Research ON Satellites Fault Diagnosis Method Based On Artificial Intelligence

Kezhen Song, Chen Zhao, Jie Liu, Hao Zhang and Zhiyu Li

Institute of Telecommunication and Navigation Satellites, CAST, Bei Jing, 100094, China
yqskz9582@163.com

Abstract: In order to enable satellites to use fault diagnosis, fault prediction, failure prediction and other data models to determine the health status of satellites autonomously, According to the statistics of satellite orbit faults, this paper gives an artificial intelligence-based satellite fault diagnosis method and compares the advantages and disadvantages of three different satellite fault diagnosis methods to ensure that when a satellite fault occurs, it can implement autonomous reconfiguration, redundancy switching, autonomous mode switching or downgrade use when its own conditions allow. The study ensures that when a satellite failure occurs, it can implement autonomous reconfiguration, redundancy switching, autonomous mode switching or downgrade use when its own conditions allow, ensuring the safety of satellite operation in orbit. Through the analysis of the application of typical fault diagnosis methods for a satellite control subsystem, it can be seen that artificial intelligence-based satellite fault diagnosis methods have gradually replaced traditional methods and become the core key technology for the future application of autonomous satellite health management system in orbit, which is also one of the core functions that future software-defined satellites should have.

1. Introduction
A satellite is a complex system involving multiple disciplines and multi-disciplinary technologies, requiring the ability to fly for long periods of time in a harsh and complex space environment. Despite a series of reliability measures taken during the design and development of satellites, it is still inevitable that one or another failure will occur during the satellite's flight in orbit, causing sudden or gradual deterioration of the satellite's health. Statistics show that out of the 1036 spacecrafts successfully launched from 1990 to 2009, 156 had malfunctions, accounting for 15% of the total number of spacecrafts. The special nature of space missions, in turn, makes it possible for a failure to occur while the spacecraft is in orbit to lead to the failure of the entire mission if no action is taken.

At present, the health management of the majority of China's satellites in orbit cannot be managed without the support of ground-based measurement and control stations, relying on a large number of professionals to analyze and judge the telemetry data, and also relying mainly on expert decision-making in the event of a fault. However, due to China's geographical constraints, it is not possible for ground stations to track satellites throughout their life cycle, and corrective measures cannot be taken in the event of a failure in an uncontrollable arc. Even in controlled arc segments, the effectiveness and real-time nature of remedial measures taken by the ground alone are quite limited, and the best time to deal with the situation may be missed resulting in the failure of the space mission. Therefore, it is important to use satellite autonomous health management systems to reduce the burden
on spacecraft ground measure and control systems and to ensure the healthy and stable operation of spacecraft in orbit[3].

Foreign research on spacecraft health management began in the 1960s, and as the understanding of satellite health management concepts and functions deepened, understandings and definitions of health management in foreign countries evolved and were updated[4]. The United States was one of the first countries to engage in space activities and is a leader in spacecraft autonomous health management technology. In terms of future strategic planning, the US also attaches great importance to the development of spacecraft autonomous health management technology, with the US Air Force 2025 plan, the US Space Command 2020 long-term plan, and NASA's New Centurion program all putting intelligent autonomous health management technology at the forefront. Three typical examples of US spacecraft health management are the Vehicle Health Management (VHM) system used in the X-33 reusable vehicle, the Livingstone health management system used in the Deep Space One rover, and the Prognostics & Health Management (PHM) for the JSF military aircraft. These autonomous health management systems can read out spacecraft health information from a troubleshooting database and perform diagnostic reasoning, the results of which can be used to supplement and verify the diagnostic results of the on-board systems. Networked technology is used to create a fault diagnosis database that can be continuously learned and improved before and after the spacecraft flight and during the in-orbit phase.

In the future, satellites with powerful computing capabilities based on space-based supercomputing[5] are able to use advanced data processing and analysis algorithms such as fault diagnosis, fault prediction and failure prediction to determine the health status of the satellite. When a fault occurs it is able to implement autonomous reconfiguration, redundancy switching, autonomous mode switching or downgrade use and other actions as its own conditions allow, ensuring the safety of satellite operation in orbit.

2. Satellite autonomous health management technology

The tasks of the Satellite Autonomous Health Management System can be summarized in the following five items:

(1) Health status check
   The ability to test and check the function and performance of spacecraft components, subsystems or external replaceable units using advanced sensors and other inspection means to obtain adequate information on the health status of the spacecraft.

(2) Fault and failure prediction and diagnosis
   The ability to determine the health status of a spacecraft using advanced data processing and analysis algorithms for fault diagnosis, fault prediction and failure prediction. On the one hand, it is important to diagnose and locate faults in time when they occur, or to use intelligent prediction methods to forecast upcoming faults on the spacecraft so that timely action can be taken; on the other hand, reliability models of components and systems are used to forecast the operational performance of components, so that they can be repaired or switched over in advance of component or system failure to avoid failure.

(3) Troubleshooting and reconfiguration
   After a failure, it is able to implement autonomous reconfiguration, redundancy switching, autonomous mode switching or downgrade use as its own conditions allow, ensuring the spacecraft's energy supply and safety.

(4) System performance evaluation and management
   Integrated management, decision making, scheduling and prediction of the health status of the spacecraft and the operational performance of its components, enabling timely deployment of resources in the event of a failure or breakdown.

(5) Smooth and rapid information communication
   The ability to record and store key data and information during the mission, such as spacecraft status, fault conditions, repair capabilities, etc., and transmit them to the ground in time.
As shown in Figure 1, the workflow of the satellite autonomous health management system includes: health information acquisition, health state determination, health state assessment and health state recovery.

3. Satellite fault diagnosis method based on Artificial intelligence

Fault diagnosis technology is the key to achieving autonomous spacecraft health management. In general, satellite fault diagnosis methods can be divided into the following three categories [6]: ① fault diagnosis methods based on direct signal monitoring, ② fault diagnosis methods based on analytical models, and ③ fault diagnosis methods based on qualitative models.

Signal processing-based fault diagnosis method based on directly measurable input and output and its change trend or the use of the system directly measurable signal and the existence of the fault of the relationship, such as correlation function, spectrum, wavelet technology, etc., to extract the amplitude, phase, spectrum and other characteristic values, with these characteristic values to analyze, judge, deal with the fault. Among such diagnostic methods, the fault diagnosis method based on direct signal monitoring is the most commonly applied diagnostic method in practical engineering, which has been successfully applied on spacecraft at home and abroad.

The analytical model-based fault diagnosis method is based on the mathematical model of the system, using the observer (group), Kalman filter and other methods to generate residuals, and then evaluate or make decisions on the residuals according to some criteria or thresholds. Its advantage is that it makes full use of the deep knowledge within the system and facilitates the accurate detection of faults occurring or not. The disadvantage of the method is that it relies too much on the mathematical model of the system, is more sensitive to modelling errors, parameter ingestion, noise and disturbances and is generally only applicable to linear objects and individual fault analysis.

Among the diagnostic methods based on artificial intelligence, the fault diagnosis method based on qualitative models is a new intelligent fault diagnosis method developed in recent years [7]. A qualitative model consists of a set of qualitative variables that represent the physical parameters of a system and a set of qualitative equations that represent the interrelationships between the parameters [8]. By describing and reasoning qualitatively about systems and processes, avoiding quantitative descriptions and complex numerical operations, it can effectively reveal the causal links that exist between various events or phenomena. Since qualitative models do not require precise models and measurements, overcoming some of the disadvantages of the analytical model approach, fault diagnosis methods based on qualitative models use qualitative information to diagnose faults and can significantly reduce computational effort.

Qualitative model-based fault diagnosis methods for artificial intelligence satellites first generate fault hypotheses based on observations and logical analysis, then build a qualitative fault model from which the system behavior is predicted, then compare the predicted behavior with the observed actual system behavior, and if the two agree, the system is faulty and the fault model becomes the current
system model. Finally, the type of fault is further determined based on the a priori knowledge available at the time the fault model was built. This process is known as the 'hypothesis-modelling-simulation-matching' cycle.

The behavior of the system is predicted by constructing a qualitative normal model. A discrepancy detector is then used to measure the difference between the prediction and the actual observation, and if a discrepancy exists it indicates a system fault. The discrepancy is then applied to the candidate generator to produce candidate faults. Finally, the candidate faults are fed back to the normal model to form the fault model until the prediction matches the actual output, thus diagnose the fault. According to the classification of satellite in-orbit faults, by comparing the advantages and disadvantages of satellite fault diagnosis methods, the typical faults in-orbit of satellite control subsystem such as gyro, Solar sensitizer, stellar sensitizer, reaction wheel and sail drive mechanism are taken as examples, and the failure mode analysis of different faults is carried out to select the suitable diagnosis method for this type of typical faults. Table 1 gives the implementation of the diagnostic methods for typical faults in a satellite control subsystem. From Table 1, it can be seen that artificial intelligence-based satellite diagnosis methods have gradually replaced traditional methods and become the core technology for the future application of autonomous satellite health management systems in orbit, as well as the core function that software-defined satellites should have.

Table 1 Application of typical fault diagnosis methods for a satellite control subsystem

| Equipment name | Fault description | Troubleshooting methods |
|----------------|-------------------|------------------------|
| Gyroscope      | No change in gyro output data due to sensor failure or control circuit failure | ①③ |
|                | Faulty gyro motor or torque converter, gyro output always zero | ①③ |
|                | Gyroscopic accuracy reduce, measurement output with random interference and increased noise | ②③ |
| Solar Sensitizer| The output is no longer sensitive to changes in the attitude of the satellite and the output data is a constant value | ①③ |
|                | Random noise in the measurement output becomes large | ③ |
|                | Measuring output ramp changes | ②③ |
|                | Output random values | ③ |
| Stellar Sensitizer | The output is no longer sensitive to changes in the attitude of the satellite and the output data is a constant value | ①③ |
|                | Measuring output pulse bursts | ③ |
|                | Increased random noise in the measurement output | ③ |
|                | Ramping of the measurement output | ②③ |
|                | The measured output varies with constant gain | ②③ |
|                | Measurement output with constant deviation | ②③ |
|                | Reflected light from the sun enters the field of view of the star sensor and causes an error message to be output | ①③ |
| Reaction wheel | Idle, wheel does not respond to normal control torque commands, output torque is zero | ①③ |
|                | Stuck at a standstill, the output torque first generates a large reverse disturbance and then rapidly changes to 0 | ①③ |
|                | The difference between the desired torque and the output torque of the flywheel is increased because the motor torque becomes smaller or the friction torque increases. | ②③ |
|                | Reduced flywheel efficiency, reduced flywheel output torque | ②③ |
According to the statistics of the faults of satellite control subsystem which was been in orbit, it is found that the single fault of star sensor accounts of 41.1% of the total faults of the control system. Using the traditional fault diagnosis technology, the faults such as the sudden change of the output pulse and the increase of the random noise of the measurement output cannot be accurately monitored. The satellite fault diagnosis technology based on artificial intelligence can improve the typical fault diagnosis rate of control system by 5%~10%.

4. Comparison of fault diagnosis methods
Table 1 gives a comparison of the advantages and disadvantages of the three different satellite fault diagnosis methods and the statistics of actual in-orbit satellite applications. As can be seen from Table 1, the artificial intelligence-based satellite fault diagnosis technique does not require the establishment of an analytical model of the system, while there is no strict limitation on the degree of fault, which is more adaptable to the actual system and is of great significance to improve the fault diagnosis capability of the system and ensure its safety and reliability.

| Proposed fault diagnosis method | Diagnostic ideas | Advantages | Disadvantages | Applications |
|--------------------------------|------------------|------------|---------------|--------------|
| Fault diagnosis method based on direct signal monitoring | Upper and lower bound determination of the value or rate of change of a diagnostic parameter | Simple, does not require modelling of the diagnostic object and is relatively easy to implement | The diagnostic process and results do not reflect the internal conditions of the system | The most widely used fault diagnosis method, which has been applied on various foreign aerospace |
| Fault diagnosis methods based on analytical models | A model of the faulty system is created, the model is processed by some algorithm (e.g. Kalman filter), the distribution of the residuals is obtained and then it is judged using fault determination criteria | Deep knowledge within the system can be fully utilized to facilitate accurate fault detection | Overly dependent on the mathematical model of the system, sensitive to modelling errors, parameter uptake and generally only suitable for linear objects and individual fault analysis | Already successfully used on foreign spacecraft |
| Fault diagnosis methods based on qualitative models based on artificial intelligence | Converting quantitative models and fault determination criteria into qualitative descriptions Establishing probabilistic transfer | No need to build a mathematical model of the system, low computational complexity and good real-time | Qualitative models are difficult to build; they overlook many details within the system, resulting in less accurate | It represents the highest level of spacecraft available. It has already been used by spacecraft such as Deep Space |
| Proposed fault diagnosis method | Diagnostic ideas | Advantages | Disadvantages | Applications |
|--------------------------------|------------------|------------|---------------|--------------|
|                                | relationships between different states of the system and using probabilities for diagnosis | performance | diagnostic results. The application of artificial intelligence has been greatly improved | One and the Earth Observation Satellite of the United States. |

5. Recommendations and outlook

This paper gives an artificial intelligence-based satellite fault diagnosis method that enables satellites to determine their health status using advanced data processing and analysis algorithms for fault diagnosis, fault prediction and failure prediction. To ensure the safety of satellite operation in orbit, it is able to implement autonomous reconfiguration, redundancy switching, autonomous mode switching or downgrade use and other actions on its own conditions allowed when a fault occurs. According to the application of typical fault diagnosis methods for a satellite control subsystem, artificial intelligence-based satellite fault diagnosis methods have gradually replaced traditional methods, becoming the core technology for the future application of autonomous satellite health management systems in orbit, and is also the core function that software-defined satellites should have. In the future, AI-based satellite fault diagnosis methods will be further improved in terms of qualitative modelling methods, integrated use of multiple methods, global and autonomous diagnosis, etc.

(1) Refining qualitative modelling methods

Qualitative modelling plays an important role in qualitative diagnosis. At present, many qualitative models can only express simple logical relationships between variables, making it difficult to reflect the internal structure of the system in depth, thus producing redundant diagnostic results, and there is a need to further improve qualitative modelling methods so that they can reflect the deep knowledge of the system.

(2) A combination of methods

Different fault diagnosis methods based on qualitative models have their own advantages and disadvantages. Several qualitative methods can be combined and applied to achieve their strengths and weaknesses in order to improve the fault diagnosis capability of the whole system; quantitative knowledge can also be introduced to improve the qualitative methods, so as to improve the diagnosis efficiency and optimize the diagnosis results.

(3) Globalized and autonomous diagnostic systems

Most of the actual qualitative diagnostic systems are specific to a local subsystem and require manual involvement in the diagnostic process. Several subsystems with similar mechanisms or functions can be considered as a whole and diagnosed using their generic methods, and then extended to other subsystems to achieve globalization. There is also a need to improve the knowledge base of the diagnostic system so that it has a learning mechanism and can diagnose agnostic faults in order to achieve autonomy.

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