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Agent-oriented intelligent control strategies for the Nano-satellite autonomous thermal system

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***Abstract*—The paper concerns the autonomous thermal control system of Nano-satellite with a study of the combination of MEMS (Micro Electro Mechanical Systems)-based efficient cooling technique and the agent-oriented intelligent control strategies issue, especially with the issue of autonomy. The particular interest and complexity are the development of the thermal control system that has the intelligent autonomous control capability to maintain the Nano-satellite optimal performance. Based on the modeling and analysis the dynamic characteristics of efficient cooling system utilizing MEMS-based micro-channel heat sink and micro louver arrays by the means of lumped parameter method, the hierarchical structure of agent-oriented intelligent control method for Nano-satellite autonomous thermal system is investigated. With the domain expert knowledge and Fuzzy reasoning, the innovative agent-oriented intelligent control strategies achieve an autonomous process to regulate several controlled variables according to the expectation of the system situations and variety tendency, the robustness of the thermal control system is accomplished as well.**

Keywords-agent control; autonomous thermal control system ; Nano-satellite;MEMS;simulation

I. INTRODUCTION

According to small-satellite classification, Nano-satellite is the wet mass of 1-10kg which is a research hotspot of astronautics from the 20th century. With the limitations on mass and the low thermal capacitance, these satellites are vulnerable to rapid temperature fluctuations. Therefore, as an auxiliary subsystem of the spacecraft, the thermal control system becomes much more important than those of typical ones due to the high heat flux densities of internal electronic components and the sharply variational temperature of external orbital environment. Furthermore, to accomplish the on-board spacecraft autonomy, one of the crucial astronautic goals, the thermal control system shows particular challenges to autonomously dissipate the heat rejection of the satellite to ensure the reliability and security [1-2].

However, so far, considerable investigations have been confined to the advanced thermal control hardware technology: MEMS-based pumped cooling system, micro-machined shutter arrays, loop heat pipes (LHPs), thermal switches, etc.; in contrast, far less attention has been paid to the application of advanced control strategies. It is obvious that the adoption of the state-of-art control methods and combination of these with the advanced spacecraft thermal control hardware technology are a more feasible and efficient solution comparing with the conventional thermal control system [3-5].

The aim of the paper is to simulate and analyze an autonomous thermal control system for the Nano-satellite which involves agent-oriented intelligent autonomous control and the MEMS-based liquid cooling system, especially with the issue of autonomy based on the agent-oriented intelligent control approaches.

The agent-oriented intelligent control approaches provide promising solutions to cope with significant degrees of uncertainty in dynamic environments and to achieve flexibility. It was once successfully employed for the first AI system to autonomously control an actual spacecraft: Deep Space One (DS-1), the first fight of NASA's New Millennium Program (NMP) [6-9].

The rest of paper is organized as follows. Section II introduces the structure of dynamical models for the MEMS-based thermal control system of Nano-satellite, then a dynamic model is established by means of lumped parameter method with physical simplification and hypothesis; Section III elaborates on the implements of agent-oriented intelligent control for the MEMS thermal system, including the hierarchical control architectures, autonomous control strategies, uncertain reasoning and corresponded algorithm. Section IV simulates and discusses the performances of the Nano-satellite MEMS thermal control system under agent-oriented intelligent control strategies. In the last section, the author draws the conclusion of the paper.

II. DYNAMICAL MODEL FOR THE MEMS THERMAL CONTROL SYSTEM OF THE NANO-SATELLITE

A. Description of the MEMS thermal control system of the Nano-satellite

The Nano-satellite MEMS-based thermal control system is a functional “loop & radiation” apparatus for heat accumulation and/or emission. Base on the principle of the single phase liquid intense heat transfer, it consists of a MEMS-based micro channel heat exchanger, a MEMS-based micro louver arrays, a micro pump, micro valves and a set of parts (Fig.1)

A single phase working fluid circulates through micro channel heat exchanger by the micro pumps to remove the

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heat dissipation from the electronics of the high power densities. Then, the heat can be transferred to a heat sink and the external radiator can reject it to the external space environment. The thermal control micro valve split the main working fluid into the bypass to provide a mixed fluid for the inlet suitable temperature of the electronics.

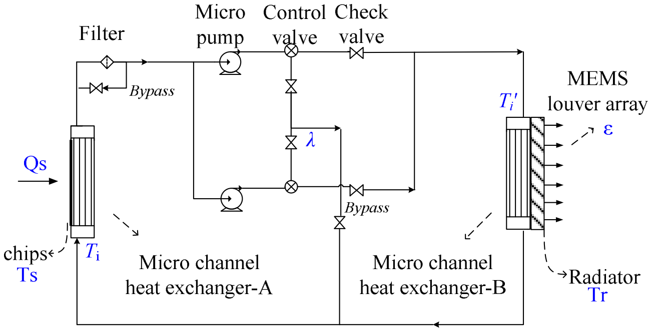
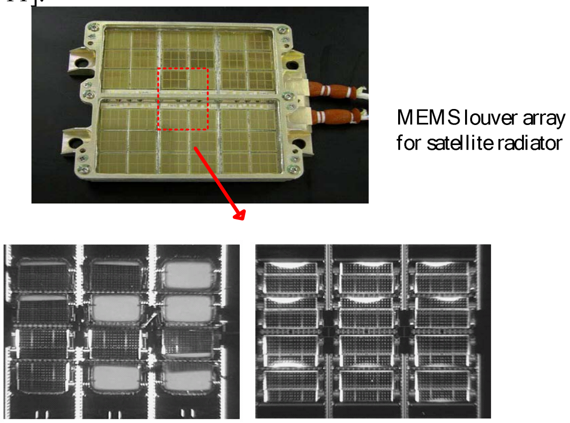


Figure 1. MEME thermal control system of Nano-satellite

MEMS-based micro channel heat sink is a brand-new technology for the high heat flux removal due to its larger area to volume ration. This heat sink is simply a substrate with numerous small channels and fins arranged in parallel, such that heat is efficient carried from the substrate into the coolant. Therefore, heat transfer is greatly enhanced. The researchers of Jet Propulsion Laboratory first suggested the use of MEMS micro channels heat sinks for Nano spacecraft thermal control to cool the high power generating components, their study was conducted for water flowing under laminar conditions through micro channels machined in a silicon wafer. Heat fluxes as high as 25W/cm^2 were achieved with the chip temperature maintained below 80℃ [10-11].



some open louvers all the louvers closed.

Figure 2. MEME louver array

MEME louver arrays are well suited for the Nano-satellite thermal control system due to the lightweight, use little power, and can be relatively inexpensive to fabricate. Using MEMS is to coat the satellite radiators with a variable emissivity coating (VEC) that can be used to actively vary the heat rejection of the satellite in response to variations in the thermal payload and environmental conditions. It is actuated by small electrostatic comb drive motors for the purposes of demonstrating thermal control by varying the effective thermal emissivity of a radiator surface, as show in Fig.2 [12-13].

B. Dynamic Modeling of the MEMS thermal control system of the Nano-satellite

To clarify the dynamics of Nano-satellite thermal control system and to analyze the effect of the external orbital thermal environment on the internal electrics temperature, a dynamic model for the temperature changing of the MEMS-based thermal system was established by means of lumped parameter method with physical simplification and the following hypothesis:

- The pipes from the heater to the heat sink are adiabatic without heat leak;
- Heat payload of electronics is totally transferred by the flowing coolant without any other approaches to exchange heat;
- Friction of pipes cannot bring on the temperature rise;
- Negligible the effect of viscous heating.

The whole cooling system can be divided into two lumped parameters: one is the controlled object including a micro channel sink and the connected electronics; another is cooling device comprising of micro pumps, micro valves, pipes of fluid-flow loops and a MEMS louver array radiator.

According to the conservation of energy principle and the First-Law of thermodynamics, the thermal dynamics of the average temperature of the controlled object T_s can be described as

$$C_s \frac{dT_s}{dt} = Q_s - \frac{T_s - T_i}{R_t} \tag{1}$$

Where C_s is the equivalent heat capacity of the controlled object; Q_s is the heat power of the controlled object; T_i is the inlet temperature of the coolant for the micro channel heat sink; R_t is the total thermal resistance of the micro channel heat sink A.

The thermal and hydraulic performance of micro channel cold plate can be predicted for a numerical model in [10]. The thermal performance is characterized by the total thermal resistance of the micro channel cold plate R_t which has three main components: (1) conductive resistance through the substrate between the heated surface and the micro channel base plane, R_1;(2) convective resistance from the micro channel surface to the working fluid, R_2; (3) temperature rise resistance from the bulk temperature rise of the device inlet, R_3. Thereby the R_t can be determined by

$$R_t = R_1 + R_2 + R_3 = \frac{h}{k_s A_h} + \frac{1}{h_c A_c} + \frac{1}{\dot{m} c_p} \tag{2}$$

Where h is the distance from the heated surface to the base of micro-channel; k_s is the substrate thermal conductivity; A_h is the footprint of the micro channel cold plate; A_c is the wetted area; h_c is the convective heat transfer coefficient; $\dot{m}$ is the mass flow; c_p is the equivalent heat capacity of the working fluid.

The hydraulic performance of micro channel heat exchanger is characterized by the pressure drop, ΔP, which is a function of the micro channel aspect ratio and the Reynolds number.

From the heat balance principle, radiator rejects the heat absorbed by the working fluid to the external space environment. The dynamics of temperature of radiator, denoted as T_r, can be estimated by

$$\begin{aligned} C_r \frac{dT_r}{dt} &= Q_r + Q_p - Q_c \\ &= \sum_{i=1}^{3} a_{r,i} Q_{r,i} + \frac{T_i' - T_r}{R_t'} - \sigma F_r \varepsilon T_r^4 \end{aligned} \tag{3}$$

Where C_r is the equivalent heat capacity of the cooling device； Q_r、 Q_c are the heat power absorbed from and dissipated to the external space environment by the radiator, respectively; $Q_{r,1}$， $Q_{r,2}$， $Q_{r,3}$ are the heat power of incident sun, albebo and Earth IR cast to the radiator per unit time, respectively; $a_{r,1}$， $a_{r,2}$， $a_{r,3}$ are absorptivities the solar, albebo and Earth IR of the radiator, respectively. The calculation model have conducted by the previous studies in [5].Q_p is heat transfer by the working fluid-loop; T_i' is the inlet temperature of the coolant for the micro channel heat sink B connecting with the radiator; R_t' is the total thermal resistance of the micro channel heat sink B; A_r, ε , σ are radiator surface area, the radiator equivalent emissity, and Stefan-Bolzmann constant, respectively.

Obviously, R_t' can be similar calculated by the formula No.2. It is clear that regulation the bypass ratio λ leads to vary R_t', which is a key control variable to such thermal system.

A thermal control micro valve could be adjusted to split the mass flow of the main working fluid $\dot{m}$ into the mass flow of the radiator $\lambda \times \dot{m}$ and the mass flow of the bypass $(1-\lambda)\times\dot{m}$, which provides a mixed temperature liquid to satisfy the cooled electronics requirements. Considering the working fluid is uncompressible, there is

$$T_i(t) = \begin{bmatrix} 1-\lambda & \lambda \end{bmatrix} \times \begin{bmatrix} T_i'(t) \\ T_r(t) \end{bmatrix} \tag{4}$$

A micro valve is a key component in this cooling system that increases energy to liquid. It converts kinetic energy into pressure potential. A pump consumes more power than it gives off because of internal frication losses. In the following calculation, the sum of the pressure drop from the pipes, micro channel cold plate and micro pump are converted to the approximate power of micro valve. Then the temperature rise from the micro pump can be estimated by

$$\Delta T = \frac{Q_e}{c_p \dot{m}} \tag{5}$$

Where Q_e is the power of the micro valve.

Equation (1)~(5)consist of a dynamic mathematical model of a MEMS-based liquid cooling system .From analysis of the model, it is important that the external orbital thermal environment and the internal heat payload power are two disturbances elements in the Nano-satellite thermal system. In addition, the bypass ratio and the radiator equivalent emissity are two significant control various for improving the control effect on the Nano-satellite thermal system.

III. AGENT-ORIENTED INTELLIGENT CONTROL ARCHITECTURE FOR THE MEMS THERMAL CONTROL SYSTEM OF THE NANO-SATELLITE

The agent-oriented intelligent control, an autonomous control system that requires less human supervision or monitoring, is well-timed suitable for the Nano-satellite thermal control system based on the a few key MEMS components in order to provide a autonomy, sociability, adaptability, and real-time performance. By sharing information and logical reasoning, the agent-oriented intelligent control can collaboratively employ the resources of the controlled system in a way that addresses whole system tasks.

A. Hierarchical architectures for the agent-oriented intelligent control system

The agent-oriented intelligent control is set up by the hierarchical control architectures which allow systems to support both real-time performance constraints and deliberative reasoning. The architecture decomposes control of the Nano-satellite MEMS thermal system into several layers (Fig. 3).

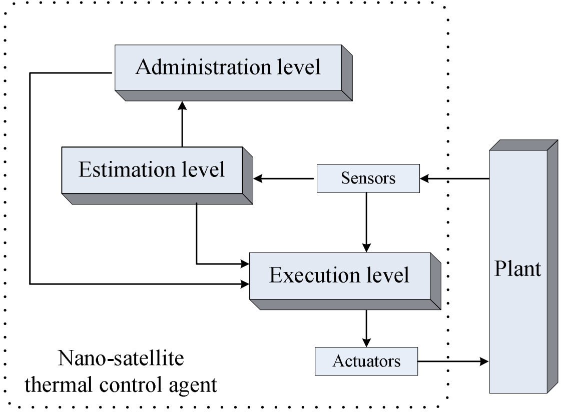


Figure 3. Hierarchical control architectures

The administer level, the highest level of the agent layout, charges information exchange with other agents of satellite subsystems to ensure a favorable performance of the Nano-satellite thermal control system with the top-priority to assort with the control commands; the estimation level aims to process intelligent reasoning algorithms for making a sound control decision based on the observed states of the system, which also transmit the data to the administer level as forecast; The execution level merely execute the substrate control command to directly regulate the actuator.

The information, captured by the plant, is the foundation of the autonomous of the Nano-satellite thermal control system, the process of dynamical programming and decision making is the kernel, and the substrate control execution embodies the implement of autonomy.

B. *Software design of the agent-oriented intelligent control system*

The Nano-satellite thermal control system has one controlled object (T_s), two controlled variables (λ,ε).Under the two uncertain disturbances elements of the external orbital thermal environment (Q_s) and the internal heat payload power (Q_r), the Nano-satellite agent-oriented thermal control system employ two reasoning mechanisms: expert system and Fuzzy reasoning, the schematic below depicts the procedure of software design for autonomous thermal control system.

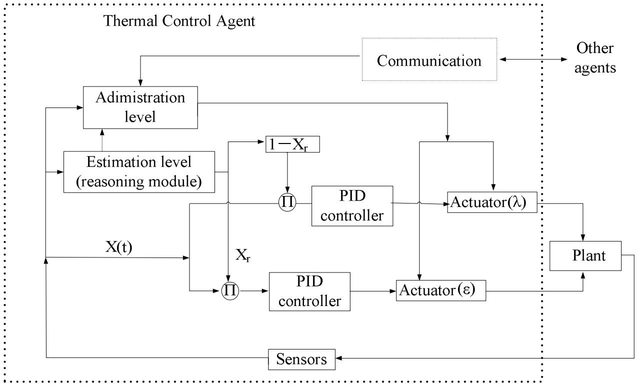


Figure 4. Autonomous control configuration

The administration level is capable of directly manipulating the actuators against the emergencies and/or the feedback information from the reasoning conclusion of the estimation level; it also transmits the performance information of the satellite to the thermal control subsystem, such as attitude, power required, etc.; furthermore, it is a core of the thermal control agent to communicate and cooperate with the other agents for the muilt-agents system of Nano-satellite. The rule-based expert systems are suggested to facilitate the immediate response to the urgent or unforeseen circumstances, which use If-Then rules to represent the expert's reasoning process. IF the available facts meet certain criteria THEN do whatever the rule specifies. The prerequisites for constructing a successful expert system are the incorporating skills of an expert in the field and available historical data.

The intelligent reasoning module in the estimation level provides a control strategy based on the connection of fuzzy logic reasoning and PID controller that would coordinate and change the controller behavior. The fuzzy logic reasoning gains a corresponding factor Xr so that one of the two controlled variables is a primary controller and another is an assistant decided by the different situations:

When the changing tendency of the controlled variable is great upgrade, the output of the Fuzzy logic system is an aggressive value with less consideration for regulation λ due to the regulation of ε can reject the heat payload flux comparable fleetly.

When the changing tendency of the controlled variable is considerable falling, the output of the Fuzzy logic output is a very conservative value in order to mainly regulate λ due to the Nano-satellite needs to be energy conservation.

When the changing tendency of the controlled variable is in a normal range scenario, the Nano-satellite system regulates both two controlled variables. λ,ε in order to remain the system stable.

There are two fuzzy variables (error and derivative error) and seven linguistic variables (from big negative to big positive).The membership functions (zmf , trimf and smf are used) and rules are design tools that give opportunity to model a surface curve and controller properties. The surface is defined with 49 rules, as shown in Fig.5. It is obvious that using this reasoning method can more precisely fulfill an intelligent harmony in uncertain space environment for Nano-satellite thermal control system.

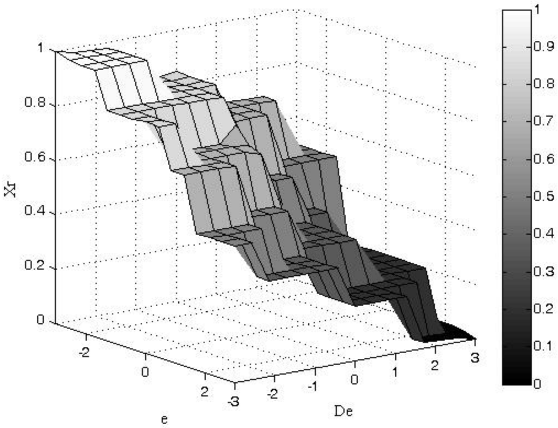


Figure 5. Surface curve of the Fuzzy control rule base

IV. ANALYSIS AND SIMULATION

TABLE I. CHARACTERS OF SIMULATION OBJECT

Parameters	Character
Solar flux	1350W/ m2
Orbit inclination	98.19℃
Orbit altitude	700km
Period	98.62min
Flow rate of fluid	20ml/min
Working fluid	water

The simulation instance is a sun synchronous Nano-satellite. The plane radiator is installed on the side of +Y; the area is 18×18cm^2. Ratio of solar absorptivity to infrared emissivity to the radiator (a/ε) is 0.15/0.8;And the orbital, constructional and thermal parameters of Nano-satellite are listed above.

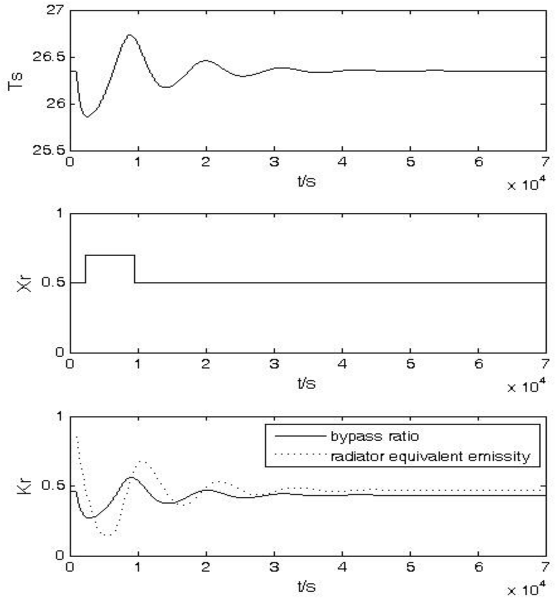


Figure 6. Control effect with electronics power step +160%

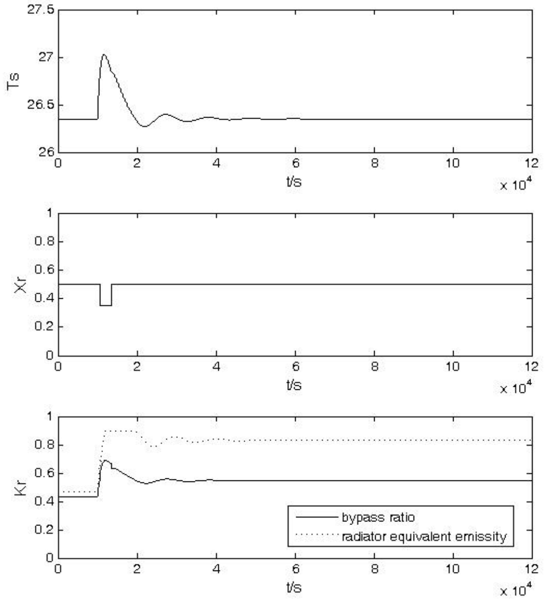


Figure 7. Control effect with electronics power step -150%

The Fig.6-Fig.7 illustrate the effects of the agent-oriented intelligent control on the Nano-satellite MEMS thermal system. The cases are that a on-orbit Nano-satellite thermal system are steady with the constant electrics power during the 200 minutes ahead, then the electronics power is step to +150% or -160%, respective. The three plots show the transient curves of controlled object temperature, the corresponding factor X_r and the controller variables against the disturbance of the heat power.

Obviously, the thermal system could approximate remain the temperature of the controlled object stable, even if the step time was happened. Furthmore, the agent-oriented intelligent control can autonomous adjust the controlled variables λ,ε : when the changing tendency of the controlled variable is great upgrade (+160%), the output of the Fuzzy logic system is an aggressive value with mainly control the radiator equivalent emissity ε ; when the changing tendency of the controlled variable is considerable falling(-150%), the output of the Fuzzy logic system is a very conservative value in order to mainly regulate the bypass ration λ ;When the changing tendency of the controlled variable is in a normal range scenario, the Nano-satellite system regulates both two controlled variables λ and ε .

V. CONCLUSION

Emerging trend in spacecraft and instrument design rigorously challenges the Nano-satellite thermal control system due to the low thermal capacitance, the high heat flux densities of thermal control components and the sharp changing external orbital environment. This paper introduces the thought of agent-oriented intelligent control strategies to the advanced thermal control hardware of Nano-satellite.

The theoretical analysis and numerical simulation results indicate that a combination of the efficient cooling technique and the agent-oriented intelligent control strategy provides a feasible solution for a Nano-satellite autonomous thermal control system. It could not only satisfy the thermal control demanding requirement, but also achieves the goal of the intelligent autonomy, which is a meaningful innovation in the field of Nano-satellite thermal control system.

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