Obstacle Tracking Results: Cartesian vs. Spherical Particle Filter

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ABSTRACT
This paper focuses on test results from an Airborne Obstacle Tracking system for Unmanned Aerial System (UAS) See and Avoid applications that is based on Particle Filtering algorithm. It performs data fusion of airborne forward looking radar and electro-optical camera by exploiting data gathered during a Sense and Avoid flight experiment at Italian Aerospace Research Centre (CIRA). The developed model resulted adequate for tracking aircraft trajectories, thus overcoming the non-gaussian and non-linear form of the most widely adopted target dynamics models.

Keywords
Unmanned Aerial Systems, Sense and Avoid, Multi-Sensor Data Fusion, Particle Filtering.

INTRODUCTION
Recently, the growing interest in UAS has required the introduction of standards and specifications to allow UAS to fly in civilian, non-segregated airspace alongside manned aircraft. Regulatory agencies prescribe UAS to be equipped with a robust and reliable Detect, Sense and Avoid System (DS&A) in order to guarantee the safety of other objects in the flight path [4-13].

Several solutions have been proposed to attain this function [5,9,6]. In particular, an integrated radar/electro-optical configuration has been selected as the most adequate solution to attain this function within the framework of the CIRA/UNINA TECVOL project. Due to the presence of multi-sensor architecture and non-linearity of the considered dynamics, innovative methodologies are needed to overcome assessed data fusion limitations [8]. In fact, assessed EKF techniques have a series of drawbacks, such as: the linearization can produce highly unstable filters if the assumption of local linearity is violated, and the derivation of the Jacobian matrices are nontrivial in most applications and often lead to significant implementation difficulties [11]. Indeed, the relative flight dynamics is properly represented by a non-linear model in the maneuvering conditions. The EKF can be viewed as providing “first-order” approximations to the optimal terms and these approximations can introduce large errors in the true posterior mean and covariance of the transformed Gaussian random variables that represent the target state; this may lead to sub-optimal performance and sometimes divergence of the filter. In addition, EKF requires both a precise system model and the statistical property of the noise to achieve accurate performance. However, model uncertainty and incomplete statistical information are often encountered in real applications and make it difficult to precisely estimate the system states, leading to a very large estimation error. The paper focuses on test results from a Particle Filter (PF) obstacle tracking system. The software performance are analyzed in order to point out the potential impact of the technique under investigation on obstacle tracking capabilities in terms of accuracy and reliability with respect to an Extended Kalman Filter (EKF) that was developed in the initial stage of the project. A more detailed presentation of the developed EKF solution and the relevant flight test results can be found in Ref. no. 6.

The developed PF tracking algorithm has been implemented in off-line simulations performed on real flight data. In particular, the software has been tested by exploiting both dynamics models in Cartesian and Spherical reference systems taking into account only radar measurements.

AIRBORNE OBSTACLE TRACKING SYSTEM
An Airborne Obstacle Tracking system is the core of a DS&A system. In fact, information about target’s position as well as target motion is considered mandatory for collision avoidance logic in order to decide whether or not an evasive maneuver must be performed.

Flight regulations about mid air collision avoidance prescribe that the minimum distance between two planes must never be less than a bubble distance of about 170 m [14]. Thus, a suitable DS&A system must be able to estimate whether the Distance at Closest Point of Approach (DCPA) between the own aircraft and the intruder will be less than the bubble distance. In case this condition is...
verified, the system must execute the proper maneuver in time to avoid the collision. It is clear that the DCPA constitutes a critical parameter for Collision Avoidance.

Numerical Results

Figure 1 shows the DCPA as estimated by EKF in frontal encounter geometry during real flight tests. The plot highlights a delay to determine the Near Mid Air Collision (NMAC) threat that is verified since the reference GPS system measures a DCPA value shorter than 170 m during all the encounter phase. The interest in innovative data fusion techniques, in particular in Particle Filters, relies on an expected consistent reduction of this delay, since non-linear dynamics models should be faster than linear ones to converge to the exact solution.

Cartesian and Spherical Particle Filter Algorithm

In tracking applications, several applicable models to describe target dynamics exist [9], depending on the choice of the state variables [1-2]. In fact, it is possible to estimate target parameters both in Cartesian and in Spherical reference system.

In Cartesian Particle Filtering algorithm, the state vector is made up by 9 components that comprise the obstacle position coordinates with their first and second time derivatives in North-East-Down (NED) Reference Frame. The target motion is based on a Singer Model [9, 12], in which the acceleration is considered as a Markov process, i.e. the acceleration at one time step depends only on the nearest neighbor values at other time instants. The proposed particle filter algorithm is constituted essentially by prediction and update steps; the choice of Cartesian coordinates is more useful in the prediction step than in the measurement equation, in fact, this choice allows for propagating the state space through a linear dynamic equation.

Instead, in the Particle Filter model developed for a Spherical Coordinate frame the measurement equation is linear, since sensor measurements are in spherical coordinates. In this case, the target dynamic model is based on a Constant Velocity Model [9]. In fact, tests of different target dynamics have shown that a less sophisticated model is able to describe the target motion properly.

Sampling Importance Resampling (SIR) Particle Filtering algorithm have been implemented in both cases [8]. This technique is based on three main steps: generation of particles, calculation of weights associated to the particles and resampling procedure. The last step allows avoiding the degeneracy phenomenon; in particular, multinomial resampling algorithm [3] has been implemented, thus enabling a great quantity of particles to survive to the resampling phase, during the propagation of the state space.

采样重要性重采样（SIR）粒子滤波算法已被在两种情况下实现[8]。该技术基于三个主要步骤：粒子的生成，粒子的权重计算和重采样程序。最后一步允许避免退化现象；具体而言，多项式重采样算法[3]已被实现，从而允许大量的粒子在重采样阶段幸存下来，期间状态空间的传播。

The algorithms output performance is based on range, azimuth, elevation, and their first time derivatives. For the sake of brevity, only the Cartesian Particle Filter range estimate is reported to give an idea of the particle pattern (figure 2). In order to estimate tracking performance, GPS measurements are used as reference.

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The considered flight segment has duration of about 70 s, corresponding to an initial range of about 200 m.

In figure 2, after few seconds a firm track is generated on the basis of only radar measurements. Moreover, a number of ground echoes are detected but they are removed by the algorithm and have no influence on tracking performance.

Since the main interest is in the filters accuracy with respect to EKF, the filters performances in terms of root mean square are reported in table 1.

TABLE I. Filter Performance in terms of rms.

<table>
<thead>
<tr>
<th></th>
<th>KF</th>
<th>PF Cartesian</th>
<th>PF Spherical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range (m)</td>
<td>0.31·10^{-1}</td>
<td>1.2·10^{-1}</td>
<td>0.85·10^{-1}</td>
</tr>
<tr>
<td>Range rate (m/s)</td>
<td>7.0·10^{-1}</td>
<td>0.23·10^{-1}</td>
<td>2.0·10^{-1}</td>
</tr>
<tr>
<td>Azimuth (°)</td>
<td>0.14·10^{-1}</td>
<td>0.18·10^{-1}</td>
<td>0.24·10^{-1}</td>
</tr>
<tr>
<td>Azimuth rate (°/s)</td>
<td>1.0·10^{-1}</td>
<td>3.0·10^{-1}</td>
<td>2.0·10^{-1}</td>
</tr>
<tr>
<td>Elevation (°)</td>
<td>8.0·10^{-1}</td>
<td>0.14·10^{-1}</td>
<td>0.16·10^{-1}</td>
</tr>
<tr>
<td>Elevation rate (°/s)</td>
<td>4.0·10^{-2}</td>
<td>3.0·10^{-1}</td>
<td>1.6·10^{-1}</td>
</tr>
</tbody>
</table>

The analysis has pointed out that Spherical Particle Filter performances are better than the Cartesian ones. In particular, the residual error is in the order of magnitude of Reference System (GPS) used to estimate accuracy for both EKF and PF.

Besides the analysis of the filters accuracy, the main objective of the research activity is the evaluation of the DCPA, defined as follows [5]:

\[
DCPA = \frac{\bar{r} \cdot \bar{V}}{\|V\|^2} \bar{V} - \bar{r}
\]

where \(\bar{r}\) and \(\bar{V}\) are the relative position and velocity vector between the own aircraft and the intruder, respectively.

This distance requires a good estimate of the intruder and own aircraft relative position and velocity. For this reason, an analysis of the velocities errors is needed in order to understand if innovative methodologies are able to provide better estimate parameter value than EKF.

A typical layout of errors in the obstacle velocity as estimated by Cartesian Particle Filter, Spherical Particle Filter and EKF during a flight test are reported in figures 3-4-5.

The plots highlight that Spherical Particle Filter is more accurate than Cartesian Particle Filter. In addition, Spherical Particle Filter converges faster than the EKF in all cases. These results justify the expectation of an improvement on the collision detection capabilities in terms of accuracy for DCPA.

CONCLUSION

The paper focused on algorithms and test results from an Airborne Obstacle Tracking system for UAS See and Avoid applications that is based on Particle Filtering algorithm both in Cartesian and Spherical Reference system. The performance analysis has shown that the Spherical Particle Filter is more accurate than the Cartesian one.
In addition, the reduced uncertainty on velocities estimates as calculated by Spherical Particle Filter is very promising for an improvement on DCPA estimate.

Future works will be addressed to the generation of a filter that is able to provide the distance at closest point of approach directly. Future tests will be performed taking into account also electro-optical data. In fact, multi-sensor architecture is expected to improve the accuracy in estimating the DCPA, i.e. the reliability of collision risk assessment.

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REFERENCES