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Physics and human-based information fusion for improved resident space object tracking

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Abstract

Maintaining a catalog of Resident Space Objects (RSOs) can be cast in a typical Bayesian multi-object estimation problem, where the various sources of uncertainty in the problem – the orbital mechanics, the kinematic states of the identified objects, the data sources, etc. – are modeled as random variables with associated probability distributions. In the context of Space Situational Awareness, however, the information available to a space analyst on many uncertain components is scarce, preventing their appropriate modeling with a random variable and thus their exploitation in a RSO tracking algorithm. A typical example are human-based data sources such as Two-Line Elements (TLEs), which are publicly available but lack any statistical description of their accuracy. In this paper, we propose the first exploitation of *uncertain* variables in a RSO tracking problem, allowing for a representation of the uncertain components reflecting the information available to the space analyst, however scarce, and nothing more. In particular, we show that a human-based data source and a physics-based data source can be embedded in a unified and rigorous Bayesian estimator in order to track a RSO. We illustrate this concept on a scenario where real TLEs queried from the U.S. Strategic Command are fused with realistically simulated radar observations in order to track a Low-Earth Orbit satellite.

Keywords: Resident Space Object tracking; Information fusion; Two-line element

1. Introduction

Maintaining information on a so-called Resident Space Objects (RSOs) can be cast as a typical *single-object detection and tracking problem*. The individual *state* of the object consists of kinematic and relevant model parameters and/or its exploitation for various activities related to space, such as mission planning, conjunction analysis to prevent collisions, etc. Typically, the individual state of an orbiting object describes a kinematic relationship (Kepler elements, or position/velocity coordinates), but may include additional characteristics such as its attitude and its ballistic coefficient.

The main challenge to the resolution of most detection and tracking problems is to appropriately address the various sources of *uncertainty* involved in its different components, due to the limited knowledge in the signal processing chain affecting the acquisition of information on the population of objects. In the context of Space Situational Awareness (SSA), the relevant sources of uncertainty can be sorted in two broad categories:

1. To first order, the perturbing accelerations on the RSO population are known, gravity being the dominant perturbing source. However, no orbital propagator is able to produce the exact dynamical state of an RSO, since

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the various physical perturbations affecting orbiting trajectories are either approximated, discarded on purpose for the sake of algorithmic efficiency, or simply unknown to the space analyst. In addition, satellites owned by others may transition to new orbital paths unknown to the analyst. New RSOs entering some specific orbital region, for example through a collision or a new launching event, are not all accounted for and thus the number of RSOs remain uncertain.

2. The mechanisms through which observations (or opinions) are produced by the data sources are partially known, at best. Traditional, physics-based sensors like radars, telescopes, or cameras are subject to missed detections, false positives, observation noise, from which some statistical description is usually available. On the other hand, the Two-Line Elements (TLEs) produced by the U.S. Strategic Command (USSTRATCOM) are publicly available, but no information regarding the accuracy of the orbital elements or the confidence in the object labeling are available.

The Bayesian estimation framework is a very popular approach to solve multi-object detection and tracking problems, and the origin of the overwhelming majority of modern tracking algorithms. Its key features are that:

(a) the uncertainty on each component of the system is modeled with a *random variable* and characterized with a *probability distribution*, and
(b) a probability distribution can be updated sequentially, or *filtered*, with the availability of new information regarding the corresponding random variable.

Bayesian filters then maintain a probabilistic description of the population of objects and propagate it through time, updating it whenever new observations are collected from a data source, also described through a probabilistic model.

One of the key challenges of Bayesian estimation is to maintain an appropriate representation of the uncertainty on the components of the system, especially when information about their state is scarce. A typical example in the context of SSA is the initial orbit determination procedure through which the possible values for the dynamical state (position, velocity coordinates) of a newly-detected RSO are restricted to a specific subspace known as the admissible region in DeMars and Jah (2013). The physical considerations behind the initial orbit determination procedure do not provide information on whether any dynamical state within the admissible region is likelier than the other, but it does *not* indicate that all states within the admissible region are equally likely *either*.[1] However, a probabilistic interpretation of the RSO's initial state can lead to a uniform probability distribution on the admissible region, thus producing a description of the RSO's state that is *not* inferred from the information available to the analyst. It thus appears that probability density functions (PDFs) are inappropriate tools to describe admissible regions, as argued in a recent study (Worthy and Holzinger, 2017b). Another example is the exploitation of human-based or semantic data sources such as TLEs or natural languages statements: they could provide a wealth of information regarding RSOs, but the lack of statistical information on their accuracy/truthfulness makes their probabilistic representation, and thus their integration to a Bayesian tracking filter, difficult and largely unexplored to this day.

Alternatives to the standard probabilistic representation of uncertainty exist, such as fuzzy logic, imprecise probabilities, possibility theory, fuzzy random sets, and Dempster-Shafer theory (Zadeh, 1965; Dempster, 1967; Shafer, 1976; Dubois and Prade, 1983; Yen, 1990; Walley, 1991; Friedman and Halpern, 2001); recently, the Dempster-Shafer theory has been exploited to approach the initial orbit determination problem with admissible regions in Worthy and Holzinger (2017a). While these methods have been widely used to describe the uncertainty referring to a *fixed* unknown state, their exploitation to the estimation of *dynamical* systems is less straightforward, limiting their applicability to sequential estimation problems – that is, to the design of detection and tracking filters.

A recent alternative is given by the *outer probability measures (OPMs)* as introduced in Houssineau and Bishop (2018). They aim at proposing a "prejudice-free" representation of the uncertainty on a system through a natural construction that is derived from the available information, and nothing more. Built from fundamental tools of measure theory, OPMs are compatible with the Bayesian filtering framework and can be integrated in a complex system where some uncertain components are described with PDFs, while others are described with OPMs.

In this paper, we will focus on the representation of uncertainty for SSA data sources supporting a RSO tracking algorithm. More specifically, we will show that radar observations (physics-based information) and TLEs (human-based information) can both be represented by OPMs and integrated into a Bayesian filtering algorithm, where the information on the RSO's state is maintained with a probability distribution. Section 2 presents the concepts of OPM and possibility function, and Section 3 describes the filtering equations of the single-object Bayesian tracking algorithm exploiting possibility functions. Section 4 focuses on the modeling of the data sources relevant to this paper, i.e., a radar with range, Doppler and angular measurements, and a "TLE-generator". Then, Section 5 describes the construction of a target tracking scenario with realistically-simulated radar observations and real TLE data provided by the USSTRATCOM, and gives a detailed implementation of the single-target tracking

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[1] It turns out that they are not, since a more restrictive initial orbit determination procedure can lead to a *constrained* admissible region (DeMars et al., 2012). Additional statistical information on the newly-detected object can also lead to a more refined probabilistic description of the admissible region (Hussein et al., 2018).