New Approach for the Evolution and Expansion of Space Debris Scenario

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The evolution of the space debris scenario consisting of a very large number of fragments is described using the propagation of the characteristics of equivalent fragments without propagating each and every individual debris fragment. This is similar to characterizing a fluid in terms of the average density, pressure, and temperature without considering the velocities of individual molecules in a fluid element. The space debris fragments are assigned to a three-dimensional bin of semimajor axis, eccentricity, and ballistic coefficient. A suitably defined representative semimajor axis, eccentricity, and an equivalent ballistic coefficient (a, e, B) are defined for the equivalent fragments in each of the bins. A constant gain Kalman filtering technique based on 1) propagating the above characteristics, and 2) updating them as and when further measurements become available, has been proposed. Further the assimilation of the information from other breakups with the passage of time is also possible. The robustness of the constant Kalman gain approach instead of using the Kalman filter statistics helps to handle better the unmodeled or unmodelable errors due to the finite bin size and the environmental perturbations. This methodology is also suggested to handle massive atmospheric data assimilation problems.

Nomenclature

A	=	reference projected area
a	=	semimajor axis
B	=	($=C_D A/m$, Ballistic coefficient)
C_D	=	drag coefficient
e	=	eccentricity
K_B	=	constant Kalman gain for ballistic coefficient update
K_N	=	constant Kalman gain for number density update
m	=	mass
N	=	number density
$\mathbf{P}_0$	=	covariance matrix of the initial state vector
$\mathbf{Q}$	=	covariance matrix of the state noise
$\mathbf{R}$	=	covariance matrix of the measurement noise
$\Re$	=	covariance matrix of the innovation
Δ	=	small change in semimajor axis or eccentricity per orbit
$\mathbf{v}_k$	=	innovation

I. Introduction

SOME of the most difficult issues in the study of the evolving low earth orbit (LEO) debris scenario [1,2] are 1) the unpredictable on orbit breakups occurring at random location, intensity and directionality, generating debris clouds made up of enormous number of fragments, 2) the presently existing debris fragments running into thousands for large objects and millions for the smaller ones, 3) the uncertainty of the fragment's physical characteristics such as the mass, shape, and size, 4) the uncertainty of the other important characteristic like the ballistic coefficient (=the product of the drag coefficient and the reference projected area divided by the mass) accounting for the aerodynamic force on

the various fragments and thus change its orbital characteristics, 5) the variability of the perturbations due to air density, gravitational anomalies, lunar solar perturbations, and solar radiation pressure, 6) the debris clouds taking about a few years to merge with the background debris scenario, 7) the uncertainty in the various measurements by radar, optical telescopes, and retrieved satellites and space objects, and 8) any simulated laboratory experiment provides only a sample characteristic of the breakup.

This paper describes a probabilistic estimation theoretic methodology [3] for tracking a group of evolving space debris fragments of various sizes in the LEO and also estimate the so-called equivalent ballistic coefficient for such group of fragments. Some of the compulsive reasons to follow the above methodology are the uncertainty, variability, complexity, enormity of the states and measurements, and the possibility of even deterministic problems be modeled as probabilistic and mathematically treated in suitable ways [3].

For studying the long-term evolution of the space debris, a model [1,2,4] has to be assumed. These models are generally derived by simulating the various historical breakups, assuming some growth rate due to later breakups, and also using the measured data. The long-term predictions of the scenario depend on the qualitative structure and the quantitative parameters in the above model. At large times the prediction could depart greatly from the real scenario due to the sensitivity of the evolution to the inaccuracies in the model or the parameters. As is well known, there are large differences in the estimated number density between many debris models [1,2,5]. The only way the prediction can be made to follow more closely the real situation is to update the predicted value of the states and the parameters by assimilating properly the available measurements at later times. Such updated states and parameters can be used for further evolution in time and later updated using subsequent measurements as and when they become available. Another way of interpreting this is to say that for proper progress "theory" and "experiments" should go together.

The present approach differs from the earlier studies by providing a systematic way of assimilating the information in the measurement data at later times with the present debris scenario. Apart from such "fusion" it also helps to expand the scenario to provide an estimate of the so-called equivalent ballistic coefficient (EQB) of the equivalent

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