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Data fusion for ballistic targets tracking using least squares

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ABSTRACT

The paper deals with the problem of state estimation of continuous-time nonlinear system using discrete-time measurements from multiple sensors. In particular, the problem of multi-radar tracking of artillery ballistic objects is considered. A batch estimator based on the iterative least squares approach is developed using simplified and accurate models of ballistic flight. The estimator is applied to process the sequences of measurements from radars tracking the same ballistic target. Estimates of the target state over time are computed and their accuracy is compared to the estimates yielded by the extended Kalman filter. Partial estimates from multiple radars are combined using track fusion approach and propagated using the 3 degree of freedom model of ballistic flight. Accuracy of target's firing point estimation is also analysed with respect to the data rates and locations of the radars with respect to the target. Practical aspects of the proposed method are also discussed.

1. Introduction

Certain physical constraints that include low RF signatures of objects, line-of-sight screening, difficult sensor-to-target geometry and interferences, may seriously limit performance of sensors. In many such cases acceptable level of confidence and accuracy of information can be achieved using specialised signal and data processing, and multisensor data fusion techniques.

In today peace keeping and peace enforcement military operations the increasing use of mortars is observed. As a matter of fact mortars become the preferred weapons in all asymmetric conflicts [1]. Since detecting, defending and denying active mortars requires sufficient accuracy, reliability and short reaction time, the primary sensors used are weapon locating radars (WLR) [2]. Key functions of WLRs in such operations include detecting shells in flight, active tracking over large portion of their trajectories, calculating positions of active mortars and predicting impact points. Reliability and accuracy of information derived from radar measurements is subject to several physical constraints, such as limited observation time or degraded measurement accuracy. In this paper the problem of tracking mortar shells in flight using generic WLRs is considered. Our work aims at increasing the estimation accuracy of target state by means of nonlinear batch estimation techniques using measurements from multiple radars.

In typical recursive state estimation problem the consecutive position measurements of the observed object are processed in order to calculate an optimum estimate of the object's state that minimises certain cost function. An example of such estimator is the Kalman filter, which is based on the quadratic cost function and minimises the single step state prediction error. Recursive nonlinear state estimation methods for ballistic trajectories have been studied extensively. Wishner and Tabaczynski [3] tested three discrete-time algorithms: the extended Kalman filter (EKF), the second-order nonlinear filter and the single stage iteration filter, against a radar tracking problem of a vertically falling body with constant ballistic coefficient. The comparison has shown that the two latter filters outperformed the EKF under all conditions, however, at the price of larger computational complexity. Recent works in nonlinear estimation (see e.g. [4]) resulted in many novel methods. Two methods that received much attention are the particle filter (PF) and the unscented Kalman filter (UKF). Farina and Ristic [5] studied the problem of radar tracking of a ballistic object by using the EKF, UKF and PF. The conclusion was that the EKF remains the preferred nonlinear filter for tracking ballistic targets in practical applications, as it combines the statistical efficiency with a modest computational cost. The problem of simultaneous recursive estimation and classification of mortar and howitzer shells using a bank of EKFs was addressed by Ravindra et al. [6]. Another multiple-model approach to adaptive tracking of artillery rockets was applied by Janczak and Grishin [7].

In contrast to the recursive methods, batch estimation aims at minimising certain (usually quadratic) cost function over the entire sequence (batch) of measurements in a single estimation step. The benefit of batch estimation is in large data sets and, as a

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consequence, improved estimation accuracy and smoothing combined in a single procedure. The well known basic batch method is the linear regression. For nonlinear problems batch estimators take the forms of iterative algorithms, so that the nonlinear model fitting the batch of measurements can be approximated with the assumed precision. A nonlinear batch estimator can typically be based on either of two techniques: the maximum likelihood (ML) [8,9] or the nonlinear regression [10,11]. Nelson et al. [11] applied the iterative least squares (ILS) algorithm, which belongs to the class of nonlinear regression methods, to estimating firing point of the mortar shell based on radar measurements of the target positions in flight. They augmented the standard ILS method with an intercept parameter that improved the iteration convergence for some specific target-to-radar geometries characterised by strong model nonlinearities.

The expected accuracy improvement when using data from multiple sensors encourages employing multisensor fusion techniques to the problem of estimating state and coordinates of firing and impact points of artillery ballistic objects, like rockets and mortars. Harman et al. [12] analysed the problem of estimating firing/launch point (LP) coordinates based on data from multiple WLRs and acoustic weapon locating sensors. A model was developed to predict coverage and performance of these sensors. The expected accuracy of multiple-sensor weapon locating was assessed using an approximate empirical formula describing so called circular error probability (CEP), which can be defined as the circle radius about the true location that encompasses 50% of the firing/launch point estimation error probability density function. Rutkowski and Sankowski [13] considered various data fusion architectures for a network of WLRs. Network design and communications constraints have been discussed and compared to the foreseen performance improvement for different architectures. Rudd et al. [14] considered the problem of tracking of a ballistic missile by means of infrared sensors located on single and multiple satellites. Three fusion approaches were considered: track fusion, measurement (centralised) fusion and a hybrid method using locally associated measurement reports. The latter fusion method was selected and combined with recursive EKFs employed at the level of sensors and in the fusion centre. Frenkel [15], on the other hand, developed a ballistic missile tracking algorithm for two ground-based radars based on recursive EKFs and the track fusion approach. Presented simulations confirm the improvement in the overall state estimation accuracy due to multisensor measurements.

Having said that we realise, that the most evident contribution of our paper is related to developing nonlinear state estimation techniques for processing measurements of mortar positions in flight coming from multiple, possibly geographically dispersed sensors. Addressing apparent radar weaknesses, which are mostly related to relatively poor angle measurement accuracy, we develop a multisensor fusion algorithm based on the batch ILS and the track fusion approach. In comparison to the single-sensor approach presented in [11] we apply more realistic target and environment models, which include the nonlinear dependence of the drag coefficient on the target speed, modelling the drag influence in three dimensions and using the altitude-dependent model of the atmosphere density. The new approach is evaluated using simulations based on various target-to-radar scenarios and for different radars' performances and working parameters.

2. Modelling

Mathematical description of mortar projectiles' trajectory can be based on the 3 degree of freedom model [16–18] with projectile dynamics modelled with respect to a coordinate systems associated either with the flying body or with the trajectory. In this case, appropriate coordinate transformations are needed. Taking into consideration the feasibility and clarity needed in the multisensor system, the Cartesian coordinate system associated with the target LP is chosen. Thus, the local coordinate system used to model the trajectory of the mortar projectile targets is the Cartesian East-North-Up (ENU) originating from the LP and denoted as O_{LP}.

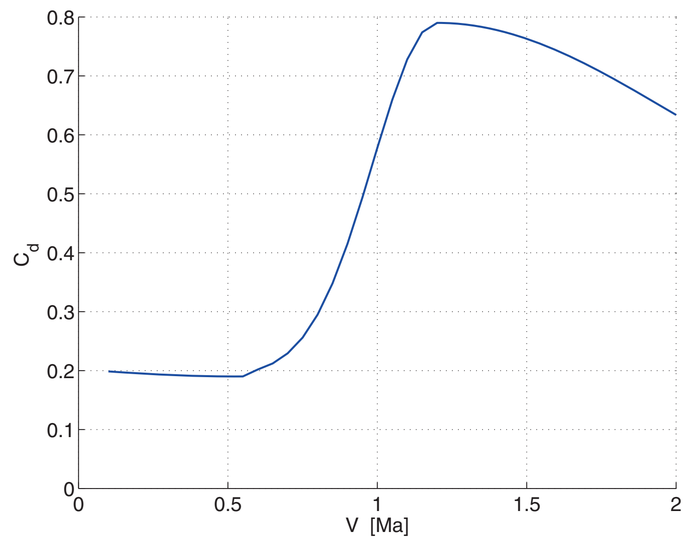

Fig. 1. An example of the drag coefficient profile.

The coordinate system for n-th radar is denoted as $O_{\mathrm{R}n}$, which is another ENU coordinate system originating from the radar location. As the flat Earth model is used, the coordinate transformation from O_{LP} to $O_{\mathrm{R}n}$ is the translation by a vector determined by O_{LP} and $O_{\mathrm{R}n}$ origins.

2.1. Model of the target trajectory

For modelling the environment the flat Earth model is used. Two forces that have primary influence on a mortar projectile trajectory are the Earth gravity and the aerodynamic drag, while Coriolis force and wind influence are omitted. Equations of missile dynamics and motion presented in the O_{LP} coordinate system have the form of

$$\begin{aligned}
\dot{x}(t) &= v_x(t)\\
\dot{y}(t) &= v_y(t)\\
\dot{z}(t) &= v_z(t)\\
\dot{v}_x(t) &= -\frac{SC_d\,[v(t)]\,\rho\,[z(t)]}{2m}v(t)v_x(t)\\
\dot{v}_y(t) &= -\frac{SC_d\,[v(t)]\,\rho\,[z(t)]}{2m}v(t)v_y(t)\\
\dot{v}_z(t) &= -\frac{SC_d\,[v(t)]\,\rho\,[z(t)]}{2m}v(t)v_z(t)-g
\end{aligned} \tag{1}$$

where $x(t)$, $y(t)$, $z(t)$ denote coordinates in the Cartesian O_{LP} system, $v_x(t)$, $v_y(t)$, $v_z(t)$ are the respective velocity components, m is the projectile mass, $C_d[v(t)]$ denotes the drag coefficient depending on projectile velocity $v(t)=\sqrt{v_x^2(t)+v_y^2(t)+v_z^2(t)}$. Function $\rho[z(t)]$ describes the air density, $S=\pi d^2/4$ is the reference drag surface, where d denotes the calibre of the projectile, while g is the constant gravitational acceleration. Eqs. (1) are nonlinear with non-stationary coefficients. Example of the drag coefficient curve is presented in Fig. 1 that is further used in simulations.

The model shown in Fig. 1 is a combination of analytic functions that for certain velocity ranges approximate a typical character of the drag coefficient curve. For a given weapon (here a 60 mm mortar) available technical and operational data are used that