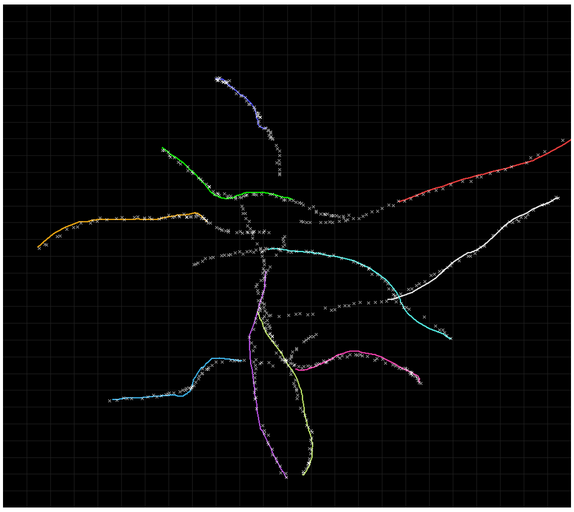

Figure 3. Tracker in simulation

In Fig. 3 and Fig. 4 simulation result is shown, where plot identification was not granted, therefore the plot classification was based on only state space predictions.

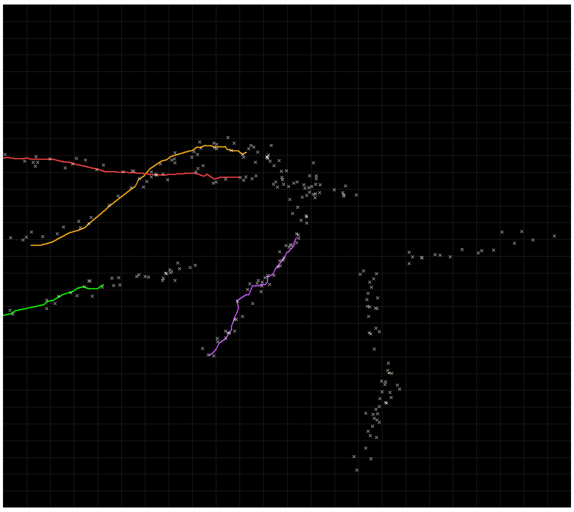

Figure 4. Sparser and noiser plots

VI. TRACK INITIALIZATION

The most challenging task in every tracker solution is the initialization of a new track, because at the beginning there is information shortage, therefore the signal to noise ratio can not be significantly improved through averaging. In our solution we have separated the initialization and tracking phases. The samples are selected with greater tolerance. At the switchover between the initialization and tracking phases, initial state estimation is based on all the collected samples during the initialization process, assuming the most probable rectilinear motion.

As radar plots can be classified almost all the time by the unique ICAO identifier, it improves the initialization process, reducing false track initialization probabilities.

In Fig. 5 a track initialization example is shown on real data. The red dots represent the locations of the receivers, the white contour is the border of Budapest. The aircraft was travelling from "left to right". The green points represent untracked plots or plots excluded from tracking. The track is represented by the blue line. At the beginning of the shown track there is a cloud of green points, which were used in the track initialization process.

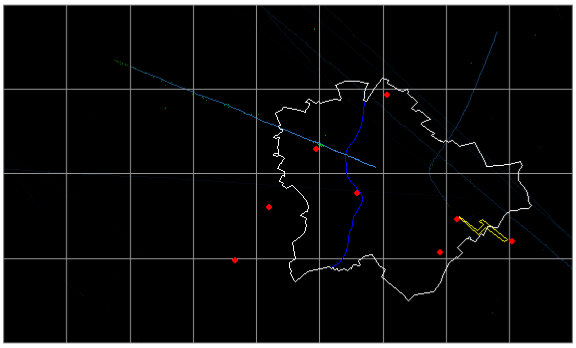

Figure 5. Track initialization example

VII. TRACKING RESULTS

In Fig. 5 after the successful initialization, tracking was performed. The few green dots around the maintained track are radar plots excluded from tracking. This exclusion is based on validity probabilities from trajectory prediction. It was necessary to introduce this signal processing step, otherwise outlier measurements result could detour the track.

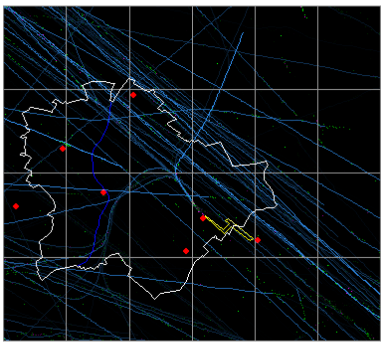

Figure 6. Tracking of maneuvering targets

In Fig. 6 tracks of maneuvering targets are shown. These are take off aircrafts from Liszt Ferenc International Airport of Budapest; the runways are represented by the yellow contour.

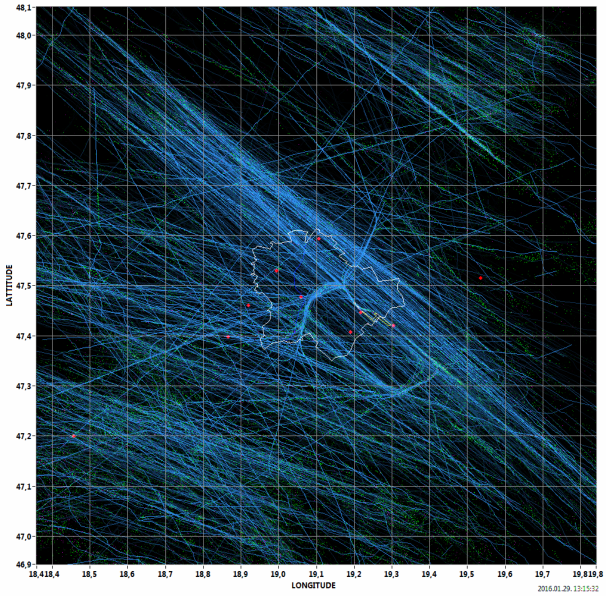

Figure 7. Long term results

In Fig. 7 long term results are shown. The measurement time was spanned over a day. It is clearly seen, that outside the zone defined by the receivers (red dots), where the position estimation errors are significantly increased due to the multilateration principle, the ratio of excluded plots from the tracking is higher away from the zone. In Fig. 7 take off path and air corridor are clearly shown.

VIII. SUMMARY

The results provided by our system show a promising application potential in air traffic control, where this type of radar system can be used as auxiliary sensor solution besides the existing primary and secondary radar systems.

Further development in the near future is planned, one of the trend is the adoption of Eurocontrol's Asterix data exchange format, which would allow the integration of the WAMLAT system into existing ATC systems. As a stand-alone application, a map service integration is required.

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