Mission Effectiveness Modeling of Remote Sensing Satellite System

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Abstract. With the update of remote sensing technology, remote sensing satellite has been applied to daily life of people. The ability of satellites to accomplish mission has become the focus of attention, this paper presented a method for modeling and analyzing mission effectiveness of remote sensing satellite system. Based on the discussion of the mission and structure of the satellite, we use the ADC model to evaluate the mission effectiveness of satellite. The state transition probabilities of the satellite in the model are calculated by continuous Markov chain with discrete states continuous time. Finally, the validity of the method is demonstrated by a case study.

Introduction

Effectiveness is an important index of system, and has been studied in many industries [1-4]. The effectiveness of a system, in short, refers to the system’s actual ability to complete an intended mission [5]. Modern remote sensing satellites have the characteristics of multi-function of structure, miniaturization and integration, so that the redundant design and the number of hardware are limited to a certain extent in volume, but the performance requirements of the entire satellite are not reduced relative to the traditional satellites. How to accomplish the mission efficiently with the existing resources has become a challenge. At present, there is not enough attention paid to the research on the effectiveness evaluation of remote sensing satellite. Although some scholars [6-10] have studied the effectiveness evaluation of remote sensing satellite for specific functions, there is still a lack of research on the effectiveness evaluation of remote sensing satellite. On the other hand, effectiveness evaluation has been widely used in the fields of weaponry, machinery manufacturing and civil aviation. According to the characteristics of different industries, many methods to evaluate the effectiveness of the system have also been proposed. The introduction of effectiveness evaluation technology in remote sensing satellite system can reflect the ability of the system to a great extent.

This paper focused on the effectiveness evaluation of remote sensing satellite. In Section II, the characteristics of remote sensing satellite are analyzed; in Section III, an evaluation model of effectiveness is proposed based on ADC model combining with Markov model. A case study is given in Section IV, and some conclusions are summarized in Section V.

Remote Sensing Satellite Characteristics Analysis

In recent years, more and more attention has been paid to satellite remote sensing technology. Many new types of remote sensing satellites have been designed and the requirements for satellite missions are getting higher continuously. How to ensure remote sensing satellite to accomplish its mission effectively and efficiently and improve its effectiveness has become a major challenge for satellite designers. To evaluate effectiveness, a characteristics analysis of remote sensing satellite and its mission is needed.

Remote sensing satellite aims to observe various phenomena on the earth and can carry out uninterrupted remote sensing of designated areas within a specified time, including reconnaissance satellite, meteorological satellite and resource satellite [11]. Generally, a remote sensing satellite is composed of three parts, i.e. satellite platforms, remote sensors, equipment of information processing and transmission. Remote sensing satellite acquires various kinds of information about the earth and
the atmosphere through remote sensors, preprocess the information through signal processing equipment and send the information back to the ground through transmission equipment. The following three points are required to accomplish a remote sensing mission:

1) the capability of high-speed attitude maneuver
2) the capability of high-resolution imaging
3) the capability of large bandwidth information transmission

According to its mission characteristics, the structure of remote sensing satellite is simplified to facilitate the analysis in this paper. The satellite is divided into three subsystems, i.e. control and propulsion system (N₁), imaging payloads system (N₂), information transmission system (N₃). These three subsystems do not affect each other as an independent event, and the logical structure of the satellite structure and functional mission is shown in Fig. 1.

![Figure 1. The logical structure of the satellite structure and functional mission.](image)

From the simplified satellite structure shown in Figure 1, it can be seen that the control and propulsion system and the imaging payloads system jointly accomplish the remote sensing satellite target imaging mission, mainly including recognizing mission objectives, obtaining desired target information and preprocessing the information. Similarly, information transmission system aims to complete the information transmission mission, including downloading the obtained information to the ground observation station and receiving ground station control instructions. These two sub-missions are the main components of the satellite remote sensing mission, and they work together to complete the whole mission, where the target imaging is the core for the entire remote sensing mission. In order to simplify the calculation, it is assumed that each subsystem only has two types of states, i.e. normal (N) and fault (N). Therefore, there are eight possible states during the remote sensing mission, as shown in Table 1:

<table>
<thead>
<tr>
<th>No.</th>
<th>system state</th>
<th>State meaning</th>
<th>Mission situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N₁N₂N₃</td>
<td>All subsystems are in normal condition</td>
<td>The function is normal and the remote sensing mission can be completed</td>
</tr>
<tr>
<td>2</td>
<td>N₁N₂N₃</td>
<td>Only control and propulsion system fault</td>
<td>Only the information transmission mission can be completed</td>
</tr>
<tr>
<td>3</td>
<td>N₁N₂N₃</td>
<td>Only imaging payloads system fault</td>
<td>Only the information transmission mission can be completed</td>
</tr>
<tr>
<td>4</td>
<td>N₁N₂N₃</td>
<td>Only information trans-mission system fault</td>
<td>Only the target imaging mission can be completed</td>
</tr>
<tr>
<td>5</td>
<td>N₁N₂N₃</td>
<td>Only information transmission system is normal</td>
<td>Only the information transmission mission can be completed</td>
</tr>
<tr>
<td>6</td>
<td>N₁N₂N₃</td>
<td>Only control and promote the system is normal</td>
<td>Loss of each function, all missions can not be completed</td>
</tr>
<tr>
<td>7</td>
<td>N₁N₂N₃</td>
<td>Only imaging payloads system is normal</td>
<td>Loss of each function, all missions can not be completed</td>
</tr>
<tr>
<td>8</td>
<td>N₁N₂N₃</td>
<td>All subsystems are in fault condition</td>
<td>Loss of each function, all missions can not be completed</td>
</tr>
</tbody>
</table>
Effectiveness Evaluation Model for Remote Sensing Satellite

The ADC model was proposed by Weapons System Effectiveness Industry Advisory Committee (WSEIAC) [12] in the middle of 1960s, and has been the classic effectiveness evaluation model. According to the model definition, mission effectiveness of system is a measure of the degree to which the system is expected to meet a specific set of mission requirements and is the aggregate effectiveness of the three indicators of system availability, dependability and capability.

Similarly, the effectiveness of remote sensing satellite system is:

\[ E = A \cdot D \cdot C \]  \hspace{1cm} (1)

where, \( A \) is the availability matrix, representing the probability of the system in different states when the satellite begins its mission. \( D \) is the dependability matrix, the probability of transition between different system states during the mission under the condition that the satellite has already begun its mission. \( C \) is the capability matrix, representing the capability of the satellite to accomplish its mission under different states.

Availability of Remote Sensing Satellite

The availability matrix (A) of the remote sensing satellite is a row vector \((A_1, A_2, \ldots, A_n)\). To get the availability matrix, the probabilities of different states in the satellite need to be analyzed.

Let’s use \( a_1, a_2, a_3 \) to represent the probabilities of normal operation of the three subsystems in the satellite respectively. According to statistical results, the fault modes of satellite can be divided into two types, i.e. short-term fault and long-term fault. Short-term fault means that satellite can continue to be used after some maintenance measures controlled by ground control station, while the latter means that the satellite cannot continue to be used, and need be replaced by the backup satellite. Because this paper focuses single remote sensing satellite, only short-term fault will be analyzed, and the mission is regarded as failure if the satellite has a long-term fault. Let MTBF represent the mean time between failures of the subsystem and MTTR represent the average repair time of the subsystem, then the probability of normal operation of the subsystems is:

\[ a_i = \frac{MTBF_i}{(MTBF_i + MTTR_i)} \]  \hspace{1cm} (2)

In Table 1 there are eight types of states in remote sensing satellite. The probability that the satellite is in a certain state at the beginning of mission is the product of the state probabilities of three subsystems, for example, \( A_1=a_1a_2a_3 \). So, the system's availability matrix is:

\[ A=[A_1, A_2, A_3, A_4, A_5, A_6, A_7, A_8] \]

Dependability of Remote Sensing Satellite

The dependability matrix (D) of the remote sensing satellite is a n-order-matrix, \( [d_{ij}]_{n \times n} \), where \( d_{ij} \) (i, j = 1, 2, ..., n) represent the probabilities of transitions between the different states during the mission, and n represents the number of states existing in the satellite. From Table 1, it can be seen that there are eight possible states during the mission; moreover, the state changes can be expressed mathematically as a random process, \( \{X(t), t \geq 0\} \), where t is time. Because of the high quality and reliability, it is a reasonable hypothesis that two faults happen simultaneously in the satellite is a small probability event and the satellite state does not change within an operation time of \( \Delta t(\Delta t \rightarrow 0) \) after a state transition. This assumption is also in line with the actual situation, and can greatly reduce the computational complexity. According to statistics, the reliability of satellite follows exponential distribution, therefore, assuming that the fault rates of the three subsystems are \( \lambda_1, \lambda_2 \) and \( \lambda_3 \) respectively, and the satellite is not repairable during space mission, i.e., the influence of maintenance is not considered. The state transition process of satellite is shown in Fig.2.
Figure 2. The state transition of remote sensing satellite system.

According to the state transition diagram of satellite system, the state transition process has the following characteristics: the probability of the system transferring from one state to another is only related to the present state. So the process can be transformed into Markov chains of continuous time. By using the mathematical expressions of Markov chains and fault rates of each subsystem, we can find out the transition intensities between the states. Based on the matrix form of Kolmogorov forward equation, the transition probability can be calculated, from which the dependability matrix D is obtained. The mathematical expression of continuous Markov chains is:

\[
P \{ X(t+u) = j | X(u) = i \} = \Pi_{ij}(u,t) = \Pi_{ij}(t)
\]

(3)

It represents the probability that the system is in state \( i \) at time \( u \) and is transferred to state \( j \) after time interval \( t \). Because the reliability of system follows exponential distribution, the transition probability is independent of time \( u \), and the Markov process is homogeneous. It is known from the previous assumptions that the satellite’s state transition process cannot jump to another state immediately after entering a state, so the transition probability \( \Pi_{ij}(t) \) satisfy regularity condition:

\[
\lim_{t \to 0} \Pi_{ij}(t) = \begin{cases} 
1, & i = j \\
0, & i \neq j 
\end{cases}
\]

(4)

And for any fixed \( i, j \in I \), \( \Pi_{ij}(t) \) is a consistent continuous function of \( t \) and has the following limits:

\[
\begin{align*}
\lim_{\Delta t \to 0} \frac{\Pi_{ij}(\Delta t) - 1}{\Delta t} &= q_{ij}, \ i = j \\
\lim_{\Delta t \to 0} \frac{\Pi_{ij}(\Delta t)}{\Delta t} &= q_{ij}, \ i \neq j
\end{align*}
\]

(5)

where \( q_{ij} \) is called transfer intensity of a homogeneous Markov process. The transfer intensity of homogeneous Markov chains of continuous time can form a matrix \( Q \), i.e., \( Q = [q_{ij}]_{n \times n} \). From the matrix \( Q \), an equation can be deduced to evaluate the transition probability for any time interval \( t \), which can be expressed by the Kolmogorov forward equation:

\[
\frac{dp_{ij}(t)}{dt} = \sum_k p_{ik}(t)q_{kj}
\]

(6)

where the initial conditions are: \( p_{ij}(0) = \begin{cases} 
1, & i = j \\
0, & i \neq j 
\end{cases} \). The matrix form of this equation can be written as:

\[
P(t) = \frac{d}{dt} P(t)Q^{-1}
\]

(7)
The transfer intensity matrix $Q$ can be obtained based on the fault rates of subsystems in the satellite, and then the state transition probability matrix $P(t)$ after a time interval $t$, that is the dependability matrix $D$ of the satellite can be calculated.

**Capability of Remote Sensing Satellite**

The capability matrix $C$ of remote sensing satellite is a measure of the degree to which the satellite performs its mission under different states. According to the mission composition of remote sensing satellite and the division of system states, the capability measures of the system in different states are classified into four categories, namely I, II, III and IV, and the corresponding value $B_1$, $B_2$, $B_3$, and $B_4$ can also be determined. The capability of the state that the function is normal and the mission can be completed normally is defined as class I. The state that the mission of target imaging can be finished but the information transmission and remote sensing mission cannot be completed is class II. The state that the mission of information transmission is normal but the target imaging and remote sensing mission cannot be completed is class III. The capability measure is regarded as class IV if none of the mission can be finished. Because there are eight states in remote sensing satellite, the capability matrix $C$ is:

$$C^T = \begin{bmatrix} B_1 & B_2 & B_3 & B_4 & B_1 & B_2 & B_3 & B_4 \end{bmatrix}$$

**A Case Study**

**The Calculation of Availability Matrix A**

MTBFs and MTTRs of each subsystem in certain remote sensing satellite are shown in Table 2:

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Control and propulsion system</th>
<th>Imaging payloads system</th>
<th>Information transmission system</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTBF[h]</td>
<td>12560</td>
<td>10350</td>
<td>15000</td>
</tr>
<tr>
<td>MTTR[h]</td>
<td>60</td>
<td>80</td>
<td>50</td>
</tr>
</tbody>
</table>

According to the formula (2) and the data in Table 2, the availability matrix can be obtained:

$$A = \begin{bmatrix} 0.9843 & 0.0047 & 0.0076 & 0.0033 & 0 & 0 & 0 & 0 \end{bmatrix}$$

**The Calculation of Dependability Matrix D**

The fault of the satellite obeys exponential distribution, so the fault rates of the three subsystems can be calculated based the data in Table 2. The mission time of this satellite is about 1000 h, so the dependability matrix $D$ is:

$$D = \begin{bmatrix} 0.7843 & 0.0650 & 0.0796 & 0.0541 & 0.0066 & 0.0055 & 0.0045 & 0.0005 \\ 0 & 0.8493 & 0 & 0 & 0.0862 & 0 & 0.0586 & 0.0059 \\ 0 & 0 & 0.8639 & 0 & 0.0716 & 0.0596 & 0 & 0.0049 \\ 0 & 0 & 0 & 0.8384 & 0 & 0.0850 & 0.0695 & 0.0070 \\ 0 & 0 & 0 & 0 & 0.9355 & 0 & 0 & 0.0645 \\ 0 & 0 & 0 & 0 & 0 & 0.9235 & 0 & 0.0765 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.9079 & 0.0921 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

**The Calculation of Capability Matrix C**

In this case, we defined that the range of capability values is between 0-10, and the higher the value, the better the capability to complete the mission. The value of 0 means the satellite loss of function completely, while the value of 10 represents the satellite work well and can complete all the missions. So we assume $B_1=10$, $B_2=4$, $B_3=2$, $B_4=0$. The capability matrix $C$ is:
\[
C^T = \begin{bmatrix}
10 & 2 & 2 & 4 & 2 & 0 & 0 & 0
\end{bmatrix}
\]

As a result, the mission effectiveness of this satellite is:

\[
E = A \cdot D \cdot C = 8.2652
\]

The example shows that, under the given conditions, the effectiveness of a remote sensing satellite is 8.2652, while the ideal effectiveness is 10.

**Conclusion**

Based on the mission characteristics and system structure, this paper established an effectiveness evaluation model of remote sensing satellite using ADC model. The possible states of the satellite, the probabilities under different states and the capability to accomplish the mission under different states are discussed. The model can supply a clear structure and simple way to assess the effectiveness of remote sensing satellite. Through the proposed model, the concept of effectiveness is transformed into a parameter that can be measured quantitatively, and this method provides a scientific decision basis for the design and actual use of remote sensing satellite.

At the same time, the model is simple relatively because the satellite is divided only into three subsystems, and we will refine the model carefully according the structure of satellite in the follow-up work.

**References**


