A study on distributed power control of heaters

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Abstract

Power consumption of a spacecraft increases rapidly on condition that each heater turns ON at the same time. Therefore, cutting the peak of power contributes to avoid a power shortage in a spacecraft. In this work, we conduct experiments and simulations to control the power consumption of multiple heaters using a decentralized control.

独立分散方式を用いた ヒーター電力制御に関する研究

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ヒーター を多数有する宇宙機において、各ヒーターが同時に ON になると，宇宙機全体の消費電力が急激に増大する．よって電力消費のピークカットを行うことは、宇宙機全体が電力不足に陥る危険を回避する。本発表では、複数のヒーターの消費電力を、独立分散式によって制御した実験結果と数値シミュレーションを示す。

1. Introduction

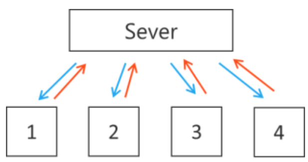
Resources aboard a spacecraft are limited and must be shared among all the components. Therefore, it is paramount to distribute resources appropriately. Heater electric power control is an example of it. Electric power consumption increases rapidly when several heaters turns on at the same time. It is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

In HAYABUSA, which performed the world's first sample return from a small body, "Server client system" was adopted. This system has a server which collects information about the states of each heater, calculates all the ideal power allocations and distributes them to the heaters. However, there were three problems. (1) 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. (2)　since it is necessary to know current power consumptions and temperature of the heaters, it is impossible to test the control unless all devices are available. Therefore, it takes a long time to develop a spacecraft. (3) since a plurality of high-cost servers is required, the cost is very large to combine redundancy. This paper proposes an autonomous distributed control system. In this system, a transmitter is located instead of a server. It broadcasts only the total power of the system continuously. Each heater calculates its own power allocation with the information. In this system, even if the number of heaters gets large, the communication time does not change, and short-time control is possible. Besides, as the transmitter only broadcasts the total power consumption and each heater does not have to know the states of other heaters, the test of the control algorithm can be performed separately and the time to develop a spacecraft can be shortened. Moreover, it does not need an expensive server. This paper demonstrates that it is possible to control power consumption and temperature of heaters by both simulations and experiments.

2. Sever 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.

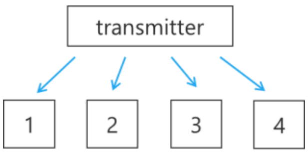
Fig.1 Sever Client System



3. Distributed control system

In a distributed control system, a transmitter is prepared instead of a server as shown in Fig. 2). The transmitter only broadcasts the total electric power consumption of all the clients, and each client calculates their own allocations. 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 as each client calculates its own allocation without the information of other clients, the test of the control algorithm can be performed separately and the time to develop a spacecraft can be shortened. Moreover, the function of the transmitter is simple unlike a server.

Fig.2 Distributed control system

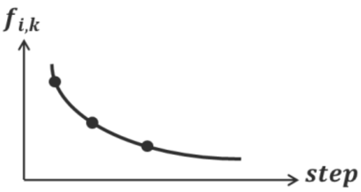


4. Counter

Distributed control system is expressed using the following equation.

$$f_{i,k+1} = f_{i,k} - \frac{1}{Q_{i,k}} \times \Delta P \qquad (1)$$

Fig.3 Continuous calculation system



In this formula, $f_{i,k}$ is power consumption of No.k, i is number of heaters, k is step number, Q is priority and ΔP is power consumption between target and real. In this way, the total consumption can converge to the target value step by step.

Distributed control system is continuous calculation method, but heater control is ON-OFF control. Therefore, we use Counter method. Counter is discrete calculation method.

$$C_{i,k+1} = C_{i,k} - \frac{1}{Q_{i,k}} \times \Delta P \qquad (2)$$

Fig.4 discrete calculation method

5. Factorization

An instantaneous power may be smoothed by applying the "factorization". Factorization is method of limiting calculation timing for each heater. For previous example, heaters have possibility to calculate Counter at the same time. In this current way, we use factorization in order not to calculate at the same time. Counter is calculated in order like Fig.5 at the blue zone.

Fig.5 Image of Factrization

	step						
No	1	2	3	4	5	6	7
1	ON	ON	ON	ON	ON	OFF	OFF
2	OFF	ON	ON	ON	ON	ON	ON
3	OFF	OFF	ON	ON	ON	ON	ON
4	OFF	OFF	OFF	OFF	OFF	OFF	OFF
5	OFF	OFF	OFF	OFF	OFF	OFF	OFF

6. Priority

Counter calculation is (2). In addition to that, stability condition is

$$0 < \sum_i \frac{1}{Q_{i,k}} < 2 \qquad (3)$$

From this, in order to stabilize the autonomous distributed system, the sum of the priorities of all heaters is set to satisfy Eq. (3) in advance.

Priority is defined as below.

$$Q_{i,k} = N - \frac{1}{T_{i,k} - T_L} \qquad (4)$$

$$Q_{i,k} = N - \frac{1}{T_H - T_{i,k}} \qquad (5)$$

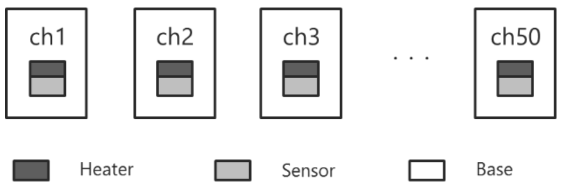
T_H and T_L are the high and low constant temperatures. N is the number of heaters. When ΔP is positive (4), or there is no power to spare, the switch of a heater whose temperature is high should preferentially be turned off. On the other hand, when ΔP is negative (5), or there is power to spare, the switch of a heater whose temperature is low should preferentially be turned on. In addition, In the case of $\Delta P > 0$, The higher $T_{i,k}$ is, the lower $Q_{i,k}$ is like below. In the case of $\Delta P < 0$, the condition is opposite.

7. Numerical simulation

7.1 simulation condition

In order to demonstrate that it is possible to control the heater electric power consumption with the autonomous distributed system using Eq. (2),(4) and (5), 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. 6. The model of the simulation



The heater power consumption is 3W. Assumed that they are in the ambient air, the ambient temperature is 25 degrees. Initial temperature of a channel is set from 25 to 26 degrees randomly. The other specifications are listed in Table 1.

Table 1. Values of the simulation.

Items	Values
Number of the channels	50
Heater power[W]	3
P_r[W]	65.0
Maximum total power [W]	150
Ambient temperature[°C]	25
Initial temperature[°C]	25
T_L[°C]	20
T_H[°C]	50
T_r[°C]	35

In this model, the channels are controlled with the autonomous distributed system and the thermal equilibrium equation shown as Eq. (6) is solved with Runge-Kutta method.

$$M\dot{\boldsymbol{T}} = \alpha(T_\alpha \boldsymbol{e}^T - T) + \boldsymbol{h} \qquad (5)$$

The values of the experimental apparatus are used for the heat capacity and the convective heat transfer coefficient of a channel. The values are listed in Table 2.

Table 2. Values of the numerical simulation.

Items	Values
M[Js/°C]	400
α[J/°C]	0.13

7.2 Results of the simulations

The simulations are conducted under two cases. First, each heater turns on or off based on its temperature. The total power consumption is not controlled. The results of the simulation are shown in Figs. 7) and 8). Fig. 7) shows the changes in total power consumption over time and Fig. 8) shows the changes in temperature.

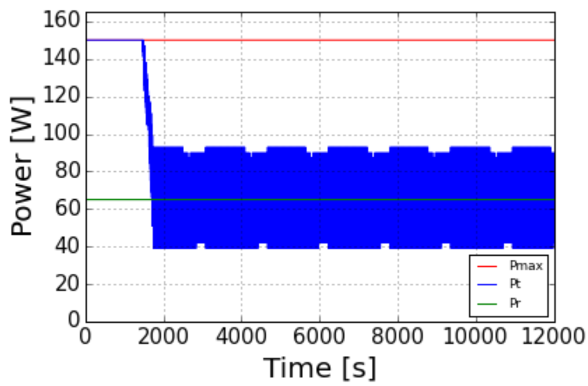


Fig. 7. Changes in total power of no power control.

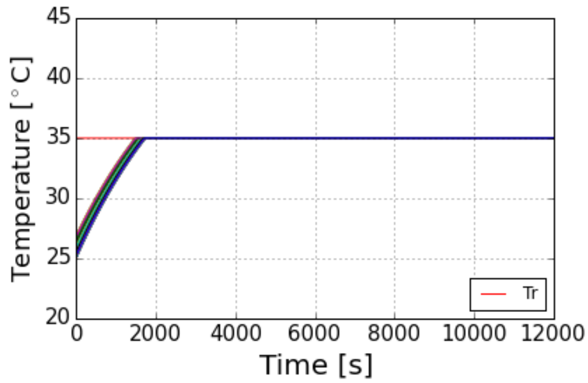


Fig. 8. Changes in temperature of no power control.

As you can see Figs. 7) and 8), it is true that the temperature of each heater is kept to the target value, but the total power consumption is the maximum value until the temperatures reach the target value, and after they reach it, the total power is greatly oscillating from 39W to 93W.

Second, the total power consumption is controlled with the autonomous distributed system. The results of the simulation are shown in Figs. 9) and 10).

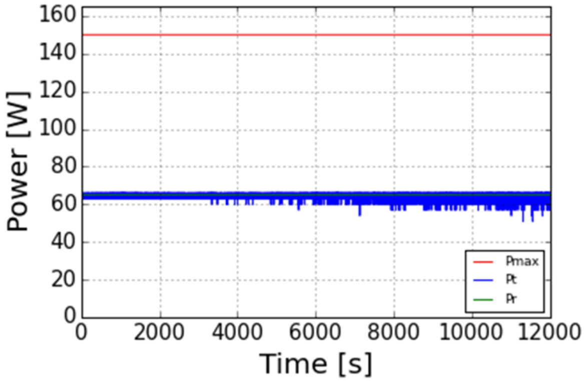


Fig. 9. Changes in total power of autonomous distributed system.

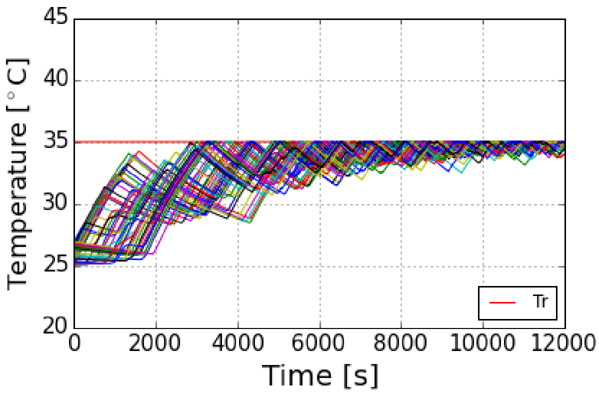


Fig. 10. Changes in temperature of autonomous distributed system.

Since the target value of total power consumption is 65.0W and the maximum value that the total power can take is 150W, the average power consumption of a heater is 1.3W. If the power consumption of a heater was 1.3W, the temperature of the thermal steady state would be 35.0°C. As you can see Fig. 10), the temperature reaches 35.0°C and oscillates around 35.0°C. From Fig. 9), regardless of whether the temperatures reach the target value, the total power consumption is suppressed from 45W to 70W. This range of power value is smaller than that of no power control. From these results of 2 cases, using the autonomous distributed control, it is possible to reduce the range of the total power value and suppress the maximum value while the temperatures are kept to the target value.

8. Experience

8.1 Conditions of the experiments

In order to compare to the result of simulation, a ground test is conducted. In the experiment, ZigBee, a wireless unit, is used to broadcast from the transmitter to the heaters.

The overall view of the experiment is shown in Fig. 11). 5 channels are compared. The transmitter calculates the total power consumption based on the information from the current sensor and transmits the information of the total power consumption.

Fig. 11. Overall view of the experiment.

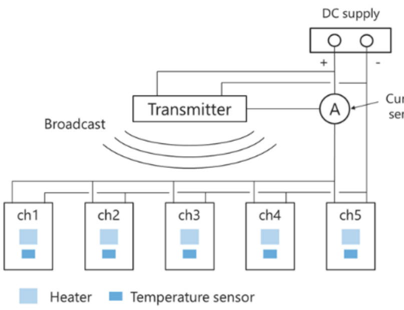


Table 3. Values of the experiment.

Chanel number	5
Target power [W]	9.5
Each Heater's power [W]	3.5
Maximum power consumption [W]	12.5
Outdoor temperature [°C]	24

8.2 result of experience

The experiments are also conducted in two cases. First, the total power consumption is controlled with the autonomous distributed system. the results of the experiment are shown in Fig. 12) and 13).

Fig. 12. Changes in total power autonomous distributed system.

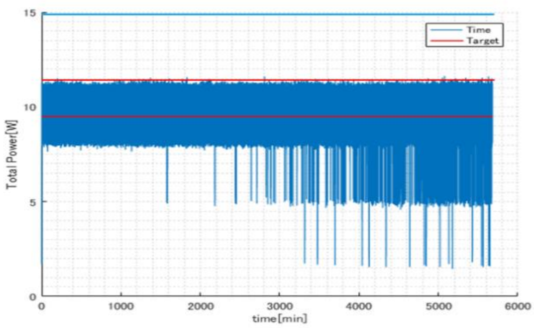
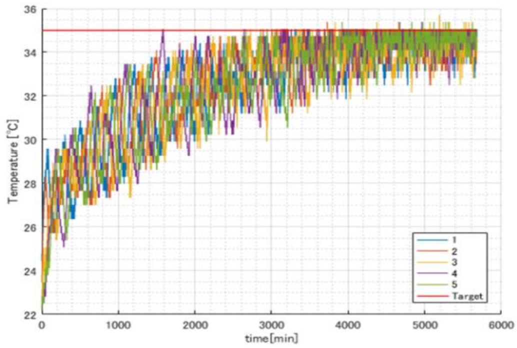


Fig. 13. Changes in total power autonomous distributed system.



Second, the total power consumption is controlled with the autonomous distributed system. Difference from the previous is target temperature. the results of the experiment are shown in Fig. 14) and 15).

Fig. 14. Changes in total power of autonomous distributed system

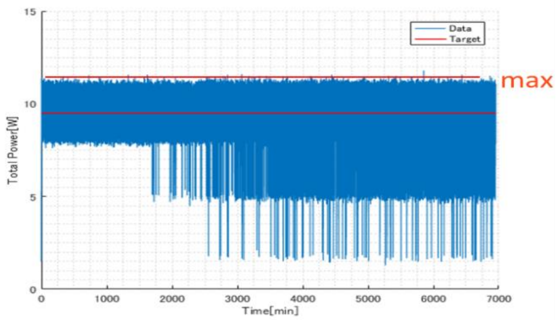
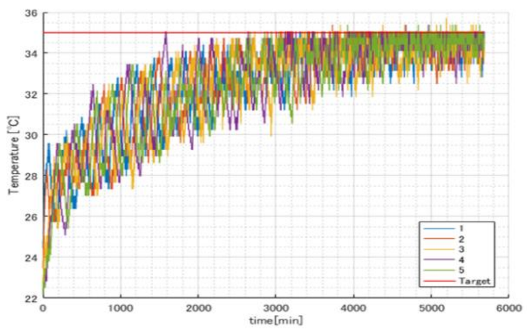


Fig. 15. Changes in total power of autonomous distributed system.



A heater power can take only two values, so the total power of 5 heaters can take only 6 values. Therefore, the total power cannot be just the target value; 9.5W. When 2 heaters turn on, the total power is 7W. When 3 heaters turn on, the total power is 11W. As you can see Fig. 12), the total power moves between the two values. Since the target value of total power consumption is 11W, the temperatures should be 35[℃] at the steady state. From these results, the total power cannot be controlled while each heater uses the power freely, but by introducing the autonomous distributed control, the total power can be controlled and the temperatures are kept to the target value.

9. Conclusion

We confirm that power consumption settles in target power in experiments and simulation with distributed control system. Power consumption is discrete, so we use counter that shows power consumption’s priority level and this system needs factorization to avoid a group demonstration. The simulation is appropriate with experiment from the above, it is capable of being realized.

References

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