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New manoeuvre detection method based on historical orbital data for low Earth orbit satellites

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Abstract

A new method of deriving satellite manoeuvring information from historical two-line element (TLE) data is proposed. The historical manoeuvres of a satellite are detected by identifying abnormal data segments in the TLE derived time series of selected orbital parameters (semi-major axis and inclination). Firstly, moving window approach is used to divide the time series into a series of equal-length data segments. Secondly, two anomaly indexes are introduced to measure the anomaly degree of the semi-major axis segment and the inclination segment with respect to the propagated states. Finally, the corresponding detection thresholds are separately derived by analysing the anomaly indexes of the two types of data segments indicative of orbit manoeuvre. When the anomaly index of a semi-major axis segment or inclination segment exceeds the corresponding threshold, a specific type of orbit manoeuvre with specific magnitude is declared. The manoeuvre detection results of two low Earth orbiting satellites indicate that the proposed method can efficiently eliminate data noise interference and accurately detect historical manoeuvres. Furthermore, manoeuvres with designated magnitudes can be exclusively detected by adjusting the user-specified arguments in the threshold expression levels.

Keywords: Manoeuvre detection; Orbital anomaly; Discrete wavelet transform; Two-line element

1. Introduction

Detecting orbital anomaly of space objects is an increasingly important field of study. Timely knowledge of space events, such as satellite manoeuvres, explosions, collisions and fragmentations, is needed to promptly take mitigation actions. Additionally, information of the historical event is a valuable resource that can be used to analyse the activity routine of a space object for any large-scale space situational awareness program (Abbot and Wallace, 2007).

Since space events will cause certain orbital elements of a satellite to change abruptly, the historical manoeuvring information of the satellite can be obtained by analysing the temporal variations in the observations of such parameters. Given their regularly updated history, publicly available two-line element catalogue data provided by US Strategic Command are particularly useful to detect space events acting on a space object. So far, several detection methods have been proposed for space events in historical TLE data. Patera (2008) first proposed a detection method by adopting the moving window curve fit technique. In this method, space events are detected by identifying anomalous deviations between the published values of an orbital parameter and the corresponding values given by polynomial fitting. Based on this technique, two modified methods were developed separately by Kelecy et al. (2007) and Swartz et al. (2010). Song et al. (2012) proposed an analysis method for orbit anomaly detection named semi-major axis change method. In this method, the mean value and standard deviation of the semi-major axis change in different time intervals are calculated according to historical data

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and used to develop the anomalous criterion. S. Lemmens and H. Krag proposed two novel methods for detecting space events based on the analysis of their TLE history (Lemmens and Krag, 2014). The first method detects non-natural anomalous events in low Earth orbit based on a consistency check between arbitrary two-line element sets of the same object. The second method uses the time series of an object containing the orbital elements, or a derived quantity thereof, and evaluates it for any type of unexpected changes by methods from robust statistics and harmonics analysis. C. Bowman and P. Zetocha proposed a method which uses neural networks to analyse and detect abnormal events in space catalogue updates of TLE records (Bowman and Zetocha, 2015).

The above methods usually detect satellite manoeuvre by identifying outliers in the TLE-derived time series of an orbital parameter because orbital manoeuvre abruptly changes certain orbital parameters (such as semi-major axis and inclination). The threshold to decide on which points in the time series become outliers is concluded using a statistical technique. When accounting for the existence of the TLE data noise (the noise results from the imperfect quality of the measurements used to derive the TLEs in the orbit determination process and uncertainties in the modelling processing), these methods may inevitably identify the outliers that belong to data noise as orbit manoeuvre.

The TLE data noise is not related with the actual orbit of a satellite but shows up as random deviation between the observed and actual values of the orbit parameter. However, an orbit manoeuvre directly reshapes the satellite orbit, and the post-manoeuvre observations of certain orbit parameters deviate from prior-manoeuvre ones within a time period. Outliers in the time series of an orbit parameter can be caused by either data noise or satellite manoeuvre, whereas abnormal data segments in the time series can only be interpreted as orbit manoeuvre (when other forms of space events are neglected). In detecting manoeuvre, identifying abnormal data segments is more reasonable than distinguishing outliers. This paper presents a method to detect satellite manoeuvre by identifying abnormal data segments in the TLE derived time series of selected orbital parameters. Firstly, the time series is divided into a series of equal length data segments by using the moving window approach. Secondly, the extent of each data segment deviating from its reference orbit ephemeris produced by orbit propagation is quantified by using the time series comparison technique. Finally, the segments with abnormal deviation degrees are referred to as historical orbit manoeuvre.

The rest of this paper is organised as follows. In Section 2, abnormal segments of the semi-major axis and inclination are selected to reveal the historical manoeuvre by analysing the temporal evolution properties of the Keplerian elements. Two manoeuvre detection indexes are proposed. In Section 3, the proposed manoeuvre detection indexes are thoroughly analysed to derive two thresholds, which can be used to identify abnormal segments of the semi-major axis and inclination corresponding to specific orbit manoeuvre. In Section 4, the data processing scheme for the proposed manoeuvre detection method is detailed. In Section 5, the manoeuvre detection results on two typical low Earth orbit (LEO) satellites with known manoeuvre history are discussed to thoroughly examine the performance of the proposed detection method. Finally, our main conclusions are summarised in Section 6.

2. Manoeuvre detection indexes based on moving window approach

An orbit manoeuvre abruptly changes certain orbit parameters and produces a consequent abnormal segment in the time series of such parameters. Hence, the abnormal segment can be used to indicate the corresponding orbit manoeuvre. Based on this idea, the detection indexes (named as anomaly indexes) of the proposed manoeuvre detection method are proposed in this section.

2.1. Definition of the manoeuvre detection indexes

Keplerian elements $\{a, e, i, \Omega, \omega, f_0\}$ are the most popular set of orbit elements used to describe the state of a satellite in space, as shown in Fig. 1.

Where the semi-major axis a and eccentricity e determine the orbit size and shape, respectively; the inclination i, the node Ω and the argument of perigee ω jointly define the orbit plane orientation; and the true anomaly f_0 specifies where the satellite is within the orbit trajectory at time t_0.

The orbit of a LEO satellite and the related orbit elements slowly change because of various perturbation forces, whereas an orbit manoeuvre rapidly changes the orbit. Active LEO satellites typically implement two types of manoeuvre. The energy manoeuvre changes the orbit shape and size and manifests as an abrupt temporal change in the semi-major axis and/or eccentricity. The inclination manoeuvre changes the orientation and/or size of the orbit and manifests as an abrupt change in the inclination or node in the TLE time history (Kelecy et al., 2007). In this paper, the abnormal data segments of the semi-major axis and inclination are detected from their time series to reveal the two types of historical manoeuvre.

Firstly, all candidate segments of semi-major axis and inclination should be extracted from the TLE time series of a given satellite. Secondly, considering that any segment might be abnormal, indexes that can separately quantify the anomaly degree of the semi-major axis and inclination segments are needed.

The moving window approach is used to obtain the candidate segment. The TLE time series of a given satellite is scanned from left to right by running a moving window of fixed size. In each step, a segment of length m is extracted, and the data window is advanced by $m/2$ TLEs. The semi-major axis and inclination segments are obtained directly from the TLE segment. By propagating the initial element of a TLE segment to the second, third and mth