Study of heater electric power control with the autonomous dispersed system

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In a Space probe with heaters, electric power of each heater needs to be controlled in order not to be in short. Conventional system in which each heater is monitored and controlled has a problem that telecommunication cost increases along with the increase of the number of heaters because it has to collect data. This paper proposes an autonomous dispersed control system, and demonstrates that it is possible to realize fast control with slow means of communication and build a flexible system.

摘要

複数のヒーターを持つ宇宙探査機では，電力が不足しないよう各ヒーターの電力を制御する必要がある．従来の，各ヒーターを集中監視し制御する方式では，データ収集の必要性から，ヒーターの増加に伴い通信コストが増大する問題があった．本稿では，独立分散方式による制御を提案し，低速の通信手段でも高速の制御ができ、柔軟なシステム構築が可能であることを示す.

1. Introduction

Resources aboard a Spacecraft are limited and must be shared among all the components. Therefore, it is paramount to distribute resources appropriately. Heater electric power control is an example of it. Electric power consumption increases rapidly when several heaters turn on at the same time. It is difficult to respond to this sudden increase of electric power consumption.

In IKAROS mission, which used the sun radiation pressure for propulsion, it was determined before launch which heater was turned on at each time.[1)] Electric power consumption was controlled by this time table. However, it was necessary to regenerate the time table when the thermal environment changed or devices broke down.

In HAYABUSA, which performed the world's first sample return from a small body, “Server client system” was adopted.[2)] This system has a server which collects information about the states of each heater, calculates all the ideal power allocations and distributes it to them. However, there were two problems. First, since it is necessary to know current power consumptions and temperature of the heaters, it is hard to build the system flexibly. Secondly, it needs two-way communication between the heaters and the server. When the number of heaters gets large, it takes much time to collect the information of the heaters and it becomes hard to control within a short time.

This paper proposes an autonomous dispersed control system, and demonstrates that it is possible to realize fast control with slow means of communication and build a flexible system.

2. Server client system

In the server client system, the server communicates with clients and calculates the allocations of resources. As shown in the Fig. 1, the server asks the state of each client first. Then the clients tell their states to the server, and the server calculates the resource allocation depending on the states of the clients and tells it to the clients.

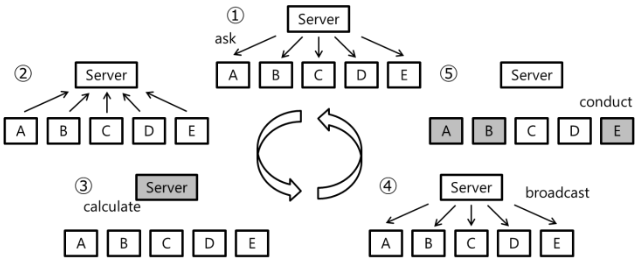

Fig. 1. Server client system.

The server calculates the resource allocation as follows. The constraint condition is that total resource allocation is constant:

$$(1\ 1\ \cdots 1)\begin{pmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{pmatrix} = \boldsymbol{e}^T \boldsymbol{f} = P \tag{1}$$

where f is an optimal resource allocation and P is total resource consumption.

The evaluation function I is defined as

$$I = \frac{1}{2}(\boldsymbol{f} - \boldsymbol{f}^*)Q(\boldsymbol{f} - \boldsymbol{f}^*) \tag{2}$$

where f^* is a resource consumption and Q is the priority of a heater.

$$Q = \begin{pmatrix} Q_1 & 0 & \cdots 0 \\ 0 & Q_2 & 0 \\ \vdots & & \ddots \vdots \\ 0 & \cdots & Q_n \end{pmatrix} \tag{3}$$

The priority of each client is decided based on the state. Here, an evaluation function J is defined using the method of Lagrange multipliers:

$$\mathrm{J} = \frac{1}{2}(\boldsymbol{f} - \boldsymbol{f}^*)Q(\boldsymbol{f} - \boldsymbol{f}^*) + \lambda(\boldsymbol{e}^T \boldsymbol{f} - P_t) \tag{4}$$

By using Eq. (5) and (6), the objective function is minimized.

$$\frac{\partial J}{\partial \lambda} = 0 \tag{5}$$

$$\frac{\partial J}{\partial f_i} = 0 \tag{6}$$

where

$$\mathrm{i} = 1,2,\cdots,\mathrm{n}$$

Optimal resource allocation is obtained by minimizing the objective function. An analytical solution exists:

$$f_i = f_i^* - \frac{\boldsymbol{e}^T \boldsymbol{f}^* - P}{Q_i\left(\frac{1}{Q_1} + \frac{1}{Q_2} + \cdots + \frac{1}{Q_n}\right)} \tag{7}$$

Optimal resource allocation is obtained in the server client system. However, as can be seen from Eq. (7), it is necessary to obtain all the priorities of the clients. Therefore, it takes a long time when the number of the clients is large, and it is difficult to control if clients participate and withdraw freely.

3. Autonomous dispersed system

3.1. Autonomous dispersed system

In an autonomous dispersed system, a transmitter is prepared instead of a server as shown in Fig. 2.

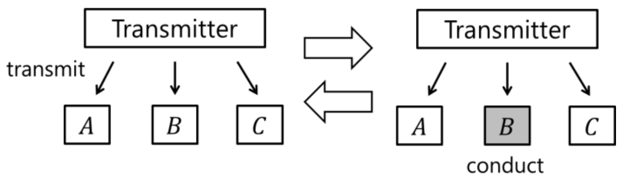

Fig. 2. Autonomous dispersed system.

The transmitter only broadcasts the total electric power consumption of all the clients, and each client calculates their own allocations. A client calculates its own power allocation at step k+1 using Eq. (8). [3)-5)]

$$f_{i,k+1} = f_{i,k} - \Delta P_k \times S \times \frac{1}{Q_i} \qquad (8)$$

where S is the system sensitivity and ΔP is the difference between the target value and total resource consumption.

In this way, the total consumption can converge to the target value step by step.

In this system, the transmitter just broadcasts the total consumption, and one-way communication is performed. Therefore, the communication time does not change even when the number of the clients changes, and the system is so flexible that it is possible to control even if clients participate and withdraw freely.

3.2. Heater electric power control

The autonomous distributed system can be applied to the heater electric power control problem. However, it is possible to directly apply Eq. (8) because heater electric power has only two values; ON or OFF. A variable is needed to judge whether to turn on the switch. Here, the variable is defined as the counter, C. Then, Eq. (9) is applied to the calculation of C.

$$C_{i,k+1} = C_{i,k} - \frac{\Delta P_k}{P} \times \frac{1}{Q_i} \qquad (9)$$

The switch of a heater is turned on when C is larger than the threshold value, C^*. Conversely, when C is smaller than C^*, the switch is turned off.

3.3. Setting of the priority

It is important how to set the priority to control the heater electric power consumption using Eq. (9). When ΔP_k is positive, or there is no power to spare, the switch should be turned off from a heater whose temperature is high. On the other hand, when ΔP_k is negative, or there is power to spare, the switch should be turned off from a heater whose temperature is low. In order to satisfy these requirements, the priority of a heater is calculated below.

$$\frac{1}{Q_{ii}} = e^{sgn(\Delta P_k) \times \frac{(T_{i,k} - T_{ir})}{T_{ir}}} \qquad (10)$$

where T_{ir} is a reference temperature of each channel.

3.4. Limits of temperature

Each heater has limits of temperature. In the system with Eq. (9), after the total electric power consumption reached the target value, C does not change. If C does not change, the switches of heaters do not change and heaters reach the limits of temperature. Here, limits of temperature are provided in this system. When the temperature is over the upper limit of the temperature, the switch is turned off regardless of C and C is set to the constant value; C_L. Similarly, when the temperature is less than the lower limit, the switch is turned on regardless of C and C is set to the constant value; C_H. By doing this, it is possible to avoid the temperature exceeding the limit.

4. Simulation

4.1. Model of the simulation

In order to demonstrate that it is possible to control the heater electric power consumption with the autonomous distributed system using Eq. (9) and (10), a simulation is conducted.

The following model is considered. 50 channels are prepared, and each channel consists of a heater, a sensor and a base.

Fig. 3. The model of the simulation.

The heater power consumption is 5W. Assumed that they are in the ambient air, the ambient temperature is -20 degrees. Initial temperature of a channel is set from -20 to 0 degrees randomly. The other specifications are listed in Table 1.

Table 1. Values of the simulation.

Items	Values
Number of the channels	50
Step time[s]	1
P[W]	200
Maximum Total Power [W]	250
Ambient temperature[℃]	-20
Initial temperature[℃]	0~20
T_L[℃]	15
T_H[℃]	45
Tr[℃]	30
Initial counter	0
Threshold counter	0
C_H	30
C_L	-30

In this model, the channels are controlled with the autonomous dispersed system and the thermal equilibrium equation shown as Eq. (11) is solved with Runge-Kutta method.

$$\mathrm{M}\dot{\boldsymbol{T}} = K\boldsymbol{T} + \boldsymbol{h} + \alpha(T_\alpha \boldsymbol{e}^T - T) \tag{11}$$

The values of Ref. 6) are used for the heat transfer coefficient between components, the heat capacity and the convective heat transfer coefficient of the components of a channel.

4.2. Results of the simulation

4.2.1. Results with heaters OFF

First, it is thought that all the heaters are off. The results are shown in Fig. 4 and 5. Fig. 4 shows the temperature of all the channels, and Fig. 5 shows the total power consumption.

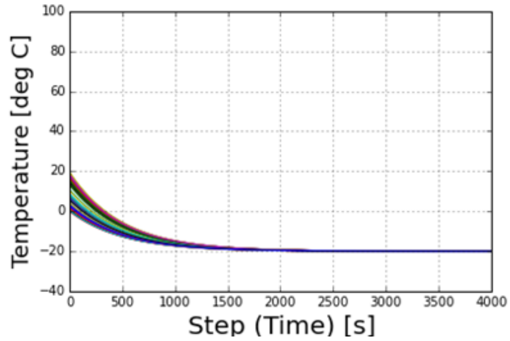

Fig. 4. The temperature of all the channels with heaters OFF

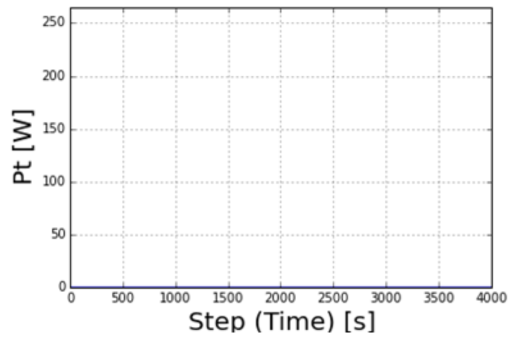

Fig. 5. The total power consumption with heaters OFF

As shown in Fig. 5, the total power consumption is always 0. Naturally, as time goes by, the temperature of all the channels get closer to the ambient temperature.

4.2.2. Results without the autonomous dispersed control

Next, it is thought the case that all the channels turn on or off based on their own temperature. When the temperature of a channel is over the designed temperature, it turns on. Similarly, when the temperature of a channel is less than the designed temperature, it turns off. The results are shown in Fig. 6 and 7. Fig.6 shows the temperature of all the channels, and Fig. 7 shows the total power consumption.

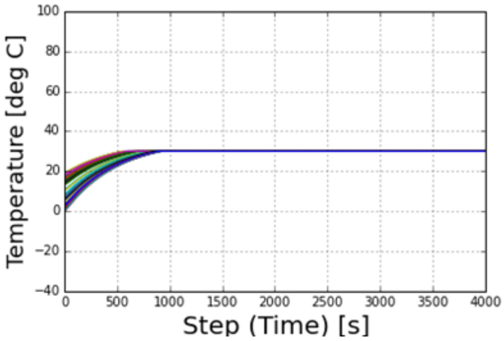

Fig. 6. The temperature of all the channels without the autonomous dispersed control

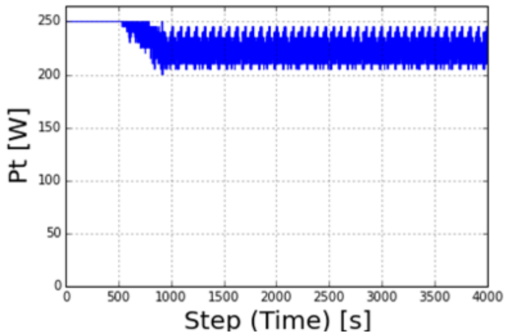

Fig. 7. The total power consumption without the autonomous dispersed control

As can be seen in Fig. 6 and 7, although all the temperatures of the channels are maintained to the designed value, the total electric power consumption is oscillating around a high value. The total power consumption sometimes reaches the maximum value.

4.2.3. Results with the autonomous dispersed control without the temperature limits

Next, it is thought that the power consumption is controlled with the autonomous dispersed system without the temperature limit. The results are shown in Fig. 8, 9 and 10. Fig. 8 shows the temperature of all the channels, Fig. 9 shows the total power consumption and Fig. 10 shows the counter of all the channels.

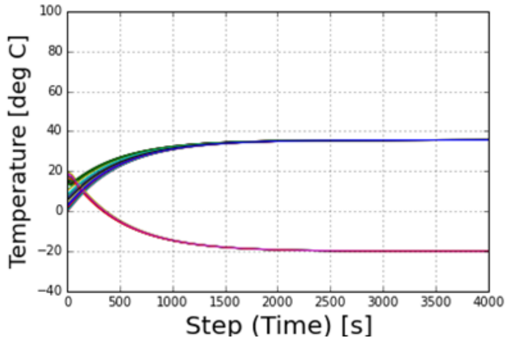

Fig. 8. The temperature of all the channels with the autonomous dispersed control

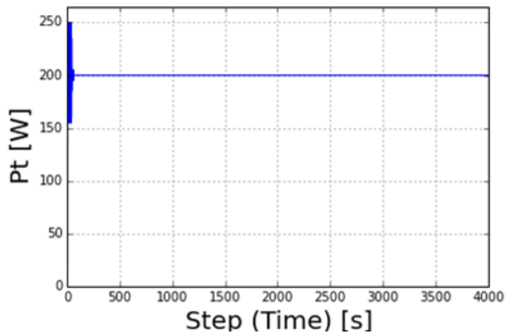

Fig. 9. The total power consumption with the autonomous dispersed control

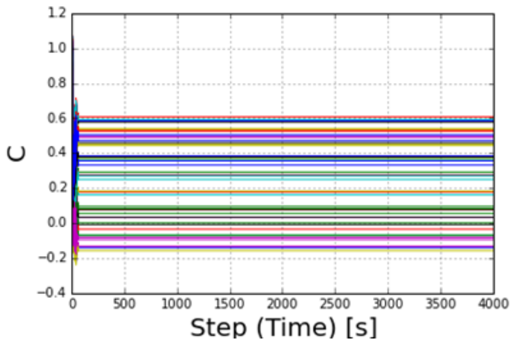

Fig. 10. The counter of all channels with the autonomous dispersed control

As can be seen in Fig. 9 and 10, it is shown that C stops moving at an early stage, and all the switches of the channels do not change. Therefore, as can be seen in Fig. 8 some channels deviate from the setting range.

4.2.4. Results with the autonomous dispersed

control and the temperature limits

Last, it is shown in Fig. 11, 12 and 13 that the power consumption is controlled with the autonomous dispersed system and the temperature limits. Fig. 11 shows the temperature of all the channels, Fig. 12 shows the total power consumption and Fig. 13 shows the counter of all channels.

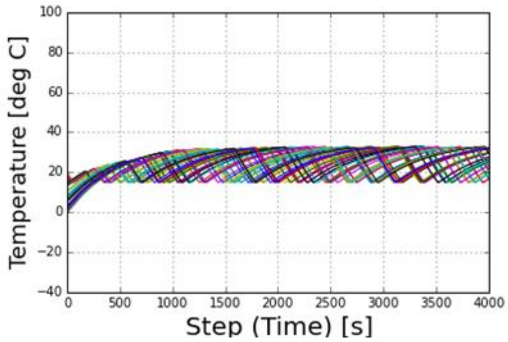

Fig. 11. The temperature of all the channels with the autonomous dispersed control and the temperature limits

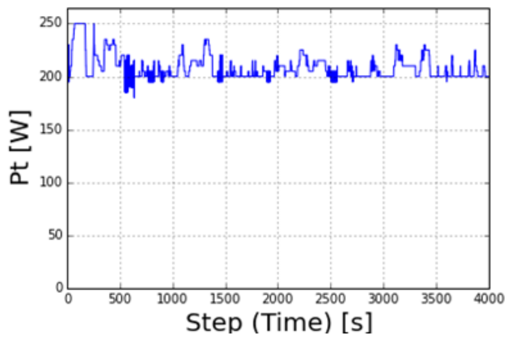

Fig. 12. The total power consumption with the autonomous dispersed control and the temperature limits

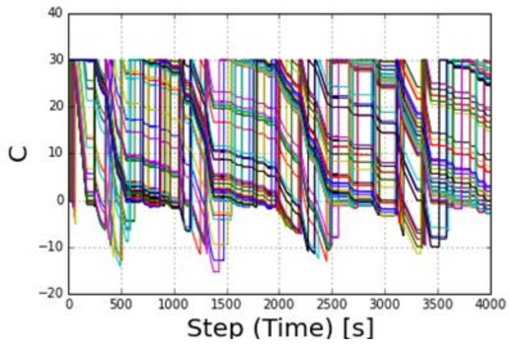

Fig. 13. The counter of all the channels with the autonomous dispersed control and the temperature limits

As shown in the Fig. 11 and 14, some of the channels periodically touch the temperature limit and C, which has been stopped, starts moving. As a result, the temperature of all channels and the total power consumption are kept within a certain range.

5. Conclusion

This paper applied the autonomous dispersed system to the heater electric power control and introduced a variable to judge whether to turn on the switch. By introducing the temperature difference from the designed temperature to the priority of each heater, it is demonstrated with simulation, that the temperature can be kept to the designed one and the total electric power is controlled.

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