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Astrometric and photometric data fusion for inactive space object mass and area estimation ☆

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ABSTRACT

This paper presents a new method to determine the mass of an inactive space object from the fusion of photometric and astrometric data. Typically, the effect of solar radiation pressure is used to determine area-to-mass ratio for space objects from angles observations. The area-to-mass ratio of a space object can greatly affect its orbital dynamics. As a consequence, angles data are sensitive to this quantity. On the other hand, photometric data is not sensitive to mass but is a strong function of the albedo-area and the rotational dynamics of the space object. The albedo-area can be used to determine the amount of energy reflected from solar radiation. Since these two data types are sensitive to albedo-area and area-to-mass, then through fusion of photometric data with angles data it is possible to determine the area and mass of a space object. This work employs an unscented Kalman filter to estimate rotational and translational states, area and mass of an inactive space object. Mass is not observable with only angles data or only photometric data alone, but it is shown in this work that with the two combined data types mass can be recovered. Recovery of space object characteristics and attitude and orbit trajectories with sufficient accuracy is demonstrated in this paper via simulation.

1. Introduction

Deep space optical surveys of near geosynchronous (GEO) objects have identified a class of high area-to-mass ratio (HAMR) objects [1]. The exact characteristics of these objects are not well known and their motion pose a collision hazard with GEO objects due to the SRP induced, large variations of inclination and eccentricity. These objects are typically non-resolved and difficult to track due to dim magnitude and dynamic mis-modeling. Therefore, characterizing the large population of HAMR objects in geostationary orbit is required to allow for a better understanding of their origins, and the current and future threats they pose to the active SO population.

Light curves (i.e., the SO temporal brightness as seen from the observer) have been used to estimate the shape for an object. In particular, light curve approaches have been studied to estimate the shape and state of asteroids [2,3]. Reference [4] uses light curves and thermal emissions to recover the three-dimensional shape of an object assuming its orientation with respect to the observer is known. The benefits of using a light curve-based approach over the aforementioned others is that it is not limited to larger objects in lower altitudes, and it can be applied to small and dim objects in higher altitudes, such as geosynchronous orbits. Here light curve data is considered for mass estimation, which is also useful since it provides a mechanism to estimate both position and attitude, as well as their respective rates [5,6].

Estimating the dynamic characteristics of a HAMR object using light curve and astrometric data can allow for mass parameters to be observable. Estimating mass for HAMR objects can help in the development of a detailed

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understanding of the origin and dynamics of these objects. It has been shown that the SRP albedo area-to-mass ratio, $C_r\mathcal{A}/m$, is observable from angles data [7] through the dynamic mis-modeling of SRP forces. The term mis-modeling represents the inappropriate modeling of the force model and this mis-modeling produces a difference between observations and prediction. These differences allow for parameters to be estimated. Reference [7] conducts a study with simulated and actual data to quantify the error in the estimates of $C_r\mathcal{A}/m$ and good performance is found using data spanning over a number of months. Also Ref. [8] shows that orbital, attitude and shape parameters can be recovered with sufficient accuracy using a multiple-model adaptive estimation approach coupled with an unscented Kalman filter. This approach works reasonably well but requires that the area-to-mass ratio is known *a priori*. The purpose of this work is to show that since $C_r\mathcal{A}/m$ is observable from angles data and shape/albedo properties are observable from photometric data, then by fusing these data types mass can be extracted with reasonable accuracy.

Filtering algorithms for state estimation, such as the extended Kalman filter (EKF) [9], the unscented Kalman filter (UKF) [10] and particle filters [11], are commonly used to both estimate hidden (indirectly observable) states and filter noisy measurements. The basic difference between the EKF and the UKF results from the manner in which the state distribution of the nonlinear models is approximated. The UKF, introduced by Julier and Uhlmann [10], uses a nonlinear transformation called the unscented transform, in which the state probability density function (pdf) is represented by a set of weighted sigma points (state vectors deterministically sampled about a mean). These are used to parameterize the true mean and covariance of the state distribution. When the sigma points are propagated through the nonlinear system, the posterior mean and covariance are obtained up to the second order for any nonlinearity. The EKF and UKF assume that the process noise terms are represented by zero-mean Gaussian white-noise processes and the measurement noise is represented by zero-mean Gaussian random variable. Furthermore both approaches assume that the *a posteriori* and *a priori* pdf is Gaussian in a linear domain. This is true given the previous assumptions but under the effect of nonlinear measurement functions and system dynamics the initial Gaussian state uncertainty may quickly become non-Gaussian. Both filters only provide approximate solutions to the nonlinear filtering problem, since the *a posteriori* and *a priori* pdf is most often non-Gaussian due to nonlinear effects. The EKF typically works well only in the region where the first-order Taylor-series linearization adequately approximates the non-Gaussian pdf. The UKF provides higher-order moments for the computation of the *a posteriori* pdf without the need to calculate Jacobian matrices as required in the EKF. The light curve measurement model is highly nonlinear, and Jacobian calculations are non-trivial; thus, the UKF is used to provide a numerical means of estimating the states of the SO using light curve measurement models.

Attitude estimation using light curve data has been demonstrated in Ref. [12]. The main goal of this current work is to use light curve data to, autonomously and in near realtime, determine the mass of a SO along with its attitude (rotational) and translational states. In order to accomplish this task, a UKF is designed for state estimation of these quantities. The translational dynamics includes both conservative gravitational and non-conservative SRP. The rotational dynamics includes classic Euler dynamics coupled with SRP torque. Light curve and angles data are employed in the UKF structure to estimate the states.

The organization of this paper is as follows. First, the methods used to recover mass are discussed. Then the models used for SO shape, orbital dynamics and attitude dynamics are discussed. Following this a description of the measurement models used in this paper is given. Next, a review of the UKF approach is provided. Finally, simulation results of the mass and albedo-area estimation approach are provided.

2. Details of the present three approaches

Three approaches are considered in this work: the first approach estimates for albedo-area, $\mathcal{A}C_{\text{diff}}$, which uses an assumed value for the albedo, a, to allow for estimation of mass, and the second approach uses estimated rotational dynamics to infer information about the area and therefore allow information about mass to be gained. The third approach estimates albedo rather than area and is an alternative to the second approach. These approaches are referred to as method I, II, and III respectively. Also this work assumes completely diffuse objects and therefore the albedo is equal to $a = C_{\text{diff}}$. As mentioned previously, light curve data is sensitive to $\mathcal{A}C_{\text{diff}}$ and angles data are sensitive to $C_r\mathcal{A}/m$, where C_r is the albedo coefficient for the SRP force [7]. The C_r coefficient is a function of the albedo of the SO; $C_r = 1+r$ for the cannonball model [7] where r is the reflectance coefficient and is a function of the albedo, and therefore, to allow for mass to be separated from area, an estimate of albedo must be determined. It will be shown in Section 2.3 that $C_r = 1+\frac{2}{3}C_{\text{diff}}$ for a diffuse sphere assuming Lambert's cosine law and $C_r = 1+\frac{4}{9}C_{\text{diff}}$ for a diffuse flat plate assuming Lambert's cosine law with the normal direction aligned with the sun direction.

Air Force Maui Optical and Supercomputing site Advance Electro-Optical System (AMOS) researchers have calibrated for nominal albedo by using observations of known SOs to determine effective albedos for different classes of objects [13]. The analysis indicated the best effective albedo and albedo range that provides a 90% confidence range for each object class. NASA and AMOS have jointly determined that, for payloads and rocket-bodies reflecting sunlight, an albedo of $a \approx 0.3$ best reproduces known sizes with a 90% confidence range of $0.1 \le a \le 0.7$ [13]. For orbital debris, an effective albedo of $a \approx 0.15$ best reproduces the sizes estimated from radar with a 90% confidence of roughly $0.05 \le a \le 0.3$ [13]. Therefore, assuming a value for the albedo that is consistent with observations of a typical SO can provide a means to estimate mass with estimates of albedo-area. The state vector for the joint attitude, position and parameter estimate problem using method I is given by

$$\mathbf{x}_k = [\mathbf{q}_I^{B^T} \quad \omega_{B/I}^{B^T} \quad \mathbf{r}^{I^T} \quad \mathbf{v}^{I^T} \quad m \quad \mathcal{A}\mathbf{C}_{\text{diff}}^T]^T|_{t_k}, \tag{1}$$

where position and velocity of an Earth orbiting SO are denoted by $\mathbf{r}^I = [x \;\; y \;\; z]^T$ and $\mathbf{v}^I = [v_x \;\; v_y \;\; v_z]^T$, respectively,