Satellite Mission Support Efficiency Evaluation Based on Cascade Decomposition and Bayesian Network

Ruixing Wang[1], Yuqing Li[1(✉)], Hailong Zhang[2], Fan Liu[2], and Mingjia Lei[1]

[1] Deep Space Exploration Research Center, Harbin Institute of Technology, Harbin 150080, China
bradley@hit.edu.cn

[2] China Xi'an Satellite Control Center, Xi'an 710043, China

Abstract. Aiming at the complexity of evaluation system construction is high due to the numerous and jumbled nodes of satellite mission support efficiency evaluation system and the difficulty in identifying the system hierarchy and the relationship between nodes, this paper proposes an evaluation method based on Cascade decomposition and Bayesian network. Firstly, establish a satellite mission support efficiency evaluation system based on Cascade decomposition. According to the basic information of satellite health status and environmental risk, the satellite mission is decomposed into multiple dimensions such as task level, attribute level, measure level and input level. Then, a method based on Bayesian network is designed to extract the experience knowledge, which can represent the complex expert experience mathematically. Finally, an example simulation analysis of earth observation mission is carried out, and the results show that this method can effectively and accurately complete the satellite mission support efficiency evaluation, and verify the validity and correctness of this method.

Keywords: Satellite · Efficiency evaluation · Cascade decomposition · Bayesian network

1 Introduction

With huge investment in the space industry and rapid changes in the situation of the space scene, the accuracy and timeliness of mission decision are highly required, Therefore, it is of great research value and practical significance to study how to build a satellite mission effectiveness evaluation system and accurately evaluate it, so as to provide effective technical support for mission command decision. When execute the satellite

This research was supported by the project: 2019001TJ20172A04097-4, the Key Laboratory Opening Funding of Harbin Institute of Technology of Deep Space Exploration Landing and Return Control Technology (HIT.KLOF.2018.076, HIT.KLOF. 2018.074), and the pre-research projects of equipment development department of China Central Military Commission (JZX7Y20190243001201).

Q. Wu et al. (Eds.): WiSATS 2020, LNICST 358, pp. 46–60, 2021.
https://doi.org/10.1007/978-3-030-69072-4_5

mission support efficiency evaluation, we need to carry out an effective and complete system for the specific mission of the satellite firstly. Then determine the support degree of the in-orbit satellite or satellites for the mission by the input of the existing quantifiable data of the satellite, finally using the support degree to provide effective technical support for the mission command decision.

In terms of satellite evaluation, there are many contents about satellite health evaluation or satellite subsystem health evaluation in the existing research results. For example, a health evaluation method based on the fuzzy variable weight principle and the improved analytic hierarchy process was proposed in literature [1], it can reflect the satellites in-orbit health more objectively. Literature [2] takes the health evaluation of the satellite power subsystem as an example, and carries out a study on the evaluation method based on the connection logic of satellite components. The evaluation is carried out from two dimensions: the capability of the satellite subsystem to complete the task and the risk accumulation to complete the task. Literature [3] proposed a multi-stage health evaluation method for in-orbit satellites based on reconfigurable degree for the health evaluation of in-orbit satellites. The introduction of reconfigurable degree solved the characterization of complex characteristics of satellite system such as high redundancy, high reliability and nonlinearity, and reduced the subjectivity of evaluation. Literature [4–7] adopted different evaluation systems and methods for different application scenarios, and carried out research on equipment system support effectiveness evaluation. Literature [8–11] studied remote sensing satellites, satellite remote sensing detection resource scheduling, index system construction and evaluation methods.

In conclusion, the current research on satellite evaluation is mainly focused on the health of satellite system, and less on the space mission support efficiency. Therefore, this paper proposes a Cascade decomposition method and combines the Cascade decomposition method with the Bayesian network, so as to provide a feasible method to determine the support efficiency of the satellite in space missions.

2 Problem Analysis

The satellite mission support capability refers to the capability of the satellite system according to the characteristics and requirements of the mission, while the satellite mission efficiency refers to the capability of achieving the specified use objectives under the specified conditions. Comparatively speaking, the mission support capability focuses on the capability of the satellite system, while the mission effectiveness pays more attention to the mission requirements.

Satellite system is a large and complex integrated system, including attitude and orbit control, temperature control, power supply, measurement and control, data management, payload and other subsystems, and each subsystem contains multiple components, which are composed of multiple sub-components. In space missions, the health of satellite systems, the performance of satellite systems, and the complexity of the space environment and external influences need to be taken into consideration. Comparatively speaking, it is easier to determine these contents. But how to determine the cause-and-effect dependence of the above indexes on the satellite mission support capability and efficiency, how to explain hierarchical decomposition, it just like a complex black-box between the input and output variables. How to effectively determine the specific content of black-box, that is the core of the research.

In practical engineering, satellite mission support efficiency is estimated in advance based on telemetry data and satellite design parameters before the implementation of space missions, which is of great practical significance to the cost control of mission completion and the effect of mission completion. In order to solve this problem effectively, this paper proposes a Cascade decomposition method, which is used to determine the network structure in the Bayesian network. The network parameters are learned from the sample data determined by the expert scoring method, and finally complete the evaluation process of satellite mission support effectiveness (Fig. 1).

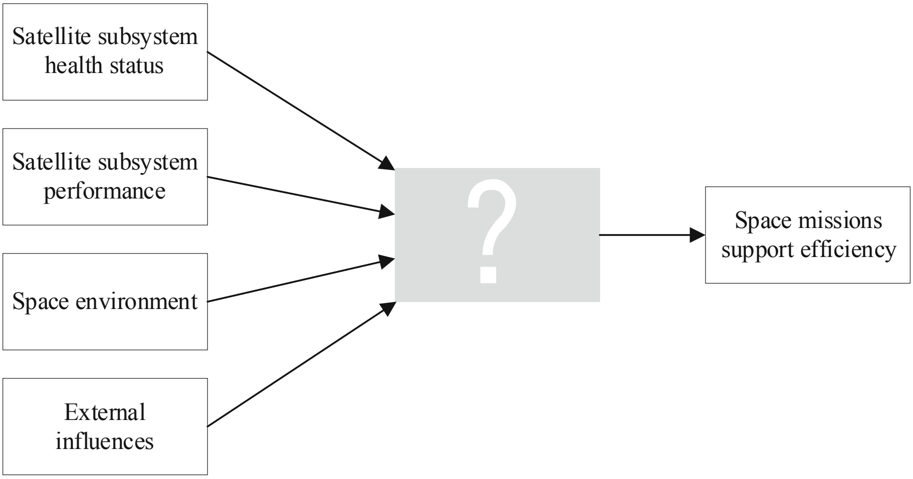

Fig. 1. Schematic diagram of analysis of space mission support effectiveness evaluation

3 The Construction of Mission Support Efficiency Evaluation System Based on Cascade Decomposition

The Cascade decomposition method is a step by step decomposition method, which provides a way to construct a satellite mission support effectiveness evaluation system.

3.1 Mission Decomposition

Mission Statement: In the process of mission decomposition, a brief statement is first made on the mission, in which the basic content and purpose of the mission are described and the actions and reasons to be taken are clearly defined. Who, what, when, where, and why should the mission statement include, but it doesn't have to be very detailed about the specifics of the mission. In short, the mission statement should be a clear and concise statement that states the content of the mission. Of course, before completing the mission statement, it is also necessary to present the mission to be performed in the form of a flow chart.

Desired Effect: In the process of mission decomposition, the desired effect of the mission is also crucial. In the process of drawing mission flowchart, the desired effect of the mission also needs to be clarified. On the one hand, in the process of clarifying the desired effect of the mission, the thinking and understanding of the mission will be deepened, which is of great benefit to the mission decomposition. On the other hand, after the mission is decomposed into tasks, it is an important test for the effectiveness and integrity of mission decomposition and an important standard to judge whether the decomposition is reasonable.

Task: In general, task can be thought as part of mission, where a mission consists of multiple tasks. If the mission statement is a further reflection and elaboration of the mission, then the determination of the task is another summary of the mission statement. A task is a mission flow with clear time or space boundary, its effectiveness depends on the extent to which it achieves the desired effect (Fig. 2).

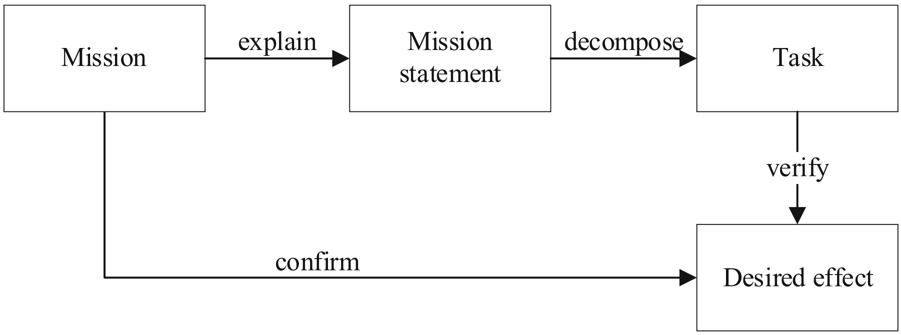

Fig. 2. Mission decomposition process

Therefore, the overall process of mission decomposition is summarized as follows: First of all, in the process of constantly clarifying the mission, draw the mission process completely and extract the mission statement and the desired effect. Then determine the tasks according to the mission statement. Finally, the validity criterion of task is whether the desired effect is well realized. If it is met, the mission decomposition is completed; otherwise, repeat the above procedures.

3.2 Task Decomposition

Timeliness: Time required to start or complete (e.g. response time).
Effectiveness: The quality of task completion.
Accuracy: The degree of accuracy with which a task is completed.
Reliability: Reliability of instruction and data transmission (e.g. anti-jamming capability).
Task attributes are different dimensions for evaluating task execution, such as accuracy of task completion and timeliness of task completion. The above-mentioned task attributes

are widely used in the evaluation process. As different dimensions of task evaluation, they play a crucial role in the decomposition process. Different tasks of the same mission have different dimensions of emphasis due to their different contents. Therefore, attribute is taken as the result of further decomposition of task. Its boundary is relatively clear, which can well guarantee the integrity and validity of decomposition. Of course, the attributes listed above cannot completely summarize all the tasks, but only serve as a reference example. When studying specific problems, the number and definition of individual attribute can be expanded and modified according to the characteristics of missions (Table 1).

Table 1. Mission – task - attribute cascading decomposition table

Task	Timeliness	Accuracy	Effectiveness	Reliability
Task 1	×	×	×	
Task 2	×	×		×
Task 3	×	×	×	

3.3 Measure Determination

After completing the above, you can determine the measures of attribute. Compared with the above decomposition process, which pays more attention to the mission to perform. This process focuses more on the ability of the subject to perform the mission. As the unit which is completely covering of task attributes and be easy to be quantified, the subject of measure is the subject to perform the mission. For the example in this paper, the subject of measure is the satellite to perform the space mission (Table 2).

3.4 Measure Decomposition

Measure is the hierarchy that connects the content of mission to the subject executing it. After a valid measure is determined, the measure should be decomposed. The results of measure decomposition, namely, the content of the input level, are the health degree of the mission executor, the performance of the mission executor, and the degree of external influence of the mission executor (Fig. 3).

Table 2. Mission – task – attribute - measure cascading decomposition table

Mission	Task	Attribute	Measure
Mission	1. Task 1	1.1 Attribute 1	Measure 1
			Measure 2
			Measure 3
		1.2 Attribute 2	Measure 4
		1.3 Attribute 3	Measure 5
	2. Task 2	2.1 Attribute 1	Measure 6
			Measure 7
		2.2 Attribute 2	Measure 8
			Measure 9
		2.3 attribute 3	Measure 10
		2.4 Attribute 4	Measure 11
	3. Task 3	3.1 Attribute 1	Measure 12
			Measure 13
			Measure 14
		3.2 Attribute 2	Measure 15
		3.3 Attribute 3	Measure 16

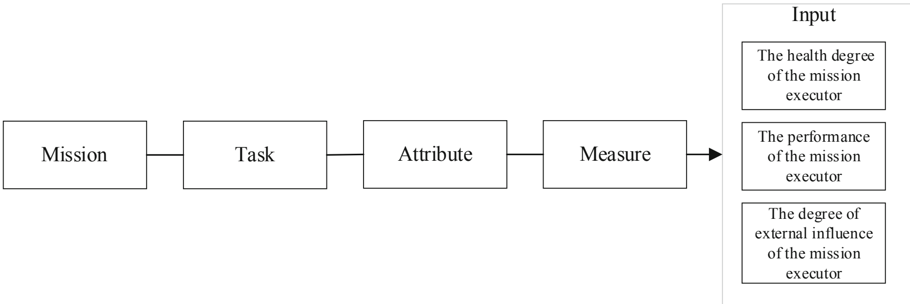

Fig. 3. Flow chart of Cascade decomposition method

4 Mission Support Efficiency Evaluation Based on Cascade Decomposition and Bayesian Network

4.1 Bayesian Network Construction in Mission Support Efficiency Evaluation

Bayesian network is a directed acyclic graph model based on probabilistic inference. It can represent the complex variable relationships in specific problem with a network structure. The network model reflects the dependence of variables in the problem domain and is suitable for the expression and reasoning of uncertain knowledge. A Bayesian network is composed of two parts, which correspond to the qualitative description and quantitative description of the problem domain respectively, Bayesian network structure and Bayesian network parameters. Bayesian network structure is the result of abstracted data instance and is a macroscopic description of the problem domain. Network parameters are the exact expression of the degree of association between variables and belong to quantitative description.

The Structure of Bayesian network is a directed acyclic graph (DAG), which consists of a set of nodes and a set of directed edges. Each node in the node set represents a random variable, which can be an abstraction of any problem and can be used to represent the phenomenon, part, state or attribute of interest, which has certain physical and practical significance. The other part of a Bayesian network is a set of local probability distributions that reflect correlations between variables namely network parameters, usually called a conditional probability table (CPT). This table lists all possible conditional probabilities for each node relative to its parent. Bayesian network takes the parent of node Xi as the condition, Xi is conditionally independent of any non-Xi child. The probability value represents the degree of association or confidence coefficient between the child node and its parent, and the probability of the node without parent is its prior probability.

For example, in Fig. 4, on the right is the Bayesian network structure of the satellite temperature control subsystem health evaluation, and on the left are part of Bayesian network parameters of the structure. Health status is divided into three levels, with high, medium and low health status represented by digital subscript 0, 1 and 2 respectively. So the conditional probability represented by $P(E_0|A_0,B_0) = 0.8$ means that under the condition that node A is low health (A_0) and node B is low health (B_0), the probability that node E has a health degree of 0 is 0.8.

A_i	A_0	A_1	A_2
$P(A_i)$	0.3	0.4	0.3

$P(E\|A,B)$	E_0	E_1	E_2
A_0,B_0	0.8	0.2	0
A_0,B_1	0.3	0.5	0.2
A_0,B_2	0.2	0.5	0.3
A_1,B_0	0.3	0.5	0.2
A_1,B_1	0.2	0.3	0.5
A_1,B_2	0.1	0.3	0.6
A_2,B_0	0.2	0.3	0.5
A_2,B_1	0.1	0.2	0.7
A_2,B_2	0	0.2	0.8

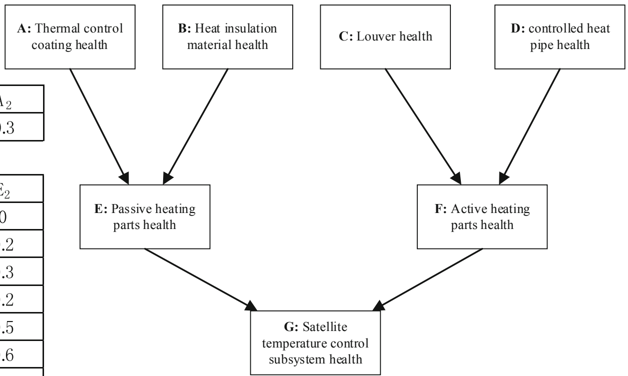

Fig. 4. Bayesian network topology and partial conditional probability table of satellite temperature control subsystem health evaluation

Therefore, the construction of Bayesian network includes the following two parts:

(1) Determination of network topology;
(2) Determination of network parameters;

In general, there are three different ways to construct Bayesian networks:

(1) Domain expert determination method: In this way, the structure and parameters of Bayesian networks are defined subjectively, the variables in Bayesian network are determined by domain experts, and the structure and its distribution parameters of Bayesian network is determined by experts knowledge. The Bayesian network constructed in this way is completely under the guidance of experts. Because of the boundary of human knowledge, the network often has a great deviation from the physical truth, so the application scope of this method is very small.
(2) Complete sample learning method: In this way, domain experts define the node variables in Bayesian networks subjectively, and then learn the structure and parameters of Bayesian networks through a large number of training data. This method is entirely data-driven and highly adaptable. And advances in artificial intelligence, data mining and machine learning have made this method possible.
(3) Partial sample learning method: This method is a combination of the first and second methods. The variables in Bayesian networks are determined by domain experts, and the network structure is constructed by expertise, the parameters of the network are learned from the data by machine learning.

As for the research of satellite mission support effectiveness evaluation, due to the large number of nodes and the difficulty in determining hierarchical relationship, it is easy to have problems of missing nodes and wrong determination of causal relationship between nodes. Therefore, this paper adopts the method of Cascade decomposition. Under this decomposition framework, according to expert knowledge and past experience in this field, variables of satellite mission support effectiveness evaluation and its Bayesian network structure are determined in a more scientific way, thus the application of Bayesian networks in such problems is supported effectively. At the same time, this method can be used for the evaluation of mission support efficiency of other large complex systems.

Due to the characteristics of its application scenarios, satellite evaluation, satellite risk evaluation and satellite efficiency evaluation are mainly conducted by experts, therefore, the sample data of Bayesian network learning will also be determined by expert scoring, through learning, data distribution rules in samples are extracted to realize digital representation of complex expert experience.

4.2 Mission Support Efficiency Evaluation Based on Cascade Decomposition and Bayesian Network

The mission was decomposed step by step according to the Cascade decomposition method, and the hierarchical system after decomposition was taken as the Bayesian network structure of the evaluation problem, and the Bayesian network parameters were obtained by learning the sample data (Fig. 5).

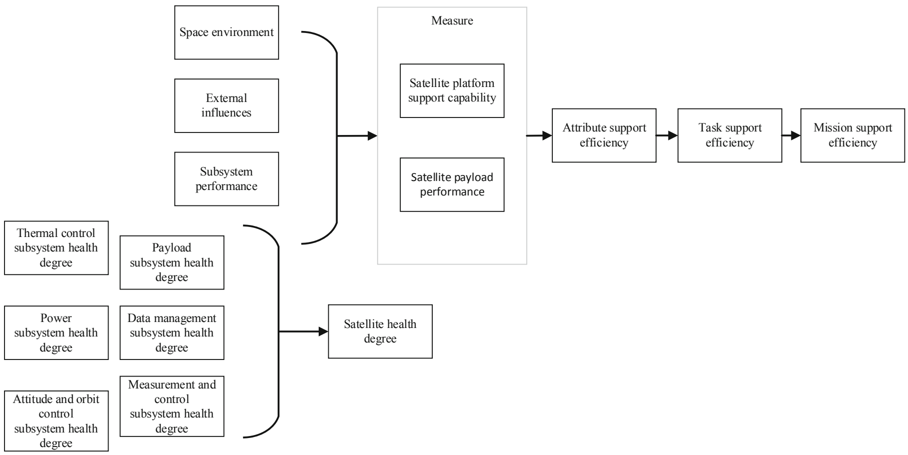

Fig. 5. Satellite support efficiency evaluation architecture

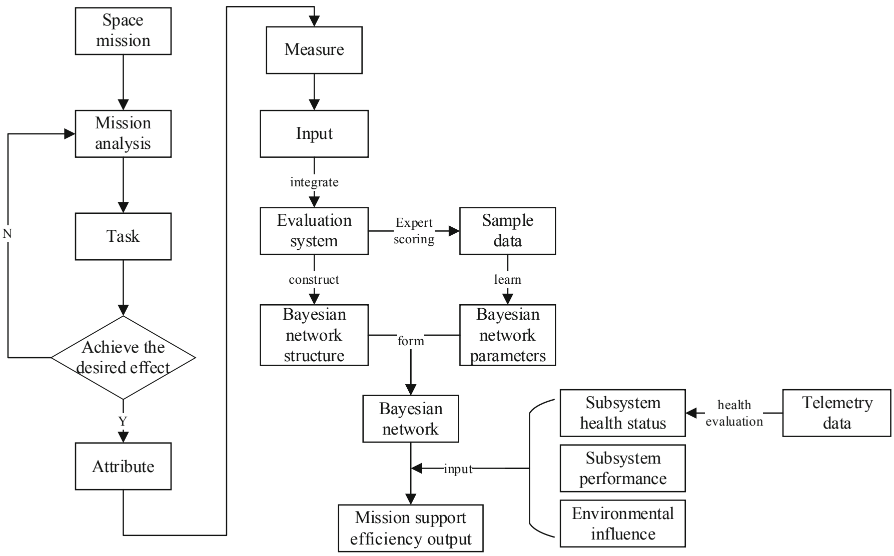

Fig. 6. Flow chart of satellite mission support performance evaluation based on Cascade decomposition and Bayesian network

On the basis of this evaluation method, the subsystem health degree, subsystem performance, space environment and external influence are taken as inputs, and the sequence of reasoning calculation is opposite to the decomposition process (as shown in Fig. 7). Finally, the evaluation results of each dimension support efficiency are obtained (Fig. 6).

5 Verification of an Example for Earth Observation Mission

5.1 Construction of the Earth Observation Mission Efficiency Evaluation System Based on Cascade Decomposition Method

The earth observation mission carried out by satellite is mainly used for space intelligence reconnaissance and information support, under the changeable situation, the importance of earth observation mission is self-evident. Therefore, it is of great significance to evaluate the support efficiency of the satellite in the earth observation mission to improve the space defense capability.

The earth observation mission flow is as follows: Submit imaging observation mission and requirements; Identify requirements attributes and priorities and generate candidate task sets; Plan the candidate task sets, allocation of satellite resources and determine the observation imaging time of the mission; According to the specific situation of the measurement and control department, convert the planning results into load control instructions; The satellite executes the relevant command, completes the observation mission, and obtains and transmits the data to the ground receiving station; Data processing and user submission.

Generally speaking, a complete earth observation mainly includes the following steps: First of all, the user requests for earth observation to the earth observation satellite management and control Center. Secondly, the management control center conducts demand analysis on the ground observation requirements submitted by users. Thirdly, the mission planning system is used to schedule the analyzed earth observation requirements. Then, form the satellite control commands, carry out earth observation, transmitted the observed information to the ground data processing center. Finally, return the final data to the user.

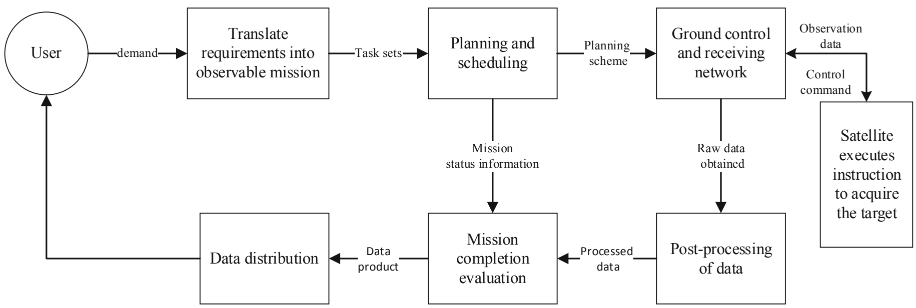

Fig. 7. Earth observation mission flow chart

Decomposition of Earth Observation Mission

Mission Statement: According to the mission scheduling of the management control center, a satellite or constellation in orbit observes a single or multiple ground objects during a specific time window, probe the state information of the observed point according to the mission requirements, then transmit the data to the ground control center, obtain space reconnaissance information and provide space information support.

Desired Effect: The satellite or constellation responds to the mission scheduling of the management center timely, fully implement the mission planning of the management control center, achieve the expected observation precision and observation period of the ground observation target, transmit the observation data to the ground data processing center timely and accurately.

Tasks: According to the above mission statement and the earth observation mission flow, the mission of earth observation was decomposed into three tasks: upload the control instruction, satellite observation and download observation data. By matching the tasks with the desired effect, it can be seen that the above three tasks achieve the accurate decomposition of the earth observation mission, so this decomposition is valid.

Task Decomposition of Earth Observation Mission

The mission of earth observation was decomposed into three tasks: upload the control instruction, satellite observation and download observation data. According to the characteristics of the task and the definition of attribute, decompose task into attributes as shown in the following table (Table 3).

Table 3. Earth observation mission - task - attribute Cascade decomposition table

Task	Timeliness	Accuracy	Effectiveness	Reliability
Upload the control instruction	×	×	×	
Satellite observation	×	×		×
Download observation data	×	×	×	

Determination of Measure of Earth Observation Mission

The scope of measure selection, on the one hand, considers the needs of the mission, namely the performance of the satellite payload. In the earth observation mission, it can be the resolution and width of the imaging load. On the other hand, considers the support capability of the satellite, such as temperature control ability, anti-interference ability, uplink information receiving and processing ability, etc. (Table 4).

Measure Decomposition of Earth Observation Mission

The mission was decomposed into tasks, attributes and measures layer by layer. In this example, measures were composed of satellite platform support capability and satellite payload performance. Finally, decompose the measure into the satellite subsystem health, the satellite subsystem performance and the safety degree of the space environment and external influence. The health of satellite subsystem is determined by the health telemetry data of satellite component. The performance of satellite subsystem is determined by

Table 4. Earth observation mission - task - attribute - measure Cascade decomposition table

Mission	Task	Attribute	Measure
Earth observation	1. Upload the control instruction	1.1 Timeliness	Satellite ability 1
			Satellite ability 2
			Satellite ability 3
		1.2 Accuracy	Satellite ability 4
		1.3 Effectiveness	Satellite ability 5
	2. Satellite observation	2.1 Timeliness	Payload performance 1
			Payload performance 2
		2.2 Accuracy	Payload performance 3
			Payload performance 4
			Satellite ability 6
		2.3 Effectiveness	Satellite ability 7
			Satellite ability 8
		2.4 Reliability	Satellite ability 9
			Satellite ability 10
	3. Download observation data	3.1 Timeliness	Satellite ability 11
			Satellite ability 12
			Satellite ability 13
		3.2 Accuracy	Satellite ability 14
		3.3 Effectiveness	Satellite ability 15

the design parameters of satellite. The safety degree of space environment and external influence are determined by the space forecast data.

So far, based on the theory of cascading decomposition method, the architecture of supporting efficiency evaluation system for satellite earth observation mission is completed (Fig. 8).

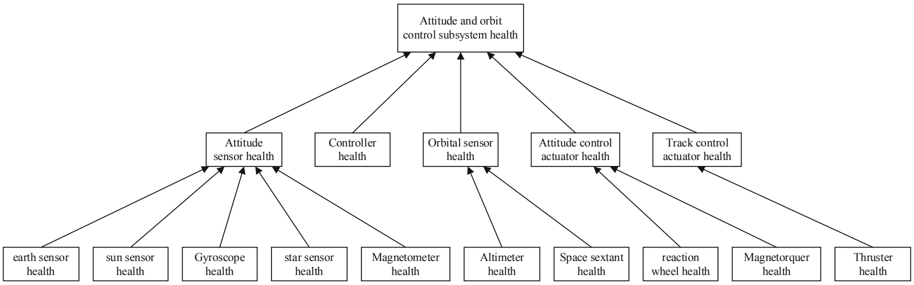

Fig. 8. Satellite attitude and orbit control subsystem health evaluation network

5.2 Efficiency Evaluation of Earth Observation Mission

In order to verify the feasibility and effectiveness of this method, Qt was used to develop a demonstration and verification software for earth observation mission efficiency evaluation method. The software includes input configuration interface, analysis method selection interface, expert scoring interface, expert scoring evaluation display interface and Bayesian network evaluation display interface.

First, the satellite subsystem health status, satellite subsystem performance status, space environment and external influence safety level are transformed to the dimensionless form properly and then filled into the input configuration interface. Then the expert scoring method is used to score the Bayesian network structure based on the Cascade decomposition method, each scoring result is saved in the Bayesian network evaluation sample file for the support efficiency evaluation of the earth observation mission. When there is some accumulation of sample data, Bayesian network method is used to learn the sample data, more accurate probabilistic relations between variables are extracted from quantitative evaluation with fuzzy boundary of domain expert knowledge. On this basis, the input of the input configuration interface is calculated step by step, and the evaluation results of each dimension of the satellite earth observation mission support efficiency are presented in the form of percentage ultimately.

Through the analysis of the above operation results, it can be seen that the mission support efficiency evaluation method based on Cascade decomposition and Bayesian network proposed in this paper, on the one hand, provides a systematic guidance for the establishment of a complex evaluation system for space missions, on the other hand, the more precise probability relationship between variables is extracted from the knowledge with fuzzy boundaries of domain experts through sample learning, guaranteeing the accuracy of this kind of uncertain knowledge inference. The effectiveness and feasibility of the method are verified by the simulation of an efficiency evaluation example for earth observation mission (Figs. 9 and 10).

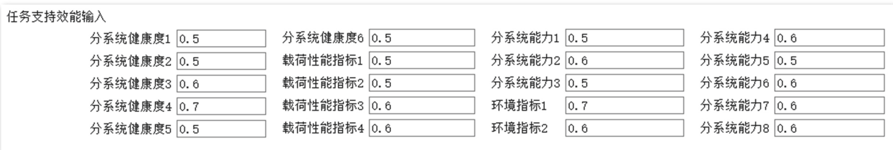

Fig. 9. The input of Earth Observation Mission support efficiency evaluation

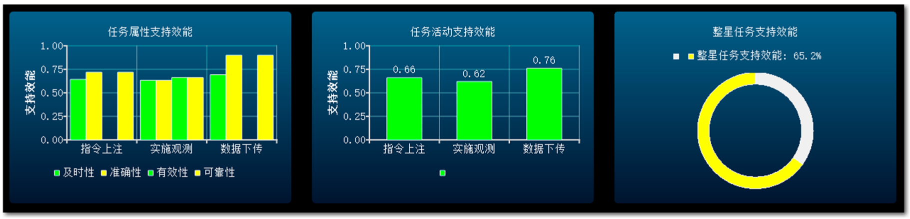

Fig. 10. The output of Earth Observation Mission support efficiency evaluation

6 Conclusion

Aiming at the problem of high complexity in the construction of satellite mission support efficiency evaluation system, this paper combines the Cascade decomposition method with the Bayesian network, decomposes the mission into tasks, attributes, measures and inputs step by step. In the process of stepwise decomposition, the object-mission in the problem is clarified constantly. Meanwhile, in the process of stepwise decomposition, more and more attentions are paid to the health degree and system performance of the subject-satellite. In the process of subject-object transformation, the relationship between subject and object in the research problem is deepened constantly, and finally the Bayesian network structure of the research problem is completed under the systematic guiding principle. Then, the most widely used expert scoring method for similar problems is adopted to generate sample data, and the probabilistic causal relationship between node variables presented in the form of network parameters is obtained by training and learning the sample data. Finally, the input data is converted into the result of mission support efficiency evaluation through reasoning calculation, so as to provide effective technical support for mission command decision-making. Of course, due to the limitations of personal experience, it is inevitable that there will be incomplete problems in the decomposition of the example for earth observation mission in this paper, but as a systematic decomposition method, the combination of Cascade decomposition and Bayesian network is indeed an effective method to solve the high complexity of satellite mission support efficiency evaluation. The research in the future will focus on improving this method, so as to further expand the scope of the application scenario of this method.

References

1. Li, X., Liu, Y., Li, G., Liu, R., Zhou, J.: Assessment of satellite health state based on fuzzy variable weight theory. Syst. Eng. Electron. **36**(03), 476–480 (2014)
2. Zhu, C., Dang, J., Zhang, M., Zahng, F., Zhuang, J.: Satellite health assessment method based on logic block diagram. Comput. Meas. Control **28**(02), 267–273 (2020)
3. Lu, Z., Jin, G., Yang, T., Wu, G., Lan, X.: Multi-level health evaluation method for on-orbit satellites based on reconfigurable degree. Syst. Eng. Electron. **40**(08), 1769–1776 (2018)
4. Li, J., Qin, G., Zhang, K., Zhang, H., Ji, X.: TT&C system operational effectiveness evaluation based on game theory. Fire Control Commend Control **44**(01), 105–109 (2019)
5. Liu, J., Sun, Y., Xing, R., Wang, H., Li, X.: Effectiveness evaluation of early warning satellite system for multi-missions. Aerospace Shanghai **36**(01), 10–15 (2019)
6. Liang, G., Zhou, X., Wang, Y.: Efficiency evaluation research on ground system of remote. Command Control Simul. **40**(05), 62–68 (2018)
7. Wang, J., Wang, K., Chen, J., Guo, J.: Research on weaponry system effectiveness evaluation based on task completion rate. Fire Control Commend Control **40**(11), 48–52 (2015)
8. Liu, F., Li, L., Meng, X.: Research on construction model of the capacity index system for remote sensing satellite system. Spacecraft Recov. Remote Sens. **38**(06), 40–45 (2017)
9. Peng, G.: Index system construction of information support capability evaluation of remote sensing satellite task-oriented. Command Control Simul. **41**(02), 15–19 (2019)
10. Xie, J., Wang, P., He, C., Cui, L., Cen, Z.: effectiveness evaluation for satellite remote sensing detect based on evidential theory. J. Sichuan Mil. Eng. **36**(02), 98–101 (2015)

11. Qin, P., Hao, S., Qin, G.: Research on evaluation method of contribution rate to SOS for remote sensing satellite application. Electron. Des. Eng. **27**(02), 70–73+79 (2019)
12. An, S., Long, J.: Model of satellite state evaluation based on bayers network. Trans. Beijing Inst. Technol. **30**(05), 548–551.