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Development of a Flexible and Agile Multi-robot Manufacturing System

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Abstract: In this paper, we address a fluctuating low-volume and high-mix manufacturing system that handles a large variety of products. The incoming products have their own task information imposed by customer demands. In other words, they are not given in advance. Consequently, the system-operating conditions vary with the changes in the given tasks over time. Because of such unpredictable fluctuations, the system might have localized heavy workloads. Therefore, workload balancing is a challenge. For this issue, we focus on multi-robots in a manufacturing system. We first describe behavioral and cooperation mechanisms among robots. Thus, by sharing their information, robots are able to respond to such dynamically changing situations reactively. We then develop a flexible and agile multi-robot manufacturing system with Automated Guided Vehicles (AGVs) and product-processing robots. Finally, we discuss the validity of the developed system.

Keywords: Intelligent manufacturing systems; Flexible and reconfigurable manufacturing systems; Multi-agent systems applied to industrial systems; Applications of intelligent autonomous vehicles.

1. INTRODUCTION

In recent years, owing to changing markets and customer demands, manufacturing has been changing in diverse ways. Flexible and agile manufacturing systems are required to meet the various demands. In flexible and agile manufacturing, items such as the product types, specifications, quantity, and due date, are intricately interrelated, and the incoming orders from customers continue to fluctuate with time. Consequently, traditional manufacturing systems may have low productivity.

In the past, to cope with changes in manufacturing systems, several investigations focused on (I) line manufacturing systems for mass production and (II) flexible manufacturing systems using cellular and holonic manufacturing in order to meet low-volume and high-mix production demands [Sugi *et al.* (2003)] [Sugi *et al.* (2005)]. However, the results of these investigations and innovations have been insufficient, in and of themselves, to support manufacturing for the following reasons:

- Fault tolerance in materials and flexibility and agility of operations in line manufacturing present challenging problems;
- Complex tasks are especially challenging in self-contained cellular manufacturing using automated machines, such as robots;
- Although holonic manufacturing systems are quite flexible, they have extremely low productivity.

Therefore, in this study, we address a simple cellular manufacturing system that makes use of robots for the processing of various products rather than a more complex self-contained cellular manufacturing operation. For fluctuating low-volume and high-mix production demands, we develop a flexible and agile multi-robot manufacturing system in which robots, i.e., Automated Guided Vehicles (AGVs) and product-processing machines, perform the tasks in the dynamically changing situations reactively by sharing their information. Finally, we report on the validity of the developed system by comparing several manufacturing systems.

2. RELATED WORKS

At the initial design stage, it is important to consider a line-balancing strategy for designing flexible assembly systems [Lee *et al.* (1991)]. Regarding the system operation, Ota has described the validity of multi-agent robot systems in which distributed autonomous robots perform tasks in a dynamically changing environment [Ota (2006)]. Matsuda *et al.* have proposed a multi-robot system that performs knowledge distribution and sharing and focused on an autonomous and evolutionary configuration in the manufacturing line [Matsuda *et al.* (2005)]. However, only two types of products were considered.

In order to solve the picking problem in a warehouse with multiple agents, a dispatching problem has been described and shown to have a non-polynomial search space with respect to the number of agents and routes [Rubrico *et al.* (2006)]. For dynamically changing situations, such as a high-frequency disturbance in semiconductor manufacturing, an online manufacturing rescheduling method has been presented [Cheng *et al.* (2006)]. A similar approach to a manufacturing environment using multi-agent-based agile scheduling has also been proposed [Zhou *et al.* (2003)]. However, in these studies, an order list of incoming products or tasks is given in advance for dispatching and scheduling.

3. CHALLENGES

In response to the related work described above, we consider the following challenges to develop a flexible and agile multi-robot manufacturing system:

(1) A list of tasks fluctuates with the changes in the incoming orders of the products;
(2) Not all operation tasks are given in advance;
(3) Due to challenges (1) and (2), a heavy workload for robots occurs as a bottleneck in the system.

In other words, from a steady state, in which incoming orders of products are constant and the entire list is given in advance, the state of the system turns into a dynamically changing situation, that is, an unsteady state. In such a case, due to a locally occurring heavy workload, the efficiency of the system using a normal operation strategy might be reduced.

In regard to these challenges, the potential for multi-agent systems in distributed artificial intelligence has been described [Chan *et al.* (2002)]. Yang *et al.* have proposed a robotic system that assists production in flexible manufacturing environments [Yang *et al.* (1999)]. In the system, off-line robots operate exclusively to support on-line robots. However, in this paper, robots are not divided into such categories for the purpose of resource utilization of a system. Therefore, we assume a system in which heterogeneous multi-agent robots are operating for imposed tasks. No robots are used exclusively for the support of the operation; however, they are used to support each other as needed.

For the challenges reported above, we intend to develop a flexible and agile multi-robot manufacturing system that responds to the fluctuating low-volume and high-mix production demands by adopting the approach described below.

- In an unsteady state, each robot reactively performs a task for workload balancing according to a situation by sharing necessary and sufficient information, such as the system environment, task, and information from other robots.

4. INTELLIGENT MULTI-ROBOT SYSTEM

4.1 Robot with Intelligence in a Manufacturing

The robot has the following information: ID number; environment map, including position and path, velocity, state, such as move and stop, and given task, such as target position and processing time. Each robot is able to refer and update its information; and then, actuate itself for moving autonomously on the basis of the feedback information. The information is necessary and sufficient for a robot to perform a task.

In this paper, we assume that the robots have no predictive capability. In other words, a robot cannot predict other robots' future actions on the basis of their current behaviors. Hence, the behavior of a robot, such as (a) routing (position and path), (b) velocity control (acceleration and deceleration), and (c) cooperation with other robots (product processing and workload balancing), is decided on the basis of the current robot information and that from other robots at the time.

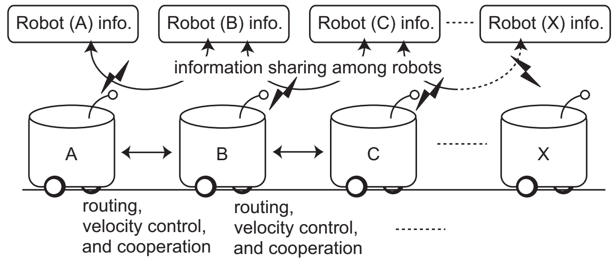


Fig. 1. Information sharing among robots

4.2 Information Sharing among Robots

Asama *et al.* have proposed a system that determines the task assignment while each robot autonomously switches both action modes using communication according to the situation at hand [Asama *et al.* (1992)]. In addition to their approach, we focus on communication among robots for information sharing, as shown in Fig.1. In this paper, we assume that each robot has a radio communication device, the robots are able to share their information with neighbors based on the distributed blackboard, namely, "sign-board" model [Wang (1994)].

First, a robot, on the basis of task information and position information, plans a route to a target position (a). Next, following the decided route, the robot shares information with other robots while moving and then controls its velocity with the use of information from other robots regarding position and velocity for collision avoidance (b). The robots, by sharing their information on their state and tasks with each other, start a cooperative operation for product processing and workload balancing (c).

To ensure the consistency of the shared information in a system, the robots follow the rules described in 5.2.

4.3 Robots Cooperation for Workload Balancing

As we described, in addition to variety and fluctuation in customer demands, there are various processing times that depend on the products in a high-mix and agile manufacturing system. Therefore, if those tasks (i.e., products that require long processing time) are imposed intensively in a certain work location at a given time, the system falls into an unsteady state. Consequently, operating robots crowd around the location, and this causes a heavy workload. For this situation, the robots, operating around the work location at which a heavy workload occurs, share their information for cooperation. After identifying current information among the robots, if there are idling-state and support-requirement robots, these robots exchange their information and then start cooperation for workload balancing. After cooperation, these robots continue to perform their own tasks if there is any.

5. FLEXIBLE AND AGILE MULTI-ROBOT MANUFACTURING SYSTEM

5.1 Overview

We developed a flexible and agile multi-robot manufacturing system with the use of a manufacturing system, as shown in Fig.2. In Fig.2, an AGV is used as a transportation robot. This robot performs the tasks using information about the products. The AGVs get task information

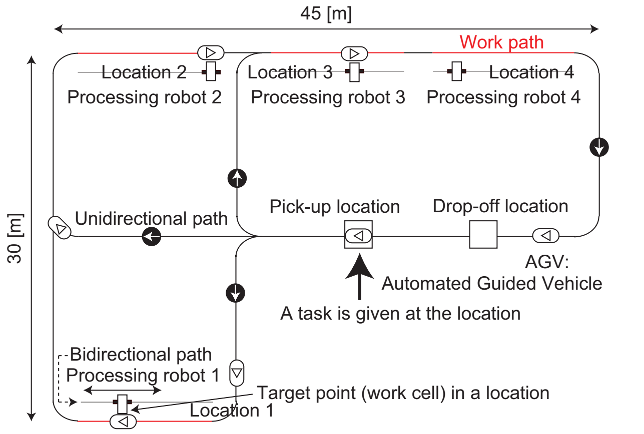


Fig. 2. Manufacturing system with AGVs and processing robots

when the incoming products are loaded onto the AGVs. A transported product is processed by a mobile product-processing robot at a location. Let us assume that these processing robots are equipped with manipulators. The location at which a processing robot operates consists of 11 cells. Processing tools are placed in the cells.

The robots share their information through a radio communication device mounted on each robot. The external configuration of the system is 45 [m] × 30 [m]. These paths consist of unidirectional paths for the AGVs and bidirectional paths for the processing robots.

5.2 System Settings

Number of robots The number of AGVs is changed from 1 to 10, and then the efficiency of the system is evaluated based on the system operation time. Four processing robots, 1∼4, operate at locations, 1∼4, respectively.

Behavior rules of robots The AGVs move in one direction on unidirectional paths. A control area is located at a junction; thus, the AGV that goes into the area first has priority to pass the junction. For collision avoidance of the AGVs, by sharing the position and velocity information with other AGVs, an AGV slows down if another AGV is in its stopping distance or, otherwise, increases its velocity up to the maximum. For cooperation with a processing robot, i.e., product processing, an AGV calls out the processing robot by sharing state information and gives a target position to the processing robot after the AGV goes onto the work path (see red paths in Fig.2) if the processing robot is idling [Hoshino *et al.* (2006)].

Under a steady state, the processing robots cooperate with the AGVs at their locations for product processing. On the other hand, under an unsteady state, they reactively move to other locations for cooperation, i.e., workload balancing. Here, the processing robot preferentially cooperates with the AGV for product processing, not workload balancing, if there is an AGV that is calling the processing robot on the adjacent work path out to the location. After cooperation for workload balancing, the processing robot returns to its location if an AGV comes to the location; otherwise, the processing robot continues to cooperate with another AGV or idles at the current location. In this regard, since we also evaluate the validity of the system from the viewpoint of the utility of the processing robots, although processing robots 2∼4 shown in Fig.2 reactively move according to the situation, robot 1 continues to operate at location 1. In this paper, we assume that processing robots 2∼4 can cross each other on a bidirectional path.

Table 1. Performance of the operating robots

AGV		
Max. traveling velocity	[m/s]	1.0
Max. cornering velocity	[m/s]	0.32
Acceleration	[m/s^2]	0.17
Processing robot		
Max. traveling velocity	[m/s]	0.52
Acceleration	[m/s^2]	0.019

On the work path, a product, which is transported by an AGV, is processed based on the First-In First-Out (FIFO) rule, if a processing robot is available.

Operational performance of robots The AGVs and processing robots that perform tasks for manufacturing have the performance shown in Table1.

Detailed task information For an AGV, a product transportation order is imposed as a task. Also, a product processing order is imposed as a task on a processing robot. A task includes the following information: pick-up and drop-off locations; target position of a work cell in a location; and operation time for loading/unloading and processing a product. In this paper, task information, such as the target location and work cell and required time for product processing, is randomly generated with uniform probability.

5.3 Operation Procedure

In the system shown in Fig.2, AGVs transport products from the pick-up location to the required work cells at the locations. The products that are handled by processing robots are transported to the drop-off location by the AGVs according to procedures (1) ∼ (7), listed below:

(1) At the pick-up location, a product is loaded onto an AGV. At the same time, a task is imposed on the AGV.
(2) Based on the task information, the AGV plans a route to a target position.
(3) The AGV controls its velocity by sharing its information with other AGVs and then moves to the target position.
(4) After the AGV goes into the work path, the AGV shares information with the processing robots and calls out a processing robot to the cell.
(5) By sharing information among the AGV and processing robot, cooperation for product processing is performed.
(6) The AGV refers to the task information in order to check for the next transportation requirements to another cell. If there are no requirements, the AGV plans a route to the drop-off location and returns to the location.
(7) The product is unloaded at the drop-off location. The AGV ascertains the presence of the next task and then moves to the pick-up location if there is any.

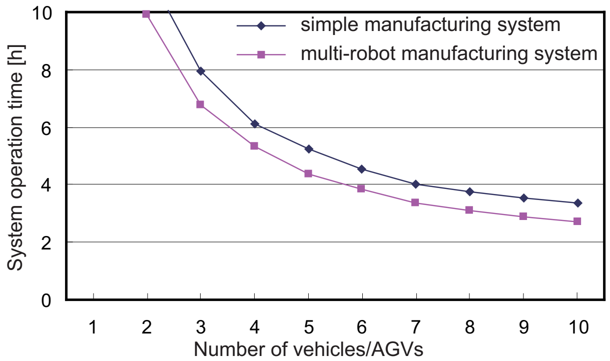


Fig. 3. Comparison of simple and multi-robot manufacturing systems based on the system operation time

6. SIMULATION EXPERIMENT

6.1 Validity of the Multi-robot Manufacturing System

In order to show the validity of the developed manufacturing system, we simulate and compare three kinds of systems: 1. a simple manufacturing system, 2. a multi-robot manufacturing system, and, for an unsteady state, 3. a distributed autonomous multi-robot system which responds to flexible and agile manufacturing.

System 1 uses an unintelligent vehicle that moves to its target position through a fixed route regardless of the product rather than an AGV. A processing machine is moved by an operator to a cell for product processing after a vehicle arrives at the cell. In system 2, since AGVs have their position information, i.e., an environment map, an AGV is able to plan the shortest path to the target position.

As we described in 5.2, operation tasks that include sets of work locations and cell information are randomly generated with uniform probability. As for the operation time, constant time (15 seconds) for loading/unloading is required at pick-up and drop-off locations. However, since the processing time depends on a product, the processing time at a cell on a location by a processing robot is randomly determined within 10 to 50 seconds. In this system, 200 tasks, i.e., products, are processed.

Fig.3 shows a comparison result for the system operation time in systems 1 and 2 when the number of vehicles/AGVs is changed from 1 to 10. From the figure, it is evident that the operation time in system 2 is less than that in system 1. Thus, the validity of the multi-robot manufacturing system in which each robot moves automatically to perform the imposed tasks is shown.

6.2 Workload Balancing in an Unsteady State

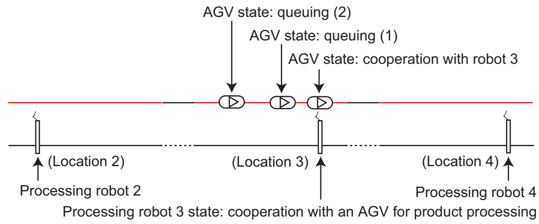
In this simulation for comparing systems 2 and 3, tasks are generated with fluctuating probabilities for each location. In other words, the system state is changed to an unsteady state in consideration of product variability and fluctuating demands.

Table2 shows the probability oscillations when the tasks are generated. The tasks are generated based on the probabilities. Note that the chart is not given to the AGVs and processing robots in advance. Up to the 50th task, each location is determined as a target location with probability 0.5. Note that, at location 2, from 50 up to 100 tasks are generated with probability 1, which means that all products are required to be transported to the location and processed at a cell. After the 101st task, they are all generated with probability 0.1, that is, one product of 10 is processed at the location. Other conditions regarding task generation are the same as described in 6.1.

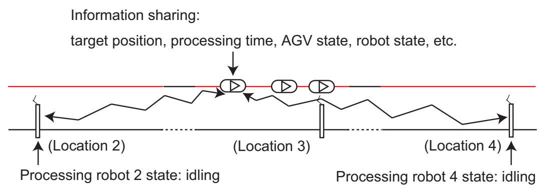
In Fig.4, the cooperation procedure for workload balancing is shown with the use of locations 2∼4 and the adjacent work (red) paths, as shown in Fig.2. Regarding a decision criterion for workload balancing, we focus on the number of AGVs that are queueing on a work path. Here, for instance, we show a case in which a second queuing AGV cooperates with other processing robots for workload balancing if there are two or more queuing AGVs.

Table 2. Task generation chart with fluctuating probability

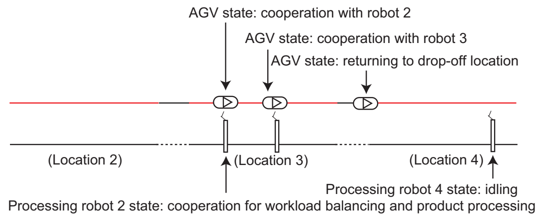
Tasks	Location 1	Location 2	Location 3	Location 4
1∼50	0.5	0.5	0.5	0.5
51∼100	0.1	1	0.1	0.1
101∼150	0.1	0.1	1	0.1
151∼200	0.1	0.1	0.1	1



(a) Three AGVs are on the same working path

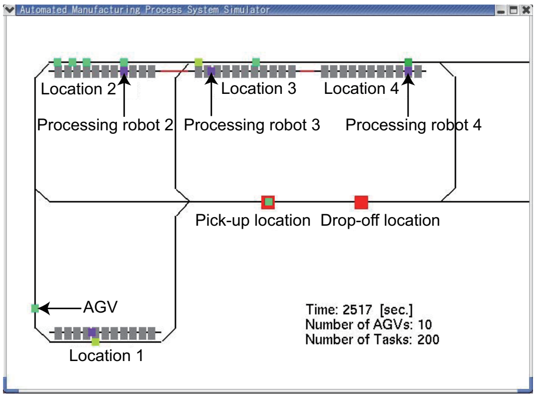


(b) The third AGV shares information with processing robots 2 and 3

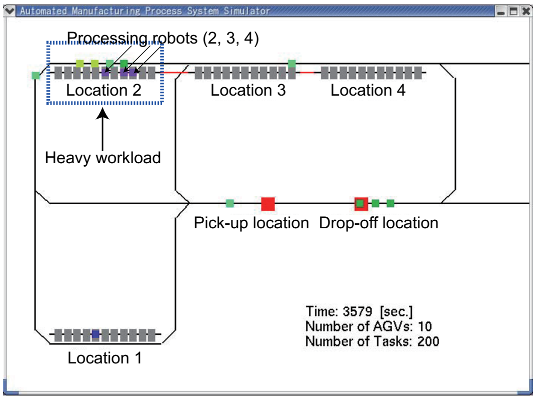


(c) The selected robot 2 moves to the target position (work cell) for workload balancing

Fig. 4. Cooperation among AGVs and processing robots for workload balancing (if there are two or more queuing AGVs)



(a) Steady state (task: 1∼50)



(b) Workload at location 2 (task: 51∼100)

Fig. 5. Cooperation among AGVs and processing robots in unsteady states

If there are three AGVs going to the same target position (a location, not a cell) on the same path (see Fig.4(a)), the first AGV begins to cooperate with the processing robot 3 for product processing. The second AGV is then represented as a first queuing AGV, and the third AGV as a second queuing AGV. The third AGV, which is the second queuing AGV, shares information with processing robots 2 and 4 for workload balancing (see Fig.4(b)); then, it selects an idling one. The AGV selects one of the two robots randomly if both robots are idling. For workload balancing, the selected robot 2 moves to the cell on the location, and then the robot begins cooperation with the AGV for product processing (see Fig.4(c)).

6.3 Validity of Cooperation for Workload Balancing

Fig.5 shows that the robots reactively perform the tasks (see Table2) in unsteady states when the number of queuing AGVs is more than one. In the system, there are 10 AGVs. In a steady state, each processing robot operates at its location (see Fig.5(a)). From Fig.5(b), we can see that cooperation for workload balancing and product processing are performed among three processing robots, 2∼4, and AGVs in case that excessive task concentration at location 2 causes a heavy workload. Moreover, at locations 3 and 4 in an unsteady state, the same cooperation among the processing robots and AGVs was noted.

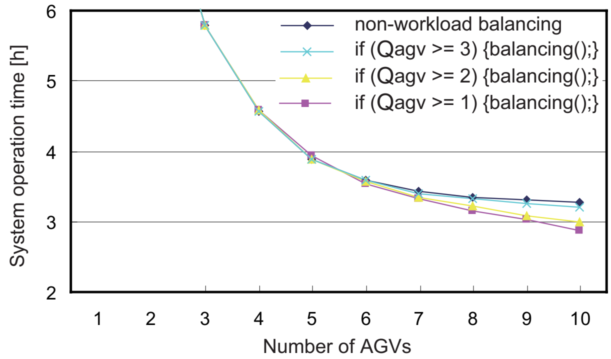


Fig. 6. Comparison of the system operation time

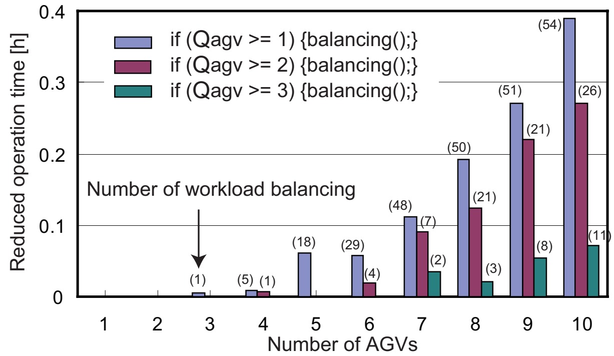
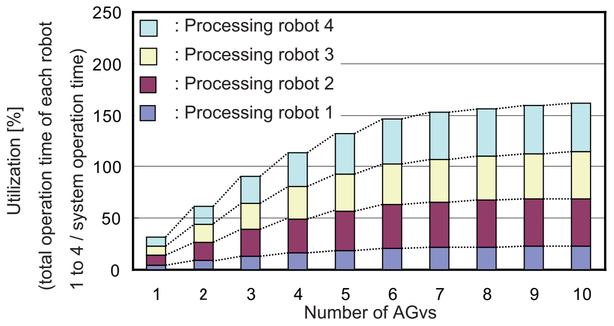


Fig. 7. Reduced system operation time

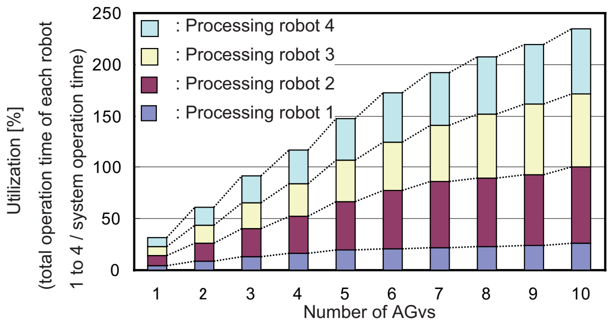
Fig.6 is a comparison of the following four systems on the basis of the system operation time for the number of AGVs 1∼10: (i) a system with non-workload balancing (this is system 2 described in 6.1); (ii) a developed flexible and agile manufacturing system, i.e., system 3 using cooperation for workload balancing if the number of queuing AGVs is more than one; (iii) the same system as in (ii) with more than two AGVs queuing; and (iv) the same system as in (ii) with more than three AGVs queuing in an unsteady state. As the number of AGVs is increased, we can see the validity of cooperation for workload balancing in case of a heavy workload, which is an unsteady state caused by a fluctuation of the operation tasks, as shown in Fig.5(b).

Fig.7 shows the reduced operation time by comparing systems (ii)∼(iv) to (i) on the basis of the results shown in Fig.6. In addition, the number of workload balancing is shown on top of the bar graphs while processing 200 tasks. From the result, it is clear that the system using cooperation for workload balancing if the number of queuing AGVs is more than one is the most efficient one. In other words, as the number of AGVs is increased, it is possible to keep the system in good working order by cooperating with other robots for workload balancing as soon as the system falls into an unsteady state.

For a heavy workload, Fig.8 shows the utilization of processing robots 1∼4 in systems (i) and (ii). Here, the utilization of processing robots is defined as "{the total operation time of a processing robot} / {the total system operation time for 200 tasks}." From Fig.8(a), it is clear that the utilization of processing robots does not increase as the number of AGVs increases. This is because the processing



(a) System (i): Non-cooperation for workload balancing



(b) System (ii): Cooperation for workload balancing (if $Q_{agv} \geq 1$)

Fig. 8. Comparison and evaluation of the utilization of processing robots

robots continue to operate at their locations even when a heavy workload occurs locally within the system. On the other hand, Fig.8(b) shows that the increase in the utilization of processing robots (2∼4) is noticeable as the number of AGVs increases. The reason for this result is that processing robots, except robot 1, reactively cooperate with the AGVs for workload balancing. In other words, the processing robots move to other locations for cooperation according to the situation; thus, the total operation time of processing robots increases. As a result, in a system with 10 AGVs, the utilization of processing robots 2∼4 was up to 60∼75 [%]. This result shows that the processing robots were effectively used as system resources, and, thus, the developed system responded flexibly to the unsteady states.

Finally, from Fig.6, Fig.7, and Fig.8, for flexible and agile manufacturing, the validity of a developed multi-robot system in which the robots reactively cooperate with other robots even in an unsteady state was presented.

7. CONCLUSIONS

In this paper, for fluctuating low-volume and high-mix demands, we developed a flexible and agile multi-robot manufacturing system with AGVs and product-processing robots. Using cooperation among the robots by sharing their information, we showed that the robots are able to perform the tasks reactively in an unsteady state. Finally, we presented the validity of the developed system by comparing several manufacturing systems.

In future works, in addition to the unpredictable fluctuations addressed in this paper, we will consider the reliability, i.e., malfunction of the operating robots.

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REFERENCES

M. Sugi *et al.* A holonic architecture for easy reconfiguration of robotic assembly systems. *IEEE Transactions on Robotics and Automation*, Vol. 19, No. 3, pp. 457–464, 2003.

M. Sugi *et al.* Motion control of self-moving trays for human supporting production cell “Attentive workbench.” *2005 IEEE International Conference on Robotics and Automation*, pp. 4091–4096, 2005.

H.F. Lee *et al.* A line balancing strategy for designing flexible assembly systems. *International Journal of Flexible Manufacturing Systems*, Vol. 3, No. 2, pp. 91–120, 1991.

J. Ota. Multi-agent robot systems as distributed autonomous systems. *Advanced Engineering Informatics*, Vol. 20, No. 1, pp. 59–70, 2006.

K. Matsuda *et al.* Knowledge based evolutional multiple robot systems. *IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, pp. 1139–1144, 2005.

J.I.U. Rubrico *et al.* Scheduling multiple agents for picking products in a warehouse. *2006 IEEE International Conference on Robotics and Automation*, pp. 1438–1443, 2006.

M. Cheng *et al.* Online rescheduling in semiconductor manufacturing. *International Symposium on Scheduling*, pp. 64–68, 2006.

Z.D. Zhou *et al.* A multi-agent-based agile scheduling model for a virtual manufacturing environment. *International Journal Advanced Manufacturing Technology*, Vol. 21, No. 12, pp. 980–984, 2003.

F.T.S. Chan *et al.* A multi-agent-based agile shop floor control system. *International Journal Advanced Manufacturing Technology*, Vol. 19, No. 10, pp. 764–774, 2002.

H.-Z. Yang *et al.* Development of a robotic system which assists unmanned production based on cooperation between off-line robots and on-line robots: Concept, analysis and related technology. *International Journal of Advanced Manufacturing Technology*, Vol. 15, No. 6, pp. 432–437, 1999.

H. Asama *et al.* Development of task assignment system using communication for multiple autonomous robots. *Journal of Robotics and Mechatronics*, Vol. 4, No. 2, pp. 122–127, 1992.

J. Wang. On sign-board based inter-robot communication in distributed robotic systems. *International Conference on Robotics and Automation*, pp. 1045–1050, 1994.

S. Hoshino *et al.* Design of an AGV transportation system by considering management model in an ACT. *Intelligent Autonomous Systems 9*, IOS Press, pp. 505–514, 2006.