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Historical-orbital-data-based method for monitoring the operational status of satellites in low Earth orbit

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ABSTRACT

A method is developed for monitoring the operational status of satellites in low Earth orbit (LEO) based on their historical two-line element (TLE) data. In this method, whether the satellite still has the maneuverability to maintain the orbital altitude is used as the criteria for judging the operational status, the whole judgment process includes two steps. The first step is to design a specialized algorithm to detect orbit maintenance maneuvers from the satellite's TLE time-history. The algorithm uses abnormal data segments of the TLE derived semi-major axis time series to identify the orbit maintenance maneuver, and various measures are taken to eliminate the noise interference and to ensure the detection accuracy. The second step is to use the detected maneuvering history to determine the current operational status of the satellite. In this step, the statistical technique is used to get the temporal regularity of the satellite to implement orbit maintenance maneuvers and the allowable range of the natural variation of the semi-major axis, so then the criteria for determining the satellite operational status is developed. Analysis of typical LEO satellites indicates that this method can accurately determine the current operational status of the satellite and provide an approximate estimation interval of the satellite retiring time, which is of practical value.

1. Introduction

Since the mankind entered the space age, a large number of satellites have been sent into space and the number is still growing continuously. After retiring, these satellites will stay in space over a long period of time if no measures are taken and can easily trigger space events such as spacecraft collisions and explosions, becoming one of the main sources of space debris. Thus, in terms of space debris mitigation, the disposal of retiring satellites is the focus of attention. The Interagency Space Debris Coordination Committee (IADC) required that the orbital lifetime of LEO spacecraft should be limited to a period not longer than 25 years after the end of life [1]. If this 25-year guideline can be complied strictly, the deteriorating space environment in LEO region will gradually be improved. Whether it is to evaluate the compliance of this guideline on the global level or to manage the space object, monitoring the operational status of LEO satellites and detecting retired satellites in time is an essential capability.

Operational spacecraft in LEO can be roughly divided into two categories: those who are not maneuverable and those who can change their orbit through executing an orbit maneuver. Although the number of non-maneuverable spacecraft (such as many cubesats and microsats launched in recent years) accounts for a large proportion and continues to grow rapidly, only maneuverable satellites are discussed in this paper. Because for a satellite without maneuverability, regardless of how long it was designed to service, it's entire orbital lifetime is determined once deployed to the mission orbit. From the perspective of space debris mitigation, attention should be paid to the entire orbital lifetime of such satellites rather than the remaining lifetime after retirement. Actually, the Joint Space Operations Center pointed out that the identification and cataloguing for this type of spacecraft mainly depends on the information from the launch provider and/or the spacecraft owner/operator, and it is faced with great technical difficulty to use orbital observation data to determine the operational status [2]. In contrast, for maneuverable satellites, since they can extend their orbital lifetime through executing orbit maneuvers (in fact, they do often maneuver to meet mission requirements), their operational status should be monitored to timely detect retired satellites. Generally, this type of satellite will conduct orbit maintenance maneuvers from time to time to make up the orbital decay caused by atmospheric drag, etc., ensuring that the orbital attitude is within an allowable range. After retiring, no orbital maneuvers will be conducted, and the orbital altitude begins to decrease continuously under the drag effect. Therefore, whether a LEO satellite still has the maneuverability to maintain its orbital altitude can be used as a criteria for judging its current

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Table 1
Segmentation of the semi-major axis time series.

NO.	Reference for extrapolation	Segment	Sequence of prediction values
1	a_1	$S_1 = \{a_2, a_3, \cdots, a_{m+1}\}$	$S_{p1} = \{a_p(t_2/t_1), a_p(t_3/t_1), \cdots, a_p(t_{m+1}/t_1)\}$
2	a_2	$S_2 = \{a_3, a_4, \cdots, a_{m+2}\}$	$S_{p2} = \{a_p(t_3/t_2), a_p(t_4/t_2), \cdots, a_p(t_{m+2}/t_2)\}$
⋮	⋮	⋮	⋮
L	a_L	$S_L = \{a_{L+1}, a_{L+2}, \cdots, a_{L+m}\}$	$S_{pL} = \{a_p(t_{L+1}/t_L), a_p(t_{L+2}/t_L), \cdots, a_p(t_{L+m}/t_L)\}$

operational status. In other words, the key to determine if a LEO satellite is retired is to determine if the satellite still performs the orbit maintenance maneuver. Since orbital maneuvers, including the orbit maintenance maneuver will cause some orbital elements of the satellite to change abruptly, the historical maneuvering information can be obtained through analyzing the temporal variation in observations of these parameters. Based on the maneuvering history, a statistical analysis of the maneuvering rule can be conducted to determine the current operational status of the satellite.

In the field of detecting satellite maneuvers using historical orbital data, some detection algorithms have been proposed so far [3–6]. In these methods, the publicly available orbital data namely the two-line element set distributed by the US Strategic Command is selected for analysis. Additionally, maneuvers are detected by locating outliers in the temporal observation sequence of certain orbital parameter. Although existing algorithms can detect maneuvers from the historical TLE data, exact information about the maneuver type cannot be obtained, making it difficult to meet the requirement of exclusively detecting orbit maintenance maneuvers from a satellite's TLE time-history. Furthermore, in terms of judging the satellite's operational status based on the maneuvering history, only few studies are found so far. In these studies, a satellite is considered to have retired as long as orbital anomalies are no longer detected from the time series of a given orbital parameter since sometime in the past. Hence, only rough information about the operational status is obtained [6], [7].

In this paper, a method for monitoring the current operational status of LEO satellites by analyzing their historical TLE data is presented. At first, an algorithm is specially designed to detect historical orbit maintenance maneuvers of LEO satellite by locating corresponding abnormal data segments in the TLE derived semi-major axis time series. Then, by performing a statistical analysis to the detected maneuvering history, the regularity of the satellite to perform orbit maintenance maneuver is obtained, and is used to determine the satellite's current operational status. The rest of paper is organized as follows: Section 2 introduces the detection algorithm of the orbit maintenance maneuver proposed; Section 3 details the method of determining the satellite's current operational status based on the maneuver detection results; in Section 4, the proposed monitoring method is applied to analyze the current operational status of 3 typical LEO satellites, so that the correctness and practicality of the method is verified; at last, main conclusions of the paper are set out.

2. Detection of the orbit maintenance maneuver

Orbital maneuvers that an active satellite may implement can usually be divided into three types: coplanar, noncoplanar, and fixed Δv maneuvers [8], all of which will result in abrupt changes in some orbital elements. The coplanar maneuver will change the orbit size and shape and the location of the line of apsides, and manifests as abrupt changes in the semi-major axis, eccentricity, and argument of perigee. The noncoplanar maneuver will change the orientation of the orbital plane and manifests as abrupt temporal changes in the inclination and the right ascension of the ascending node. Whereas the fixed Δv maneuver is really a combined maneuver because it typically changes the size, shape, and orientation of the orbital plane simultaneously. The orbit maintenance maneuver is a typical coplanar maneuver and it definitely causes abrupt temporal changes in the semi-major axis. Designing a suitable algorithm, this type of maneuvers can be exclusively detected from the TLE derived time series of the semi-major axis observations. However, due to existence of the TLE data noise [9], the semi-major axis time series need to be smoothed to eliminate the noise interference before being analyzed to reveal historical maneuvers. Here, a filter based on the principle of local regression using weighted linear least squares and a 2nd degree polynomial model, called RLOESS, is applied to fulfill the smoothing mission. Detailed information about the filter can be easily found in published literatures such as [10] and [11].

If a satellite is free from any non-natural disturbance, arbitrary two elements in the time series of the semi-major axis observation will satisfy the consistency condition determined by the satellite's orbital motion model. That is, if use the SGP4/SDP4 model [12] to propagate an observation to the subsequent one, the resulting prediction error should be small. However, if an orbit maintenance maneuver is performed before a certain observation, subsequent observations of the semi-major axis will significantly deviate from those predicted by extrapolation of pre-maneuver observations. After segmenting the semi-major axis time series and measuring the extent of each data segment deviating from the corresponding sequence of prediction values, data segments with abnormal deviation degree can be used to identify historical orbit maintenance maneuvers.

Here, the semi-major axis time series is segmented by running a moving window of fixed size. Denote the time series as $S = \{a_1, a_2, \cdots, a_N\}$ and the window size as m, a total of $L = N - m$ data segments are obtained, as shown in Table 1. The SGP4/SDP4 model is used to propagate each reference data in the table to epochs at the subsequent m elements sequentially, so that prediction errors corresponding to elements in each segment are obtained. As shown in Table 1, $a_p(t_{i+j}/t_i)$ represents the prediction value corresponding to the jth element of the ith data segment. Accordingly, the prediction error is $\Delta a_{i,i+j} = a_p(t_{i+j}/t_i) - a_{i+j}$ and the prediction duration is $\Delta t_{i+j,i} = t_{i+j} - t_i$. Taking into account the regularity of TLE data release, the prediction duration generally equals to an integer multiple of the orbital period, so it can be directly replaced by this integer multiple. For example, $\Delta t_{i+j,i}$ is replaced by $n_{i+j,i} = round(\Delta t_{i+j,i}/T)$, where T represents the orbital period. Hereafter the prediction durations involved in this paper are handled in this way.

As was narrated above, when an orbit maintenance maneuver occurs, the corresponding segment of the semi-major axis observations will obviously deviate from the sequence of prediction values. By analyzing whether or not values of corresponding prediction errors are within a reasonable range, this type of data segment can be identified. In related references [13] [14], the prediction error of an orbital parameter is usually regarded as a random variable and has different numerical characteristics at different prediction durations. Before determining whether the value of a specific prediction error is within a normal range, numerical characteristics of the prediction error such as the mean and the variance need to be figured out first. To this end, we group all prediction errors (There are L segments of the semi-major axis, each segment corresponding to m prediction errors, hence $L \times m$ prediction errors are obtained finally) according to their prediction