Improving Recovery Capability of Multiple Robots in Different Scale Structure Assembly

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Abstract

This paper investigates the recovery capability in the distribution control of the multiple robots which may be broken through the simulation of space solar power satellite assembly with changing its scale. For this purpose, we conduct simulations with changing the failure rate of robots that employ our proposed deadlock avoidance method. Through the intensive simulations, we have revealed that (1) the recovery capability of our proposed method is revealed because the upward tendency of our method as increasing of number of robots and (2) the tendency changes when the ratio of broken robots is under 30%, which does not depend on the scale of the SSPS or the number of robots. From these findings, the recovery capability of our method is high without depending on the scale of SSPS so that the cooperation between robots works well in the robots broken case.

1 Introduction

Although the large-scale structure assembly by multiple robots has been much attention on in the space development, it includes the significant problem that the robots may be broken during the assembly. Such problem becomes serious when its scale becomes larger because the broken robots may be increased, due to a lot of movements which causes the deadlock situation where a lot of broken robots obstruct the movement of other robots and disturb the assembly. From this fact, it is required to propose the multi-robot control method which can complete the assembly task with solving the deadlock situation even when the robots are broken.

Regarding the multi-robot control with solving the deadlock problem, several methods are proposed, e.g., the Duhaut’s deadlock avoidance method in multi-agent system [6], the Arai’s collision avoidance method [1]. However, these methods do not consider the robots broken case. To solve this problem, our previous research proposed the multi-robots control method where two robots that have different roles move together as on one set and change their roles between robots [3], and verify its effectiveness through the simulation on the space solar power satellite (called SSPS [2]) assembly as one of the space large-scale structure with including the robots broken case [4]. However, our previous research verified the effectiveness of this method in only one scale structure assembly simulation.

From such background, this paper aims at (1) revealing the recovery capability of robots, i.e., the capability that the robots complete the SSPS assembly when some of robots are broken and (2) investigating the robustness of the proposed method to the different scale structure assembly in the environment where the robots may be broken. Concretely, we address the issue that the recovery capability of the robots through the change of the number of robots and the scale of SSPS (i.e., small, medium, and large SSPSs) to reveal the increase of recovery rate which indicates the rate of the number of completed assembly in the case that some robots are broken.

For such purpose, this paper applies our deadlock avoidance method for the environment in which the robots may be broken and verify the effectiveness of the method with changing the scale of the SSPS. Concretely, this paper aims the following achievements: (1) to reveal the recovery capability of our method which is the completion count in the failure case from the viewpoint of the recovery rate (i.e., the rate of completing a task when some of robots are broken) and maximizes the assembly in the robots broken case; and (2) to reveal the change of the recovery capability in our deadlock avoidance method when the number of robots change.

This paper is organized as follows. In the next section, we describe SSPS as an example of the large-scale structure. We describe our proposed deadlock avoidance method in Section 3 and the intensive simulations in which the robots may be broken in Section 4, and discuss the recovery capability of our deadlock avoidance method in Section 5. Finally, our conclusions are given in Section 6.
2 Space Solar Power Satellite (SSPS)

2.1 Overview of SSPS

SSPS is the power generation satellite as an alternative approach of thermal or nuclear powers, and generates electric power by sunlight on the satellite orbit of the earth. The left and right of Figure 1 show one of the model of SSPS and its simplified model that is required to simulate the SSPS assembly, respectively. In right of Figure 1, each hexagon indicates the SSPS panel module which will be explained in next subsection. To generate the same quantity of the power of a nuclear power plant, SSPS should be very large-scale structure, which size is planned to be several kilometers in length, i.e., over a hundred robots are needed to assemble SSPS with over ten thousands modules. Several research laboratories institution such as NASA, JAXA, and USEF have proposed a variety of SSPS concepts (e.g., NASA Reference System [5]).

2.2 SSPS Panel Module

According to [7], SSPS is composed of the hexagon panel modules as shown the left figure in Figure 2. This module is based on the inflatable tensegrity and its membrane is filled by the solar cell. This module inflates and stiffens once the robots deploy it. In right figure in Figure 2, the diamond and square objects indicate the robot with two arms and the panel module. This figure shows that two robots carry one module with their arms. The details of these robots will be explained.

Its diameter is planned to be 4 meters when the module is not deployed and about 20 meters when the module is deployed.

2.3 SSPS Assembling Robot

Since the robots which assemble the SSPS should be lightweight to transport maximum robots by rockets, the hardware function should be minimum mechanism. From the restriction that robot is planned to have only two arms as shown in the right of Figure 2, i.e., the two robots are able to have only one module. In this figure, two robots hold a panel module with their one side arms, and move on the frame of the panels by their another side arms. In this framework, two types of functions at the robots are assumed in this paper to assemble SSPS, i.e., the deployment and connection functions.

Concretely, the robot using the former function carries a module and deploys it, while the robot using the latter function connects unconnected modules to already constructed modules. Note that the deployment robot must keep to hold the deployed panel until the connection robot connects it. Figure 3 shows how the robots assemble the SSPS with their functions. In this figure, the light grey diamond, dark grey diamond, and hexagon indicate the deployment robot, connection robot, and solar panel module, respectively. This figure shows that (1) the deployment robot deploys the module which
he has; (2) the connection robot finds the unconnected module; then (3) the connection robot connects the modules.

In our research, we regard the central panel module as the *dock* in which the many robots and modules are stored as shown in the right side of Figure 5. The robots come from this dock in order and fetch the new module if they have no module.

### 2.4 Deadlock Problem

In the SSPS assembly with distributed control of the multiple robots, it is serious problem that the robots get into the deadlock situation where the robots cannot move by other robots. When the deadlock situation occurs, the robots cannot continue to assemble SSPS. In the related research, Duhant approached the deadlock avoidance among multiple robots [6], which is based on the environment in which the robots can pass each other by using passable spaces. However, the deadlock situations in the large-scale structures are very hard to be avoided because of the following limitations: (1) the limitation of a movement space of the robots, *i.e.*, the robots usually do not have enough space to avoid other robots on the large-scale structures because the robots can only move on the frame of the large-scale structures; (2) the limitation of a function of the robot, *i.e.*, the space robot should be simple and lightweight because the complicated robots are easy to be broken, which suggests that the robots should not have extra hardware functions like the structure relay transportation [10] to get out of the deadlock situations (*i.e.*, the robots hand over modules to other robots like the bucket brigade relay); and (3) the limitation of a communication among the robots, *i.e.*, the robots usually have no precise location information of the other robots because they cannot acquire the global information due to the large scale of the structures.

### 3 Leader-Follower Algorithm

#### 3.1 Leader and Follower

From the structure of the robots shown in the right of Figure 2, we consider the pair of two robots that hold a module with their one side arms and move with their another side arms. The advantage of this cooperation is to check whether either of the pair robots become broken each other. However, this cooperation cannot always succeed to avoid the deadlock situation described in Section 1 which obstructs the SSPS assembly.

To overcome this problem, our previous research proposed the approach where two robots with different roles move together as one set and exchange their roles between them to get out of deadlock situations [otani08]. The roles assigned to the robots are called *Leader* and *Follower* which based on [8]. In the cooperation, the leader robot decides their destination which they are going deploy the panel next, while the follower robot follows the leader robot and connects unconnected modules. When the distance between the leader and

![Figure 4 Deadlock Avoidance by Leader-Follower Exchange](image-url)
follower robots becomes larger, the faster robot makes its speed slow down to adjust to the slower robot, i.e., they move together with the same speeds.

3.2 Leader-Follower Exchange Method

Figure 4 shows how robots employ our proposed deadlock avoidance method exchange the roles of the robots when they get into the deadlock situations. Note that all marks shown in this figure have the same meaning of the previous figures, i.e., the leader robot (the light gray diamond) and the connection robot (the dark gray diamond) are one set, and they move toward the destination (the double circle). In detail, this figure shows that (1) when the leader and follower robots get into the deadlock situation, (2) they exchange their roles to get out it; (3) since the destination is located at the opposite direction, (4) they take one step (note that each robot can conduct one movement in one step) movement. However, the destination is still located at opposite direction and thus (5) they take one more step movement, which makes it the destination at the right direction. This method contributes to both reducing the movement cost and increasing the possibility of getting out deadlock situations.

What should be noted here is that this method keeps the role of robots two steps from getting out of the deadlock situation. If the robots do not keep two steps, they exchange their roles again when they take one step and return to get into deadlock situations.

3.3 Asymmetric Movement

Our deadlock avoidance method employs the additional rule that enables robots to get out the exceptional deadlock situation in which the robots move symmetrically shown in Figure 5. In this figure, (1) when the directions of two robot teams conflict each other, (2) both robots move the vacant space. However, (3) the confliction of two teams occurs again due to the symmetric structure. Since such repeated movements interrupt the SSPS assembly, the additional rule of our deadlock avoidance method forces the robots to move asymmetrically by giving the priority on their movement to left direction shown in Figure 2. Note that all marks shown in this figure have the same meaning of the previous figures. This figure shows that (1) the robot teams 1 and 2 become obstacles each other and move to the other direction where no robots exists; but (2) when the destination of each team is located at the opposite direction, (3) the robot team 2 located at the left side exchanges their roles, while the robot team 1 located at the right side keeps their roles and goes ahead; then (4) each team moves toward their goal by passing each other.

3.4 Demand Map and Destination Decision

Figure 7 shows the complete and demand maps that each robot has (the latter is based on the potential map in [9]). The left side of Figure 7 shows the final shape of SSPS that the robots have to assemble. In this figure, the white hexagon indicates the module that should be assembled, while the gray hexagon indicates the dock (i.e., the central module). The right side of Figure 7, on the other hand shows demand map where the gray/white hexagons and gray diamond indicate the already connected/unconnected modules and robot, respectively. For example, the grey modules with the number of 3 indicate that three modules should be deployed at the location, while the white modules with the no number
indicate that the modules have not yet deployed. When
the demand map of the robots becomes to be the same as
the complete map, the robots recognize that the SSPS
assembly is completed.

One SSPS assembly is regarded as completed when
all the robots recognize the completion of assembly and
come back to the dock.

4 Simulation

4.1 Experimental Design

To investigate the recovery capability and the robustness for the scale of our proposed method, we
conduct the SSPS assembly simulations with following setting.

Table 1 shows the each simulation case which
corresponds to each scale of SSPS, the number of panels
which should be assembled, and the maximum number
of robots which is enough to assemble, i.e., over this
number of robots is not required to assemble because
usually the assembly is already finished when the over
the number of robots go out from the central dock. We
employ the robots from four (two couple of two robots)
bodies to maximum number of bodies. In each number of
robots, we calculate the average values from the results
of 100 simulations. For example, Case 1 indicates the
assembly simulation in the small scale SSPS in which the
number of panels and maximum number of robots are 19
and 16, respectively. In all cases, we set the numbers of
panels and maximum numbers of robots as the ratios
between them are the same, i.e., the ratio of Case 1
(48/61) nearly equal the ratio of Case 2 (30/37).

<table>
<thead>
<tr>
<th>Table 1 Simulation Cases</th>
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<tr>
<td>Scale</td>
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<td>Panels</td>
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<td>Max robots</td>
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Regarding the failure rate of the robots, each robot
becomes broken in the rate just after taking one behavior.

We conduct simulations with changing the failure rate
with changing the range of the failure rate as the average
ratio of the number of broken robots to the total number
of robots becomes from about 10% to 40%. We also
change the interval of the failure rate as the scale change
(i.e., we set the intervals as 0.10%, 0.05%, and 0.025%
in the Case 1, 2, and 3, respectively) because the difference of the failure rates becomes larger when the
scale of SSPS becomes larger, i.e., we should change the
resolution of the failure rate according to the scale of
SSPS.

We mainly investigate the recovery rate which
indicates the rate of the completed assembly including
the failure robots in 100 simulations since this rate
indicate the recovery capability of our deadlock
avoidance method in the failure case, i.e., it shows how
many failure cases our method can recovers.

The behaviour of the robot is defined as follows:

- Movement from a vertex of the module to the next
  vertex.
- One panel module deployment
- One panel module connection
- Role exchange between the leader and follower
  robots

The robots can take one behavior among these
behaviors in one step. However, some period of time is
required to complete one behavior. The time required for
each behavior depends on the speed of each robot.
Concretely, the speed of movement is determined by the
normal distribution function in which the average is 0.8v
and the standard deviation is 0.2v (i.e., v is defined as the
speed to complete one behavior in a unit time of the
simulation), the speeds of deployment and connection
are determined by the normal distribution function in
which the average is 0.4v and the standard deviation is
0.1v, and the speed of role exchange is 1.0v. We give the
robots to such different speeds because the movement
and deployment/connection speeds are usually different
in real world. Furthermore, the value of 0.8v indicates
the practical value when we regard the 1.0v as the
maximum speed of the robots (i.e., it indicates the
possible speed for robots).

4.2 Evaluation Criterion

We evaluate the simulation results on the criterion of
recovery rate which is the rate of completed trials with
some broken robots. For example, in the case that the
total number of trials is 100, total number of trials with
some broken robots is 80, and the number of completed
trial with some broken robots is 42, the recovery rate is
calculated to 52.5%. If this rate is high, the robots
can complete to assemble SSPS with the high probability even in the failure case.
4.3 Simulation Result 1: Recovery Rate

Figures 8, 9, and 10 show the results of recovery rate in the Case 1, 2, and 3, respectively. The horizontal and vertical axes in each figure indicate the number of robots and the recovery rate, respectively. Each line in each figure indicates the polynomial approximation which corresponding each result of the recovery rate. In these figure, the thicker line indicate the lower failure rate.

In each figure, we can find the tendency change of the recovery rate as the failure rate. For example, in Figure 9, the recovery rate is constantly high when the failure rate is under 0.15% while the recovery rate makes curves which depend on the number of robots when the failure rate is over 0.20%. In Figure 8 and 10, the failure rate of tendency change is between 0.30% and 0.40%, and between 0.125% and 0.150%.

5 Discussion

5.1 Discussion 1: Increase of Recovery Rate

In generally, the number of robots becomes higher, the recovery rate of deadlock avoidance method would be down as shown in Figure 11 because the number of broken robots increases as the total number of robots increases. However, this result shows the increase of recovery rate. This fact reveals the recovery ability of our method in robots broken case.

5.2 Discussion 2: Tendency Difference

To analyze the details of the tendency difference between low and high failure rates, we investigate the failure rates. Concretely, we compare the ratio of broken robots as shown in Figures 12, 13, and 14. The horizontal and vertical axes in each figure indicate the number of robots and the average ratio of broken robots.

From this result, the average ratio of broken robots is almost under 0.3 when under the failure rate on each tendency change ratio. Since our method keeps constantly high recovery ability when the failure rate is under the tendency change line, it may be regarded that the 30% ratio of broken robots as the border ratio of broken robots to keep high recovery ability of our
method. These tendency change ratio does not depend on the number of robots and the scale of SSPS.

These results suggest that the cooperation of the robots works well because the recovery rate increases although the ratio of broken robots is constant. In addition, we can calculate the rough estimation of the failure rate to keep the recovery ability of our method. For example, the failure rate which is required to keep high recovery rate is 0.00034% when the number of panels is 10000.

6 Conclusions

This paper focused on the recovery capability of the deadlock avoidance method and investigated it in the several scale of the large-scale structure assembly task in which the multiple robots may be broken. Intensive simulations have revealed that the following implications: (1) the recovery capability of our deadlock avoidance method is revealed because its upward tendency as increasing of number of robots; (2) the tendency changes when the ratio of broken robots is 30%, which does not depend on the scale of the SSPS or the number of robots. These findings derive that our deadlock avoidance method is able to assemble SSPS in different scale of SSPS when the ratio of broken number of robots is under 30%.

For future challenges, the following issues should be tackled in the near future: (a) the theoretical approach of the recovery rate; (b) revealing the exact number of robots in the failure case; and (b) analyzing the case that panels are also broken.

References


