Modular Structure Assembly Using Blackboard Path Planning System

Yuzuru Terada
Tokyo Institute of Technology
Interdisciplinary Graduate School of Science and Engineering
P.Box G3-53, 4259 Nagatsuta, Midori, Yokohama, Kanagawa
string@mrt.dis.titech.ac.jp

Satoshi Murata
Tokyo Institute of Technology
Interdisciplinary Graduate School of Science and Engineering
P.Box G3-53, 4259 Nagatsuta, Midori, Yokohama, Kanagawa
murata@dis.titech.ac.jp

Abstract: Construction work should be simplified by introducing modularity into both structural components and means of assembly. Based on this idea, we have proposed a novel concept of fully automated construction system called Automatic Modular Assembly System (AMAS), which drastically reduces the difficulty of automated construction task. In this paper, we focus on distributed control method of the assembler robots. The area on which the assembler robots can move dynamically expand during the construction process. We introduce a gradient field to indicate the directions based on current map to the assembler robots. The structure modules generate the gradient field by using neighbor-to-neighbor communication. We assume large number of modules and robots; therefore we need to organize the motion paths of these robots to avoid collision among them. An algorithm which is based on blackboard algorithm allows robots to search their paths in the spatiotemporal space.

Keywords: Automatic Modular Assembly System (AMAS), Swarm Robotics, Gradient field, Distributed Autonomous Systems (DAS)

1. INTRODUCTION

The use of industrial robot is increasingly common in the modern world [1]. Robot system is necessary for cutting down the cost of labor as well as reducing the risk of injuries to human workers. Moreover, robots are capable of continuing of the operations 24 hours a day, providing much superior productivity compared to human laborers. Other than the assembly-line applications, the operations in hazardous or extreme environment, for example work performed in high place such as construction, should be considered ideal work for the robots.

Already there have been some cases where robots are actually utilized in construction. A typical example of such challenge is the unmanned construction of landslide prevention dam [2]. While remote controlled construction is the easiest way to avoid casualties in these scenes [3]-[5], many problems remains in its practical application. Construction works remote-controlled by human workers are usually very inefficient due to its communication delay and poor human interfaces. Moreover, large-scale construction involves many processes, where each process requiring many specific robots (or tools or machineries), which consequently makes this attempt virtually impractical cost performance-wise. Complete automatization of the construction is the technique which is truly desirable.

We think the problem lies in the complexity of construction processes. Construction work should be simplified by introducing modularity into both structural components and means of assembly. Based on this idea, we have proposed a cubic structure module as a building component, and a specially designed assembler robot to manipulate modules. This system, which is called Automatic Modular Assembly System (AMAS), drastically reduces the complexity of construction task [6].

In this paper, we focus on distributed control method of the assembler robots. During construction, structure modules are supplied at the supply area. The assembler robots pick up the modules at the area and carry them to the construction site. They shuttle back and forth between the module supply area and the construction site. We assume large number of modules and robots; therefore we need to organize the motion paths of these robots to avoid collisions among them. Werfel et. al. proposed a similar assembler robot system [7]. This system relies on a property of two-dimensional space, i.e. the robots search for a place to put a module only on the periphery of the structure. In contrast AMAS is basically designed for three dimensional constructions.

The surface on which the assembler robots operate dynamically expands during the construction process. In order to optimize the complex coordinated motion among the assembler robots on the changing field, we introduce a distributed algorithm based on a gradient field. The structure modules generate the gradient field by using neighbor-to-neighbor communication. the proposed method is very simple; the gradient indicates the direction of the assembler robots both when it is heading to the construction site and returning to the supply area. Incorporating some additional rules for the assembler robots, we can make a kind of self-organized flow on the construction field, and it enables collision-free and time-effective assembly.

2. AUTOMATIC MODULAR ASSEMBLY SYSTEM

AMAS is a system composed of standardized modules and assembler robots. All the modules have only one geometric form in principle (Fig.1).

In Fig. 2 AMAS is compared to other construction techniques. AMAS is more flexible than others in a sense that it can built various kinds of structure with general-purpose modules. Therefore it allows onsite design change according to the circumstances. On the other hand, a large number of modules are needed to build a structure for AMAS because it doesn't contain any specific components such as panels and frames. In other words, AMAS is a system which employs numerous robots to build a structure which is an aggregation of modules.

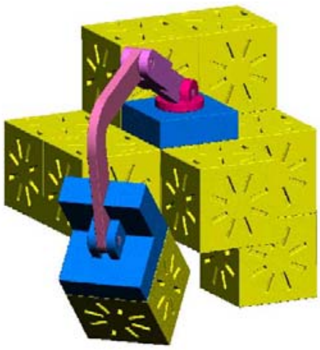


Fig. 1 Concept of AMAS

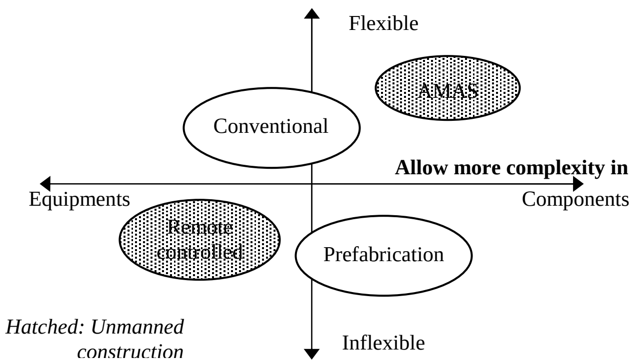


Fig. 2 Comparison of construction techniques

2.1. Structure Module

The proposed design of structure module in AMAS (Fig. 1) has two features that simplify the assembly process. First, every structure module is a regular hexahedron, used as a component of the modular structure (Fig. 3). Second, mechanical connector to fix the module is implemented on each surface of the module.

The connector, which is driven by an assembler robot described below, are genderless and rotation-symmetric to have complete modularity.

Built-in power transmission lines are connected automatically when the modules are assembled. Assembler robots use this power network. Structure modules have no actuators but they have a microprocessor and sensors for information processing.

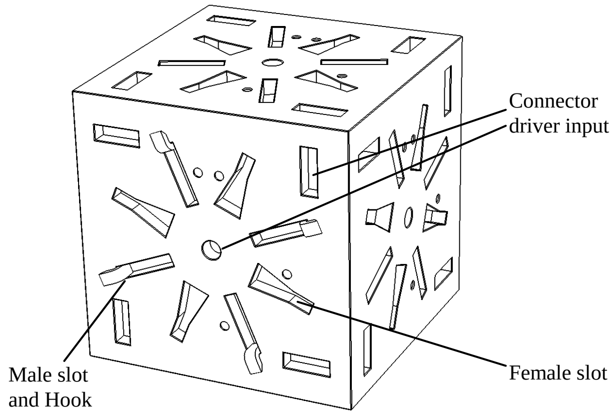


Fig. 3 Structure module

2.2. Assembler Robot

Another important component of AMAS is the assembler robot. The assembler robot can walk on the modules by using connector on their hands. The robot can carry a module with its hand (L shaped part). Because any modular structure made of this module can be described on a cubic grid, a finite set of motion patterns is sufficient to build any shape. We took advantage of this and simplified the assembler robot. Only four degrees of freedom is enough for locomotion and putting a module on arbitrary surface of the modules. This development reduced the complexity of the system, and therefore cutting the total cost and time for construction.

The assembler robot (Fig. 4) with four degrees of freedom can move on the structure using an inchworm motion, repeating connection and disconnection actions (Fig. 5). Rotation is also possible. Connectors and links are sufficiently strong to hold and support the robot's entire body. Therefore, it can climb a vertical wall and hang onto a ceiling. The assembler robot can construct nearly any structures by combining basic assembly actions [6].

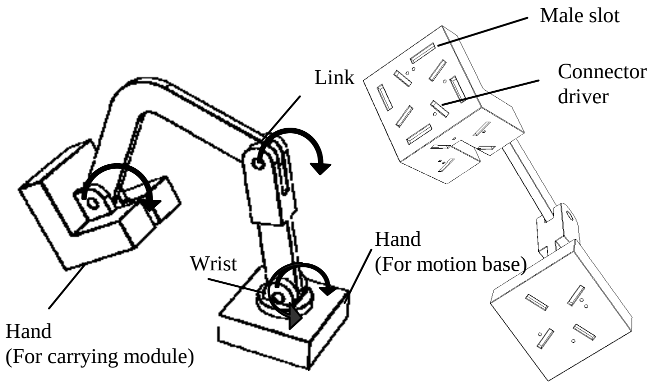


Fig. 4 Assembler robot

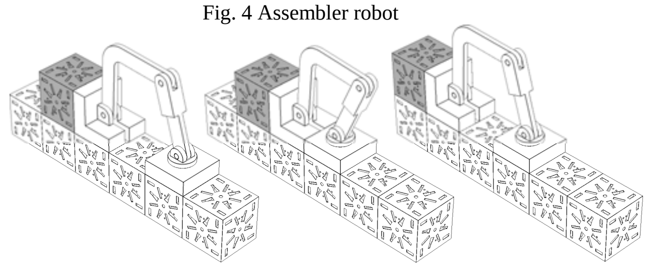


Fig. 5 Inchworm locomotion

2.3. Connection Mechanism

Connection mechanism among the modules is the most important component of AMAS, namely it is a combination of hook and hole. Each surface of the module is equipped with both hook and hole to maintain the genderless feature of the connection. The module itself does not contain any actuators to drive the mechanism, thus it is passive. Otherwise, the assembler robot drives the mechanism via a connector driver transmission.

3. ASSEMBLY TASK

In order to assemble a large-scale modular structure, concurrent construction is needed; in other words, we have to use a large number of robots. Our problem is multi-robot assembly planning. In AMAS, assembler robot can move only on the structure, meaning the working space for robots extend during assembling. And robots go back and force between the module supply area and the assembling area. The nature of this operation makes assembly planning difficult.

Mobile robot motion planning can be classified into two categories: centralized and distributed.

Centralized algorithm is usually used in off-line system. Because planning for multi robot is too hard to do real-time. It can search for optimal solution exhaustively but depends on assumption on pre-determined environment. Therefore these plans are not resistant to disturbances. Moreover, amount of calculation grows exponentially as the combination of robots grows exponentially.

More feasible way is using distributed on-line system. Both modules and robots have some degree of intelligence, and they cooperate to achieve the construction task through real-time and local information exchange. But distributed algorithm is unable to use global information such as motion paths of other robots. Robots know only local information and it sometimes causes deadlock. We propose a new algorithm, which utilizes a gradient field generated by the modules. The details are explained in the following sections.

3.1. Assembly Task: planer structure

In this paper, we only treat the assembly problem of planer (two-dimensional) structures. However, this does not mean restriction on the possible class of construction. The idea can be naturally extended to various shell structures in which the surface is composed of one layer of the module (Fig. 7). This type of shell structure is seen in most of large-scale structures. Panels made of modules with various shape assembles the shell structure. We consider various shapes of panels in this paper, and the shell structure can be regarded as a folded panel. Our assembler robot can overcome the ridge or valley.

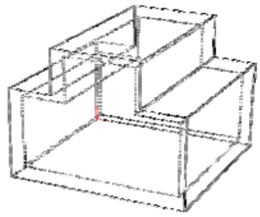


Fig. 7 Shell structure

Fig. 8 shows the typical task environment we consider hereafter. A belt conveyor at the bottom supplies structure modules to the assembler robots. We assume that the number of modules on the conveyor is sufficient so that the assembler robot can pick up a module at any time. After the robot picks up a module, it carries the module toward the growth front where the carried module will be placed and connected to the panel. Then it returns to the supply area. The robot shuttles back and forth between the supply area (conveyer) and the growth front until the modules occupy all the vacant grid points.

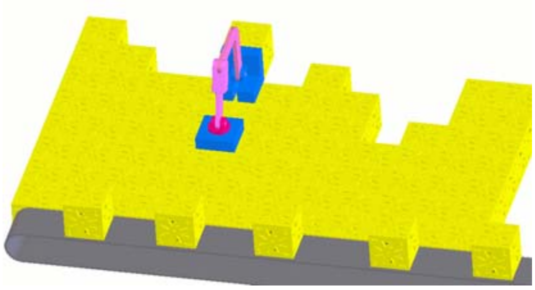


Fig. 8 Task environment

Here, we assume that both the robots and the modules are equipped with microprocessors and some contact sensors. These processors can exchange digital information when they are adjacent (local communication between modules or between a module and a robot). Namely, the planer lattice of the modules functions as an intelligent field, which is capable to simulate computational model such as a partial differential equation. An absolute coordinate system is defined on the lattice, and each module or robot can identify their coordinates by the communication. The desired shape of the panel is given a priori to both the robot and the structure modules. The modules can identify that they are at the growth front, when they are inside of the shape and their neighbor point is not occupied.

4. ALGORITHM BASED ON GRADIENT FIELD

We built a simulator to develop a distributed algorithm for assembly task. Fig. 9 shows the simulation model. The same size cube represents the robot for simplicity. (This may be over simplified, which affects collision rate.) The bottom row represents the module supply area. Yellow area represents the growth front.

In the simulation, each module or robot has its own location as a pair of integers. They have some internal states also represented by integers. They are able to access to the internal state of neighbor modules/robots by local communication. Robot can move onto the next module located on Up/Down/Right/Left according to its internal state. We assume discrete time series, and internal state of each module and robot is synchronously updated in a step.

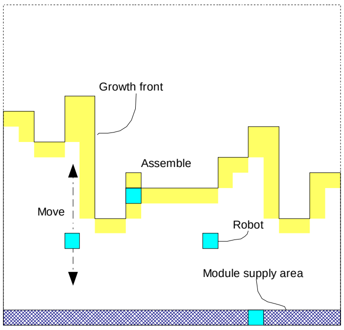


Fig. 9 Simulation model

4.1. Gradient Field

We assume that both structure modules and assembler robots are only able to communicate neighbor to neighbor. Based on such local communication, robots have to identify their location, location of growth front and module supply area. An idea using gradient field to guide robots to a destination is suggested in [8] The gradient field is generated by bucket-brigade process of the positional information. Robots can read the value of gradient, and they recognize which direction they should go to reach the destination. To generate the gradient field, we can use continuous value or discrete value.

A) Gradient field using continuous value

It is realized by the following diffusion equation:

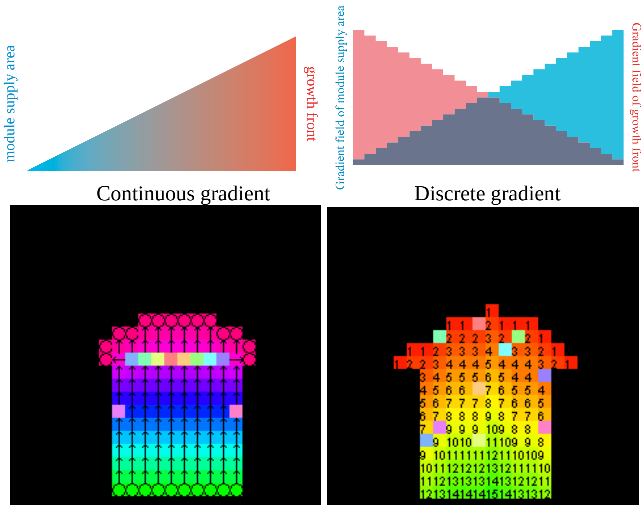
$$\frac{\partial P}{\partial t} = D\nabla^2 P \qquad (1)$$

Where P is neighbor's potential, D is diffusion coefficient. There are three kinds of boundary conditions for this system.

On the growth front, the potential value is fixed at constant high value. On the supply area, it is fixed at constant low value. They act as source and drain. Other kind of boundary appears at the edge of the panel, where desired shape is already assembled. On this edge, we assume no leakage of potential. Therefore no gradient appears along the completed edges. Generated path is not the shortest, but they are not crossed on the way. This character is useful to reduce the collision rate of the robots.

B) Gradient field using discrete value

To generate the field, the modules which are on the destination area should be of a fixed value. All the modules repeat this calculation that propagates the potential field (bucket-brigade process). The other modules read the value of four neighbors and the smallest plus one is set as its value. This value presents the Manhattan-Distance from the destination module. Therefore it represents the shortest path. Gradient field using discrete value can indicate only one destination area. Hence, our system has two destination areas; growth front and module supply area, thus we need two fields for each destination. (Fig. 10)



Continuous field Discrete field (of growth front)

Fig. 10 Continuous field and discrete field

4.2. Robot

The robots carrying a module should move to the growth front according to the gradient direction. While robots carrying no module should move to the module supply area. The robots can see only the nearest four neighbor modules and sometimes more than one robot tries to move onto the same module. Collision occurs in this situation. We use two methods to deal with collision.

A) Module relay method

This method is to reduce the loss caused by collisions. When a robot collides with another robot, the robot hands off the module to the other. This method is effective to improve the efficiency and preventing deadlock [9].

B) Blackboard planning method

This method prevents the collision only by using local communication. When a robot plans to move to a next module, the robot writes down the plan on the module. Other robot can read the plan before they move to the module. It means that they can know which module will be empty. This kind of method is called a black board system.

5. SIMULATION

The process executed in each robot time step is;

- Motion planning.
- Moves by the plan.
- Checking structure completion.
- Updating gradient field ten times (to accelerate the diffusion).

At the initial condition, only the module supply area exists and the assembler robots located on the area.

To evaluate the performance of methods, which is combination of two gradient fields and two collision handling, we use three target structures as benchmarks.

They are straight structure, T-shaped structure, and T-shaped structure (Fig. 11).

Lower bound of the assembly step can be calculated by sum of Manhattan distance of all of the modules.

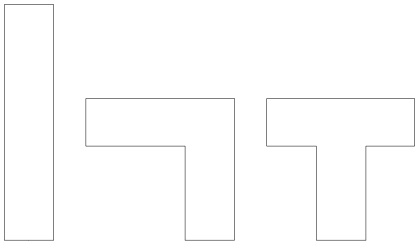


Fig. 11 Benchmark structures which made of 500 modules. Passageway's width is ten.

6. SIMULATION RESULTS

Total steps to complete the three kinds of structures are evaluated by the simulation. Total step is the step to complete the structure multiplied by the number of robot. It is the total amount of the working time steps. Therefore large value of total step shows low efficiency and small value indicates high efficiency. Lower bound of the assembly step based on Manhattan distance is shown as green dots.

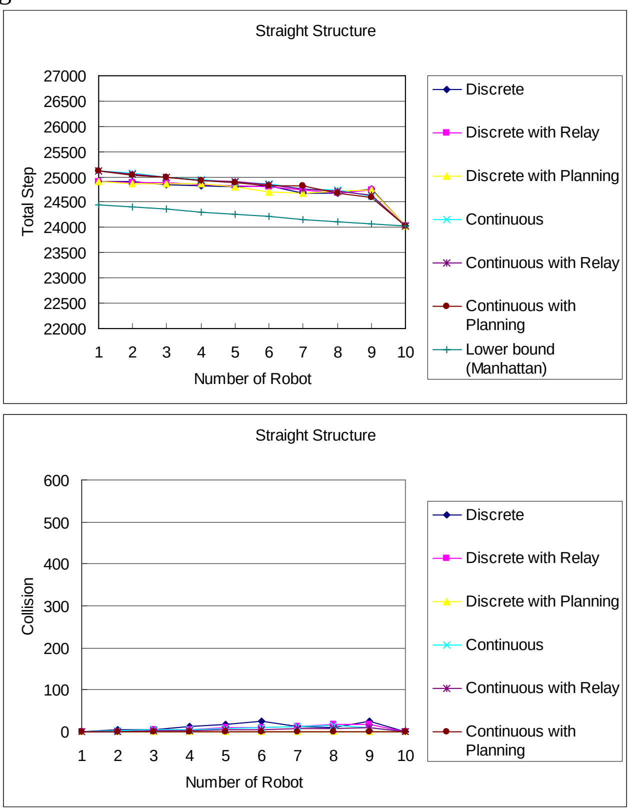


Fig. 12 Total step and collision required to assemble straight structure.

When assembling straight structure, efficiency is improved as the number of robot increased. It is caused by robots moving mainly vertically and collision number is small for any robot density. When the robot number is ten, total step coincides with the lower bound. In this case, number of robots equals to structure's width and the entire robots move in parallel without any interference.

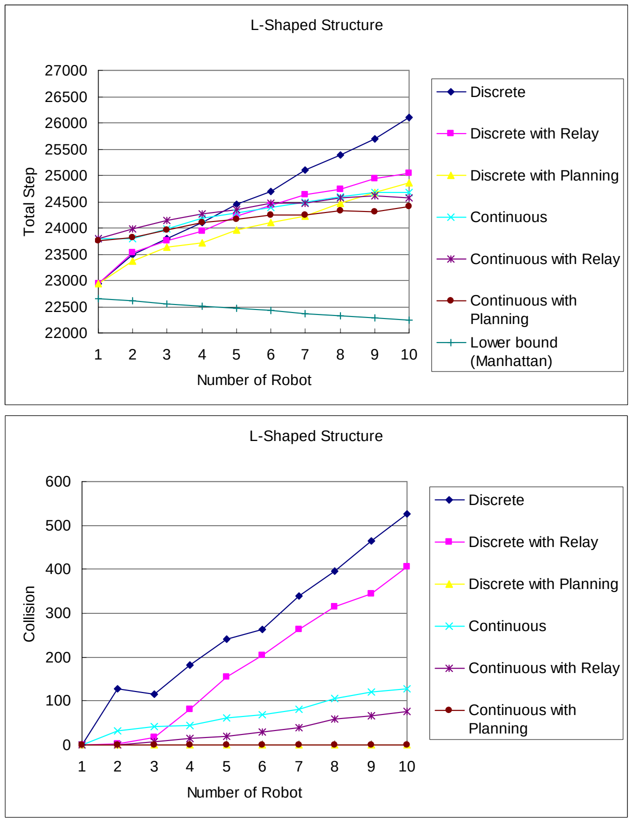


Fig. 13 Total step and collision required to assemble L-shaped structure.

Assembling L-shaped structure, efficiency goes down as the numbers of robots are increased becomes of collisions. In the L-shaped structure, paths at the corner makes the bottle neck. Discrete field makes only shortest path, and thus all the robots paths one concentrated to the corner. Continuous field generate paths with more clearance (Fig. 14). This is the reason why the continuous fields result is better than discrete field in high robot density.

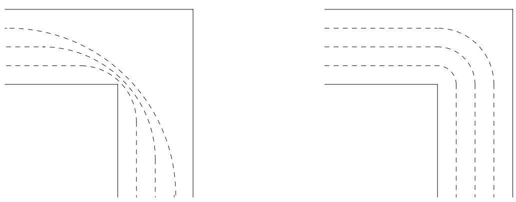
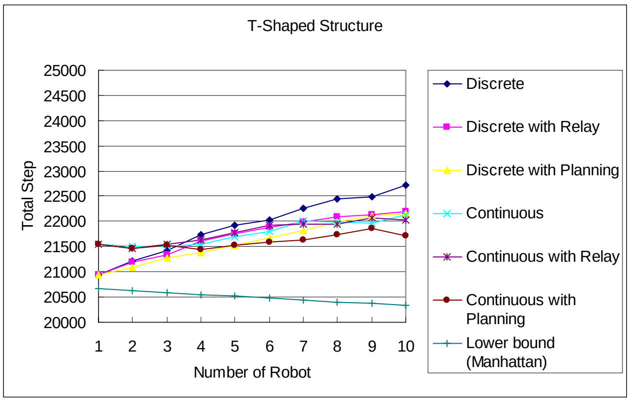


Fig.14 The image of moving path on the corner



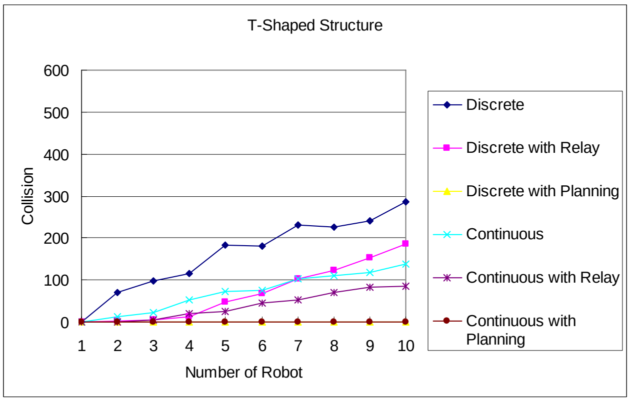


Fig. 15 Total step and collision required to assemble side road structure.

The result of assembling T-shaped structure is quite similar to that of assembling L-shaped structure. But the number of collisions is almost a half of L-shaped structure's, because T-shaped structure has two corners and collisions mainly occurred at the corner.

Concerning the total numbers of steps, blackboard planning is better than module relaying. But blackboard planning needs more space for bypass way than module relaying. Module relaying works well even in narrow space and high robot density situation. This character is useful to avoid dead-locks.

7. CONCLUSION

We have been studying on Automatic Modular Assembly System (AMAS). The system consists of cubic structure modules and assembler robots compatible with the modules. The assembler robots transport and assemble the modules to build a large-scale structure without any human intervention.

In this paper, we focused on the coordination problem among multiple assembler robots, and proposed a distributed algorithm based on the gradient field. By the algorithm, completely decentralized control of the robot group is realized by the gradient field generated on modular structure by inter-module communication. It is a kind of self-organizing system in the sense that robots build the structure and structure controls the robots.

Simulations of two-dimensional construction by a group of assembler robot have been conducted. Performances of the two kinds of gradient and two kinds of methods are evaluated in terms of the efficiency, for various density of the robot. By simulation, the discrete field is better for small robot density and the continuous field is better for high robot density. The balanced point between those two methods depends on the shape of the structure. This is the trade-off between moving distance and collision avoidance. We think this is based on the basic character of multi robot assembly and they can be useful for other multi-robot system.

REFERENCES

[1] United Nations Economic Commission for Europe (UNECE) and International Federation of Robotics (IFR): World Robotics 2005, 2005

[2] K. Chayama et al.: Implementation result of unmanned construction of a sabo dam using steel slit structure at Unzen Fugen-Dake, Proceedings of The 10th Symposium on Construction Robotics in Japan, pp.123-142, 2004

[3] William Whittaker et al.: Robotics for Assembly, Inspection, and Maintenance of Space Macrofacilities, AIAA-2000-5288

[4] Junichi Mitsunaga: Construction Machinery/Robot Business, Journal of Robotics Society of Japan, Vol. 20, No.7, pp.696-700, 2002

[5] Yuichi Ikeda, Takashi Shiokawa, Hironobu Kawakami, and Hidenori Miyajima: Development of an Automated Building Construction System (Part 3) - Improvement of System and Application of Super High-rise Hotel - the Obayashi Corp. Technical Lab. Report, No. 66, 2003

[6] Yuzuru Terada and Satoshi Murata: Automatic Assembly System for a Large-Scale Modular Structure -Hardware design of module and assembler robot- Proceedings of 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2004), pp.2349-2355, 2004

[7] Werfel, Justin, Yaneer Bar-Yam, and Radhika Nagpal: Building patterned structures with robot swarms. Nineteenth International Joint Conference on Artificial Intelligence (IJCAI'05), Scotland, UK, pp.1495-1502, 2005

[8] K. Stoy: Controlling Self-Reconfiguration using Cellular Automata and Gradients, Proceedings of the 8th International Conference on Intelligent Autonomous Systems (IAS-8), pp. 693-702, 2004

[9] Alexis Drogoul and Jacques Ferber. From Tom Thumb to the Dockers: Some experiments with foraging robots. In Proceedings of the Second International Conference on Simulation of Adaptive Behavior, pp. 451-459, 1992