Satellite Lifetime Prediction with Random Failure

*Haitao Zhao**
Beijing Institute of Spacecraft System Engineering
Beijing, China
zhtsailor@163.com

Hui Yang
Beijing Institute of Spacecraft System Engineering
Beijing, China

Xiao Xiong
Beijing Institute of Spacecraft System Engineering
Beijing, China

***Abstract*—The remaining life prediction of the satellite is of great significance in the operation of the satellite and the maintenance strategy of the constellation. The existing life prediction methods only consider the propellant consumption, thus a new dynamic life prediction method considering not only consumption but also random failure and degradation is proposed in this paper. Firstly, the failure characteristics of the satellite are analyzed, and then the satellite life model is established which contains three kinds of mechanisms including random failure, degradation and consumption. Secondly, according to current satellite operation data and Monte Carlo simulation model, the satellite remaining life is obtained through the comparison of the different lifetime determined by each mechanism. Finally, in a case study, the remaining life of 5 satellites on orbit is analyzed. The analysis results show that this new method is more accurate and credible.**

Keywords—satellite; remaining life; life prediction; reliability

I. INTRODUCTION

Satellite is a complex system consisted of a variety of types of products, such as electronics, electromechanical, institutions, structure, thermal control, etc. The remaining life of the satellite is directly related to the actual service time and the disposal strategy at the end of life. In a constellation, the satellite remaining life affects directly not only the maintenance plan, but also the constellation availability and continuous operation stability. Therefore, an accurate prediction of the satellite life has important significance in engineering practices.

Research on the life prediction of satellite products mainly concentrated on components [1-7] not system, generally for the products with degradation characteristics, such as thruster and battery. Involved methods for specific products only solve the problem of the life prediction of components. Report on the life prediction of satellite system is very rare, and the remaining life of the satellite is often predicted by estimating the residual propellant [8]. In these methods, the sudden failure and degradation have not been considered that bring inherent limitations to their applications.

According to the statistic analysis of on-orbit failures, the end of satellite life is due to not only propellant consuming, but also random failure or degradation. A new method for satellite life prediction considering consumption, degradation and random failure is presented in this paper. Based on satellite operation data and Monte Carlo simulation model, the satellite remaining life can be predicted dynamically.

II. SATELLITE FAILURE CHARACTERISTICS

Life characteristics of satellite products generally can be divided into three categories:

1) Random life. Product life obeys random failure distribution, in this circumstance, the products on orbit may soon break down that causes a permanent failure, or operate for a long time that is far more than design life. Most of products in satellite belong to this category.

2) Degraded life. Product life is subject to some specific laws and such products as solar arrays and some travelling-wave tube amplifier may fail after a particular period of time.

3) Consumable life. It generally refers to the propellant and other consumable materials. When the consumption reaches a specified threshold value, the product comes to the end of life.

Life characteristics of some products may be more complex. For example, the atomic clock has both degradation and random failure. For this kind of product, the main mechanism should be determined.

Corresponding to above three kinds of product life, there are three causes for the end of satellite life:

1) Random failure. Some sudden faults lead to the whole satellite failure, such as power loss and attitude out of control. Sudden failures of satellite generally follow Weibull distribution and conservatively follow exponential distribution.

2) Degradation. Performance of some products degradates to an unacceptable degree. For example, the efficiency of solar arrays seriously decreases that cannot meet the requirement of satellite power.

3) Consumable materials are exhausted. Generally, when the propellant margin reaches a specified value, the satellite will deorbit and the service will end.

III. Comprehensive Analysis Method for Satellite Life Prediction

A. Basic Principles

1) Determination of product range

As mentioned before, satellite products can be divided into three categories, whose life characteristics is random life, degraded life and consumable life, respectively. Therefore, considering only one type of product is not enough, and the satellite life prediction should include all of these products.

2) Product with complex failure mechanism

Some products have many failure mechanisms. For example, a battery failure may be caused by sudden fault of circuit performance degradation. If it is difficult to identify the dominant one from possible failure mechanisms, all failure mechanisms should be considered.

3) Selection of random failure distribution

Random failure of satellite generally follows Weibull distribution and conservatively follows exponential distribution. Weibull distribution can provide more accurate results but it is more complex than the latter. The exponential distribution gives more conservative results and the analysis process is simplified.

B. Life Modeling

A typical satellite life model is shown in Fig. 1.

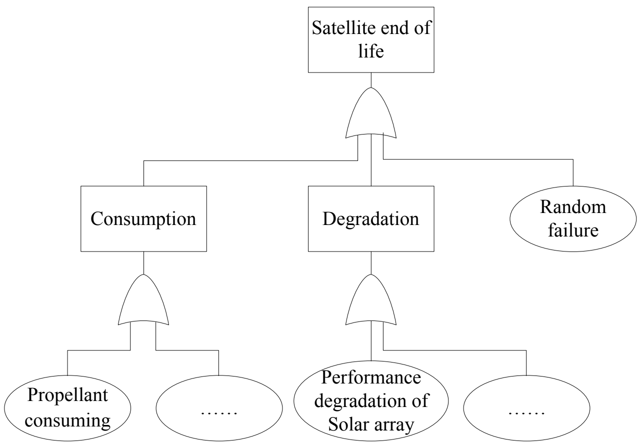

Fig. 1. A typical satellite life model

From Fig. 1, among consumption, degradation and random failure, any type of mechanism may cause satellite failure. In the system level, life model is a competent model in form of an "OR" gate. Based on the three life mechanisms, according to the distribution characteristics of product life, the basic unit list can be analyzed step by step. In the analysis process, the consumption and degraded failure should be listed separately, and all the random failures can be merged as one unit.

C. Simulation Analysis Steps

Simulation process of satellite life prediction is illustrated in Fig. 2.

According to Fig. 2, the analysis process is as follows:

1) Estimating the random life

For the random life estimation, on one hand, the failure distribution of satellite and its parameters should be consistent with current redundant configuration status. On the other hand, on-orbit time should be considered. Generally, assuming on-orbit time of a satellite as T_0 and the random failure time by simulation as T_1. Then T_1 must be greater than T_0 in reality. The random life of a satellite is equal to $T_1 - T_0$.

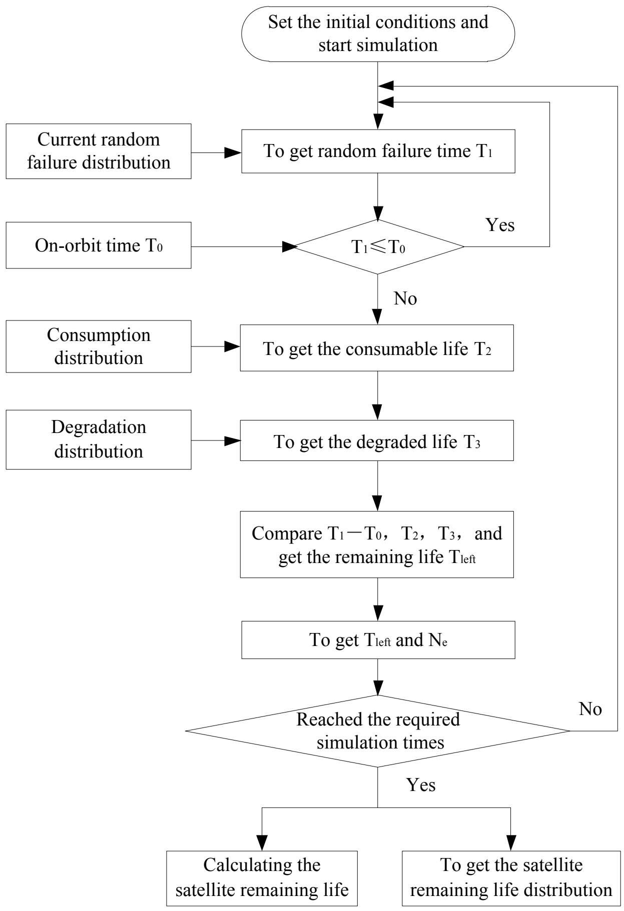

Fig. 2. Simulation process of satellite life prediction

According to the current status, assuming that the satellite follows an exponential distribution and its failure rate is λ, then the random failure time of satellite is

$$T_1 = -\frac{1}{\lambda}\ln(1-\eta) \tag{1}$$

where η is a random number, $0 < \eta < 1$.

If the satellite follows Weibull distribution and its probability density function is

$$f(t)=\frac{c}{b}\left(\frac{t}{b}\right)^{c-1}e^{-\left(\frac{t}{b}\right)^{c}} \tag{2}$$

where b is the scale parameter and c is the shape parameter.

Then, the random failure time of satellite is

$$T_1=b(-\ln\eta)^{\frac{1}{c}} \tag{3}$$

If $T_1>T_0$, one effective simulation is recorded, and then the process is transferred to step 2.

2) Estimating the consumable life

For most satellites, the consumable life depends only on the propellant. For more general situation, assuming that there are m kinds of consumption factors, and the satellite consumable life depends on the fastest consumption factor, then

$$T_2=\min(T_{21},T_{22},\cdots,T_{2m}) \tag{4}$$

where T_{2i} is the estimated life of the i kind of consumption factor, which is calculated by the corresponding life model.

Taking the propellant as an example, assuming that the remaining quality of the propellant is X kg, the propellant consumption every year is from X_1 to X_2 kg, and the deorbit requirement is X_r kg. Furthermore, assuming the propellant consumption follows a uniform distribution, then the consumption life of satellite determined by propellant is

$$T_2=(T_a+\eta(T_b-T_a))\times 8760 \tag{5}$$

where $T_a=\dfrac{X-X_r}{X_2}, T_b=\dfrac{X-X_r}{X_1}$.

3) Estimating the degraded life

Assuming that there are n kinds of degradation factors, the degraded life of satellite depends on the fastest degradation factor, then

$$T_3=\min(T_{31},T_{32},\cdots,T_{3n}) \tag{6}$$

where T_{3i} is the estimated life of the i kind of degradation factor, which is calculated by the corresponding life model.

Taking the solar array as an example, assuming that the current power is P W, the power degradation every year is from Y_1 to Y_2 W, and the specified power requirement is P_0 W. Furthermore, assuming that power degradation follows a uniform distribution, then the degraded life of satellite determined by the solar array is

$$T_3=(T_a+\eta(T_b-T_a))\times 8760 \tag{7}$$

where $T_a=\dfrac{P-P_0}{Y_2}, T_b=\dfrac{P-P_0}{Y_1}$.

4) Determining the satellite remaining life in one simulation

Based on the competing failure model, the satellite remaining life T_{left} in one simulation depends on the minimum value among the random life (T_1-T_0), the consumable life (T_2) and the degraded life (T_3). That is

$$T_{left}=\min(T_1-T_0,T_2,T_3) \tag{8}$$

5) Calculating the satellite remaining life

The above steps are repeated until the specified simulation times are reached. The effective simulation times (N_e) and T_{left} of each time are recorded and then the average satellite remaining life is

$$\overline{T}_{left}=\frac{\sum_{i=1}^{N_e}T_{left}}{N_e} \tag{9}$$

6) Obtaining the satellite remaining life distribution in a given period of time

Due to the uncertainty in the random failure, degraded failure and consumption, there is a confidence interval for the estimated result of the remaining life. In order to describe the uncertainties, a remaining life distribution is necessary to be given.

With given statistical interval (N_Δ), the times of the satellite remaining life (F_i) falling into each interval are recorded, the remaining life distribution can be obtained from

$$P_T=1-\frac{F_i}{N_e}, i=1,2,\cdots N_\Delta \tag{10}$$

IV. CASE STUDY

A constellation consists of five satellites. Assuming

- the design lifetime of each satellite is 8 years,
- the random failure of each satellite follows the same exponential distribution, and the consumable and degraded life of each satellite is only determined by the propellant and solar array, respectively,

- the propellant consumption every year is from 5 to 10 kg and the propellant deorbit requirement is 10 kg,
- the specified power requirements is 1000 W.

Other assumptions of each satellite are listed in Table 1.

Based on the data in Table 1 and the method described in the previous section, the estimated remaining life of each satellite is demonstrated in Fig. 3.

According to Fig. 3, the remaining life of satellite A is the shortest and it is the weakness of the constellation. Thus, it is necessary to make a redundancy plan for satellite A. The satellite remaining life is closely related with the operation status.

TABLE I. INFORMATION OF EACH SATELLITE

Satellite code	**Operation data**				
	***On orbit time* (years)**	***Current failure rate* (10^{-9}/h)**	***Current power of solar array* (W)**	***Power degradation* (W/year)**	***Current remaining propellant* (kg)**
A	4.8	4000	1080	15～20	102
B	4.5	4000	1150	8～12	115
C	4.2	3600	1190	8～12	90
D	3.8	3950	1180	15～20	100
E	2.5	3600	1200	5～8	85

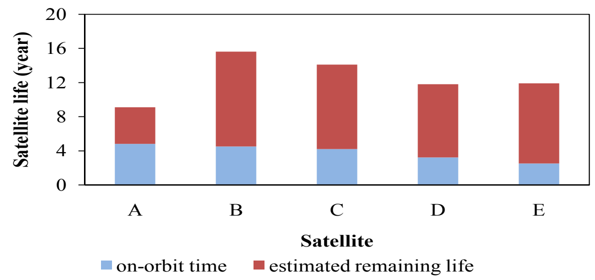

Fig. 3. The estimated remaining life of each satellite

If only the propellant consumption is considered, the estimated remaining life of each satellite is shown in Fig. 4.

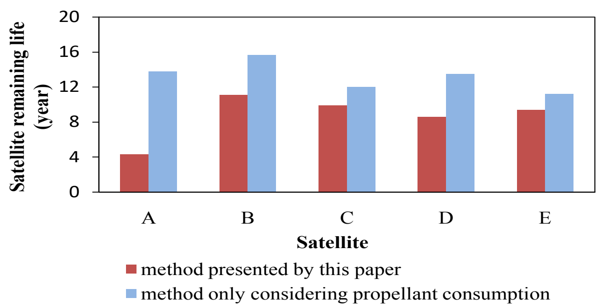

Fig. 4. A comparison of the remaining life obtained from different methods

From Fig. 4, it can be seen that there are obvious differences between the method considering the random failure, degradation and consumption and that only considering propellant consumption. For example, the remaining life of satellite A is no more than 5 years according to the former method, however, it is more than 12 years if employing the latter. Therefore, considering all three factors in the estimation of satellite remaining life is more credible, providing a reasonable basis for the identification of satellite life weakness.

V. CONCLUSIONS

Based on the analysis of satellite life mechanisms and the case study, the following conclusions can be drawn in the life prediction method of satellite considering the random failure, degradation and consumption:

1) The end of the satellite life is caused by three mechanisms including random failure, degradation and consumption, and satellite remaining life prediction should cover all of these mechanisms. A life model was established.

2) Based on the satellite life model and Monte Carlo simulation, the satellite remaining life and its distribution can be analyzed and a more credible result can be obtained. With the updating of operation data, the satellite remaining life can be predicted dynamically.

REFERENCES

[1] X. Y. Li and T. M. Jiang, “Constant-stress accelerated degradation testing of satellite assemblies,” Acta Aeronautica et Astronautica Sinica, vol. 28, no. z1, pp. S100-S103, 2007.

[2] F. Y. Wang, “Health evaluation and life prediction method study of the dual-axis drive mechanism for satellite antenna,” Harbin Institute of Technology, Master thesis, 2013.

[3] H. Wang, “Research on remaining useful life prediction for satellite lithium-ion battery,” Harbin Institute of Technology, Master thesis, 2013.

[4] L. Ai, H. Z. Fang, G. J. Yu, et al, “Research on data-driven life prediction methods of satellite lithium-ion battery,” Computer Measurement & Control, vol. 23, no. 4, pp. 1262-1272, 2015.

[5] H. M. Qi, B. Jiang, N. Y. Lu, et al, “The residual life prediction of the satellite attitude control system based on Petri net,” Prognostics and System Health Management Conference (PHM-2014 Hunan), pp. 266-270, 2014.

[6] C. S. Byington, M. Watson and D. Edwards, “Data-driven neural network methodology to remaining life predictions for aircraft actuator components,” 2004 IEEE Aerospace Conference Proceedings, Big Sky, MT, United States, pp. 3581-3589, 2004.

[7] P. H. Wang, B. Y. Fan and H. M. Fu, “Reliability assessment and life prediction for satellite engine,” Journal of Aerospace Power, vol. 19, no. 6, pp. 745-748, 2004.

[8] J. C. Li, Y. G. Yang and J. W. An, “Geostationary satellite’s end-of-life predication based on propellant-remaining estimation,”.Chinese Journal of Space Science, vol. 26, no. 3, pp.193-196, 2006.