Multi-Robot Manipulation and Maintenance for Fault-Tolerant Systems

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***Abstract*— Ensuring fault tolerance of robotic systems is a challenge for factory automation. This paper focuses on multi-robot manipulation and maintenance for fault-tolerant systems. For this purpose, a manipulation strategy of multiple mobile robots, that enables a system to continue operating even if a working robot undergoes preventive maintenance or fails and undergoes corrective maintenance, is implemented. In addition, a robot failure and a maintenance policy for preventive and corrective maintenance activities are mathematically modeled on the basis of reliability engineering. Thus, working robots are allowed to undergo preventive maintenance at an optimal interval and corrective maintenance each time they fail. Finally, through simulation experiments, the effectiveness of an integrated multi-robot manipulation and maintenance in industrial applications is shown.**

I. INTRODUCTION

Fault tolerance is one of the major topics of robotics researches. This paper is devoted to a discussion of this topic in terms of the multi-robot technology in industrial applications. In recent years, autonomous mobile robots for material transport in manufacturing plants have attracted attention. The robot is a so-called AGV (Automated Guided Vehicle). As a result, for the AGVs, routing and operational dispatching methods (e.g., [1] [2] [3]), an integrated scheduling model using a Petri net (e.g., [4]), and a deadlock control model (e.g., [5]) have been proposed.

These previous researches have achieved some positive results for factory automation with the AGV-robots. However, in automated robotic systems, reaction behavior of working robots to cope with the following robustness issue has not been taken into account: robots undergoing preventive maintenance (i.e., inspection) and corrective maintenance (i.e., repair) may interfere with operations of other working robots. The system robustness against such a disturbance caused by these stopped robots is defined as fault tolerance in this paper.

In a recent paper [6], it has been suggested that faults in mobile robots are quite frequent (e.g., statistically-averaged mean time between failures was found to be 8 hours). For this reason, ensuring fault tolerance of robotic systems is a challenge for factory automation. Besides, as long as robots fail, we have to tackle the challenge even if the mean time between failures is improved.

This paper, therefore, focuses on multi-robot manipulation and maintenance for fault-tolerant systems. The manipulation strategy consists of a combination of robot operations, and it enables a system with robots to continue operating even if a working robot undergoes preventive maintenance or fails and undergoes corrective maintenance. In addition, a robot failure and a maintenance policy for preventive and corrective maintenance activities are mathematically modeled on the basis of reliability engineering. Thus, working robots are allowed to undergo preventive maintenance at an optimal interval and corrective maintenance each time they fail. Finally, through simulation experiments, the effectiveness of an integrated multi-robot manipulation and maintenance is shown.

II. RELATED WORK

Since multi-robot systems have the capability for the substitution and complement of a failed robot, many researchers thus far have focused on this system. Parker has proposed the software architecture, ALIANCE, that facilitates the fault tolerance cooperative control of teams of mobile robots [7]. Gerkey *et al.* have proposed a robots behavior algorithm for the object manipulation that enables fault tolerance [8]. In addition, an environment adaptation algorithm has been developed to enable an autonomous decentralized multi-legged robot to continue walking despite a broken leg [9]. In a biologically inspired approach, artificial immune systems (AISs) have even been proposed [10].

These related works have not, however, taken into account a harmful influence of a failed robot on other working robots. In other words, the failed robot was assumed not to disturb operations of other robots. In fact, only Dias *et al.* have demonstrated the efficacy of removing and repairing a failed robot and inserting it again afterward [11]. However, since the entire system operation in an actual plant has to be halted for safety reasons, it is preferable to halt the operation partially by repairing the robot on site.

Furthermore, although the importance of preventive maintenance in addition to corrective maintenance of machines has been stated [12], this has not been treated for multi-robot systems. The contribution of this paper is, therefore, an integration of the multi-robot manipulation and preventive and corrective maintenance for fault-tolerant systems in industrial applications.

III. MULTI-ROBOT SYSTEM IN INDUSTRIAL APPLICATIONS

In this paper, a material transport system is treated in order to introduce the multi-robot technology in industrial applications. In this robotic system, wheel mounted autonomous mobile robots accomplish repetitive tasks, and transport various materials to designated places through different routes. A robot failure is defined as the loss of the transport capacity in the system, including damages to mounted communication devices and the robot itself, e.g., control board or blowout.

Fig.1 illustrates an intended material transport system with multiple mobile robots. The layout structure itself is, as can

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be seen in literature [13], general for the manufacturing and transport systems with the AGVs. In this system, we assume that the robots are allowed to share and exchange information on their states — operation, failure, maintenance, etc., on the basis of a distributed blackboards communication model. Note that, since each blackboard is connected for the communication to a centralized controller, even if a communication device of a robot is broken, this is made known to other robots via the centralized controller by referring to its communication history using the blackboards.

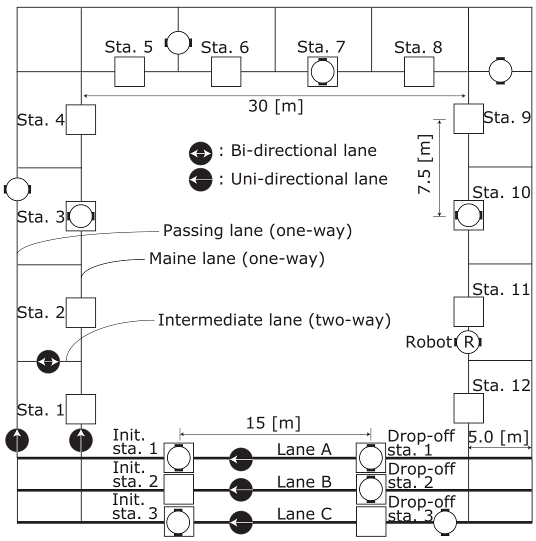


Fig. 1. Robotic Material Transport System with Cyclic Layout Structure

This system consists of 1 $\sim$ 12 material handling stations and three initial and drop-off stations. The 12 stations are arranged on a one-way main lane. Initial and drop-off stations are arranged on one-way lanes A, B, and C. In addition, a lane for passing (one-way) and an intermediate lane (two-way) that connects the main and passing lanes are provided. In this system, robots transport materials cyclically from initial to drop-off stations; also, they stop and undergo maintenance on site on the lanes for a while.

Once a robot performing a task fails, while remaining unexecuted tasks are performable by other working robots, the robots are not allowed to perform the task of the failed robot instead. Therefore, working robots are periodically inspected for failure prevention and failed robots are repaired; after that, they restart the operations again. In this regard, since robots are allowed to move only on provided lanes in an actual plant system, these robots stopped for maintenance may interfere with operations of other working robots. Eventually, the operating efficiency of the entire system could get worse. Therefore, each working robot is required to cope with the disturbance caused by the stopped robots and to continue the operation to the maximum extent possible considering the maintenance activities.

IV. MULTI-ROBOT MANIPULATION STRATEGY

A. Framework

In a general material transport system, once a task is assigned to a vehicle (robot), the vehicle plans the route to a destination according to the task, and then performs the transport task. To achieve the task, a multi-robot manipulation strategy for the following problems is required: (I) task assignment, (II) route planning, and (III) destination exchange. In addition, the multi-robot manipulation strategy is required to ensure fault tolerance of the system.

In recent research work, we have presented specific operations of robots to the material transport system in consideration of the issues described above. Therefore, we adopt these operations as the manipulation strategy. For changing circumstances of the system, this strategy switches the normal and fault-tolerant operations of robots [14] [15] in a hybrid manner based on whether a robot is undergoing maintenance.

B. Fault-Tolerant Task Assignment Strategy

In the normal operational status, a transport task that consists of several target stations is assigned to a robot on the basis of the following objective function while partially referring to unexecuted tasks.

$$min \sum_{k \in K_p} \sum_{n \in N} Task_{n,k}(ExeTask_n - Task_{n,k}), \qquad (1)$$

where k and K_p are a reference task and a partial task reference range, and K_p shifts toward the end of the unexecuted tasks queue, K, one by one, i.e., $K_p \in K$. n represents a station from N stations. $ExeTask_n$ represents the total number of robots moving to and operating at stations n. As for $Task_{n,k}$, a binary variable, 0 or 1, is given whether or not station n of the k-th reference task is a destination. The objective function as can be seen in Eq.(1) denotes that a task with the lowest similarity to the state of all the tasks being executed in the system is assigned to the robot.

The objective function, Eq.(1), equalizes the workload to each station that arises from the assigned tasks. However, existence of robots undergoing preventive and corrective maintenance was not taken into account in this objective function. Therefore, in the event of that a robot undergoes maintenance near a handling station and tasks to transport material to the station are assigned to robots, these robots are forced to stop due to the robot.

For this problem, we introduce the objective function expressed by Eq.(2) combining the objective function of Eq.(1) with the number of robots undergoing maintenance, mr_n, near station n. Thus, the tasks assigned to the robots based on this strategy are allowed to keep the equalized workload to each station and ensure fault tolerance. The set of the range is 10 (i.e., $K_p = 10$).

$$min \sum_{k \in K_p} \sum_{n \in N} Task_{n,k}\{(ExeTask_n + mr_n) - Task_{n,k}\} \qquad (2)$$

C. Fault-Tolerant Route Planning Strategy

A normal route planner that considered a distance to the target station and operating robots at stations on a planning route enabled a robot to move to its destination through the shortest or most indirect (quasi-shortest) route and go around the operating robots provided that no robot undergoing maintenance. However, if a robot on the route planned by a moving robot to go around other operating robots suddenly fails or undergoes preventive maintenance, this moving robot is forced to stop due to the preceding robot. For this problem, we additionally introduce the following objective function:

$$min \sum_{r \in R} (\alpha r_o + \beta r_m). \tag{3}$$

Eq.(3) denotes that, for the set of robots on a planning route, R, the route minimizing the function value for the number of robots operating at stations, r_o, and undergoing maintenance on the route, r_m, is obtained as the optimal route. α and β indicate weighting coefficients of the robots operating and undergoing maintenance determined depending on the impact of the obstruction by these robots.

As shown in **Fig.2**, a moving robot (R 1) is, thus, enabled to replan a new route in consideration of the preceding robot (R 4) undergoing maintenance in addition to other operating robots (R 2 and R 3) and move to a destination without disturbance by these stopped robots as much as possible. Furthermore, if either an operating robot or a robot undergoing maintenance exists on every route, the moving robot is enabled to obtain a route minimizing the stop time, i.e., the disturbance due to the robots.

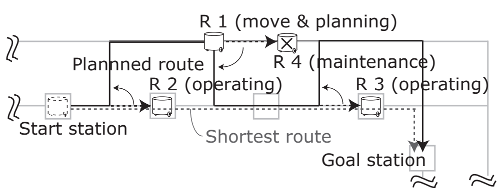


Fig. 2. Robot Planning Routes Considering Distance and Obstructions

D. Fault-Tolerant Destination Exchange Strategy

The two manipulation strategies described in IV-B and IV-C ensure fault tolerance as follows: a task that orders a working robot to transport materials to a station near a robot undergoing maintenance is not assigned; moreover, working robots are enabled to transport and move without any disturbance by stopped robots for operation and maintenance elsewhere. As shown in **Fig.3**, however, if a robot (R 4) undergoes maintenance newly on the main lane near the target station of other moving robots (R 1 and R 2) while R 1 and R 2 are performing the tasks already assigned, R 1 and R 2 are not able to go around the disturbance of R 4 and are forced to stop. A similar problem occurs if a robot undergoes maintenance on lanes A, B, and C in **Fig.1**.

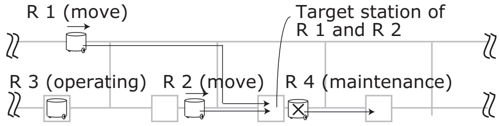


Fig. 3. Robot Undergoing Maintenance near Target Station

For this problem, we focus on the robot performing the assigned task as follows: if a robot undergoes maintenance near the target station, this robot cancels the task and returns to the drop-off station and then the initial station; after that, a new task is assigned. For a robot undergoing maintenance on the lanes of A, B, or C, destinations of the drop-off and initial stations of a moving robot located on these lanes are changed according to its destination (i.e., lane) as follows: A $\rightarrow$ B or B $\rightarrow$ C or C $\rightarrow$ A. Not that the canceled task is reassigned to and performed by the same robot after the new task was finished if the inspection or repair for the robot near the target station was finished.

V. MULTI-ROBOT MAINTENANCE POLICY

A. Preventive and Corrective Maintenance

Regarding the failure rate, in general systems in which maintenance activities are conducted, the increasing-failure-rate (IFR) period of the bathtub curve is assumed. In this period, items that compose a robot deteriorate over time, and thus, the failure rate of the robot is also increased. For this system, in addition to corrective maintenance for failed robots, preventive maintenance for working robots to check status and exchange items in some cases before failure is effective. As mentioned in I, two maintenance activities for preventive and corrective maintenance are defied as the inspection and repair, respectively.

For the efficient maintenance activities, an optimal maintenance policy that minimizes the number of robots stopped for both preventive and corrective maintenance is required. For this purpose, on the basis of reliability engineering, the robot failure and maintenance policy are modeled so that working robots undergo preventive maintenance at an optimal interval of the inspection and corrective maintenance for the repair each time they fail following a failure rate.

B. Robot Failure

In order to consider the IFR period of the bathtub curve on the robots, a probability density function of a robot failure is assumed to follow a Weibull distribution. Based on this assumption, the failure rate of a robot at given time t is expressed by Eq.(4). Here, m and η represent a shape parameter and scale parameter of the Weibull distribution. These parameters are $m > 0$ and $\eta > 0$.

$$h(t) = \frac{mt^{m-1}}{\eta^m} \tag{4}$$

If shape parameter m is given as $0 < m \leq 1$, the Weibull distribution depicts the decreasing-failure-rate (DFR) or constant-failure-rate (CFR) period of the bathtub curve. In order to change the shape of the curve that corresponds to the IFR period, the shape parameter must be $1 < m$. Scale parameter η defines a time scale; hence, the shape of the distribution is allowed to be elongated and expanded in conjunction with the scale parameter. Given mean time between failures (MTBF) of all the robots, three parameters, m, η, and $MTBF$ are expressed by Eq.(5).

$$MTBF = \eta \Gamma \left(\frac{1}{m} + 1 \right) \tag{5}$$

In this equation, $\Gamma(1/m+1)$ denotes the gamma function that we can obtain by giving the shape parameter. The gamma function is defined as $\Gamma(n) = \int_0^\infty exp(-x)x^{n-1}dx$.

Therefore, scale parameter η is obtained from Eq.(5) when shape parameter m and MTBF are given, and thus, failure rate $h(t)$ is calculated from Eq.(4) at each simulation step. Following this failure rate at time t, $h(t)$, a robot incidentally fails and stops for corrective maintenance on site each time.

C. Robot Maintenance

In general, preventive maintenance for working robots is conducted at fixed intervals and corrective maintenance is conducted each time the robots fail. In this paper, the failure rate of a working robot after preventive maintenance is reset to zero (i.e., $h(t) = 0$) at the time reset to zero ($t = 0$). For a failed robot, in the same way, the time and failure rate are reset to zero, i.e., $t = 0$ and $h(t) = 0$ after corrective maintenance.

In this regard, frequent inspections enable each robot to keep the lower failure rate and prevent the failure. However, such a maintenance policy might increase the number of robots stopped for preventive maintenance. In contrast, rarely inspections raise the failure rate; eventually, the number of failed robots that require to be repaired increases. In other words, these robots stopped due to unreasonable maintenance policies might interfere with other working robots.

For this problem, we take into account an evaluation criterion, i.e., availability that involves both reliability and maintainability and develop a maintenance policy that conducts preventive maintenance at an optimal inspection interval determined on the basis of availability. In reliability engineering, availability is defined as the amount of time a robot is actually working as the percentage of total time it should be working. That is to say, higher availability represents that a robot fully works even though it undergoes preventive and corrective maintenance.

Qualitatively, availability approaches a certain value in the seas of time (i.e., $t \to \infty$). Therefore, availability of a robot is expressed by Eq.(6).

$$A(T) = \frac{T}{T_2 \int_0^T h(t)dt + T_1 + T}, \tag{6}$$

where T denotes the inspection interval, i.e., time until a robot undergoes preventive maintenance, and T_1 and T_2 are mean time to inspection and repair, respectively.

Since the probability density function of a robot failure is assumed to follow the Weibull distribution in this paper as described in V-B, we obtain Eq.(7) by substituting Eq.(4) into Eq.(6).

$$A(T) = \frac{T}{T_2 \left(\frac{T}{\eta}\right)^m + T_1 + T} \tag{7}$$

Therefore, inspection interval T that maximizes availability is given as a solution to a partial differential equation expressed by Eq.(8).

$$\frac{\partial A(T)}{\partial T} = \frac{T_2 \left(\frac{T}{\eta}\right)^m + T_1 + T - T\left(\frac{T_2 m}{\eta^m} T^{m-1} + 1\right)}{\left\{T_2 \left(\frac{T}{\eta}\right)^m + T_1 + T\right\}^2} = 0 \tag{8}$$

Eq.(8) is replaced by T as expressed by Eq.(9). Hence, this is the optimal inspection interval for preventive maintenance. As can be seen in Eq.(9), note that T becomes infeasible or infinite under DFR ($m < 1$) or CFR ($m = 1$) period.

$$T = \eta \left\{ \frac{T_1}{T_2(m-1)} \right\}^{1/m} \tag{9}$$

Based on this model, the maintenance policy decides the optimal inspection interval and conducts preventive maintenance for working robots.

VI. SIMULATION EXPERIMENT

A. Simulation Settings

In this simulation experiment, the effectiveness of the integrated multi-robot manipulation and maintenance is discussed. Weighting coefficients in IV-C were determined to be $\alpha = 1$ and $\beta = 3$. In total, 1000 transport tasks are given to the robots in each simulation. In the task, several destinations for stations, $1 \sim 12$, are given with a probability of 0.25. Two parameters required to calculate the failure rate are as follows: the MTBF is given as $MTBF = 8$ [h] in consideration of the result of [6] and the shape parameter is $m = 2$. The initial failure rate of each robot is randomly given. Time taken for preventive maintenance, T_1, is 600 [s] ($\simeq$ 0.167 [h]) and corrective maintenance, T_2, is 1800 [s] (0.5 [h]).

Regarding preventive maintenance, from Eq.(9) and given parameters listed above, the optimal inspection interval is 18762 [s]. Therefore, the working robots are allowed to undergo preventive maintenance every 18762 [s] by applying the optimal maintenance policy. For comparison, three other maintenance policies are applied. Policy 1 only conducts corrective maintenance and policies 2 and 3 conduct frequent and rarely preventive maintenance every 10000 and 30000 [s] in addition to corrective maintenance. Averaged data for a 10-time simulation yielded the experimental result.

B. Experimental Results

Fig.4 shows increased operation time with each maintenance policy, as compared to a result of the ideal system in which robots do not fail and undergo both maintenance. Moreover, operation time of the ideal system is depicted by the heavy black line. Hereafter, preventive and corrective maintenance are abbreviated to PM and CM in figures.

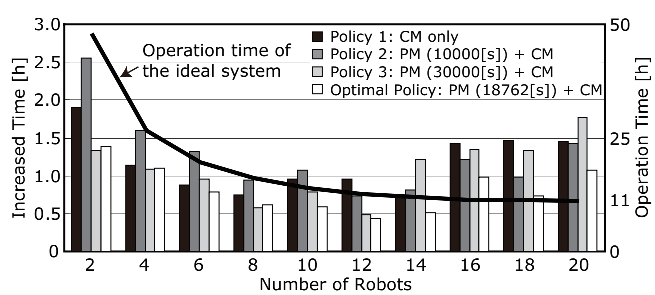


Fig. 4. Fault Tolerance of Integrated Robots Manipulation and Maintenance

From this result, the system operation efficiency was increased as the number of robots increased up to 12.

However, after operation time of the ideal system approached to 11 [h], the efficiency was decreased. This is due to the system capacity, rather than the manipulation strategy and maintenance policy. Note that, even though operation time increased over the result of the ideal system, this does not indicate that the entire system operation was suspended. This performance decrement is proportional to the severity of a robot undergoing preventive or corrective maintenance. Therefore, fault tolerance was successfully ensured. The mean operation time increment of the four results compared to the result of the ideal system is listed in **Table I**.

TABLE I
MEAN OPERATION TIME INCREMENT COMPARED TO IDEAL SYSTEM

# of robots	Policy 1	Policy 2	Policy 3 [%]	Optimal Policy
$2 \sim 12$	5.3	6.3 (worst)	4.2	3.8 (best)
$14 \sim 20$	11.4	10.0	12.7 (worst)	7.4 (best)
$2 \sim 20$	7.8	7.8	7.6	5.3 (best)

This table shows that the optimal maintenance policy resulted in best fault tolerance. On the other hand, policies 2 and 3 have the opposite effects on fault tolerance depending on the number of robots used in the system. As a result, even though these policies conducted preventive maintenance, each of them resulted in worst fault tolerance in the systems with fewer and many robots, respectively. **Fig.5** compares the time ratio for preventive and corrective maintenance with each maintenance policy.

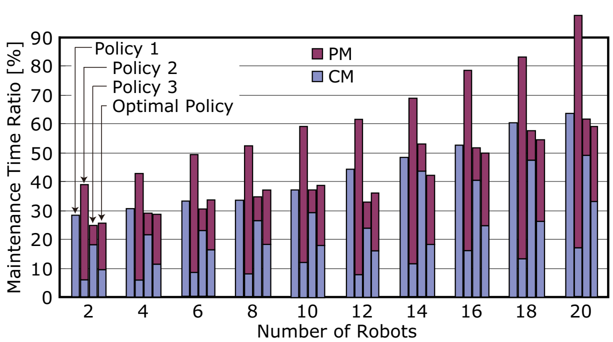


Fig. 5. Preventive and Corrective Maintenance Time Ratio

From the result, it can be seen that the optimal policy conducted preventive and corrective maintenance at the same rate, namely, symmetrical maintenance. It is noticeable that while the total maintenance time ratio were not so different among the policies, 1, 3, and optimal, these policies have different effects on fault tolerance. Furthermore, although policy 2 resulted in second-best fault tolerance for the system with many robots as shown in **Fig.4** and **Table I**, it conducted maintenance the most times. To analyze the reason of these results, we focus on the average number of failed robots.

C. Result Analysis

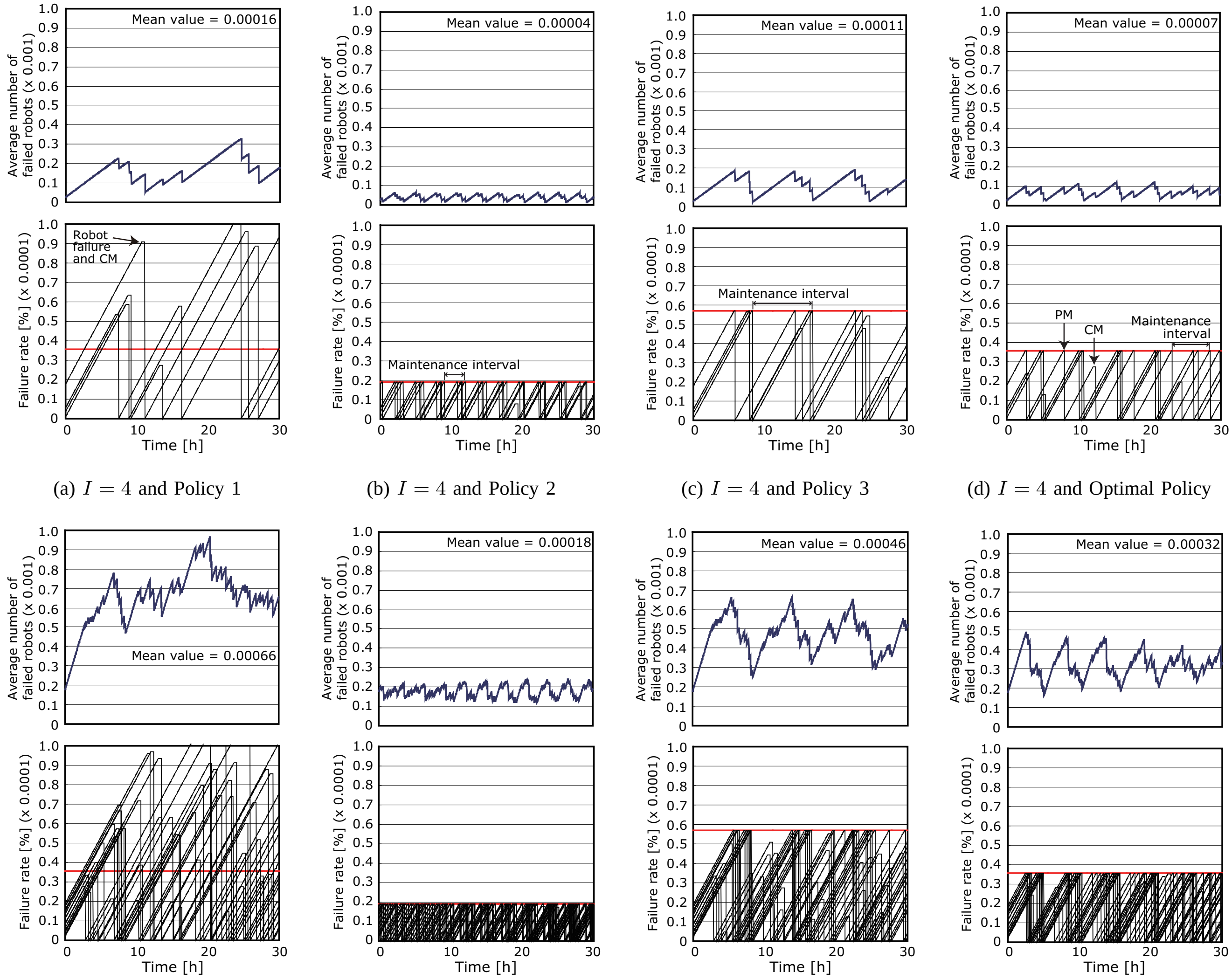
With the same MTBF, the average number of failed robots in the systems with fewer and more robots differed as follows: $\sum_{i \in I} h_i(t)$ and $\sum_{j \in J} h_j(t)$, where I and J denote the number of robots. Given $I < J$, the average number of failed robots is $\sum_{i \in I} h_i(t) < \sum_{j \in J} h_j(t)$; thus, a density of the failed robots in the system with many robots (J) became higher. For comparison, 4 and 18 robots, $I = 4$ and $J = 18$, were used in the systems. **Fig.6** shows the transitions of the failure rate of each robot $h(t)$ and average number of failed robots $\sum h(t)$ for 4 and 18 robots after the simulation up to 30 [h].

From the results of $I = 4$, the mean value of the average number of failed robots in **Fig.6(b)**, **Fig.6(c)**, and **Fig.6(d)** was less than that of **Fig.6(a)**. This result indicates that preventive maintenance was appropriately performed. However, the difference in the mean value was small. Moreover, in addition to corrective maintenance, the robots also have to stop on site to undergo preventive maintenance. Therefore, it was found that, since the manipulation strategy enabled the robots to handle the failed robots in a low-density system with fewer robots, frequent preventive maintenance was not necessary, whereas the optimal policy showed the effectiveness even in the system. In this case, rarely preventive maintenance was effective; thus, policies 1 and 3 increased fault tolerance than that with policy 2.

In contrast, from the results of $J = 18$ shown in **Fig.6(e)** $\sim$ **Fig.6(h)**, we can see that the differences in both the average number of failed robots and mean value were larger. This result shows that the average number of failed robots was increased as the number of robots increased and a density of the system became higher. In this case, although the maintenance time ratio was the longest, frequent preventive maintenance successfully curbed the average number of failed robots. Eventually, the manipulation strategy worked properly with policy 2. On the other hand, policies 1 and 3 could not curb the average number of failed robots. For this reason, although the total maintenance time ratio were not so different from the one of the optimal policy, the working robots were not able to handle the failed robots; consequently, these two policies decreased fault tolerance of the system with many robots.

VII. CONCLUSIONS

This paper focused on multi-robot manipulation and maintenance for fault-tolerant systems. For this purpose, previously-proposed operations of robots were adopted as a manipulation strategy. This enabled a system to continue operating even if a working robot undergoes preventive maintenance or fails and undergoes corrective maintenance. In addition, a robot failure and a maintenance policy for preventive and corrective maintenance activities were mathematically modeled on the basis of reliability engineering. Thus, working robots were allowed to undergo preventive maintenance at an optimal interval and corrective maintenance each time they fail. Through simulation experiments; finally, the effectiveness of an integrated multi-robot manipulation and maintenance was demonstrated. Moreover, even if the optimal policy is not applied, it was shown that the reasonable system operation is possible if the interval of preventive maintenance considering the number of robots in addition to the manipulation strategy was selected.



(a) $I = 4$ and Policy 1 (b) $I = 4$ and Policy 2 (c) $I = 4$ and Policy 3 (d) $I = 4$ and Optimal Policy

(e) $J = 18$ and Policy 1 (f) $J = 18$ and Policy 2 (g) $J = 18$ and Policy 3 (h) $J = 18$ and Optimal Policy

Fig. 6. Transitions of Failure Rate and Average Number of Failed Robots with Four Maintenance Policies, 1, 2, 3, and Optimal

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