# Research on Satellite Autonomous Fault Detection and Recovery Framework

Xunjia Li[1, a], Xin Ma[1, b], Tao Zhang[1, c], Xiaodong Han[2, d] and Yajie Liu[1, e, *]
[1]College of System Engineering, National University of Defense Technology, Changsha 410073, China
[2]Institute of Telecommunication Satellite, China Academy of Space Technology, Beijing 100081, China

Keywords: Autonomy, Fault detection, Recovery, Task re-planning, Artificial intelligence.

Abstract: During the operation of the satellite in orbit, the operating state may change due to the fault. The impact of satellite failures on satellites is enormous. In this paper, satellite fault detection and recovery is taken as the research object, and an automatic fault detection and recovery framework (AFRF) for fault recognition and recovery of satellite autonomous operation and task re-planning is proposed. Artificial intelligence methods are used in the framework to implement on-board rapid diagnosis faults, autonomous fault repair, and autonomic task re-planning. The experimental results show that the proposed framework can solve the satellite fault problem well and has a good engineering application prospect.

## 1. INTRODUCTION

A satellite is a platform that runs in space and can perform a variety of shooting, communication, and navigation tasks. The normal operation of the satellite is the basic condition for the successful completion of the mission. Due to the influence of various factors such as the environment and its own equipment on the satellite, the fault may occur during the operation of the satellite. The impact of the fault on the satellite is serious. After the fault occurs, the satellite will suspend the task being performed and enter the satellite fault diagnosis and recovery mode. After the satellite passes the fault diagnosis and detection, it will resume normal operation and can continue to perform tasks. A fault self-detection diagnosis and recovery framework is set up, and artificial intelligence is used to detect various data in the satellite state to determine the occurrence of the fault. After detecting the fault, the satellite enters the emergency mode to achieve rapid satellite state recovery and task re-planning, so that the satellite can start performing new tasks in the fault repair.

With the increasing complexity of satellite systems, various sensors obtain massive telemetry parameters and perform anomaly detection for telemetry data. Currently, there are four methods for anomaly detection of satellite telemetry data: manual monitoring combined threshold-based method, expert system-based method, model building method based on expert experience and data driven method. Telemetry data tends to be regular and periodic, and the data will fluctuate within a large range. For these characteristics, this paper focuses on data-driven methods. The data-driven method does not require prior knowledge and data distribution requirements, and is highly scalable and can be detected in real time for streaming data. Among many methods, prediction-based methods are currently hot topics (Yang, Y., & Hou, N, 2013). The prediction based anomaly detection methods include ARMA (Weizheng, L. I., & Qiao, M, 2014), LSSVM (Bing, C., Gang, L., Hongzheng, F., & Li, A, 2014), and RVM [4], dynamic Bayesian network (Yairi, T., Kawahara, Y., Fujimaki, R., Sato, Y., & Machida, K, 2006), ANN (Sadeghi, B. H. M, 2000; Elman, J. L, 1990) and so on. This paper mainly uses artificial neural network algorithm.

Satellite mission planning research is also an important part of the satellite field. Literature (Song, Y., Huang, D., Zhou, Z., & Chen, Y, 2018) proposed an autonomous satellite autonomous re-planning method, and set up three task insertion algorithms. In (He, Y, Xing, L., & Chen, Y, 2016), from the perspective of software design, an automatic mission planning software based on new satellite is designed.



Li, X., Ma, X., Zhang, T., Han, X. and Liu, Y.
Research on Satellite Autonomous Fault Detection and Recovery Framework.
DOI: 10.5220/0008385602930298
In *Proceedings of 5th International Conference on Vehicle, Mechanical and Electrical Engineering (ICVMEE 2019)*, pages 293-298
ISBN: 978-989-758-412-1

Literature (Song, Y. J., Zhou, Z. Y., Zhang, Z. S., Yao, F., & Chen, Y. W, 2019) considers several problems in satellite mission planning and proposes a generalized solution framework including mobile edge computation. Literature (Zheng, Z., Jian, G., & Gill, E, 2018) studied the multi-star system and designed a multi-star synergy. Literature (Song, Y. J., Zhang, Z. S., Sun, K., Yao, F., Chen, Y. W, 2019) solved the problem of satellite data downlink mission planning by using genetic algorithm. This paper will consider both satellite fault detection and satellite mission planning, and design an efficient and versatile autonomous operation framework.

The structure of this paper is as follows. In the second part, the satellite autonomous fault detection and recovery framework proposed in this paper will be introduced. The third part will adopt the effect of an application scenario verification framework. Finally, the conclusions and prospects of this paper will be given.

# 2. AUTONOMOUS FAULT DETECTION AND RECOVERY FRAMEWORK(AFRF)

Using satellite autonomous fault detection and recovery technology can quickly diagnose faults, allowing satellites to return to normal operating conditions and perform new tasks in a short period of time. The autonomous fault detection and recovery framework provides a solution for the satellite to quickly detect and diagnose faults and transition from an abnormal state to a normal working state. First, we will analyze the functional requirements of the autonomous fault detection and recovery framework for satellites to meet autonomous operation and fault recovery. After that, we will give the overall structure of AFRF and give the specific content of each module.

## 2.1 Functional Requirements

Combined with the characteristics of satellite autonomous operation and execution tasks, according to the high reliability and high stability operation requirements of satellites, the functional requirements for rapid fault detection, autonomous fault recovery and on-board mission re-planning are proposed for satellite autonomous fault detection and recovery.

Fast fault detection the occurrence of the fault is serious for the satellite, which will result in the satellite not functioning properly or even the satellite being scrapped. The satellite needs to establish a complete fault detection mechanism, monitor the satellite health status according to the data of each sub-system on the star, and adjust the abnormal sub-system to a normal level. When a fault occurs, quickly locate the sub-system in which the fault occurred based on the satellite's existing fault template library and determine the specific fault location.

Autonomous fault recovery Satellites will not function properly after a satellite failure, which requires a quick return of the satellite to its normal state. The traditional way of using ground commands for satellite fault repair has strict requirements on satellite position, and the timeliness of repair is not high. Autonomous fault repair allows the satellite to initiate the fault repair process at the same time as the fault occurs, and the satellite can be quickly restored to normal operation in a short period of time, and the task can be continued.

On-board task re-planning after the satellite failure occurs, the original task will be aborted until the fault is repaired. At this time, since the satellite position is different from the position before the fault, many tasks will not be executed. The satellite should regenerate a new mission execution plan after the fault is fixed and complete the subsequent tasks according to the new scheme.

## 2.2 Overall Design

Throughout the framework, the main functions completed are training and improvement of fault detection models, fault detection and re-planning, and fault repair. Among them, the training and improvement of the fault detection model is carried out on the ground, because the ground has more sufficient computing resources than the satellite, which can better support the training and improvement process of the artificial intelligence model. Fault detection and re-planning, fault repair is performed on the satellite. Satellite self-execution fault diagnosis and repair has the ability to quickly detect faults, quickly diagnose faults and repair, and ensure that the satellites return to normal operation in a short time.

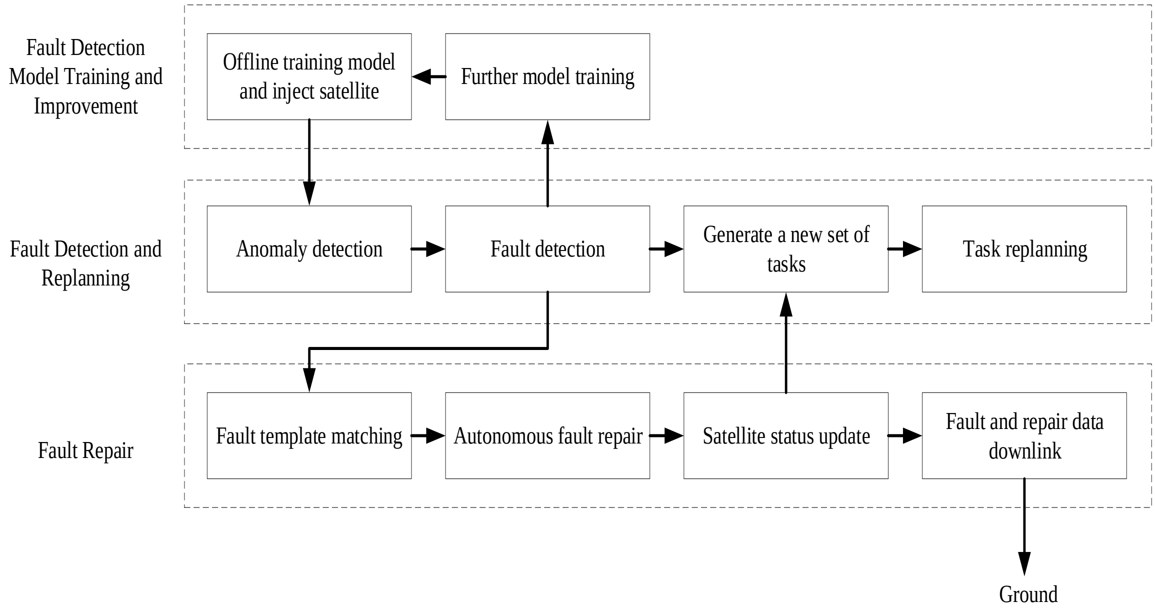


Figure 1. AFRF overall framework.

The artificial intelligence model is trained and injected into the satellite before the satellite starts to run. After acquiring the satellite fault data, the model is transmitted to the ground for retraining of the model to improve the prediction accuracy. The improved model is re-injected to the satellite when the satellite has an available satellite communications link.

After the satellite is injected into the satellite, the operational status of each satellite system is monitored according to the operational data of each satellite subsystem, and the model is used to determine whether there is a possibility of failure. If it is determined according to the model that the satellite has a possibility of failure, the fault is automatically detected. After the satellite detects the cause of the fault, the template library is used for autonomous fault matching and autonomous repair is performed. After the repair process is completed, the satellite parameters are updated and the fault and repair information is transmitted to the ground via the star link.

After satellite autonomous fault repair, the satellite returns to the normal state, and the corresponding data is provided to the task planning part. The task planning part updates the task status according to the data, generates a new task set, and performs task re-planning according to the new task set.

Through the ground model training and learning in the whole framework, the satellite independently detects faults and repairs faults, and re-plans the tasks to be performed according to the new mission situation after the satellites resume normal operation. Our proposed AFRF can detect faults and fix faults more quickly, adjust the task execution plan in time, and let the satellites detect the faults and repair process after rapid detection, and continue to run normally and complete various types of tasks.

## 2.3 Module Design

In AFRF, the core part is fault diagnosis and identification, autonomous fault repair, and task re-planning. In the following, the module design will be carried out separately for these three parts.

### 2.3.1 Satellite Fault Diagnosis Module Design

The satellite fault diagnosis module includes satellite data anomaly detection and fault identification. The data anomaly detection function uses artificial intelligence tools to run on ground, run on the star, and use new data to further improve the model's way of running. The fault identification function uses the satellite's existing fault template library for fault analysis and identification based on the abnormality found by the anomaly detection function, and accurately identifies the satellite subsystem and the specific fault cause in which the fault occurs in the shortest possible time.

The module adopts neural network-based prediction method. The algorithm is based on traditional time series prediction technology. It is assumed that the telemetry data has temporal correlation. The new data can be obtained by historical data recursively by establishing a time window model. The range of new data is passed. The established model predicts the mean and variance. When the real data arrives, if the real data is in the interval, no abnormality occurs; otherwise, an abnormality is considered.

Considering that BP neural network (Sadeghi, B. H. M. 2000) has the disadvantages of slow learning speed, limited network promotion ability and cannot effectively process different historical time information in data, Elman neural network (Elman, J. L. 1990) overcomes the above shortcomings, and Elman neural network will hide the previous moment. The information in the layer-containing unit is used as part of the input data of the unit at the current time, so that the units in the network have a memory function, and can be continuously updated as the data changes, thereby better learning information and rules in different time series. . It can realize the modeling of static systems and the mapping of dynamic systems. Its computing power and network stability have obvious advantages over BP neural networks.

#### 2.3.2 Satellite Autonomous Fault Repair Module Design

After the satellite fault diagnosis module finds and detects the cause of the fault, the satellite performs emergency treatment and satellite fault repair according to the fault plan. The specific process of fault repair is determined according to the severity of the fault. After the fault repair is completed, the satellite summarizes the fault information and the repair result and then transmits it to the ground to facilitate the ground control center to decide whether to further repair the faulty satellite or take other measures to ensure the normal operation of the satellite in orbit.

#### 2.3.3 Satellite Independent Task Re-planning Module Design

The satellite returns to normal operation after the fault is repaired and needs to perform new tasks. The autonomous task re-planning module is used to add the tasks that are not successfully executed and will be executed in the future to the to-be-planned task set, and use the on-orbit dynamic programming algorithm to solve the task set and generate a new task execution plan. The satellite performs the corresponding tasks in the next phase based on the results of the re-planning.

## 3. APPLICATION EXAMPLES

In order to verify the validity of the proposed AFRF framework, we conducted a complete application example experiment. First of all, in the process of satellite operation, there may be a situation of failure. The autonomic fault detection is performed by using Elman neural network for telemetry data. The detection result is shown in Figure 2. The blue line is the real data, the red line is the prediction data, and the two green lines are the upper and lower bounds of the prediction interval respectively. The fault occurs at about 1400 and 1700. It can be seen from the figure that when there is no fault, the real data is basically in the prediction interval. When the fault occurs, the real data value is outside the prediction interval, thus detecting the abnormality, which proves the accuracy of the method.

After fault detection, the satellite uses the AFRF framework for autonomous fault repair, and the task can be re-executed by restoring the satellite to normal state. We use three commonly used heuristic rules for autonomous re-planning. The goal of the plan is the completion rate of task re-planning. The results are shown in Table 1.

Table 1. Task re-planning result.

| Instance | Heuristic1 | Heuristic2 | Heuristic3 |
|---|---|---|---|
| 25 | 0.92 | 0.92 | 0.96 |
| 50 | 0.92 | 0.92 | 0.92 |
| 75 | 0.88 | 0.88 | 0.89 |
| 100 | 0.90 | 0.88 | 0.92 |
| 125 | 0.83 | 0.83 | 0.85 |
| 150 | 0.74 | 0.80 | 0.81 |

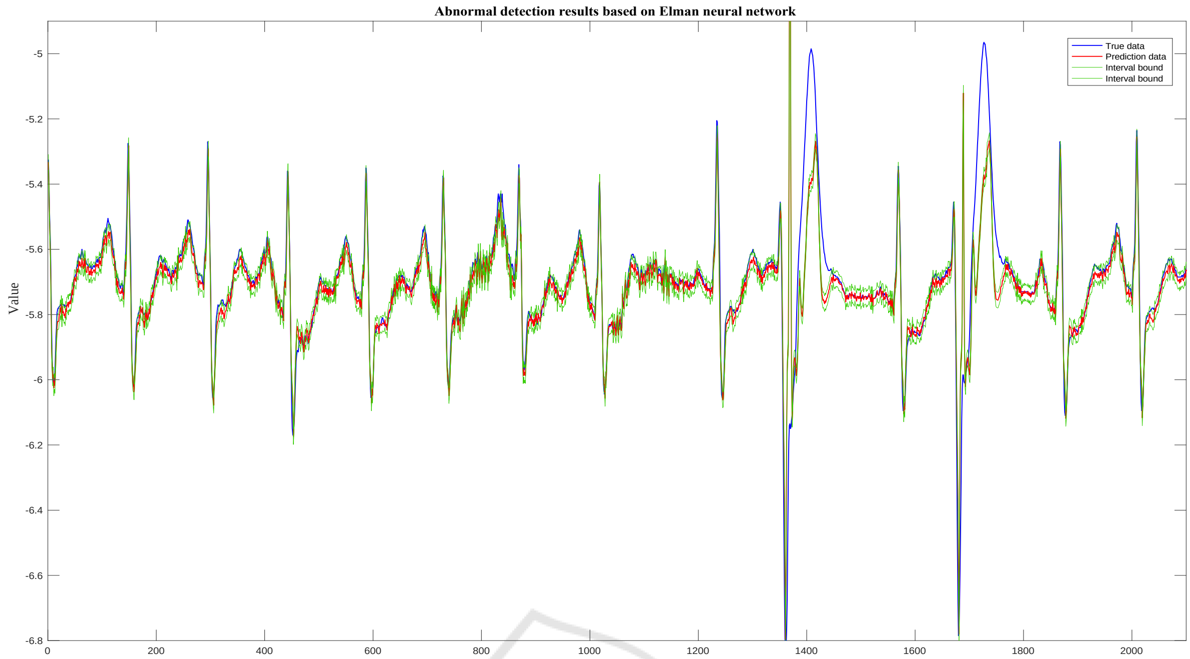


Figure 2. Fault detection result.

As can be seen from Table 1, the use of these three heuristic rules can quickly achieve satellite mission re-planning. After completing the re-planning of the mission, the satellite performs the mission according to the new mission, and the value of the satellite is utilized. It can be seen from the above experiments that the AFRF framework proposed by us is effective for fault detection and repair and task re-planning, and can well restore the satellite to normal operation.

## 4. CONCLUSION

Satellite fault detection and repair is of great significance for ensuring the normal operation of the satellite and successfully completing the mission. This paper takes satellite fault detection and repair as the research object, analyzes the satellite fault repair and re-planning process, and proposes a satellite autonomous fault detection and recovery framework. In our proposed satellite autonomous fault detection and recovery framework, it includes ground model training and improvement, on-board autonomous fault detection and re-planning, and satellite autonomous fault repair walking. We use artificial intelligence methods in the framework to detect satellite faults using artificial intelligence. The task re-planning is implemented by a heuristic algorithm after the satellite resumes normal operation, allowing the satellite to function better.

In the following research, we will try our use of the autonomous fault detection and repair framework on the actual application platform. At the same time, the verification of multiple artificial intelligence models under the framework of autonomous fault detection and repair, the selection of the most appropriate model method is also the next step.

## REFERENCES

Bing, C., Gang, L., Hongzheng, F., & Li, A. (2014). Method of satellite anomaly detection based on least squares support vector machine. Computer Measurement & Control.

Elman, J. L. (1990). Finding structure in time. Cognitive Science, 14(2), 179-211.

He, Y., Xing, L., & Chen, Y. (2016). Software design of autonomous mission planning for new imaging satellite. International Conference on Space Operations.

Sadeghi, B. H. M. (2000). A bp-neural network predictor model for plastic injection molding process. Journal of Materials Processing Technology, 103(3), 411-416.

Song, Y., Huang, D., Zhou, Z., & Chen, Y. (2018). An emergency task autonomous planning method of agile imaging satellite. Eurasip Journal on Image & Video Processing, 2018(1), 29.

Song, Y. J., Zhang, Z. S., Sun, K., Yao, F., Chen, Y. W. (2019) A Heuristic Genetic Algorithm for Regional Targets' Small Satellite Image Downlink Scheduling Problem, International Journal of Aerospace Engineering, 2019, 1-13.

Song, Y. J., Zhou, Z. Y., Zhang, Z. S., Yao, F., & Chen, Y. W. (2019). A framework involving mec: imaging satellites mission planning. Neural Computing and Applications, 1-12.

Weizheng, L. I., & Qiao, M. (2014). Fault detection for in-orbit satellites using an adaptive prediction model. Chinese Journal of Space Science, 34(2), 201-207.

Yairi, T., Kawahara, Y., Fujimaki, R., Sato, Y., & Machida, K. (2006). Telemetry-mining: A machine learning approach to anomaly detection and fault diagnosis for space systems. IEEE International Conference on Space Mission Challenges for Information Technology. IEEE Computer Society.

Yang, Y., & Hou, N. (2013). Data series forecasting and anomaly detection methods based on online least squares support vector machine. Control Conference. IEEE.

Zheng, Z., Jian, G., & Gill, E. (2018). Onboard autonomous mission re-planning for multi-satellite system. Acta Astronautica, 145, 28-43.