Architecture and Strategy of the Intelligent Hybrid Autonomous System for Complex Mixed Spacecraft

Yanchao Gao, Ke Liang, Xiaoqiang Ren
Beijing Manufacture and Experiments Centre of Space Technology, Beijing, 100094, China
gaoyanchao86@163.com

Abstract. For manned spacecraft, constellation and other types of complex mixed spacecraft, in view of the complexity of the system construction and the long-term nature of their on-orbit service including multiple spacecraft building, system multi-module integration, changeable operation and working mode and uncertainty of on-orbit environment, the ability of autonomous operation is essential for long-term reliable flight, automatic emergency disposal and the reduction of ground resource commitment. In this paper, the construction of the intelligent autonomous system of single spacecraft centralized mode and multi-spacecraft networking hybrid mode is researched, in order to realize efficient communication and effective negotiation among multi-agents. Based on mixed method of data, model and expert rules, an intelligent autonomous strategy with combined hierarchical structure is formed at spacecraft, subsystem and equipment levels, which can provide a good reference for autonomous management of highly-integrated single spacecraft system, constellation and complex multi-spacecraft system.

1. Introduction
At present, on-orbit spacecraft still rely on ground management and operation, with little involvement of autonomous management, which requires massive commitment of human and material resources from ground. When the spacecraft is in orbit, the status are generally acquired by humans or equipment on the ground through the space-to-earth measurement and control link, who will keep close watch and determine whether the spacecraft is operating normally in orbit. This traditional method of spacecraft management based on ground operation may be feasible for spacecraft with simple system architecture and functions. However, for some complex spacecraft, they have complex system architecture, huge functions, diverse operating modes, and long-term orbital flights. This traditional method can no longer meet the needs of normal functional maintenance and major failure emergency handling during long-term orbit flights. In case any major fault happens, which may endanger the safety of spacecraft platform or astronaut, it needs to be responded immediately. However, there may be objective delay in space-to-earth transmission of data. It is time consuming to detect and locate the faults and finally work out specific response plans on the ground. As a result, such failures can easily spread among the functional modules of the spacecraft, they are likely to cause local fault of the spacecraft or even failure of the entire spacecraft [1].

Autonomous system is a system with self-management capabilities. It can achieve autonomous management within the range of various functional performance indicators during long-term system operation without external intervention. It also has the capability of self-detection, self-adaptability, self-reconfiguration, and self-fault tolerance in abnormal and unknown states [2].
2. Multi-Agent and its Application
Agent is an intelligent system with autonomous management ability, which can be a component, sub-system or system, and which can independently complete autonomous management of its internal functions according to self-operation status and the change of environment. A Multi-Agent (Multi-Agent System, MAS) is composed of multiple monolithic interacting intelligent agents. Monolithic intelligent agents can collaborate and consult with each other based on autonomous strategy to achieve self-management within the intelligence system [3]. Meanwhile, each agent in MAS can complete autonomous management of its internal functions and has its own unique autonomous strategy and database. It can communicate, collaborate, and consult with other agents according to the function of the entire system. MAS adopts multi-agent to communicate and consult, which can make up for the defects of a monastic agent with incomplete information and limited functions and improve the performance of the whole system [4].

At present, MAS has been widely studied and applied in real applications of spacecraft abroad. Remote Agent system is a typical application of single spacecraft autonomous technology, such as Deep Space 1 spacecraft (DS-1). Remote Agent (RA) is validated for autonomous management of DS-1, with its system architecture shown as the figure below [5]. According to the division of functions, RA system is mainly composed of three intelligent agents, including PS for intelligent planning and mobilization, EXEC for intelligent implementation, and MIR for intelligent mode recognition and reconstruction. Based on the MAS technology, the three agents in the Remote Agent (RA) system work with the real-time control unit agent RT, the monitoring agent MON and other agents through collaboration and consultation to achieve autonomous management of DS-1 and realize long-term autonomous management of spacecraft in-orbit.

![Figure 1. Autonomous system architecture of DS1](image)

3. Autonomous System Architecture based on Multi-Agent
Agent technology represents an important research option to realize intelligent autonomous management. In terms of intelligent autonomous management of spacecraft, agent technology has been introduced into the spacecraft field by many aerospace research institutions at home and abroad with certain achievements. However, they are rarely used in multi-spacecraft networking. The research of intelligent autonomous system architecture for single spacecraft and multi-spacecraft based on agent technology to build a Multi-Agent System and validate the spacecraft with intelligent autonomous management has become an important direction of spacecraft autonomy [6].

3.1. Intelligence Classification of Spacecraft Agents
In a spacecraft system represented by a constellation or multi-spacecraft, each spacecraft is an agent in the system, which together constitutes a multi-spacecraft agent system; each subsystem is designed as an agent in the spacecraft, which together constitute the Multi-Agent System inside the spacecraft. At the same time, the spacecraft agents or subsystems are intelligently classified according to functions and importance of each spacecraft [7]. We classify spacecraft Agents into three grades of intelligence,
with I1 to be the highest grade and I3 to be the lowest grade based on the functions and characteristics of spacecraft and its subsystems, as shown as the figure below.

- Spacecraft level Grade I3 Agent: “the least intelligent” agent. It can only receive orders and assignments from other agents in the spacecraft system or from the ground and then implement such orders or assignments.
- Spacecraft level Grade I2: has local planning and diagnosis functions. It can generate and implement plans related to its own tasks.
- Spacecraft level Grade I1 Agent: the most “intelligent” agent. The difference between Grade I1 Agent and other spacecraft level agents lies in its capability to monitor all the spacecraft level agents and make overall organization and planning.

3.2. Autonomous System Architecture of Single Spacecraft

In order to realize intelligent and autonomous management of the internal functions of spacecraft, the Multi-Agent technology can be applied to the various subsystems of the spacecraft, with each subsystem corresponding to an agent. Each subsystems of a single spacecraft are relatively small and its status is determined before launch and generally subject to the data and instruction management of the spacecraft central control unit. Therefore, a single spacecraft is suitable to adopt centralized multi-agent system architecture. The internal multi-agent intelligent management architecture of a single spacecraft is shown in the following figure. The central controlling agent conducts centralized management of other subsystem agents, realizing autonomous management of the entire spacecraft.

The Central Controlling Agent is Grade I1 intelligence, while subsystems are set as Grade I2 and Grade I3 according to intelligence level and division of functions.

1) The Central Controlling Agent: A single spacecraft is an agent responsible for the autonomous management of the entire vehicle-level functions, and its intelligence level is at the highest level I1.

It independently commands and coordinates the various subsystems to jointly complete normal functions and fault handling at system level in accordance with the autonomous management strategy of the entire spacecraft system. It is composed of master controller(MC), Planning and Scheduling(PS), Mode Identification and Reconfiguration(MIR)S, the reconstruction function module.
2) Subsystem Agent: It refers to the autonomy agent of each subsystem, which is responsible for the autonomous management of the partial functions of the subsystem, and accepts the command and coordination of the central controlling agent.

3) Interfacing Agent: It is responsible for the interaction of information between spacecraft and between space and earth, receiving information from other spacecraft agents, and responsible for global mission planning for the entire spacecraft system. Besides, the interfacing agent receives ground commands to ensure control intervention capabilities ground.

3.3. Autonomous System Architecture of Multi-spacecraft

Networking or multi-spacecraft systems need to work in orbit according to a certain network topology to realize autonomy of multi-spacecraft systems.

Each spacecraft is defined as an agent in the networking. According to the complexity and functional positioning of the networked multi-spacecraft system, the system architecture generally includes centralized, stepwise, and hybrid mode [8].

In consideration of the complexity and adaptability of multi-spacecraft system, multi-agent hybrid mode is generally adopted [9], as shown in the figure below.

Figure 3. Autonomous system architecture of multi-spacecraft networking hybrid mode

In the hybrid multi-agent autonomous system architecture, Spacecraft 1 Agent and Spacecraft 2 Agent are both at I1 level, with the capabilities of global mission planning and management, and the two are mutually backup. Under normal circumstances, Spacecraft 1 Agent is the main working vehicle (that is, plan the overall situation). In case Spacecraft 1 Agent fails, Spacecraft 2 Agent will switch to the main working state.

At the same time, Spacecraft 1 Agent and Spacecraft 2 Agent are each responsible for autonomously managing a corresponding number of spacecraft in the network.

The hybrid architecture addresses the challenges of single-point failure bottlenecks in the centralized mode and lack of unified organizers in distributed systems, which can improve system performance, thus avoiding communication bottlenecks. Therefore, it is an ideal architecture for multi-spacecraft networking autonomous management system.

4. Combined Hierarchical Architecture of Multi-Spacecraft Autonomous Strategy

For complex multi-spacecraft systems constructed or networked by multiple vehicles, given the different mission function planning within a single spacecraft and between multiple spacecraft, it is necessary to combine the system autonomous architecture and the functional characteristics of the agents at each level to adopt specific autonomy strategy for the most optimal autonomy of agent at each level. Spacecraft system autonomy strategies are generally rule-based, model-based, and data-based. Analysis of the characteristics and applicable levels of the autonomy strategy are demonstrated in table 1.

Table 1. Analysis of characteristics of autonomous strategy

| Strength analysis | Disadvantage analysis | Normal Algorithm | Adaptation level |
|-------------------|-----------------------|------------------|-----------------|
| Autonomy          | Relative criteria     | Difficult        | Threshold       | Spacecraft level, |
strategy based on rule handling methods are clear. Reasoning and positioning are efficient, and requirements for hardware are low. system rules, and with poor adaptability rules, consistency rules, expert systems subsystem level, equipment level

Autonomy strategy based on mode Able to penetrate the dynamic nature of the system and real-time diagnosis System-level model is difficult to establish, due to the objective existence of factors such as model errors, disturbances, and noise in the model. The robustness is poor Qualitative model, quantitative model Subsystem level, equipment level

Autonomy strategy based on data With intelligence and self-learning ability; there is no need to establish a mathematical model; and the accuracy and comprehensiveness of fault diagnosis increase over time Need to learn a lot of data, long training period, high hardware requirements. Support vector machine, naive Bayes, KNN clustering, K-means clustering System level

For complex multi-spacecraft systems constructed or networked by multiple vehicles, the multi-agent autonomous system architecture is made up three levels, namely, spacecraft-level agent (level I1), subsystem-level agent (level I2 or I3), and equipment-level agent (level I3). Given the advantages of three types of autonomy strategy based on rules, models, and data and the objective to realize autonomy of the spacecraft with the full system at full-level, the complex spacecraft constructed or networked with multi-spacecraft should adopt combined hierarchical architecture [10], specifically shown in the figure 4.

4.1. Spacecraft level agent adopts combined autonomous strategy based on data and rules
If the comprehensive status of the subsystem remains unknown or in case of autonomy management of unknown status, the spacecraft level agent monitors based on data cluster analysis and makes disposes according to the cluster analysis results. It autonomously manages the comprehensive state of the spacecraft system, performs unsupervised machine learning on all or key telemetry data of the spacecraft to form a spacecraft state cluster database [11] and indexes and clusters the cluster database formed by real-time telemetry and self-learning analysis.

As the spacecraft level agent adopts autonomous strategy based on data, it requires excellent hardware to carry out data cluster analysis. It is necessary to prioritize the configuration of high-performance, high-reliability processors, memory and other hardware devices on the spacecraft-level processors. Rule-based autonomous strategies are generally adopted for known major failures at spacecraft-level to carry out failure mode countermeasures and response design, such as energy failures, etc.

For this type of autonomous management, the rules on system failure and response are generally pre-designed. If the real-time remote measurement of the system exceeds the upper and lower limits set by the fault remote measurement, the system will quickly perform system-level autonomous processing according to the pre-set fault processing strategy.

4.2. Subsystem level agent adopts combined autonomous strategy based on mode and rules
Spacecraft subsystems can generally establish quantitative or qualitative models, such as orbit control subsystems, energy subsystems, etc. to achieve autonomy with mode-based strategies. It autonomously manages the comprehensive status of the subsystem. The actual measurement data and model simulation data of the subsystem work together to form failure detector and obtains the fault detection result through residual analysis and signal processing. It determines whether the subsystem level can autonomously manage itself or apply for system management.
In case the subsystem has designed failure mode, the autonomous management is accomplished based on threshold value. When the it exceeds the prescribed value, the subsystem will resort to the pre-designed failure solutions to carry out autonomous procedures rapidly.

**Figure 4. Combined hierarchical architecture of multi-spacecraft autonomous strategy**

**4.3. Equipment level agent adopts combined autonomous strategy based on mode and rules**

Rule-based methods can be adopted for rapid detection and autonomous disposal of the key equipment status of the spacecraft system. The types of spacecraft telemetry data generally include digital parameters, switch parameters, smoothly and slowly varying parameters, slowly varying parameters, etc. Corresponding strategies can be taken in consideration of telemetry parameter types and its changing rules to decide whether to carry out autonomous management at equipment level or apply for subsystem-level.

A) Digital parameters: They are generally characterized as the working mode or working state of spacecraft equipment. The specific parameter definition value of such type of parameters corresponds uniquely to one type of the working mode or working state of the equipment. For example, AAH is defined as "Equipment working normally" and BBH is defined as "Equipment working abnormally". It determines whether the working status of the equipment is normal by using the rules of consistency comparison between the theoretically defined values of the parameters and the actual working values of the equipment.

B) Switch parameters: They represent the different states of equipment switches on the spacecraft. This type of parameter is related to the equipment mode or drive command. It makes judgement based on the parameter related to the command or mode, such as pump valve status, wireless link lock status, relay status, etc.

C) Smoothly and slowly varying parameters: It generally characterizes the relative stable state of the equipment on the spacecraft, such as the spacecraft energy storage battery voltage, equipment
working voltage, link status, etc. It can achieve autonomy based on the normal value range of the parameter by using threshold rules.

D) Slowly varying parameters: generally, characterizes the characteristics and state of equipment changes on a spacecraft, such as cylinder pressure, tank capacity, bus current, etc. This type of parameters generally changes slowly within its normal range. It can achieve autonomy by using threshold value according to the law on parameter change.

For equipment that can build accurate and simple models and consume little computing resources, such as pumps and valves in spacecraft pipelines, quantitative model-based methods can be used for status detection, equipment-level autonomous disposal or application for subsystem-level autonomous management.

5. Conclusion
In this paper, the construction of the intelligent autonomous system of single spacecraft centralized mode and multi-spacecraft networking hybrid mode are researched, in order to realize efficient communication and effective consultation among multi-agents. Based on mixed method of data, model and expert rules, an intelligent autonomous strategy with combined hierarchical structure is formed at spacecraft, subsystem and equipment level. It can provide a good reference for autonomous management of highly integrated single spacecraft system, constellation and complex multi-spacecraft system.

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