Reduction of Calculation Amount of Mental-model Creation for Complex Material Circulation Control on Life Support System

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We have proposed a method to identify the importance of equipments in advanced life support system automatically in order to deal with simultaneous multiple faults. In this paper, we proposed a method to reduce calculation cost of identification of device importance based on a branch and bound method. As a result of the numerical calculation, we could obtain the reasonable identification results, and it was possible to further reduce the computational costs. For the future work, we need to conduct calculation with more detailed circulation model, and consider effective calculation algorithm when there are branch paths between main flow routes.

I. Introduction

Advanced Life Support System (ALS) is a system which make it possible to for living beings to survive in space by recycling and recirculating many substances. ALS must control the environment so as to support human life, so it must allow for adding or changing of components without stopping operating. The exigencies of a manned base dictate that the ALS must be sufficiently flexible in its functions to handle malfunctions of its components and conduct the necessary modifications to itself without stoppages of the system.[1, 2]

We have proposed a hierarchical control procedure for flexibility of system modifications, consisting of a centralized control system with a decentralized autonomous system. In this procedure, the ALS is split into an upper layer which controls the movement of substances between element clusters, and a lower layer which controls the distribution of substances within each of the clusters. The upper layer controls the movement of substances between clusters with a centralized scheduling procedure. The lower layer carries out control within each cluster using a decentralized autonomous learning control methods in order to meet the requirements specified by the upper layer. This procedure allows the upper layer to maintain stable material circulation throughout the ALS. Also, almost any necessary modification to the system can be handled by the lower layer, leaving margin for the learning control procedure to operate the system in a flexible way. In simulations, we have in fact succeeded in both expanding arrays of equipment without stopping the system and in removing disabled equipment while maintaining constant conditions.[3-5]

Here, we extended our analysis of device failure by considering a case of simultaneous failure of multiple devices. When this happens, the devices need to withdrawn from the system, and to be repaired or new replacements will be fabricated. If devices of the same type, such as waste processors, for example, failed simultaneously, the devices would be removed and replacements installed in the order of failure. For simultaneous failure of devices of different types, such as a material transportation pump and a waste processor, it may not be immediately obvious which of the two should be replaced first; it is a critical issue to set proper priorities in reacting to simultaneous failures. We addressed this question in a previous study and were able to counteract the problem with simple ordering of priorities based on simple rules using the model (called mental model) for deciding priorities in dealing with repair.[6, 7]

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In the present study, we discussed how to create this mental model with more reasonable calculation costs.

II. Control Procedures

The control procedures used in this study are almost the same as those proposed in the previous study. Therefore, only a summary of the basic concepts and control procedures are presented below. The reader is directed to previous reports[3-7] for details about the procedures. The final section here describes the approach used for reduction of calculation amount of mental-model creation.

A. Basic Concepts of Hierarchical Control

We propose the application of a hierarchical control procedure to provide the ALS with the functions of automatic control and autonomous response. This approach involves the following control system. First, the system is grouped into clusters of elements with the same function. Next, an automatic scheduling procedure on the functional stage (upper layer) which has a bird's-eye view of the entire system determines how much of any material is to be provided from one element cluster to another. The element clusters (lower layer) are treated as a decentralized autonomous system employing multi-agent learning Control (MALC) to bring about the inputs and outputs commanded by the scheduling procedure. Figure 1 shows an image of this control scheme.

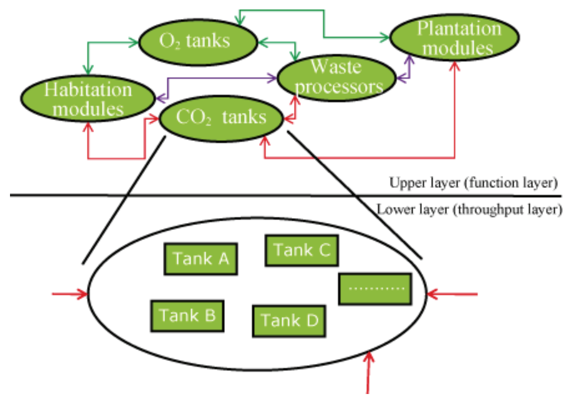

Figure 1 Hierarchical control system.

Use of a centralized control procedure in the above approach prevents computational explosion, because there are no variations in the numbers of control objects handled by the scheduler at the upper functional stage. Thus, we expect to be able to guarantee stable overall control. Application of a decentralized autonomous system for the lower layer should enable the system to cope autonomously when the processed volume fluctuates due to an increase or reduction in device numbers, which could occur when it is necessary to increase redundancy, expand capacity, or to isolate malfunctioning devices. In this study, the lower layer does not exercise control of material circulation, so the decentralized autonomous control methods employed by the lower layer are not discussed.

Since the previous study, the upper layer has been equipped with an automated routine for generating the order of repairs when malfunctions occur simultaneously. This routine is based on that of Miyajima et al., but modified using a redefined version of the Rasmussen system skill-rule-knowledge (SRK) model[8]. The upper layer model and the control system use knowledge-level control. A mental model based on simple rules was created, and was employed to address the malfunction issues.

B. Control Methods for Each Layer

The operation schedule is automatically generated for control of the complete upper layer of the ALS model in Figure 1. The upper layer model incorporates all of the functions necessary for the circulation-supplied life support system, so no elements are added during system modifications, and only the total values of the parameters for the grouped devices change. Thus, the upper layer handles system modification simply by updating parameter values and schedules.

The schedule writing procedure we employed was based on the Lagrangian Decomposition and Coordination (LDC) method. Functions that minimized deviation from the target values for the O_2 and CO_2 concentrations in the human habitation and plantation modules were defined as schedule evaluation functions.

On the other hand, the role of the lower-layer control devices is operation of the actual material transport and treatment devices required to maintain the flow volumes between the groups commanded by the upper-layer control devices. Increases or decreases in the numbers of devices due to physical arrangement and system modification can be expected to occur, so the lower-layer control employs a multi-agent system, in which each device is treated as an "agent". The reinforced learning algorithm employed here for control of inter-tank transfer was Q-Learning. A rule-based scheme was used for learning control in the waste processor start algorithm and for control of material transport between tanks and modules.

C. Automatic Recognition of Importance of System Devices (Mental Model)

In order to automatically decide which device should be repaired and replaced first when multiple devices have malfunctioned at the same time, the decision system must have a material circulation model, which must allow the mechanism to evaluate the degree of risk of collapse of the circulating system. This material circulation model with this device importance is called the mental model.

The most essential factor in calculating such risks is the importance of any set of system devices with respect to material circulation. This importance varies with the scale of the system and its operating conditions; a complicating factor is that the ALS itself is a circulating system. Therefore, the results of its actions will influence itself, after a certain time lag. This makes it impossible to identify "importance" perfectly. However, in this extremely simple model, a few calculations regarding the connections between the devices suffice to make a rough estimate of the relative importance of the devices.

Therefore, in the previous study[7], the following simple method was used to calculate importance. A device was selected for virtual repair and replacement by the upper layer controller, and the material circulation environment over a 3-day period was predicted by the model of the upper layer. This was performed for every device assumed to fail. The conditions in the plantation module and the human habitation module after 3 days were then evaluated using the schedule evaluation function described above in B, and this evaluation value was taken as the importance of this broken device.

However, if this method is applied to a real ALS, calculation explosion will occur because the system has the large number of device. Therefore, it is necessary to reduce the amount of calculation for the mental model creation.

D. The Method of Calculation Amount Reduction for Mental Model Creation

The system must try all combinations of devices in order to create the accurate mental model without any previous knowledge. However, since ALS is an artifact, it cannot be thought that circulation network is designed chaotically. Also, because it is associated directly with human life, at least three independent material flow paths should be required, in the same way as safety requirement in ISS9. And the fault detection system judges how many paths are healthy at first, and if all paths cannot use, the system is judged the catastrophic state, or if two paths cannot use at the same time, the system is considered very dangerous state. Then, the easiest path of repair will fix first.

As seen above, the circulation system is divided into two levels for mental model; "path" and "devices in the path". And if each path break, the detection system refers the difficulty level of repair the path in the path level first, then the system decide which path is mended first. At the same time, in the level of devices in the path, the importance of each device detected automatically by the system. By doing this, the system can apply the branch and bound approach, that is, the system just have to detect only the importance of devices in the same route. And this method reduces the calculation cost to 1/3 or less than brute-force method. In this paper, we defined the sum of day to mend the all fault devices in same path as the difficulty of path repair.

III. Control Objects

A. Control Requirements

The purpose of an ALS is to create and maintain a self-contained environment in which human beings can live and actively perform their mission duties while surrounded by an environment in which they cannot survive, such as outer space. The following are the only assumptions made in this study.

1) Food production is implemented within the system.
2) Material circulation in the system is fully automated.
3) Two people live in the human habitation module and all the food they eat is grown in plantation modules.
4) The failure is detected without previous warnings, and the simulation does not address automatic detection of the device failure per se.

B. Model of System Upper Layer

The material circulation model shown in Fig. 2 was created in accordance with the control requirements described above. Since the primary objective was to obtain a sketch of the characteristics of the procedures, a gas system circulating only oxygen (O_2), carbon dioxide (CO_2) and waste (containing C and O_2), was used as the model. The following circulations take place in the system. First, plants transform CO_2 into O_2 by photosynthesis in the plantation modules. The O_2 is stored in tanks and transported to the human habitation modules and physico-chemical processors, as required. The human habitation modules are home to two people, who subsist on a diet of plants grown in the plantation modules. The human inhabitants convert O_2 into CO_2 through respiration; the CO_2 is then filtered out of the living environment and stored in CO_2 tanks. From there, it is transported, as required, to the plantation modules and re-used in plant photosynthesis. The non-edible parts of the plants, along with human waste products, are stored in waste tanks and subsequently oxidized in the system's waste processors. In this model, which consists of a gas system only, the waste processors use O_2 and wastes to create CO_2, which is then stored in the CO_2 tanks. The plant types and cultivated area were determined in order to provide all necessary nutrition to the inhabitants. We decided model-parameters with the software made by Miyajima et al.[2], which was based on the biochemical stoichiometry. Data about plant growth in the software were obtained from Ref. 10. The values for the upper-layer model appear to be reasonable, when compared with the results in Ref. 11.

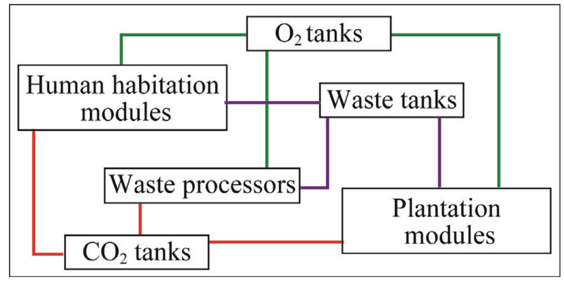

Figure 2 Model of ALS material circulation. *Green lines represent O_2 flow, red lines CO_2 flow, and purple lines, waste (carbon atoms) flow.*

C. Model of System Lower Layer

The devices that are handled in lumped form on the upper layer are, on the lower layer, modeled on the basis of their actual physical arrangement. In this study, however, in order to restrict the scope to a specific determination of which device has malfunctioned, only the oxygen flow is considered, as shown in Fig. 3. The calculations in this study were initiated with three O_2 tanks, nine material transportation pumps and three waste processors. The capacities of the tanks and of the material transport devices here were the same, and the capacity of the waste processors was designed to be able to process the amount of one day's wastes with one unit. Thus, it allowed up to two paths of failures. The abilities of tanks and processors are shown in Table 1. These values are determined based on the values of CEEF (Closed Ecological Experiment Facilities) at Insutitute for Environmenatl Sciences[12].It was assumed that the inflows of carbon dioxide and wastes from outside the system always flowed in the ideal amount.

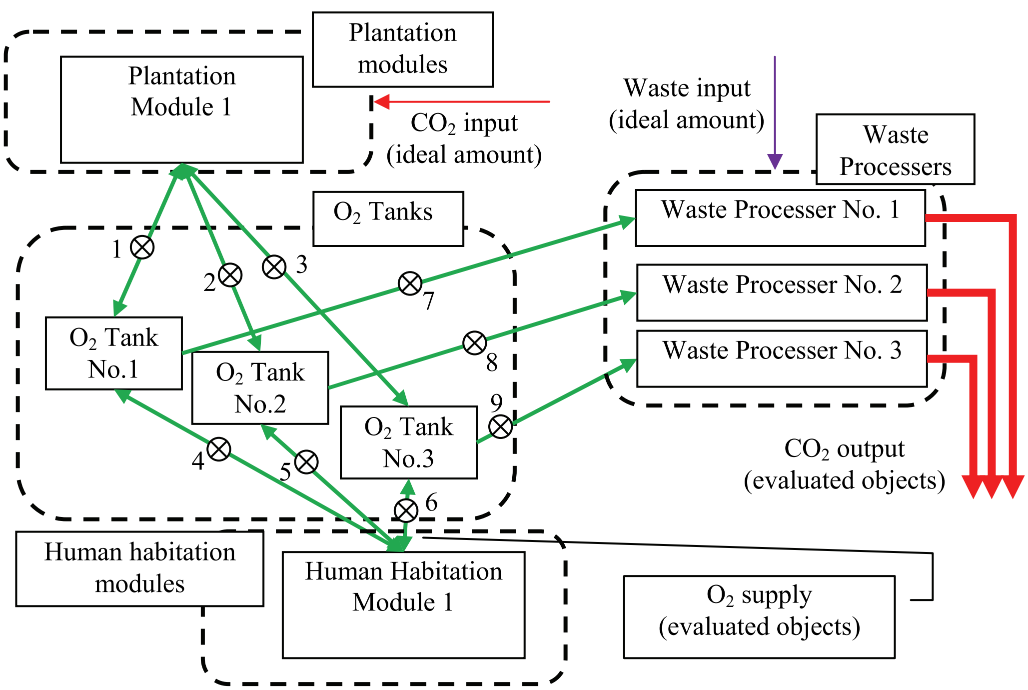

Figure 3 Model of ALS lower layer (normal operating conditions).
⊗ indicates a material transport pump (MTP). The number near ⊗ indicates serial number of MTP.

In the case of failure, there is no leakage of material to the outside of system. It was also assumed that the repair and replacement of failure oxygen tank would require 1 day and failure waste processor would require 2 days.

Table 1 O_2 tank, material transport pump and waste processor abilities

O_2 tank capacity [g]		7926
Material transport pump capacity [g/min]		20
Waste operation processor	Process time [min/batch]	480
	Required O_2 [g/batch]	2627.3
	Required waste [g/batch]	3268.8
	CO_2 produced [g/batch]	891.5

IV. Numerical Calculations Conditions and Results

A. Numerical Calculation Conditions

The following numerical calculation was performed in order to identify importance. First, a 3-day simulation of material circulation under normal conditions was carried out through midnight of the third day. Next, five equipments (material transport pump and waste processor) were selected in a random manner, and these five equipments were assumed to fail. The upper layer then selected the path for repairing, and determined an order of malfunctioning devices in the selected path for virtual repair. A 5-day schedule for the subsequent material circulation environment was then created by the upper layer, and the movements of the materials were calculated on that basis.

The evaluation of CO_2 output is differences between total produce amount in the waste processors at 5 day and the target produce value. This value normalized by dividing by the target produce value. The evaluation of O_2 supply is differences between total supply amount from the tank at 5 day and the target supply value. This value normalized by dividing by the target supply value, too. The total evaluation value (importance) is the sum of these CO_2 and O_2 evaluation. Here, the target produce or supply amounts were assumed to be the 1/3 of planned supply amount to the carbon dioxide tank or human habitation module. In other words, the target amount was the value obtained when the necessary amount was equally shared among 3 series in 5 days. Concretely, the target produce amount of CO_2 was 7,760 g/5-day and the target supply amount of O_2 to human habitation modules was 2021 g/5-day. We calculated this random failure trial 100 times.

B. Results of Identification Experiment

Table 2 shows the calculated O_2 evaluation, CO_2 evaluation and identified importance. Although evaluations and importance fluctuated due to use random numbers, the overall tend shows the following features.

First, we will discuss about the number of trials. We checked the importance of equipments each 10 trial. These values changed a lot for about 50 times from beginning, after that however, it converged to the nealy same value. Therefore, we showed tha values calcurated after the 100 trials as the results. Also, this trial numbers will increase as that the model will be more detailed. This is important problem, however, we could reduce the calculation amount as shown below, so we think that it can be calculated in a real system.

Table 2 The importance of material transport pump and waste operation processor.

	path 1				path 2				path 3			
	MTP 1	MTP 4	MPT 7	WOP 1	MTP 2	5MT P	MTP 8	WOP 2	MTP 3	MTP 6	MTP 9	WOP 3
O_2 evaluation	0.499	0.129	0.010	0.011	0.488	0.168	0.004	0.010	0.489	0.127	0.000	0.010
CO_2 evaluation	0.514	0.098	0.525	0.558	0.545	0.100	0.532	0.571	0.525	0.102	0.532	0.573
Importance	1.013	0.227	0.534	0.569	1.033	0.268	0.536	0.581	1.014	0.229	0.532	0.583

*MTP: material transport pump, WOP: waste operation processor

As the second of discussion point, paths 1, 2 and 3 showed similar tendencies. This is because each path is exactly the same clone. Focusing on the each path's devices, the importance of material transport pump 1, 2 and 3, which are connected from plantation modules, were relatively high values. The next higher values were marked by waste operation processor 1, 2 and 3, followed by the material transport pump 7, 8 and 9, which connected to waste operation processors. Lastly material transport pump 4, 5, and 6, which connected to the human habitation modules, became the lowest importance. This will be discussed below.

If the material transport pump 1, 2, and 3, which is the uppermost devices of each path, fail, it became impossible to supply O_2 both human habitation modules and waste operating processors. That is, the failure of these three pumps raised path-interruption, so importance of these three pumps became high.

Next, we show the reasons why the importance of material transport pumps 7, 8 and 9 and waste operation processors became high. Since these material transport pump and waste operation processor are connected in series, if these devices failed at the same time, the process will not recover by merely repairing either one. Therefore, if these devices failed at the same time, it is impossible to produce CO_2 at least for a total of three days; one day to repair the material transport pump, and two days to restore the waste operating processor. This is why the importance of this part's devices became high. The reason that the importance of waste processor is higher than the one of material transport pump is the CO_2 produce amount relativity low because the time required for repair the waste operation processor is longer than the time on material transport pump. This is because CO_2 the produce amount is reduced.

Finally, we explain the reason why the importance of material transport pumps 4, 5 and 6 were the lowest value. There are three reasons. The first is to repair the material transport pump, the O_2 supply to human habitation module will be restored. The second is that repair of material transport pump will be completed in only one day. And the third is that target O_2 supply amount is smaller than the target CO_2 produce amount.

To summarize the results, the importance of the most upstream material transport pumps was highest due to influence all the downstream. Then the importance of waste operating processors and the pumps connected to these processors was the second highest value because these pump and processor connect in series and because the target CO_2 produce amount is large. Regarding the material transport pumps connected to human habitation modules, it became the lowest importance because it was easy to repair and the amount of O_2 to be supplied was relatively small.

In this way, the result was reasonable.

C. Evaluation of Reduction of Calculation Amount

We check how much the calculation amount had decreased by suing our presented sequence. The brute-force method used last year is to select 5 fail devices from a total of 12 equipments, and calculate all the repair order of these selected devices. At that time, the number of trials is calculated followings;

$$ {}_{12}C_5 \cdot {}_5P_5 = 792 \cdot 120 = 95040 \tag{1} $$

which is an enormous number.

On the other hand, we calculate only 100 trials by presented method and almost satisfactory results are obtained. Also, even if searching only for one path,

$$ {}_4C_1 \cdot {}_1P_1 + {}_4C_2 \cdot {}_2P_2 + {}_4C_3 \cdot {}_3P_3 + {}_4C_4 \cdot {}_4P_4 = 4 + 12 + 24 + 24 = 64 \tag{2} $$

which is reduced to 1/1485.

V. Conclusion

We proposed a method to reduce the calculation cost for mental model creation used in the method of automatically identifying the importance of the equipment in the system proposed last year. This method is based on the branch and bound method. Automatic identification was carried out using presented method. As a result, it was possible to obtain reasonable results and succeeded in greatly suppressing the calculation amount.

For future studies, models incorporating the circulation of the elements C, H, O and N, not considered here, should be created, and an attempt should be made to prioritize between devices of different types undergoing simultaneous failures.

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