Optimal Maintenance Strategy in Fault-Tolerant Multi-Robot Systems

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***Abstract*— This paper focuses on the effectiveness of maintenance in fault-tolerant multi-robot systems. Such a system is enabled to work as long as one robot works; namely, completely parallel. For this system, it is required to ensure fault tolerance and maintain high performance taking robot failures and maintenance, such as prevention and correction of robots, into account. Therefore, we propose an optimal maintenance strategy on the basis of reliability engineering. This strategy enables robots to undergo preventive maintenance at optimal intervals and corrective maintenance each time they fail. Through simulation experiments, the effectiveness of the optimal maintenance strategy is investigated. In addition, the influence of robots undergoing maintenance on system performance is mathematically and experimentally discussed on the basis of the number of robots and maintenance strategies.**

I. INTRODUCTION

In the field of industrial automation with robotics technology, each robot is required to work autonomously in response to demands given on site. Therefore, many researchers have focused on autonomous mobile robots. However, although robot failures and maintenance might affect fault tolerance and performance of robotic systems, they have not paid much attention to the actual issues.

Thus far, a literature has reported that mobile robots often failed; consequently, an averaged mean time between failures was about 8 hours [1]. This is because robots are required to accomplish more advanced tasks compared to machines; thus, mounted devices on them are complex. Therefore, it is important to ensure fault tolerance of systems and maintain high performance taking the robot failures and maintenance into account. In this paper, fault tolerance is defined as a property that enables a robotic system to continue operating even if a robot in the system fails.

To ensure fault tolerance of robot systems, it is required for swarms of robots to respond to a failed robot. Multi-robot systems have a potential for this requirement. Therefore, previous researches have focused on the coordination of the multi-robot systems so as to ensure fault tolerance. Parker has proposed the software architecture, ALIANCE, that facilitates the fault tolerance cooperative control of teams of mobile robots [2]. Gerkey *et al*. have proposed a robot behavior algorithm for the object manipulation that enables fault tolerance [3]. In addition, an environment adaptation algorithm has been developed to enable an autonomous decentralized multi-legged robot to continue walking despite a broken leg [4]. In a biologically inspired approach, artificial immune systems have even been proposed [5].

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For mechanical systems, the importance of periodic inspections to prevent failures and repairs of failed parts have been indicated [6]. In the field of robotics, on the other hand, only a few researchers have referred to the importance of the robot failures, inspections, and repairs so as to ensure fault tolerance of robot systems. Hereafter, the periodic inspection (including parts replacement) and the repair of failures are defined as preventive maintenance and corrective maintenance on the basis of reliability engineering. These two maintenance activities are collectively called maintenance.

We have engaged in research for fault-tolerant material transport systems with multiple mobile robots in industrial applications [7]. As a result, a fault-tolerant robots operational strategy considering maintenance activity was developed on the basis of reliability engineering. However, since intervals of preventive maintenance for robots were empirically determined, the optimality of maintenance was ignored. Moreover, it was a specialized robots operational strategy for a layout based on the robotic material transport system. For this reason, fault tolerance was heavily dependent on them; additionally, it was impossible to purely investigate the influence of maintenance only.

Preventive maintenance for working robots dominates the number of robots that undergo maintenance depending on its interval. The same holds true for systems with fault tolerance. Furthermore, the robots undergoing maintenance shall affect system performance, e.g., working ratio regardless of presence or absence of fault tolerance. Therefore, we aim to conduct optimal maintenance for robots, rather than the coordination problem, in order to ensure fault tolerance of the robot system while maintaining high performance. For this purpose, we propose an optimal maintenance strategy that conducts preventive maintenance for working robots at optimal intervals and corrective maintenance each time they fail, in this paper. As for robot coordination, we assume that robots are able to avoid a stopped robot for undergoing maintenance. A layout does not affect fault tolerance. In other words, fault tolerance is ensured as long as all the robots do not fail, and the system is enabled to continue working regardless the layout.

Through simulation experiments with various parameters associated with robot failures, the optimal maintenance strategy is compared to other two strategies that conduct preventive maintenance at empirically-determined intervals [7] and corrective maintenance each time robots fail. From the results, the effectiveness of the optimal maintenance strategy is investigated. In addition, the influence of robots undergoing maintenance on system performance is mathematically and experimentally discussed on the basis of the number of robots and maintenance strategies.

II. COMPLETELY PARALLEL AND FAULT-TOLERANT MULTI-ROBOT SYSTEM

A. Fault Tolerance

In this paper, we focus on a system with wheeled robots taking vehicles used for the material transport into account. Unlike line production systems with fixed machines and buffers, since each robot is given an independent task, these mobile robots are allowed to move and execute their own tasks in a system even if a robot stops and undergoes maintenance. In other words, such a system is enabled to work as long as at least one robot works. Assuming that a system layout does not affect fault tolerance, the system is completely parallel. Therefore, we can rigorously reveal the effectiveness of the optimal maintenance strategy for maintaining high performance in multi-robot systems with fault tolerance.

In a completely parallel system, the failure rate of the entire system, $H_p(t)$, is derivable from failure rates of individual robots that compose the system as follows: $H_p(t) = \prod_i h_i(t)$. t indicates the time and h_i represents a failure rate of a robot, i. In contrast, if a robot failure affects the entire system and thus the system is forced to stop working, it is called a serial system. In the serial system, the failure rate of the entire system, $H_s(t)$, is derivable from $H_s(t) = 1 - \prod_i\{1 - h_i(t)\}$. If a sufficiently small value is given to $h_i(t)$, the failure rate of the entire system is approximated by the sum of failure rates of individual robots as follows: $H_s(t) \simeq \sum_i h_i(t)$. Thus, the failure rates of the parallel and serial systems are $H_p(t) \leq H_s(t)$ when the failure rates of the robots are given as $0 \leq h_i(t) \leq 1.0$ and the same robots are used in both systems.

Both of the parallel and serial systems stop working when the failure rates are $H(t) = 1.0$. In this case, it is impossible to ensure fault tolerance of the systems. Let the entire system failure rate, H, be fault tolerance, fault tolerance of the parallel system is obviously higher than that of the serial system. In addition, fault tolerance in the parallel system increases as the number of robots is increased, whereas that in the serial system decreases. These are the advantages of the parallel system in fault tolerance over the serial system.

B. Influence of Maintenance on System Performance

Even in the parallel system, it is required to conduct maintenance in consideration of robot failures. While a robot is undergoing maintenance, the number of working robots in the system is decreased. For this reason, although fault tolerance of the system is ensured, the robot undergoing maintenance degrades the entire system performance. Especially, focusing on preventive maintenance, the frequency has the following influence on the system performance.

- While frequent preventive maintenance reduces robot failures and decreases the number of robots that undergo corrective maintenance, it increases the number of robots that undergo preventive maintenance and degrades the system performance.
- Although infrequent preventive maintenance decreases the number of robots that undergo preventive maintenance, it increases the number of robots that fail and undergo corrective maintenance, and degrades the system performance.

Therefore, it is first required to increase the number of robots used in the system in order to ensure fault tolerance. In addition, it is important to conduct maintenance at reasonable intervals so as to maintain high performance collaterally. That is to say, maintenance has to be conducted so that working robots do not fail and undergo neither too much corrective maintenance nor too much preventive maintenance. This is a challenge of this paper as compared to our previous work [7].

III. MAINTENANCE ACTIVITY

A. Maintenance

In general systems in which maintenance activities are performed, the increasing-failure-rate (IFR) period of the bathtub curve is assumed. In this period, since components of a system deteriorate over time, they become fragile and are likely to break. In this paper, therefore, the IFR period is assumed. Thus, failure rates of robots that compose a system increase with duration, and the robots become fragile

For this period, in addition to corrective maintenance for failed robots, preventive maintenance for working robots at planned intervals to check status and replace parts in some cases before failure is effective. In this regard, however, maintenance might degrade the system performance as described in II-B. To solve the challenge, it is necessary to minimize the number of robots that undergo maintenance or the influence from the robots undergoing maintenance on performance. Therefore, we propose an optimal maintenance strategy. For this purpose, on the basis of reliability engineering, the robot failure is modeled; then, an interval of preventive maintenance is derived.

Hereafter, preventive maintenance and corrective maintenance are abbreviated as PM and CM in this paper.

B. Robot Failure

In order to consider the IFR period of the bathtub curve, a probability density function of robot failures are assumed to follow the Weibull distribution. On the basis of this assumption, the failure rate of a robot at given time t is calculated from the following failure rate function expressed by Eq.(1):

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

where m and η represent a shape parameter and scale parameter of the failure rate function. These parameters are $m > 0$ and $\eta > 0$.

The Weibull distribution can depict all the failure rate functions of the decreasing-failure-rate (DFR), constant-failure-rate (CFR), and IFR periods of the bathtub curve depending on the shape parameter. If shape parameter m is given as $0 < m \leq 1$, the failure rate function corresponds to the DFR and CFR periods. In the DFR period with $m < 1$, the root cause of a defect is contained in a robot at the time of manufacturing. In the CFR period with $m = 1$, a probability density function of robot failures corresponds to an exponential distribution and the failures occur regardless of time as expressed by $h(t) = \lambda$, where λ is a reciprocal of mean time between failures. Hence, while failed robots undergo CM, PM has no effect in these periods. Since this paper focuses on both PM and CM, these two periods are not discussed.

When the shape parameter is given as $1 < m$, the failure rate function of robots corresponds to the curve of the IFR period. Scale parameter η defines a time scale; hence, the shape of the function is allowed to be elongated and expanded in conjunction with the scale parameter. Given mean time between failures (MTBF) of all the robots derivable from statistics on the robot failures, three parameters, m, η, and $MTBF$ are expressed by Eq.(2).

$$MTBF = \eta \Gamma \left(\frac{1}{m} + 1 \right) \tag{2}$$

In this equation, $\Gamma(1/m+1)$ denotes the gamma function that we can obtain by giving the shape parameter under conditions of $1 < m$. 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.(2) when shape parameter m and MTBF are given. Through the procedure, the failure rate of a robot at time t, $h(t)$, is calculated from Eq.(1) at each simulation step. Following this failure rate, robots incidentally fail.

C. Optimal Maintenance Strategy

Intervals of PM affect system performance. In conducting maintenance for robots, we have to carefully consider the problem. Therefore, we propose the optimal maintenance strategy that enables the following maintenance.

1) Working robots are allowed to undergo PM at optimal intervals.
2) A failed robot is allowed to undergo CM in each case.

The effect of maintenance is reflected in a failure rate. The failure rate of a working robot after PM is reset to zero (i.e., $h(t) = 0$). For a failed robot, in the same way, the failure rate is reset to zero, $h(t) = 0$ after CM. **Fig.1** illustrates that a failure rate of a robot kept at low level. The shape parameter is given as $m = 2$.

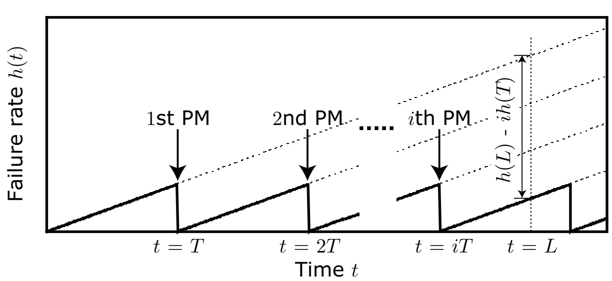


Fig. 1. Effect of PM on Failure Rate of Robot ($m = 2$)

If a robot does not undergo PM, its failure rate increases following Eq.(1) as depicted by dashed lines and is sometimes reset to zero because of CM. On the other hand, the robot failure rate is reset to zero at intervals, T, by undergoing PM. This is the effect of maintenance in the IFR period. Thus, ith PM conducted at intervals of T reduces the failure rate of $h(L)$ at time $t = L$ by $ih(L)$.

The optimal maintenance strategy determines the intervals of PM on the basis of availability. In reliability engineering, availability is a function of time, which is defined as the amount of time a robot is actually working as the percentage of total time it should be working. In other words, availability is a criterion that quantifies robustness combining the following two probabilities: a working robot does not fail until it undergoes PM and a failed robot is repaired within a time frame because of CM. Therefore, higher availability represents that a robot fully works even though it undergoes maintenance.

Qualitatively, availability approaches a certain value in the seas of time (i.e., $t \to \infty$). In a system in which only CM is conducted for failed robots, availability of a robot is uniquely derived from the following eigenvalue: $MTBF/(MTBF+MTTR)$, where $MTTR$ represents the mean time to repair. This corresponds to the duty cycle. On the other hand, in a system in which PM is conducted for working robots in addition to CM, availability of a robot is generalized as expressed in Eq.(3) following the definition based on "{working time}/{total time}" described above.

$$A(T) = \frac{T}{T_c \int_0^T h(t)dt + T_p + T} \tag{3}$$

In this equation, T denotes the intervals of PM, i.e., time until a working robot undergoes PM without failing, and T_p and T_c are mean time spent for PM and CM. Thus, the denominator of the right side corresponds to the total time that a robot undergoes maintenance and works.

Since the probability density function on robot failures is assumed to follow the Weibull distribution with a shape parameter m a failure rate of the robot at time t, $h(t)$, is derivable from Eq.(1). Hence, from Eq.(1) and Eq.(3), availability of a robot in the IFR period, when PM is conducted at intervals of T, is calculated by Eq.(4).

$$A(T) = \frac{T}{T_c \left(\frac{T}{\eta}\right)^m + T_p + T} \tag{4}$$

Therefore, the optimal interval, T, that maximizes availability is given as a solution to a partial differential equation expressed by Eq.(5).

$$\frac{\partial A(T)}{\partial T} = \frac{T_c \left(\frac{T}{\eta}\right)^m + T_p + T - T\left(\frac{T_c m}{\eta^m} T^{m-1} + 1\right)}{\left\{T_c \left(\frac{T}{\eta}\right)^m + T_p + T\right\}^2} = 0 \tag{5}$$

Eq.(5) is replaced by T as expressed by Eq.(6). Hence, this is the optimal interval for conducting PM. As can be seen in Eq.(6), note that T becomes infeasible or infinite ($T = \infty$) and PM has no effect under the DFR ($m < 1$) or CFR ($m = 1$) period.

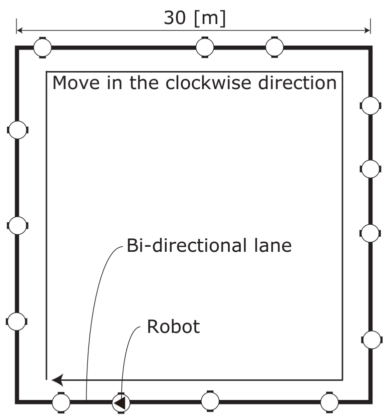
$$T = \eta \left\{ \frac{T_p}{T_c(m-1)} \right\}^{1/m} \tag{6}$$

From Eq.(6), working robots are allowed to undergo PM at optimal intervals of T following the proposed maintenance strategy. In addition, a robot that failed at time t depending on the failure rate calculated by Eq.(1) is allowed to undergo CM in each case.

IV. SIMULATION EXPERIMENT

A. Simulation Settings

1) Multi-robot system: **Fig.2(a)** shows the robots system that consists of a cyclic layout structure. 1 to 20 wheeled robot(s) is/are used in this system. The optimal maintenance is conducted for the robots that move around the lane in the clockwise direction for 500 times. Traveling time is regarded as the system performance.



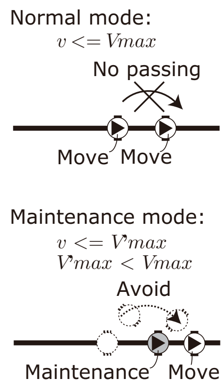


Fig. 2. Simulation Condition

Dias *et al.* have demonstrated the efficacy of removing and repairing a failed robot and inserting it again afterward [8]. On the other hand, since we assume the completely parallel system with fault tolerance, the robots stop and undergo maintenance on site.

2) Robot coordination: **Fig.2(b)** shows the robot behavior model. Although the robots are not allowed to pass the preceding one, they move fast in the normal mode if no robot undergoes maintenance. In the maintenance mode, while the robots have to move slowly, they are allowed to avoid the preceding one undergoing maintenance. This coordination enables the robots to ensure fault tolerance of the system. The maximum velocity of the robots, V_{max} and V'_{max}, is 2.1 [m/s] in the normal mode and 0.3 [m/s] in the maintenance mode.

3) Parameters: As for two parameters required to calculate a failure rate, the mean time between failures is given as $MTBF = 8$ [h] according to the result of [1]. The shape parameter of the Weibull distribution associated with robot failures is given as $1 < m$. An increasing tendency of the failure rate in the IFR period varies widely depending on the shape parameter. For this reason, three shape parameters are given as $m = 2$, $m = 5$, and $m = 10$. A failure rate with the shape parameter of $m = 2$ increases linearly with time. In other cases, it increases exponentially with shape parameters more than 2, $m > 2$. The initial failure rate of each robot is randomly given. Time taken for PM, T_p, is 500 [s] ($\simeq 0.139$ [h]) and CM, T_c, is 1500 [s] (0.417 [h]).

B. Optimal and Other Two Maintenance Strategies

From Eq.(6) and other related parameters given in IV-A.3, the optimal intervals of PM are determined as $T = 18762$ [s] ($m = 2$), $T = 19082$ [s] ($m = 5$), and $T = 21772$ [s] ($m = 10$). Therefore, the optimal maintenance strategy allows the robots to undergo PM when their accumulated working time at t is 18762, 19082, and 21772, according to each shape parameter.

In this simulation experiment, other two maintenance strategies, that conduct PM at empirically-determined intervals, are applied. Strategies 1 and 2 determine short and long intervals, i.e., $T = 10000$ and 50000 [s], so as to conduct frequent and infrequent PM. Although the intervals of PM vary with the strategies, time spent for PM is given as $T_p = 500$ [s] regardless of the strategies. For failed robots, three strategies conduct the same CM with the same time $T_c = 1500$ [s].

C. Experimental Results

1) Ideal system: **Fig.3** shows the traveling time of all the robots and its throughput in an ideal system. In this system, robots never fail even if they do not undergo PM; thus, they do not undergo CM.

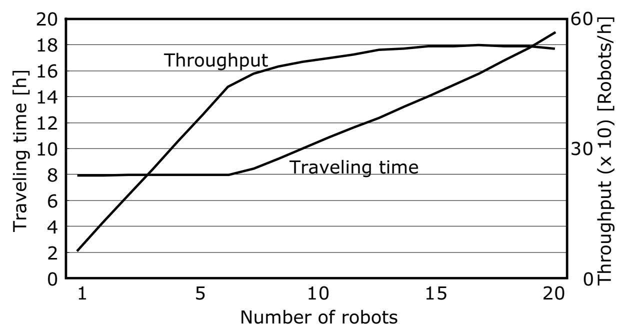
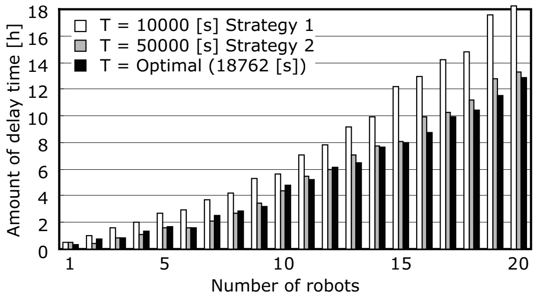


Fig. 3. Simulation Result of Ideal System

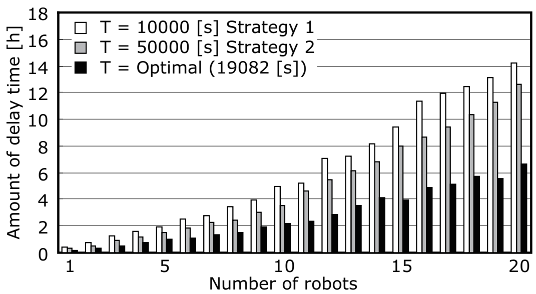
Since the ideal system was in the normal mode all the time, the robots were enabled to move fast. In the crowd system with robots more than 8, they reduced velocity, and this resulted in longer traveling time. On the other hand, the throughput increased in the system with robots up to 15. For more robots than 15, it remained on the same level. This result indicates that the performance of the fault-tolerant system, in which maintenance is not required and notable jams do not take place, increases with the number of robots.

The highest fault tolerance ensured in the ideal system is hereafter used as a criterion of the effectiveness of each maintenance strategy for the performance of the actual system in which robots fail and undergo maintenance.

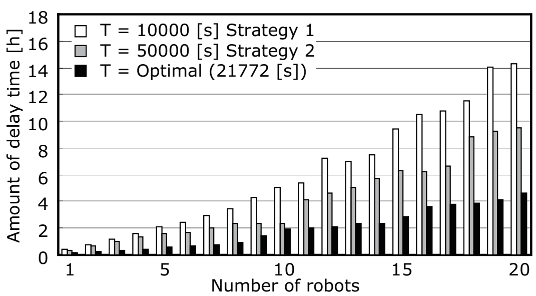
2) Effectiveness of maintenance strategies: **Fig.4** shows the results of three maintenance strategies depending on each shape parameter m. Each bar for the number of robots indicates the amount of delay time with strategy 1 (white),



(a) $m = 2$



(b) $m = 5$



(c) $m = 10$

Fig. 4. Comparison of Delay Time (Degraded System Performance)

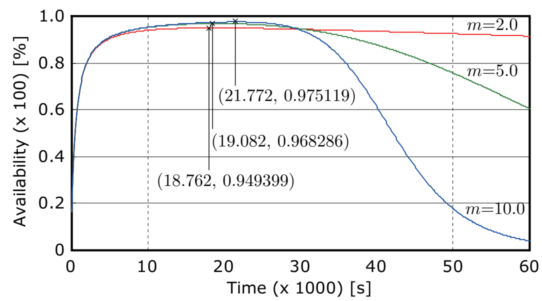
strategy 2 (gray), and optimal (black), as compared to the traveling time of the ideal system shown in **Fig.3**.

These maintenance strategies resulted in the different delay time. Furthermore, the gap increased with the shape parameter. It is noticeable that the delay time in **Fig.4(a)** with robots more than 13 and those in **Fig.4(b)** and **Fig.4(c)** were relatively least with the optimal maintenance strategy. In addition, while the other strategies, 1 and 2, increased the delay time with the number of robots, the optimal maintenance strategy minimized the increment up to 6 [h] in **Fig.4(b)** and 4 [h] in **Fig.4(c)**. This result shows that higher fault tolerance was ensured as the number of robots was increased; moreover, the optimal maintenance strategy and shape parameter of $m = 10$ resulted in the highest system performance.

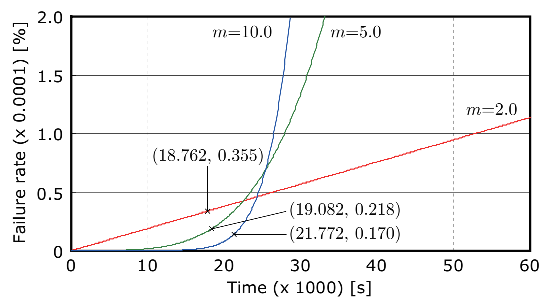
D. Result Analysis Based on Shape Parameters

From the result in IV-C.2, it is obvious that a maintenance strategy and shape parameter m affected the system performance. In other words, compared to the result of $m = 2$ shown in **Fig.4(a)** where the failure rates of robots in the IFR period increased linearly, the difference in the performance between the maintenance strategies became clearer when the shape parameters were given as $m = 5$ and $m = 10$ and the failure rates increased exponentially as shown in **Fig.4(b)** and **Fig.4(c)**. Therefore, we analyze the result focusing on availability and failure rate based on the shape parameters.

Fig.5 depicts availability and failure rate curves based on the three shape parameters. Availability and failure rate when PM was conducted at the optimal intervals, T_{Opt}, are marked by $\times$. These values when the other two maintenance strategies conducted PM at intervals of $T_{10000} = 10000$ [s] and $T_{50000} = 50000$ [s] are indicated by points at the intersection of each curve with dashed lines. All the detailed values are listed in **Table I**. In this table, Opt represents $T_{Opt} = 18762$, 19082, and 21772 [s] depending on $m = 2$, 5, and 10.



(a) Availability Curves



(b) Failure Rate Curves

Fig. 5. Availability and Failure Rate Based on Shape Parameters

From the result shown in **Fig.5(a)**, we can see that the optimal maintenance strategy resulted in the highest availability, $A_m(T_{Opt})$, on each curve. A magnitude relation of availability for each shape parameter was as follows: $A_{m=10}(T_{Opt}) > A_{m=5}(T_{Opt}) > A_{m=2}(T_{Opt})$. Therefore, as shown in **Fig.4**, the optimal maintenance strategy maintained the highest performance and the effectiveness increased as the shape parameter was incremented.

From the result shown in **Fig.5(b)**, we can see that the difference in failure rates between T_{10000}, T_{50000}, and T_{Opt} on each curve based on the shape parameter of $m = 2$ was the smallest, i.e., $h_{m=2}(T_{10000}) < h_{m=2}(T_{Opt}) < h_{m=2}(T_{50000})$. On the other hand, since the failure rates increased exponentially when $m = 5$ and $m = 10$ were given, the difference in failure rates between the maintenance strategies extremely widened, i.e., $h_{m=5,10}(T_{10000}) \ll h_{m=5,10}(T_{Opt}) \ll h_{m=5,10}(T_{50000})$. This denotes that the intervals of PM based on the maintenance strategies greatly

TABLE I

AVAILABILITY AND FAILURE RATE FOR THREE SHAPE PARAMETERS AND MAINTENANCE INTERVALS

		$A_m(T)$					$h_m(t)$		
			T [s]					$t = T$ [s]	
		10000	50000	Opt			10000	50000	Opt
	2	0.93967	0.925054	0.949399		2	1.89×10^{-5}	9.47×10^{-5}	3.55×10^{-5}
m	5	0.951933	0.758288	0.968286	m	5	1.67×10^{-6}	1.03×10^{-3}	2.18×10^{-5}
	10	0.952379	0.180436	0.975119		10	1.55×10^{-8}	3.02×10^{-2}	1.70×10^{-5}

affected the system performance as the shape parameter was incremented. For your information, a failure rate function depicts a logarithmic curve if the shape parameter is given as $1 < m < 2$. In this case, although a robot state is in the IFR period at the beginning, the failure rate is approximated by the CFR period during the passage of time. Eventually, the effect of PM is even further reduced.

Outside the optimal interval, availabilities of the two maintenance strategies, 1 and 2, were $A_m(T_{10000}) > A_m(T_{50000})$ regardless of the shape parameter. This indicates the effectiveness of strategy 1 that conducted PM at intervals of 10000 [s] compared to strategy 2. In **Fig.4**, however, strategy 2 resulted in higher system performance. This is because the mean time between failures of robots was given as $MTBF = 8$ [h] $= 28800$ [s]. As a result, since the interval of PM conducted by strategy 2 was 50000 [s], almost all the robots failed before PM and underwent CM only. Note that availabilities when $T_{28800} = 28800$ [s] were $A_{m=2}(T_{28800}) = 0.944941$, $A_{m=5}(T_{28800}) = 0.95116$, and $A_{m=10}(T_{28800}) = 0.953297$. These were almost the same values as the $A_m(T_{10000})$ or more as shown in **Table I**.

V. ROBOTS UNDERGOING MAINTENANCE

A. Average Number of Robots Undergoing Maintenance

As shown in **Fig.4**, the number of robots used in the system also affected the performance. In fact, even for the same maintenance strategy and shape parameter, delay time increased and the system performance was degraded as the number of robots was increased. To discuss the result in terms of the mathematical aspect, we focus on the average number of robots undergoing maintenance derivable from the number of robots, interval of PM, and failure rate.

Given a system with N robots, intervals of PM, T, and failure rate, $h(t)$, the average number of robots undergoing maintenance at time t is expressed by $\sum_{n \in N}\{1/T_n + h_n(t)\}$. $\sum 1/T$ and $\sum h(t)$ represent the average number of robots undergoing PM and CM, respectively. Hence, let the number of robots in two systems be I and J and $I < J$, the average number of robots undergoing maintenance at time t in the systems are $\sum_{i \in I}\{1/T_i + h_i(t)\} < \sum_{j \in J}\{1/T_j + h_j(t)\}$, provided that each robot in both systems has the same MTBF and the same maintenance strategy is applied. The intervals of PM are thus $T_i = T_j$.

This relationship indicates that the number of robots undergoing maintenance increases in a system with many robots. Eventually, while fault tolerance is ensured, the robots often have to move slowly because of maintenance and this degrades the performance. From the mathematical discussion, it is obvious that the interval of PM T and failure rate $h(t)$ depend on a maintenance strategy, and thus, the number of robots undergoing maintenance is dominated by the strategy in addition to the number of robots used in the system. For the reason discussed above, the three maintenance strategies resulted in the different performance degradation as shown in **Fig.4**.

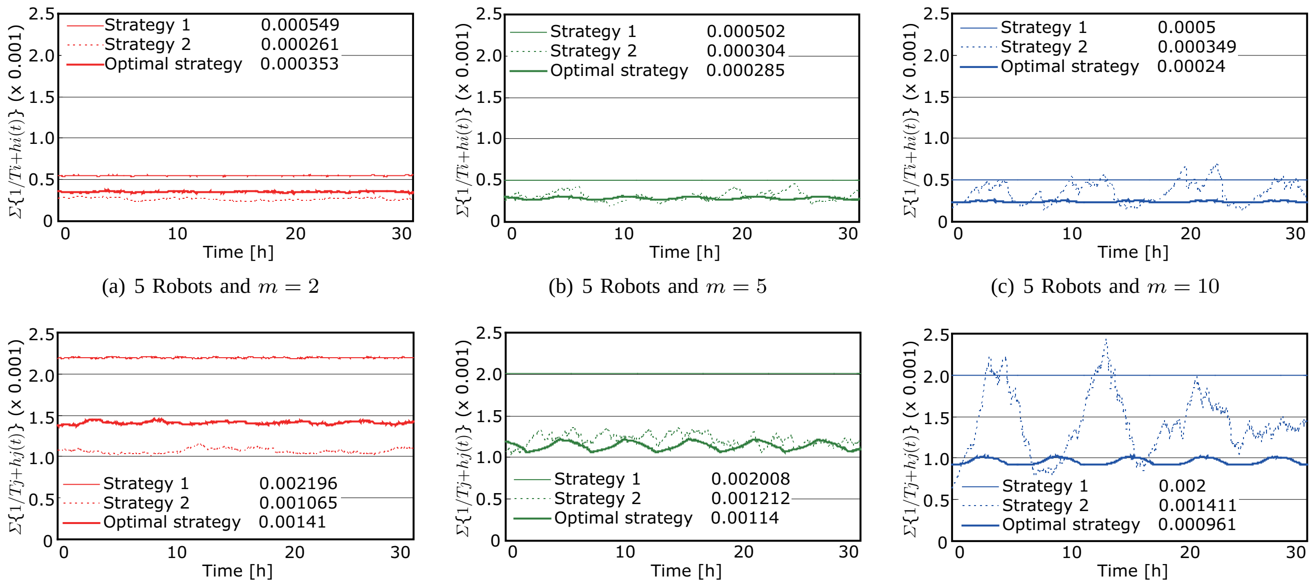
B. Influence of Robots Undergoing Maintenance

The three maintenance strategies were applied to the systems with 5 robots ($I = 5$) and 20 robots ($J = 20$). **Fig.6** shows transitions of the average number of robots undergoing maintenance in each shape parameter. In addition, mean values of the transitions during the 30 hours are listed beside the name of each strategy.

As for the average number of robots undergoing maintenance based on the maintenance strategy, whereas the difference in the system with fewer robots, i.e., $I = 5$ was small, it was increased in the system with many robots, i.e., $J = 20$ for the same shape parameter. Furthermore, maintenance strategy 1 resulted in the most robots undergoing maintenance regardless of the shape parameter.

As shown in **Fig.5**, the influence of maintenance on availability and failure rate increased as the shape parameter was incremented. For this reason, although the optimal maintenance was conducted, it yielded more robots that underwent maintenance compared to the result of maintenance strategy 2, as shown in **Fig.6(a)** and **Fig.6(d)** for $m = 2$. For $m = 5$, in contrast, the average number of robots that underwent maintenance with the optimal strategy was below the result of strategy 2 as shown in **Fig.6(b)** and **Fig.6(e)**; and for $m = 10$ shown in **Fig.6(c)** and **Fig.6(f)**, the optimal maintenance strategy further reduced the average number of robots that underwent maintenance, and the gap resulting from the other strategies, 1 and 2, was definitely widened.

Another reason for the result of $m = 2$ shown in **Fig.6(a)** and **Fig.6(d)** is time required for PM and CM given as $T_p = 500$ [s] and $T_c = 1500$ [s]. While maintenance strategy 2 conducted little PM and only failed robots that underwent CM were added to the average number of robots undergoing maintenance, the optimal maintenance strategy conducted PM at the intervals that were determined so as to minimize the influence from the robots stopped for maintenance in consideration of each time cost for PM and CM. As a result, the optimal maintenance strategy minimized the total stop time of the robots if the difference in average number of robots undergoing maintenance between the strategies was small and the ratio of the robots undergoing PM was relatively high. In **Fig.4(a)**, since the ratio was clearly increased



(a) 5 Robots and $m = 2$ (b) 5 Robots and $m = 5$ (c) 5 Robots and $m = 10$

(d) 20 Robots and $m = 2$ (e) 20 Robots and $m = 5$ (f) 20 Robots and $m = 10$

Fig. 6. Transitions of Average Number of Robots Undergoing Maintenance with Maintenance Strategies

with the number of robots in comparison to the system with fewer robots, the optimal maintenance strategy resulted in the highest performance as the number of robots was increased.

Therefore, the system with fewer robots degraded the performance slightly and yielded less difference in the average number of robots undergoing maintenance between the strategies. In contrast, the average number of robots undergoing maintenance was increased and the difference between the strategies was widened in the system with many robots. In this regard, the optimal maintenance strategy successfully minimized the performance degradation of the system. From the result, it was finally shown that fault tolerance was ensured as the number of robots was increased in the completely parallel system and the optimal maintenance strategy maintained the highest performance.

VI. CONCLUSIONS

This paper focused on the effectiveness of maintenance in fault-tolerant multi-robot systems. For a completely parallel system, we proposed an optimal maintenance strategy so as to ensure fault tolerance and maintain high performance taking robot failures and maintenance into account. By applying the strategy to the system, robots were allowed to undergo PM at optimal intervals and CM each time they failed. Through simulation experiments with three shape parameters, the effectiveness of the optimal maintenance strategy was shown. In addition, the influence of robots undergoing maintenance on the system performance was mathematically and experimentally discussed on the basis of the number of robots and maintenance strategies.

In conclusion, regarding the maintenance strategies in the fault-tolerant multi-robot system, the results from the simulation experiments revealed the following matters:

- when a failure rate increased logarithmically or linearly for the shape parameter given as $1 < m \leq 2$, the difference in the effectiveness between the optimal maintenance strategy and another strategy 2 that conducted CM only (including infrequent PM) was small;
- when a failure rate increased exponentially for the shape parameter given as $2 < m$, the optimal maintenance strategy resulted in the highest system performance and the difference in the effectiveness between the maintenance strategies was definitely widened; and
- while the performance degradation of the system with many robots is more serious than that with fewer robots, fault tolerance of the completely parallel system was ensured as the number of robots was increased and the optimal maintenance strategy successfully maintained the highest performance.

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