Optimal Fault-Tolerant Multi-Robot Team Design Using Robot Reliability

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***Abstract*—This paper presents an optimal multi-robot team design using robot reliability for satisfying desired probability of mission completion in fault system. Previous studies in this area mainly described a quantitative analysis, but an analytic solution for optimal multi-robot team organization was not presented. The proposed method, however, suggests not only a quantitative analysis but also provides necessary information for optimal team organization. In addition, an algorithmic solution is also provided for the optimal multi-robot team design when a faulty robot occurs. Simulated experiments are presented for verifying the proposed method, which proves the efficiency of the method.**

***Index Terms*—reliability, multi-robot, fault-tolerant system reliability function**

I. Introduction

Reliability is a critical issue in real robot applications. Robots are not reliable if we cannot guarantee fixed probability of mission completion. We cannot apply the robot system to important missions, such as planetary rover mission or disposal of waste matter, if a faulty robot unexpectedly occurs. Thus, an expected multi-robot system considering the probability of mission completion and faulty robot is necessary for robust team operation.

There, however, are rare previous studies on robot reliability. Carlson *et al.* presented the reliability analysis of mobile robots using collected failure data [1]. They examined practical data from 15 robots representing 3 manufacturers and 7 models. They calculated diverse metrics concerned with reliability analysis using measured data, such as mean time between failures (MTBF), mean time to repairs (MTTR) and availability. Stancliff *et al.* presented quantitative methods and precise language for measuring the mobile robot reliabilities [2]. They adopted a reliability concept from reliability engineering, and applied the concept to mobile robots. The mean time to failure (MTTF) was introduced and the extension of the MTTF for operating conditions was described in their paper. Some researchers conducted diverse simulations using the MTTF. Asikin *et al.* showed planetary robot missions with a fixed budget [3], [4]. The planetary mission was divided into several missions and they simulated optimizing the probability of mission completion with fixed cost. Stancliff *et al.* also presented a planetary exploration mission and they concluded that larger teams of less reliable robots are better than smaller teams of more reliable robots [5]. A quantitative analysis was used for optimal team design and cost reduction.

Other researchers have concerned the situation when a faulty robot occurs. Bereton *et al.* compared repairable robots team with non-repairable robots team [6]. They proved the efficiency of repairable robot teams. Kannan *et al.* also showed quantifying fault tolerant multi-robot team [7]. They presented a new evaluation metric to measure fault-tolerant system. A fault tolerant system could be identified using the metric.

In this paper, we present an optimal fault-tolerant team design technique using robot reliability. This paper is based on our previous studies [8], [9], and we present detailed analysis by applying to the multiple mission scenarios. The minimum number of robots is calculated in limited conditions, such as predetermined reliability and desired probability of mission completion. Also, we present an optimal fault-tolerant system by considering a faulty robot. We can calculate the optimal number of robots whenever periodic or aperiodic faulty robot occurs.

Section II presents terminologies of this research. Section III describes mission scenarios for applying to the proposed method. Section IV and V present optimal multi-robot team design methods using reliability and repairable robots. Simulation results are shown in Section VI and conclusions are described in Section VII.

II. Terminologies

A. Reliability

Reliability is the performance index that a system operates normally in a given time [2]. In other words, the reliability function $R(t)$ shows the probability that the system works well while time t without failure. Generally, the reliability function is known as bellowed equation in reliability engineering:

$$R(t) = e^{\left(-\int_0^t \lambda(t)dt\right)} \tag{1}$$

where $\lambda(t)$ is hazard rate at t. The hazard rate is acquired by *bathtub curve* which describes the life cycle of mechanical device, as shown in Fig. 1 [10].

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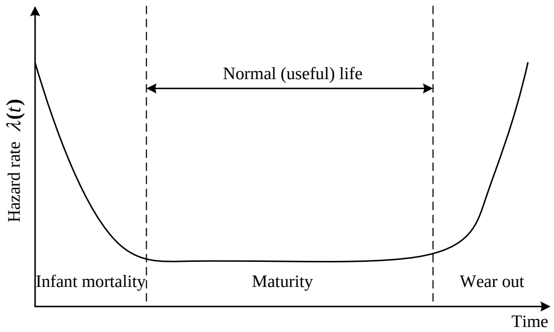

Figure 1. Bathtub curve description [10]. A mechanical device has a constant hazard rate in the normal (or useful) life.

According to the bathtub curve, we can regard the hazard rate as a constant value because the hazard rate is unchanged in normal (or useful) life. Thus, (1) is rewritten as:

$$R(t) = e^{-\lambda t} \tag{2}$$

where λ is constant hazard rate.

The reliability function $R(t)$ can be described another expression using unreliability function $F(t)$:

$$R(t) = 1 - F(t) \tag{3}$$

B. Mean Time to Failure

Mean time to failure (MTTF) is average time until a system failure occurs. The MTTF can be described using reliability function (2):

$$MTTF = \int_0^\infty R(t)dt = \int_0^\infty e^{-\lambda t}dt = \frac{1}{\lambda} \tag{4}$$

The relation between MTTF and reliability is given using (2) and (4):

$$R(t) = e^{\frac{-t}{MTTF}} \tag{5}$$

In general, the hazard rates are provided by mechanical device manufacturer. Thus, the MTTF is calculated by (4), and the reliability function $R(t)$ is acquired by (5).

C. Probability of Mission Completion

The probability of mission completion (PoMC) is a probability that a system execute a specific mission successfully. The PoMC is related to the reliability function but slightly difference. The reliability function $R(t)$ is measured at a specific time t, but the PoMC is the general term of completion probability about a specific mission. Thus, the PoMC is one of primary performance indices to evaluate the system.

D. Combining Reliability Functions

In general, each device has a unique reliability function. Thus, the PoMC is acquired by the combination of reliability functions. There are two types of combination methods: *series* and *parallel*.

- Series combination: All modules should be operational for successful mission execution in the series combination. If one of modules has a trouble, the mission is failed. Thus, the series combination of reliability functions $R_s(t)$ is described as:

$$R_s(t) = \prod_{i=1}^{N} R_i(t) \tag{6}$$

where N is the number of modules and $R_i(t)$ is the reliability function of i^{th} module at time t. In addition, total hazard rate of series combination λ_s is calculated by adding each hazard rate of modules:

$$\lambda_s = \sum_{i=1}^{N} \lambda_i \tag{7}$$

- Parallel combination: The mission is completed if at least one module is operational in the parallel combination. In other words, the mission fails when all modules have faults. Thus, the unreliability function $F_p(t)$ of parallel combination is given as:

$$F_p(t) = \prod_{i=1}^{N} F_i(t) \tag{8}$$

And the reliability function $R_p(t)$ of parallel combination is given as:

$$R_p(t) = 1 - F_p(t) = 1 - \prod_{i=1}^{N} \left(1 - R_i(t)\right) \tag{9}$$

Equation (9) is rewritten as (10) when all hazard rates are identical ($\lambda_1 = \lambda_2 = \cdots = \lambda_N$):

$$R_p(t) = 1 - (1 - e^{-\lambda t})^N \tag{10}$$

III. Mission Scenarios and Reliability Analysis

A. Three Mission Scenarios

We choose three mission scenarios for verifying the proposed optimal multi-robot system design and analysis: cleaning, target capturing and fire extinguishing. Each scenario executes different work as follows.

- Cleaning: Multiple cleaning robots clean up a specific region.
- Target capturing: Multiple patrol robots surround an invader.
- Fire extinguishing: Fire extinguisher robots put out the fire.

The three missions need different modules because each mission has different objectives. In addition, each module has different MTTFs because the components of module are not identical. We determine the MTTFs and the usages of modules by referring [11], as shown in Table I and Table II. The usages of modules are different according to the mission scenarios and the usages are measured by durations of use with respect to total usage.

TABLE I. MTTFs OF MODULES (HOURS)

Module	MTTF	Module	MTTF
Power	4202	Extinguisher	8554
Camera	4769	Fire Hose	12931
Heat sensor	3481	Manipulator	13793
Mobility	19724	Vacuum Cleaner	9461
Communication	11876		

TABLE II. USAGE OF MODULES (%)

Module	Cleaning		Target Capturing		Fire Extinguishing	
	Covering	Collecting Trash	Patrol	Capturing	Patrol	Extinguisher
Power	100	100	100	100	100	100
Camera	100	100	100	100	100	50
Heat sensor	0	0	0	0	0	100
Mobility	100	60	100	80	100	60
Communication	25	25	25	80	25	80
Vacuum Cleaner	100	50	0	0	0	0
Extinguisher	0	0	0	0	0	50
Fire Hose	0	0	0	0	0	50
Manipulator	0	50	0	0	0	0

B. Reliability Analysis of Missions

We can calculate the reliabilities of modules for each mission using (5), as shown in Table III. In (5), the reliability of unused module is 100% because the module usage is zero ($t = 0$). In other words, the reliability of 100% is meaningless and impossible in a real system.

Total reliability of the mission, i.e., PoMC, is acquired by combining the reliabilities of component modules. The combination method follows series connection because total system will be non-operational if one of modules is broken down.

Fig. 2 shows the PoMC of 3 mission scenarios for 1 robot. The mission duration indicates how many the mission is executed. The PoMC gradually decreases as mission duration increases because the reliabilities of modules are not 100%.

IV. OPTIMAL MULTI-ROBOT TEAM DESIGN FOR USING THE MINIMUM NUMBER OF ROBOTS

A system designer should be mainly concerned to satisfy the desired PoMC for an optimal multi-robot team design. A successful mission execution is the most important objective of the multi-robot team. If the desired PoMC is satisfied, applying the minimum number of robots becomes a crucial issue. The less the number of robots is used, the more an economic benefit occurs. Thus, we present an optimal multi-robot team design method for using the minimum robots when the desired PoMC is guaranteed.

The mission will be completed if at least 1 robot of multi-robot team executes the mission successfully. This means that the multi-robot team consists of the parallel combination of robots, and thus, the PoMC is given as follows using (10):

$$\mathrm{PoMC} = 1 - (1 - e^{-\lambda t})^{M} \tag{11}$$

TABLE III. RELIABILITIES OF MODULES (%)

Module	Cleaning		Target Capturing		Fire Extinguishing	
	Covering	Collecting Trash	Patrol	Capturing	Patrol	Extinguisher
Power	99.88	99.88	99.88	99.88	99.88	99.88
Camera	99.89	99.89	99.89	99.89	99.89	99.94
Heat sensor	100	100	100	100	100	99.85
Mobility	99.97	99.98	99.97	99.98	99.97	99.98
Communication	99.99	99.99	99.98	99.96	99.98	99.96
Vacuum Cleaner	99.95	99.97	100	100	100	100
Extinguisher	100	100	100	100	100	99.97
Fire Hose	100	100	100	100	100	99.98
Manipulator	100	99.98	100	100	100	100
Total	99.39		99.46		99.35	

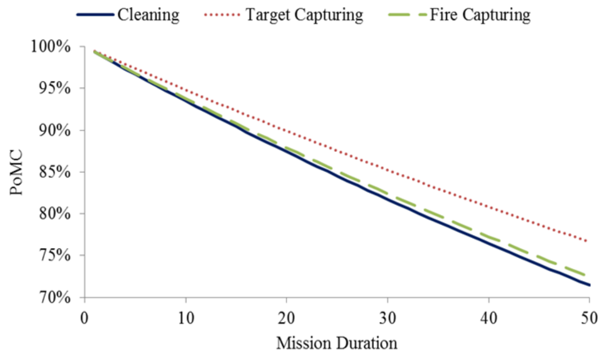

Figure 2. The PoMCs of 3 mission scenarios for 1 robot.

where M is the number of robots. The first constraint is given as bellows because the PoMC should be satisfied the desired PoMC:

$$\mathrm{PoMC} \geq \mathrm{PoMC}_{desired} \tag{12}$$

where $\mathrm{PoMC}_{desired}$ is the desired PoMC. Thus, an inequality with respect to the number of robots is derived from (11) and (12):

$$\mathrm{M} \geq \log_{1-e^{-\lambda t}}(1\text{-}\mathrm{PoMC}_{desired}) \tag{13}$$

From (13), we are able to calculate the minimum number of robots if the mission duration and the desired PoMC are provided. Fig. 3 shows the graph of the minimum number of robots with respect to the mission duration t and the $\mathrm{PoMC}_{desired}$. In this graph, we assumed that the reliability of single robot is 99.35 % for applying the fire extinguishing mission. The required number of robots increases as the mission duration and the desired PoMC increase. More robots need in higher PoMC than lower PoMC for satisfying the desired PoMC.

In addition, we describe the PoMC graphs for 3 missions by changing the number of robots, as shown in Fig. 4. The PoMC dramatically decreases if the less number of robots is used. If the mission duration and the reliabilities of robots are preliminary known to the system designer, we can calculate the minimum number of robots for guaranteeing the desired PoMC. For example, we expect more than 99% PoMC until 75 mission durations using 5 robots for all missions.

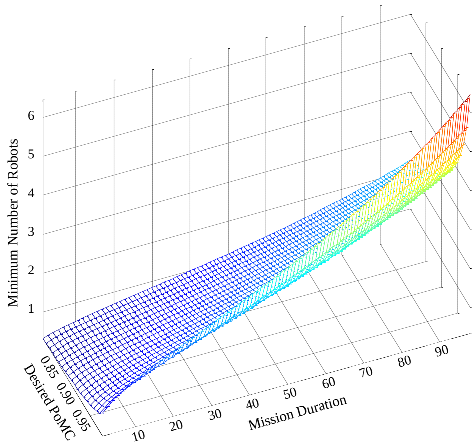

Figure 3. The minimum number of robots with respect to the mission duration and the desired PoMC.

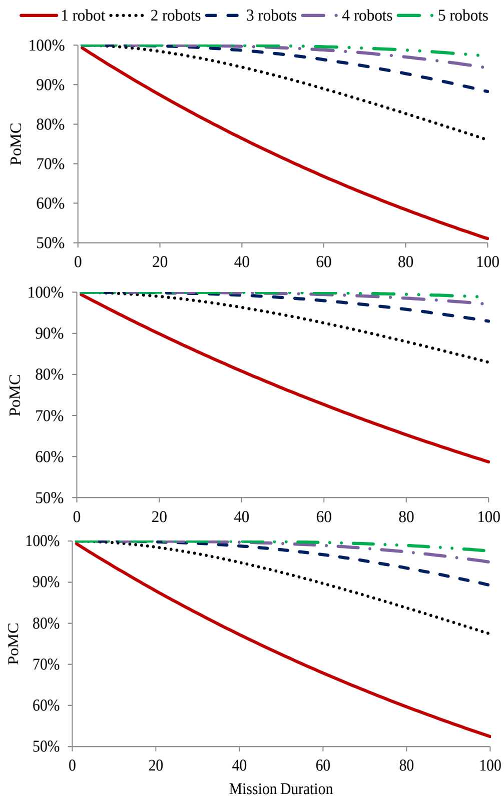

Figure 4. The PoMC graphs for diverse number of robots. (up) Cleaning (middle) Target capturing (down) Fire extinguishing

V. Optimal Multi-Robot Team Design for Fault Tolerance

We calculated the minimum number of robots for accomplishing the desired PoMC in the previous section. There, however, is a possibility that a robot has a trouble in the real system, which makes the system degrade performance. We, therefore, present an optimal multi-robot team design for fault-tolerant system in this section. The faults are divided into two categories: *periodic fault*, *aperiodic* (*or random*) *fault*. The periodic fault is mainly led to the deterioration of module. The robot is broken down if a certain time is passed because each module has a unique MTTF. The aperiodic fault is caused by external shock or unexpected error.

A. Periodic Fault System

We assumed that if a robot has failure, the robot is repaired by user and is reassigned to the mission after repairing. The PoMC has a regular period and should not descend below a specific value for guaranteeing constant PoMC. A system designer expects the periodic change of PoMC and designs the optimal multi-robot team.

We have two assumptions for designing periodic fault-tolerant system. First, all robots have identical normal operational time t_{normal}, fault time t_{fault} and recovery time $t_{recovery}$. A robot operates normally during the normal operational time t_{normal}. The fault time t_{fault} is the duration that the robot cannot execute the mission because the robot has a fault. The faulty robot is repaired in the recovery time $t_{recovery}$. These assumptions involve that the system has a periodic fault and recovery, which makes the PoMC changed periodically. Second, a faulty robot exists in a specific time. In other words, we consider only one faulty robot for designing the fault-tolerant system. In reality, it has a possibility that multiple faulty robots can exist. This, however, is a rare situation in the periodic fault system. We leave a future work that multiple robots have faults in the random fault system.

The necessary number of robots in the periodic fault system is calculated by following process:

- Periodic time T_p :

$$T_p = t_{normal} + t_{fault} + t_{recovery} \tag{14}$$

- The minimum $\text{PoMC}_{\min}$:

$$\text{PoMC}_{\min} = 1-(1-R^{(M-1)T_p})\times(1-R^{(M-2)T_p})\times\cdots\times(1-R^{T_p}) \tag{15}$$

- The constraint for minimum number of robots:

$$\text{PoMC}_{\min} = 1-\prod_{i=1}^{M-1}(1-R^{(M-i)T_p}) \geq \text{PoMC}_{desired} \tag{16}$$

In (16), the $\text{PoMC}_{\min}$ is the minimum PoMC during mission duration. The $\text{PoMC}_{\min}$ is only affected by the number of robots M because periodic time T_p is a constant in the periodic system. Therefore, we are able to examine whether the constraint is satisfied or not by substituting diverse number of robots. Among them, the minimum number is the optimal solution in the periodic fault system.

B. Aperiodic Fault System

We assumed that periodic time T_p is a constant in the periodic fault system, which enables us to expect a fault. In real system, however, we cannot only expect the time to failure but the failure also arise irregularly. Therefore, the multi-robot team design method is necessary when a fault occurs randomly for accomplishing the desired PoMC.

We assumed that the PoMC of the aperiodic fault system is evaluated when all robots are operational because we cannot expect time to failure. In extreme case, there is no method to satisfy the desired PoMC when the all robots have failure. Thus, it is reasonable to evaluate the PoMC when all robots are normal.

In addition, if all robots are always operational without failure, the system cannot achieve the desired PoMC because the PoMC gradually decreases by mission duration. For preventing this case, we assumed that the oldest robot is out of order when all robots are normal and the system does not satisfy the desired PoMC. Thus, the oldest robot is repaired and reassigned the mission when it is impossible to achieve the desired PoMC.

```
for t ← 1 to total mission duration
begin
  if state = fault                          : More than one robot has a fault
  begin
    PoMC(t) ← 1 − ∏_{j=1}^{M} [1 − R(idx(j))] / (1 − R(fault(idx)))   : PoMC calculation
    for k ← 1 to M                          : The increase of robot indices
    begin                                     except the faulty robot
      if k ≠ fault(idx)
      begin
        idx(k) ← idx(k) + 1
      endif
    endfor
      if recovery is completed              : Recovery completed
      begin
        idx(fault(idx)) ← 1
        state ← operational
      endif
  endif
  else if state = operational               : All robots are operational
  begin
    PoMC(t) ← 1 − ∏_{j=1}^{M} [1 − R(idx(j))]   : PoMC calculation
    for k ← 1 to M                          : The increase of robot indices
    begin
      idx(k) ← idx(k) + 1
    endfor
    if PoMC(t) ≤ PoMC_desired               : Constraint check
    begin
      PoMC(t) ← 1 − ∏_{j=1}^{M} [1 − R(idx(j))] / (1 − R(arg max(idx)))
      state ← fault
    endif
  endif
endfor
```

Figure 5. The pseudo algorithm of PoMC calculation in the aperiodic (random) fault system

Fig. 5 shows the pseudo algorithm of PoMC calculation when a fault occurs randomly. The *state* indicates whether more than one robot has a fault or not. The $idx(j)$ is the usage of j^{th} robot and has increased one by mission duration. The function $fault(\cdot)$ is the index of faulty robot. The algorithm consists of two major cases as follows:

- A fault occurs: If the faulty robot occurs, the PoMC is calculated except the faulty robot. The usage of the faulty robot is initialized and the state is changed to operational when the faulty robot is repaired.
- All robots are operational: If all robots are operational, the PoMC is calculated by combining the reliabilities of all robots. The oldest robot is regarded as a faulty robot when the PoMC is not satisfied the desired PoMC.

VI. SIMULATIONS

We conducted on simulations in different constraints for verifying the proposed optimal multi-robot team design method. We decided the mission scenario as the fire extinguishing and the reliability of a robot is 99.35%. We assumed that the faulty robot is repaired immediately from the fault time: $t_{fault} = 0$. In addition, we determined the repairing time is 5 mission duration because the repairing time is not affected other robots and environmental information: $t_{recovery} = 5$. The normal operational time is different to the periodic or the aperiodic fault system. The detailed environmental information is presented in the Table IV.

TABLE IV. ENVIRONMENTAL INFORMATION IN THE PERIODIC / APERIODIC FAULT-TOLERANT SYSTEM

Mission duration	100 / 200 step
Initial reliability	0.9935 (cleaning mission)
Fault time (t_{fault})	0 / 0
Recovery time ($t_{recovery}$)	5 / 5
Interval between faults	23, 37, 50, 65 / 3~20 step (random)
The number of faults	7 / 16
Desired PoMC	0.95

The periodic and aperiodic fault systems are classified by forward slash (/).

A. Periodic Fault System

In the periodic fault system, the PoMC is affected by normal operational time t_{normal}. We, therefore, have simulated in the diverse condition by changing normal operational time. Fig. 6 shows the PoMC graphs according to the number of robots in the periodic fault system. If a fault occurs in the multi-robot team, the PoMC sharply decreases. However, the faulty robot was reassigned the mission after repairing time, which enables the PoMC to be recovered. The variation between the highest PoMC and the lowest PoMC was smaller in case of many robots because operational robots can cover a part of the faulty robot. In addition, the small normal operational time led to the sharp growing down of PoMC. The minimum PoMC was 99.8% and the standard deviation was 0.0004% in 5 robots case ($t_{normal} = 65$).

The minimum PoMCs were calculated by changing the number of robots from Fig. 6. Fig. 7 shows the minimum PoMCs according to the number of robots. As the number of robots increased, the minimum PoMC increased. The increase range, however, decreased when many robots are applied to the mission. It is due to that many robots are not effective for raising the PoMC in the high PoMCs. In addition, the minimum PoMC was not exceeded to the initial reliability of robot.

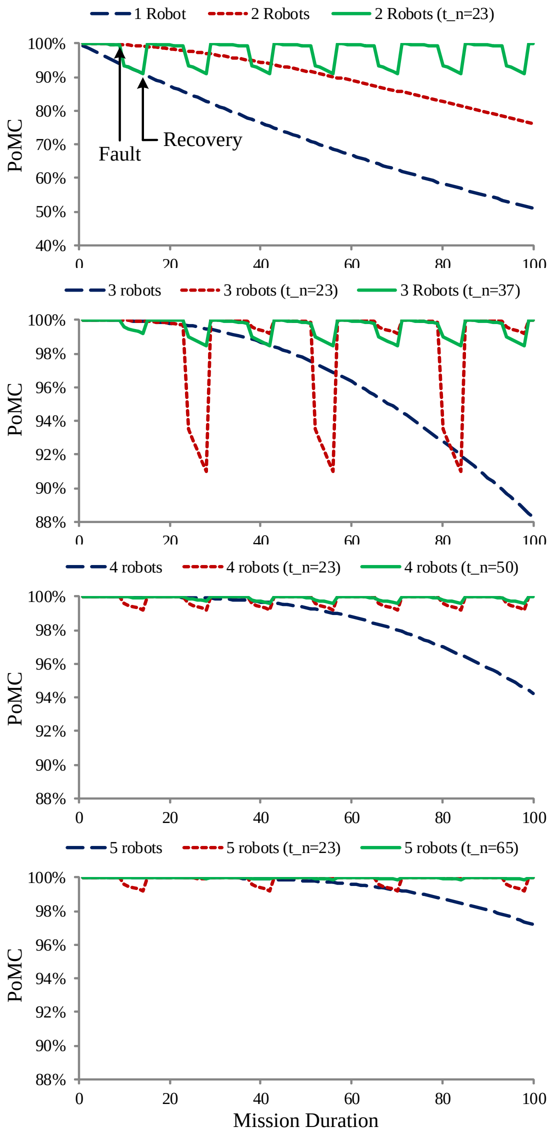

Figure 6. The PoMC graphs according to the number of robots in the periodic fault system. The value of t_n indicates t_n in the graph.

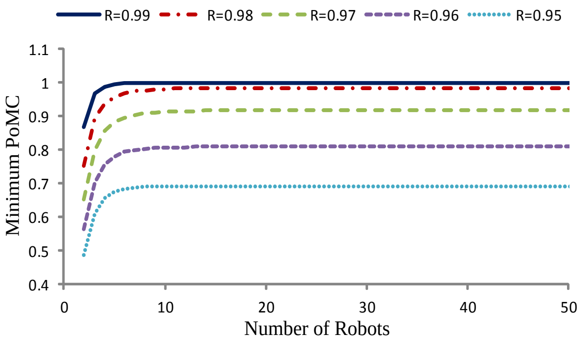

Figure 7. The minimum PoMC graph by changing the number of robots in the periodic fault system.

B. *Aperiodic Fault System*

In the aperiodic fault system, a fault occurs randomly. Thus, we assumed the interval between the faults is from 3 to 20 durations in the simulation.

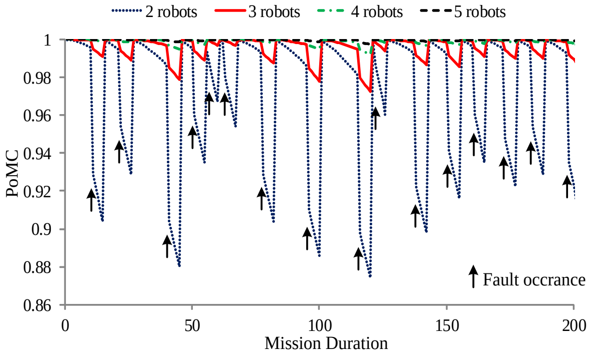

Figure 8. The PoMC graph by changing the number of robots in the aperiodic fault system.

Fig. 8 shows the PoMC variation according to the number of robots in the aperiodic fault system. Applying to the mission using 1 robot is meaningless because the PoMC is 0% if a fault occurs. Thus, we did not concern 1 robot case. The minimum PoMC was 87.42 % when 2 robots are used for mission completion, which means that it ensures at least 87.42 % success rate whenever a fault occurs. Likewise, the minimum and the maximum PoMCs were calculated in the graph. Total results are presented in Table V.

TABLE V. THE RESULTS OF POMC IN APERIODIC FAULT SYSTEM

	1 robot	2 robots	3 robots	4 robots	5 robots
Minimum PoMC	0	0.8742	0.9710	0.9914	0.9972
Maximum PoMC	0.9933	0.9999	1.0000	1.0000	1.0000
Standard deviation	0.4864	0.0359	0.0059	0.0014	0.0004

The value of 1.0000 does not mean 100% PoMC in Table V, which is lead to rounding off. The more robots are used, the more the minimum and the maximum PoMCs increase as we expect. In addition, standard deviation decreased as many robots are used, which implies the system is more robust to a fault.

VII. CONCLUSIONS

This paper presents an optimal fault-tolerant multi-robot team design method based on robot reliability. A system designer is able to expect the probability of mission completion using robot reliabilities. In addition, we can design optimal multi-robot system when periodic or aperiodic fault occurs. Although a faulty robot exists, the system can be operated normally with the desired PoMC. The proposed method can be applied to the various fields of multiple robots, e.g., industrial robots, manufacture robots and cleaning robots system.

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