Design of Universal Software Architecture for Spacecraft Autonomous Thermal Control

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Abstract. The traditional design method of spacecraft autonomous thermal control software is difficult to reuse because of the tight coupling between software logic and corresponding user requirements. Based on the present and foreseeable autonomous thermal control requirements, a universal software architecture is proposed. The process of thermal control is divided into five steps that include temperature acquisition, temperature preprocessing, duty cycle calculation, energy optimization and on-off switching of heater. The generalized software components are realized. Different requirements of different spacecraft can be met by setting different parameters and assembling software components. The engineering practice proves that proposed universal autonomous thermal control software architecture can significantly reduce the time cost of software development, and has excellent adaptability to different requirements. Proposed software architecture has been applied to some agile remote sensing satellites and deep space probes, and it can provide a reference for future spacecraft software design.

Keywords: Spacecraft · Avionics · Autonomous thermal control · Software architecture · Universal design

1 Introduction

As a basic function of the spacecraft, effective thermal control is essential to ensure proper functioning of the devices in spacecraft. Thermal control can be divided into two categories: passive thermal control and active thermal control. Passive thermal control takes coating, heat pipe, multi-layer thermal insulation material and phase change material as control means, and active thermal control takes shutter, electric heater, fan and fluid loop as control means [1]. Under the guidance of agile remote sensing satellites, manned spaceflight, deep space exploration and other missions, China’s spacecraft thermal control technology has made great progress [2, 3]. Based on passive thermal control, active thermal control has become a key mean to meet the requirements of complex tasks in various fields [4–6].

With the evolution of intelligent spacecraft, it is not necessary to set a specific device for thermal control. The common choice of current spacecraft is to integrate the thermal control function into the onboard data handling (OBDH) system [7]. With the construction of space-based information network, the performance improvement of spacecraft has generated an urgent need for precise thermal control; traditional OBDH

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system is insufficient to accomplish more and more heavy workload [8]. On the other hand, the new missions require that the information system of spacecraft be promoted to the direction of information-processing-centered and multi-spacecraft collaborative work [9].

To satisfy the urgent need of intelligent and networked spacecraft, the avionics system is rapidly evolved. After decades of development, China's avionics system has established a business and protocol framework that selectively applied CCSDS and ECSS standard [10–12]. Under the guidance of demand analysis and overall design, a centralized avionics system [13] was designed for micro and small spacecraft and a distributed avionics system [14] was designed for medium and large spacecraft. On the basis of intelligent avionics system and according to the principles of universalization, intelligentialize and networking, the development of avionics software based on software components is promoted [15, 16].

Electric heater is widely used in active thermal control. Based on intelligent avionics system, thermal control of spacecraft is evolved towards the direction of precision, intelligence, and joint optimization design with other fields. The joint optimization design can be further divided into two directions: one is to ensure energy balance; another is to optimize the impact of thermal control on energy. By adjusting the number of heater channels involved in thermal control, the peak power can meet the energy constraints. Zhang H B et al. proposed that when predicting spacecraft energy imbalance, the thermal control should be transferred to the minimum mode to reduce the number of active heaters [17]. Wei Y Q et al. proposed to reduce the peak power by time-sharing batch switching of heaters when judging the total thermal control power is at risk of exceeding the energy constraint [18]. In active thermal control, the on-off of heaters cause the fluctuation of the load power of battery. Lan T et al. propose using duty cycle mode to control heater's on-off, and rationally arrange the heaters on-off combination in each time slot within a control period to suppress the fluctuation of power, so as to relieve the negative influence of thermal control on voltage and current [19]. Those two design directions are not in conflict with each other and can be used in thermal control simultaneously.

Though there are various joint optimization designs, the thermal control software architecture of current spacecraft has not been unified yet. Causing by the strong coupling of the code, traditional thermal control software needs a lot of changes when the functions are changed, upgraded or expanded. The amount of Chinese spacecraft in orbit will grow significantly in the foreseeable future. Generalized design of thermal control can effectively help the design and implement of onboard software, promote flight support effect and increase the on-board maintenance capability of avionics system. To improve the scalability and portability of thermal control software, an universal architecture based on software components is proposed. According to the existing thermal control requirements and the "energy, thermal control and avionics" joint optimization needs, the influence of control elements on thermal control performance is analyzed. Based on avionics system, an universal software architecture compatible with existing and foreseeable spacecraft optimization needs is implemented and testified.

2 Analysis of Control Elements of Active Thermal Control

To accomplish precise thermal control, the heat capacity of control object and thermal environment should be planned. To ensure the effective implementation of the thermal control strategy, it is necessary to analysis and optimizes the performance of control elements, such as temperature accuracy, thermal control cycle, thermal control time slot, heater switching mode, energy constraints and software control process.

2.1 Temperature Accuracy

The temperature accuracy depends on both the acquisition accuracy and the processing of raw data. To improve acquisition accuracy, AD converter with better acquisition accuracy and stability should be selected. Traditional OBDH system saves the control threshold directly in the form of raw data, compares the raw data with the threshold, and decides the on-off state of heater according to comparing results. In the solution, the temperature accuracy is greatly affected by the voltage stability of the acquisition circuit. If the tension voltage of the acquisition circuit is changed, the stratification value corresponding to the same temperature would be changed accordingly. As the corresponding threshold remains unchanged, the voltage fluctuation will lead to the change of the actual temperature threshold used for control, and affecting the control effect. As an effective way to solve the problem, the raw data can be converted into temperature according to the homologous calibration voltage of the acquisition circuit.

2.2 Control Period and Time Slot of Thermal Control

Thermal control period refers to the time interval between two adjacent executions of thermal control logic to update the heater on-off state and duty cycle. Thermal control time slot refers to the time interval of switching the heater on-off state according to the duty ratio within a control period. The thermal control period should be an integer multiple of the thermal control time slots. A thermal control period should contain at least one thermal control time slot.

The control period influences the responding speed of temperature change, and the amount of time slot determines the granularity of the duty cycle. More precise thermal control effect requires shorter control period and more time slots. The foundation to realize shorter control period is higher computing power, and the foundation to realize more time slots is heater batch switching capability. Those two aspects demands promote the transformation from traditional OBDH system to avionics system.

2.3 Switch Mode of Heater

When the heater needs precision control in a control period, the duty cycle control should be applied. Traditional OBDH system uses the pulse command to control the on and off of the heater. Subject to the instruction sending ability, it can only realize duty ratio temperature control in a continuous way, and the control effect is limited by the command sending ability. To reduce the temperature fluctuation of the controlled object, the batch switching of heater on-off state is a good choice. In current avionics system, the pulse command is replaced by electronic switch, which has the ability to batch switch the heater on-off state rapidly and effectively.

2.4 Energy Constraints

Electricity is the main energy source of spacecraft. The thermal control power consumption influences the energy balance of spacecraft. In current designs, the constraints of energy on thermal control are mainly reflected in the energy balance and peak power consumption. Most of those designs need to forecast the energy imbalance by testifying whether the thermal control actions can meet energy constraints. When the spacecraft energy imbalance is predicted, thermal control should be transferred to the minimum working mode to decrease the number of active heaters and reduce power consumption, or adopted to time-sharing switch mode to reduce the peak power consumption.

3 Universal Architecture for Active Thermal Control

3.1 Universal Software Architecture Based on Software Components

Based on the commonness and characteristics of the existing solutions of spacecraft active thermal control, the key steps of thermal control are summarized.

Temperature Raw Data Acquisition. Temperature acquisition is generally realized by thermistor measurement circuit. The acquisition circuit that supports homologous calibration can meet the control requirements of all existing spacecraft.

Temperature Raw Data Preprocessing. Different spacecraft uses temperature in different ways: using raw data directly, using converted data based on thermistor coefficients, or using statistics of multiple thermistors, such as maximum, minimum or average. The software architecture needs to support various patterns of temperature processing needs.

Thermal Control Logic. Thermal control logic includes generalized logic and personalized logic. Through related control logic, software determines how to perform on-off control or duty cycle control of the heater based on temperature. Generalized control logic includes On-Off control algorithm, proportional control algorithm, proportional integral (PI) control algorithm and proportional integral differential (PID) control algorithm. Personalized control logic involves collaborative control between multiple heaters, such as specialized control of fuel tanks and thrusters.

Energy Optimization Constraints. From the percept of energy, the influence of the constraints would be reflected in heater's on-off. When the predicted peak power exceeds the constraints, the power used by thermal control can be reduced by switching off some heaters or reducing the heating time.

Heater Switch Control. The control of heater can be classified into two categories, on-off control and duty cycle control. The on-off control can be implemented as a special case of duty cycle control, so the duty control mode can be a universal solution.

Based on the analysis of the above five elements, the universal software components are implemented in temperature raw data acquisition and heater switch control, and the configurable software components are introduced in the other three elements: temperature raw data preprocessing, heater control logic and energy optimization design. Spacecraft with different backgrounds can insert, modify or expand the software components to achieve specific intention.

3.2 Hardware Composition of Avionics System

As a basis of proposed software architecture, the avionics system consists of System Management Unit (SMU) and Data Interface Units (DIU), as shown in Fig. 1. The devices adopt universal module design; DIU has the same computing power as SMU. Data exchange among modules is realized through the internal bus inside device, and communication between devices is implemented by intra-satellite data bus.

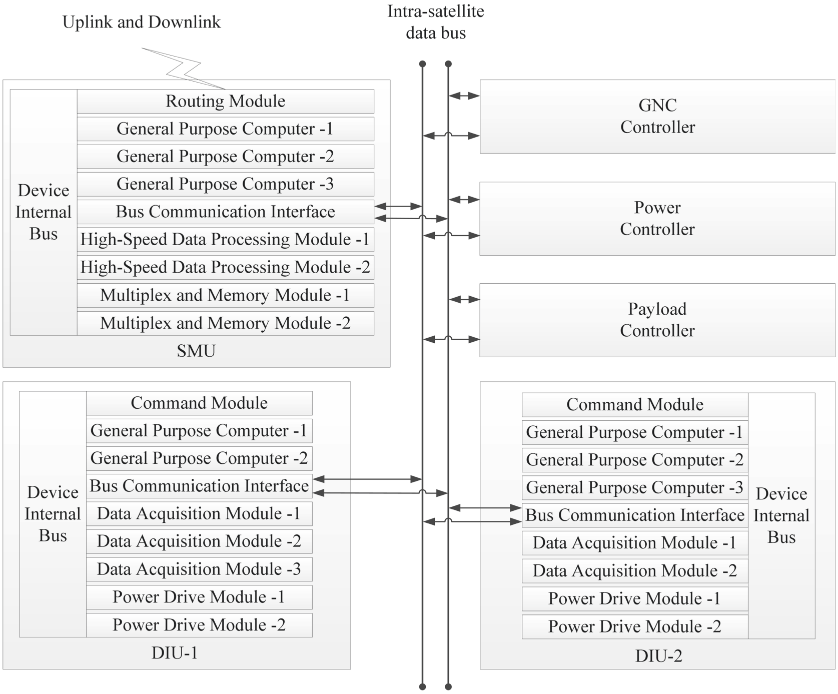

Fig. 1. A block diagram of a distributed avionics system

The applications of high performance General Purpose Computer (GPC) module achieve the balance of distributed computing ability available system-wide. The task division between SMU and DIU is optimized, more complex control tasks are assigned to the DIU within computing power support range. For example, the autonomous thermal control is realized by DIU, and the control logic is running on the first GPC module of each DIU. The raw temperature and homologous calibration voltage are collected by the Data Acquisition Module (DAM), the heater switch is controlled by the Power Drive Module (PDM), and the safety switch is controlled by the Command Module (CM).

The independent PDM ensures that DIU can batch switch the heater's on-off state in a short time slice. With its support, the action of heaters in thermal control can be described as a matrix indexed by heater and time slot. Each element in the matrix represents the on-off state of heater in a certain thermal control time slot. The action of thermal control can be abstracted as updating the matrix according to the temperature periodically, and switching the heater's state according to the matrix.

3.3 Control Process of Software Architecture

The control process of proposed architecture is shown in Fig. 2.

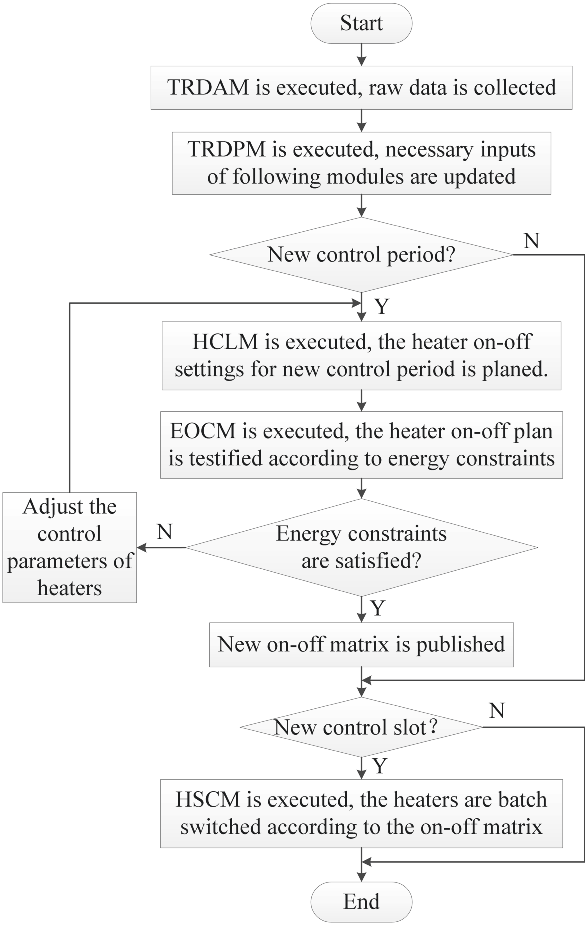

Fig. 2. Control flow of autonomous thermal control process

As shown in Fig. 2, the autonomous thermal control process is called periodically by external logic as a process, and the internal process is controlled according to the schedule cycle. According to the control object, the process can be further divided into the control of the thermistor and the control of the heater. The control of thermistor is divided into two modules: the Temperature Raw Data Acquisition Module (TRDAM) and the Temperature Raw Data Preprocessing Module (TRDPM). The control of heater is divided into three modules: heater control logic module (HCLM), energy optimization constraint module (EOCM) and heater switch control module (HSCM).

Every time the autonomous thermal control process is called, the TRDAM is first executed. In the TRDAM, the original data needed to be used in thermal control is updated. To eliminate the coupling, an independent telemetry acquisition process is designed to complete the data acquisition, and the collected data is stored in the global data pool. When the thermal control process runs, it directly obtains the latest raw data from the global data pool and refreshes it to the thermistor data structure.

After the TRDAM, the TRDPM is executed. In TRDPM, configurable software components are provided. Users can use different plugins to achieve raw data format conversion, data statistics, thermistor health monitoring and other functions according to personalized needs. Virtual temperature can be generated according to the statistical results for subsequent heater control. Through those two modules, the processing requirements of thermistor in existing spacecraft autonomous thermal control can be met, and the input data needed for heater control can be obtained.

The input of HCLM is the control state of the heater and the output temperature of the thermistor, and the output of HCLM is the switching matrix of the heater in the next control cycle. As an example shown in Fig. 3, the matrix illustrates the distribution of switching states of 10 heaters in a control period divided into 10 time slots. According to the switching states of each time slot and the power consumption of corresponding heater, the total power consumption of every time slot can be obtained.

Heater No.	Power consumption /W	Time slots in a control period									
		1	2	3	4	5	6	7	8	9	10
1	10	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
2	10	ON	ON	ON	ON	ON	ON	ON	OFF	ON	ON
3	10	ON	ON	ON	ON	ON	ON	ON	ON	OFF	OFF
4	10	OFF	ON	ON	ON	OFF	ON	OFF	ON	ON	ON
5	5	ON	OFF	OFF	OFF	ON	OFF	ON	ON	ON	ON
6	5	OFF	OFF	OFF	OFF	ON	OFF	ON	ON	ON	ON
7	13.1	ON	OFF	OFF	OFF	OFF	OFF	OFF	ON	ON	ON
8	10.6	OFF	ON	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF
9	11.9	OFF	OFF	OFF	OFF	ON	ON	OFF	OFF	OFF	OFF
10	12.1	OFF	OFF	OFF	OFF	OFF	OFF	ON	OFF	OFF	OFF
Total power consumption/W		48.1	50.6	50.6	50.6	51.9	51.9	52.1	53.1	53.1	53.1

Fig. 3. Heater switching state matrix compatible with duty cycle control

The EOCM takes the total power consumption of each time slot and the energy constraints as inputs, judge whether the power consumption can meet energy constraints or not, and outputs the switching choice of the heaters when current power consumption could not meet the energy constraints. When the power consumption is at risk of exceeding the energy constraints, the control state of the heater is switched according to the corresponding strategy, and the HCLM needs to execute again.

If the power consumption of the switch matrix output by the HCLM can meet the energy constraints, the HSCM is executed. In HSCM, the heaters are batch switched according to the on-off states in switch matrix through the interface with the power drive module.

In the three modules, HCLM and EOCM provide configurable software components support and run once each control cycle. The HSCM runs once each time slot. Through cooperation of those three modules, the control needs of the heater in spacecraft autonomous thermal control can be met.

4 Analysis and Evaluation of Application Effect

The development of thermal control software in four satellites is analyzed and evaluated. Satellite 1 adopts the traditional thermal control software architecture; Satellite 2 inherits the universal thermal control logic of Satellite 1 and upgrades the personalized control logic. Satellite 3 adopts the design of proposed universal thermal control software architecture, and Satellite 4 is developed base on the software architecture of satellite 3. In Satellite 4, the special thermal control logic is changed, and a new energy constraint strategy is applied. The utilization data of software development of the four satellites are shown in Table 1.

Table 1. Utilization data of spacecraft thermal control software architecture

Satellite No.	Lines of software components reused	Lines of application layer software	The number of global variables and arrays	The number of structures	Development cost/(man-day)
1	0	5167	150	18	60
2	0	5696	126	19	25
3	7591	1288	23	0	36
4	7591	1430	29	0	5

Compared with the traditional architecture of spacecraft thermal control software, proposed software architecture has achieved significant improvement in the development efficiency, and the software complexity is effectively controlled. The application effect of proposed software architecture in spacecraft software development process is shown in Fig. 4.

As shown in Fig. 4 (a), the software development efficiency of Satellite 3, which adopted the universal thermal control software architecture for the first time, showed no significant change compared with previous satellites. Compared with Satellite 2, which inherited the traditional thermal control software development mode of Satellite 1, the development efficiency of Satellite 4, which continued to apply the software architecture of Satellite 3, was greatly improved. The development cost is reduced by 66.5% and the efficiency is increased about 3 times.

As shown in Fig. 4 (b), the number of global variables and arrays required by the thermal control software of satellite 3 and satellite 4 based on software components is significantly reduced compared with that of the traditional thermal control software. The number of global variables and arrays of satellite 4 is only about 23% of the traditional thermal control software in satellite 2. The thermal control related structures of satellite 3 and satellite 4 are encapsulated in the software components. The software components contain a total of 10 structures, nearly half of the structures used by traditional thermal control software. After the adoption of proposed universal thermal control software architecture, the development efficiency of satellite 3 and 4 is greatly improved. At the same time, the robustness of thermal control is also improved.

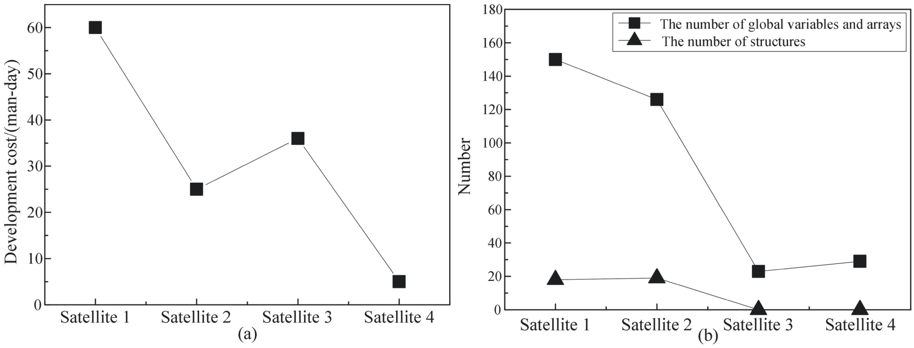

Fig. 4. Comparison of software development efficiency and complexity of thermal control in different satellites

5 Conclusions

Based on the envelopment analysis of existing spacecraft thermal control requirements, a universal autonomous thermal control software architecture is proposed. The application effect is statistically analyzed after the engineering practice. Research shows that the configurable software components in the preprocessing of raw temperature, the control logic and the energy optimization, can realize common control logic of thermal control and can effectively support the personalized thermal control needs, energy constraint strategies of different spacecraft.

The application of proposed software architecture does not increase the occupancy rate of system resources. In the process of software development, the generalizable and configurable software architecture can significantly improve the efficiency of software development, reduce the complexity of code design and improve the robustness of code. Proposed software architecture has been applied to several agile remote sensing satellites and deep space probes, and has obtained positive effect, it can be a reference for future spacecraft software design.

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