

Behavior Control Methodology for Circulating Robots in Flexible Batch Manufacturing Systems Experiencing Bottlenecks

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Abstract—This paper focuses on an automated batch manufacturing system with material-handling robots (MHRs) and material-processing robots (MPRs). In this robotic manufacturing system, materials transported by the MHRs are processed by the MPRs. These operations cause a bottleneck in the system. Furthermore, the bottleneck induces congestion of the MHRs. In the system, the effect of an operational delay due to bottlenecks affects the entire operation. Accordingly, there is an event in which the congestion extends and the system throughput not only fails to increase but also may become worse, even if more robots are used to improve the productivity. For this challenge, we propose a behavior control method for the MHRs to eliminate or ease the congestion that arises from a bottleneck. Each MHR controls its own behavior adequately by using the external force of a virtual damper in order not to become involved in the congestion. Finally, through a simulation experiment, we show that the proposed control method improves the system throughput and its effectiveness for a more efficient system operation.

I. INTRODUCTION

In accordance with the diversification of product demand, high-mix low-volume manufacturing systems have attracted attention. A batch manufacturing system is listed as one such system. In a batch manufacturing system, a production batch, i.e., order, is given to operating machines as a recipe format that consists of a series of tasks. Each recipe varies according to the products; herewith, multi-product manufacturing in one system is made possible. In general manufacturing systems, materials and components are transported to designated places; production processes are conducted at these places; and then, final products are produced. In a batch manufacturing system, more complex and various tasks are executed on the basis of recipes.

We have so far focused on the operation technologies of a plant for chemical products as an applicable environment of the flexible batch manufacturing system. In chemical process industries, batch manufacturing systems that consist of pipe networks experience a serious problem, i.e., material contamination. For this problem, we have developed a flexible batch chemical manufacturing system that uses industrial robots, such as material-handling robots and material-processing robots, instead of pipes and fixed process equipment [1]. In such systems, materials are transported to designated locations by a movable material-handling robot with a vessel; they are then processed by the material-processing robot that has various equipment. For executing chemical production

tasks, process stations are set up. Around these stations, the transport and processing operations cause a bottleneck in the system. Furthermore, the bottleneck induces congestion of the material-handling robots.

In general, manufacturing systems are located in a closed plant facility. Therefore, the effect of an operation delay due to a bottleneck at a certain place affects the entire system. Accordingly, there is an event in which the congestion extends and the system throughput not only fails to increase but also may become worse, even if more robots are used to improve the productivity. To meet this challenge, we propose a behavior control method for material-handling robots to eliminate or ease the congestion that arises from a bottleneck. Finally, through a simulation experiment, we show that the proposed control method successfully improves the system throughput and, therefore, its effectiveness for a more efficient system operation.

II. ROBOTIC BATCH MANUFACTURING SYSTEM

In this decade, most new automated material-handling systems have usually been designed with a spine- or perimeter-type of configuration that formed a material flow loop within a plant facility [2]. Furthermore, in terms of reliable and safe automation of robots with limited maneuverability, we adopt a cyclic layout structure, as shown in Fig. 1. In this system, multiple robots are in operation, i.e., material-handling robots (MHRs), which transport materials of products to process stations and material-processing robots (MPRs), which have various equipment to conduct production tasks, such as coupling, feed, blending, separation, discharge, and cleaning processes at the stations.

In order for the MHR to move agilely, three types of lanes, i.e., main (one-way), passing (one-way), and intermediate (two-way), are provided. The MHR moves flexibly in the clockwise direction while selecting lanes and planning a suitable route to a destination. Inside the main lanes, four bi-directional lanes for four MPRs are provided. Each MPR basically works at its own two or four stations and reciprocates among the stations. In addition, the MPR supports another adjacent MPR if it has a heavy workload. These robots also share and exchange information on the basis of the communication model proposed in the literature [3].

Process stations, 1 ~ 12, are placed on the main lanes. A required task at a station is executed by the MPR. As for the discharging of a final product and cleaning of the empty MHR, these are the requisite processes in one batch; therefore, exclusive stations are set up for each of them. In the batch manufacturing system, the MHR circulates from the cleaning station to the discharging station through any

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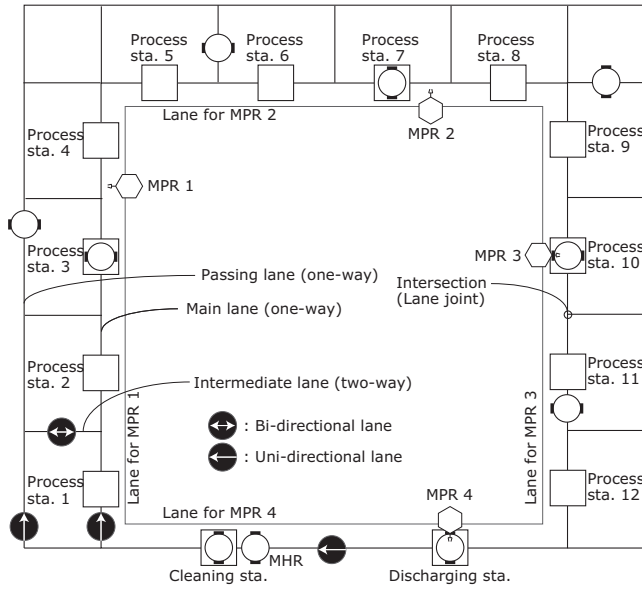


Fig. 1. Cyclic Layout Structure of the Robotic Batch Manufacturing System

of the stations, 1 ~ 12, to execute a transport task, and the MPR receives a task information from the MHR; it then executes the production task at each station. By doing so, a final product is produced from the materials.

III. CHALLENGE AND APPROACH

When autonomous mobile objects travel in one direction in a system with a cyclic structure, even if there is no bottleneck, congestion of the mobile objects spontaneously takes place as the number of mobile objects increases; after that, the congestion moves in the opposite direction of the traveling one. This phenomenon has been mathematically proven and formulated [4] [5]. Nishinari *et al.* have presented experimental evidence that the emergence of a traffic jam or congestion with no bottleneck is a collective phenomenon similar to the dynamical phase transitions and pattern formation on a circuit [6]. In their result, the traveling flow of the mobile objects became worse.

In a cyclic batch manufacturing system without a bottleneck that ignores the existence of the process station, as in the result described above, congestion takes place according to the number of circulating MHRs and then moves in the opposite direction. This is because the follow-on MHRs join the tail of the congestion continuously, while other MHRs gradually leave the head of the congestion. Similarly, in a system with a bottleneck, once congestion occurs around the process station due to an operation delay (the operation rate of an MPR < arrival rate of MHRs), the MHRs join the tail of the congestion, i.e., they queue, while the MHR in front, to which the production task was executed, leaves the station. In consequence, the queue is extended in the opposite direction of the station. This localized queue probably results in low productivity as a whole. Therefore, the following challenge needs to be solved regardless of the bottleneck:

- Congestion emerges as the number of mobile objects increases; eventually, the congestion has a harmful

effect on the system throughput.

For this challenge, a behavior control method for mobile objects, which is commonly effective for both systems regardless of a bottleneck, is required. In this regard, the following two approaches have been proposed: vehicles are controlled by one controller not to go to a concentrated place [7]; and each mobile object avoids congested regions and moves towards less congested regions, respectively [8]. However, these approaches are insufficient for a system in which a robot automatically moves on fixed lanes. Therefore, we propose a control method in order for the circulating MHRs to eliminate or ease the congestion and improve the system throughput through the following approaches:

- When congestion occurs in a system, an MHR that moves behind the congestion controls its behavior in order not to become involved in it.
- In this regard, the external force of a virtual damper inserted between the stopping MHR at the end of the congestion and the moving MHR behind the congestion is used to keep the inter-robot distance.

IV. OPERATIONAL TECHNIQUE FOR ROBOTS

A. Centralized and Decentralized Control Architecture

To begin with, since the operations regarding the transport and production tasks around the stations cause a bottleneck, these operations have to be conducted as efficiently as possible to restrain the effect of a bottleneck. For a batch manufacturing system with two different types of multiple robots, therefore, it is necessary to assign appropriate tasks to the robots and coordinate them in order to achieve a given task in cooperation with other robots as necessary.

A control architecture for flexible manufacturing systems has been previously proposed [9]. Decentralized controllers in order for an automated guided vehicle (AGV) to achieve tasks cooperatively with other AGVs and a centralized controller to solve the task allocation problem for considering the global performance have been used. However, cooperative work among different kinds of robots has not been taken into account.

In this paper, decentralized controllers are mounted on MHRs and MPRs. In other words, each robot controls its own behavior autonomously on the basis of the position information. In addition, we take into account the cooperative work among the robots, that is, the production task executed by the MPR to the MHR at a station. The transport tasks are assigned to the MHRs in consideration of information regarding the state of the task execution in the system with the use of a centralized controller. Under the centralized and decentralized control architecture, we apply the following operational techniques (see [1] for more details) via the communication model [3].

B. Route Planning Method for the MHR

Algorithm 1 denotes that an MHR (MHR_i) selects lanes according to information from other MHRs (MHR) and then achieves a transport task while planning and changing a route to a target station adequately. Here, T is a target station, and

x shows a position. Hence, x_T and x_{MHR} represent the positions of the target station and MHR. $flagOperation_{MHR}$ denotes if a production task is being executed to an MHR at a station ($= true$) or not ($= false$).

Algorithm 1: ROUTEPLANNING(MHR)

```

Route( $MHR_{i_{x_T}}$ )  $\leftarrow$  Shortest route to  $x_T$ 
for  $j \leftarrow 1$  to  $n$ 
do
  if  $x_{MHR_i} < x_{MHR_j}$  and  $x_{MHR_i} < x_T$ 
  and  $flagOperation_{MHR_j} = true$ 
  then
    erase(Route( $MHR_{i_{x_T}}$ ))
    Route( $MHR_{i_{x_T}}$ )  $\leftarrow$  Breadth-first
    search with regard to  $x_T$ 

```

An MHR determines a route to the next station after a production task is executed by an MPR. In this regard, the shortest route is first planned using the breadth-first search method with an objective function regarding the distance to the destination. After that, the MHR erases the current route and plans a route again if an MHR is stopping for the production task at a station located on the selected route.

C. Operational Dispatching Rule for the MPR

MPRs 1 ~ 3 and 4 work on production tasks at four and two stations, i.e., 1 ~ 4, 5 ~ 8, 9 ~ 12, and discharging and cleaning stations, respectively. Accordingly, when multiple MHRs arrive at different stations (e.g., the 1st, 2nd, 3rd, and 4th stations) at the same time, it is required to appropriately dispatch one MPR (e.g., MPR 1) to the site to execute the tasks in order to improve the robot's operating efficiency. For this purpose, the task execution sequence has to be appropriately determined. Therefore, we apply a dispatching rule to the MPR in order to minimize the total moving distance between the stations and execute the production tasks using the full-search method for a combination of all stations. This task execution sequence is repeatedly determined each time one task is finished according to the state of other stations if there is an MHR stopping for the task.

D. Cooperation among the MPRs for Workload Balancing

A localized heavy workload of the MPR occurs as the number of MHRs increases due to the bottleneck that arises from the given tasks and the system layout even if each of the MHRs and MPRs achieved its task efficiently. To overcome this problem, we have shown the effectiveness of reactive robot behavior [10]. Therefore, for a heavy workload in a manufacturing system, we attempt to balance the workload by applying a reactive cooperation heuristics among adjacent MPRs (see Algorithm 2).

In Algorithm 2, MPR_i represents a host MPR that has its own two or four process stations, denoted as S_{MPR_i} . $flagOperation_{MPR}$ shows whether an MPR is operating ($true$ represents operating, and $false$ represents free). NT_{MPR} represents the next task of an MPR. Thus, if there is an MPR that has a heavy workload, other adjacent free MPRs are able to support it by executing its task instead.

Algorithm 2: COOPERATIVEOPERATION(MHR, MPR)

```

if  $flagOperation_{MPR_i} = false$ 
{
  if  $x_{MPR_i} = x_{S_{MPR_i}}$ 
  {
    if  $x_{MHR} = x_{S_{MPR_{i-1}}}$ 
    {
      if  $flagOperation_{MPR_{i-2}} = true$ 
      then  $NT_{MPR_i} \leftarrow$  Cooperation
      else
      {
        if  $x_T - x_{MPR_i} < x_T - x_{MPR_{i-2}}$ 
        then  $NT_{MPR_i} \leftarrow$  Cooperation
        else if  $x_{MHR} = x_{S_{MPR_{i+1}}}$ 
        {
          if  $flagOperation_{MPR_{i+2}} = true$ 
          then  $NT_{MPR_i} \leftarrow$  Cooperation
          else
          {
            if  $x_T - x_{MPR_i} < x_T - x_{MPR_{i+2}}$ 
            then  $NT_{MPR_i} \leftarrow$  Cooperation
          }
        }
      }
    }
  }
  else
  {
    if  $x_{MHR} \neq x_{S_{MPR_i}}$ 
    then  $NT_{MPR_i} \leftarrow$  Cooperation
    else
    then  $NT_{MPR_i} \leftarrow$  Return to  $x_{S_{MPR_i}}$ 
  }
}
else
{
  if  $x_{MHR} \neq x_{S_{MPR_i}}$ 
  then  $NT_{MPR_i} \leftarrow$  Maintain cooperation
  else
  then  $NT_{MPR_i} \leftarrow$  Return to  $x_{S_{MPR_i}}$ 
}

```

E. Multi-Task Assignment to MHRs

In a recipe, which is given as one production batch, multiple tasks are described. Following the recipe, an MHR moves to several stations to execute the transport tasks, and the materials transported are then processed by an MPR at the stations as production tasks. Therefore, it is necessary to assign a suitable batch that includes a series of tasks to the MHR. This is a "multi-task problem [11]." To solve this problem, we introduce the following objective function and assign a batch to the MHR on the basis of Eq. (1) while partially referring to unexecuted batches.

$$\text{minimize } \sum_k \sum_n Task_{n,k} (ExeTask_n - Task_{n,k}), \quad (1)$$

where k is a reference batch number and n represents a station number. $ExeTask_n$ represents the total number of MHRs that are being processed and are going to be processed at stations n based on the production recipes, i.e., the transport and production tasks. As for $Task_{n,k}$, a binary variable, 0 or 1, is given whether or not station n of the k -th reference batch is a destination in the recipe.

V. BEHAVIOR CONTROL METHODOLOGY

A. Previous Control Law for the Vehicle and Robot

Autonomous intelligent cruise control systems (AICCSs) have been developed to adjust a vehicle's velocity to that of a preceding vehicle and keep it at a safe distance. A control law for the AICCS based on a constant time headway safety distance has been proposed [12]. In this system, autonomous

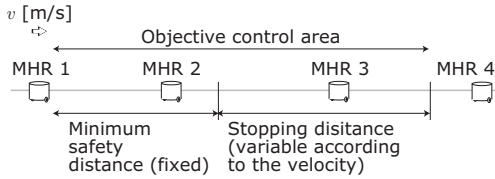


Fig. 2. Forward Control Area of the MHR

vehicles successfully followed the vehicles in front of them while avoiding a collision. However, the vehicle was not able to control its velocity with respect to a vehicle in front of it outside of a given control area.

We have applied a behavior control method to a robot based on the position information of other robots. Fig. 2 shows a forward control area of the MHR that has been used for behavior control. In other words, the MHR controls its velocity by accelerating or decelerating on the basis of the control area. In order for an MHR to avoid a collision with the MHR in front of it, the minimum safety distance area is provided regardless of the velocity. In other words, the MHR has to keep a fixed distance when it has to stop due to the MHR in front of it. Additionally, each MHR has another control area, i.e., the stopping distance area, which includes response and braking distances outside of the minimum safety distance area. The range of this area changes as follows: $vt + \frac{v^2}{2a}$, where t and a represent the response time and maximum braking rate.

On the basis of the position information of other MHRs, the MHR moves while switching the following three control modes: 1) maximum deceleration; 2) deceleration; and 3) maximum acceleration or constant. An MHR (MHR 1), which is moving behind another one, switches the control mode to 1 if the preceding MHR (MHR 2) is inside the minimum safety distance area; to 2 if the preceding MHR (MHR 3) is inside the area of the minimum safety distance plus the stopping distance, that is, the objective control area, in order to stop the minimum safety distance short of MHR 3; and to 3 within the limiting velocity if the preceding MHR (MHR 4) is outside of the objective control area, as shown in Fig. 2.

However, an MHR that is following another one does not reduce the velocity for an MHR outside the objective control area. Consequently, a stopping MHR is gradually taken into the objective control area of a moving MHR; eventually, the MHR also has to stop after switching the control modes, i.e., $3 \rightarrow 2 \rightarrow 1$. This continuous phenomenon causes and expands the congestion of the MHRs.

B. Proposed Behavior Control Method

To correct the occurrence of congestion of MHRs described in V-A, we introduce an external force that acts on a moving MHR behind another stopping one with control mode 3 so that the MHR keeps the inter-robot distance with the stopping MHR in front of it even if it is outside the objective control area.

In related studies on robots or vehicles control using an external force, Arai *et al.* have proposed a virtual impedance method. Multiple mobile robots accomplished a real-time

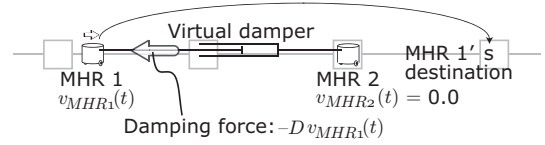


Fig. 3. External Force between the MHRs

plan to follow a generated trajectory while avoiding obstacles and avoiding or cooperating with other robots [13]. Similarly, impedance control methods for a vehicle platoon system [14] and the behavior control of a vehicle using a virtual spring and damper in order to follow a vehicle in front of them [15] have been proposed. These methods have, however, focused on a position control that is based on an external force, i.e., impedance for collision avoidance and object following among the robots, vehicles, and obstacles, rather than congestion. Therefore, the control area was limited around the objects, and the velocity was not an immediate control parameter.

On the other hand, we propose a behavior control method in which the MHR circulating to a target station with control mode 3 reduces its velocity for a stopping MHR in front of it by inserting a virtual damper in between and exerting a damping force on the moving MHR. As long as two MHRs continue moving, the virtual damper is not inserted. Thus, the relative velocity between two MHRs, when the virtual damper is inserted, is always equal to the velocity of the moving MHR. It must be noted that, since the moving MHR aims at controlling the longitudinal velocity using the damping force, which is generated according to the current velocity, the spring used in compliance and impedance control methods is not used. In other words, the proposed method is based on a velocity-dependent damping control.

C. External Force Using a Virtual Damper

Fig. 3 shows an MHR (MHR 1) moving while being affected by an external, damping force. At a given time, t , when an MHR (MHR 2) stops at a station located outside of the objective control area on the route of MHR 1 for a production task, a virtual damper is inserted between the two MHRs. As a result, the velocity of MHR 1 after a derivative time Δt , i.e., $v_{MHR1}(t + \Delta t)$, is reduced by $Dv_{MHR1}(t)\Delta t$, where D denotes the stickiness factor of the virtual damper and $v_{MHR1}(t)$ is the current velocity. The damping force that acts on MHR 1 is expressed as $Dv_{MHR1}(t)$. Therefore, when the damping force acts on the MHR, the reduced velocity of the MHR is expressed by Eq. (2), where a represents the acceleration of the MHR. In this regard, the damping force does not affect the MHR (i.e., $Dv_{MHR}(t) = 0.0$) if no MHR is stopping at any of the stations on the MHR's route to a target station.

$$v_{MHR}(t + \Delta t) = v_{MHR}(t) + a\Delta t - Dv_{MHR}(t)\Delta t \quad (2)$$

The right side of Eq. (2) is replaced by Eq. (3), in consideration of the discrete sampling time, Δt , so that the reduced velocity of the MHR does not become a negative value, $v_{MHR}(t + \Delta t) \geq 0$. In this regard, assuming the sampling time, $\Delta t = 1.0$, and velocity, $v_{MHR}(t) \gg a$,

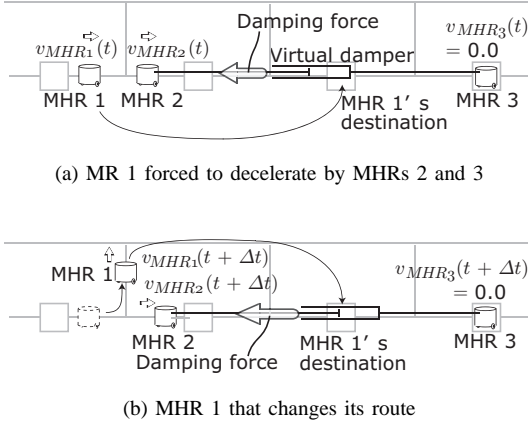


Fig. 4. Route Planning Due to the External Force

the stickiness has to satisfy $D \leq 1.0$ regardless of the velocity. Therefore, the MHR controls its behavior to reduce the velocity by determining the stickiness, D , appropriately based on the inter-robot distance.

$$D \leq \frac{1}{\Delta t} + \frac{a}{v_{MHR}(t)} \quad (3)$$

The MHRs behind the lead moving MHR are not affected by the external force from the stopping MHR, but they are forced to reduce their velocities due to the lead decelerating MHR, as shown in Fig. 4. Due to this disturbance, if the target station of an MHR (MHR 1) is located between a stopping MHR (MHR 3) and a decelerating MHR (MHR 2) that is affected by an external force (Fig. 4(a)), MHR 1 plans a new route to detour MHR 2 with the use of the routing method described in Algorithm 1 (Fig. 4(b)).

VI. SIMULATION EXPERIMENT

A. Effectiveness for a System without a Bottleneck

In this simulation experiment, each MHR continues circulating around the main lanes 200 times, and the MHRs do not stop at the stations. The maximum velocity of the MHR is 2.1 [m/s], the maximum acceleration is 0.05 [m/s²] (~ 0.7 [m/s]), 0.08 [m/s²] (0.7 \sim 1.4 [m/s]), and 0.12 [m/s²] (1.4 \sim 2.1 [m/s]), according to the velocity, and the maximum deceleration (braking rate) is 0.2 [m/s²]. The length of the main lane is 30; the total perimeter is 120 [m]. The intermediate and passing lanes are not used. The number of MHRs is changed 1 \sim 20 in each simulation. The stickiness of the virtual damper to generate the external force is given as $D = 1.0$ and $D = 1.0/\{\text{inter-robot distance}\}$ for comparison.

Fig. 5 shows the simulation result regarding the total circulating time obtained by using three control methods: the previous control method without the external force and the two proposed control methods with the use of virtual dampers with different stickiness. In the result obtained applying the proposed methods, when the number of MHRs was more than 12, the MHRs finished circulating earlier than they did in the result of the previous method. The reason for this result is that, by applying the previous control

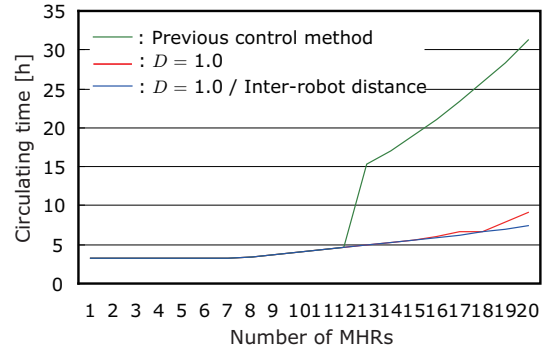


Fig. 5. Simulation Results of a System without a Bottleneck

method, the congestion of the MHRs emerged spontaneously; eventually, this worsened the throughput. On the other hand, the MHRs reduced the velocity for the stopping MHR by using the external force of the virtual damper; thus, congestion did not occur or was eliminated even if it occurred due to the increased number of MHRs. As a result, compared to the previous method, the proposed methods successfully improved the throughput. Therefore, the total circulating time did not increase precipitously due to the increased number of MHRs.

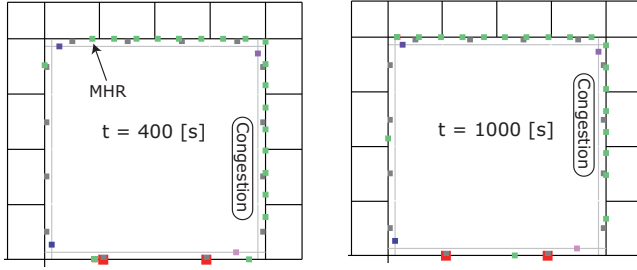
Fig. 6 shows a snap shot of the circulating simulation with 20 MHRs. The previous control method resulted in the congestion of the MHRs at around 400 seconds after the simulation; then, the congestion was not eliminated 1,000 seconds later, as shown in Fig. 6(a). This shifting congestion was not eliminated until the end of the simulation. In Fig. 6(b), on the other hand, the proposed control method using stickiness, $D = 1.0/\{\text{inter-robot distance}\}$, eliminated the congestion that was being formed at around 400 seconds. The results showed that each MHR circulated while keeping an equal interval.

These results demonstrated that the proposed control method is effective for a system without a bottleneck. In the next section, therefore, we apply the method to a batch manufacturing system in which the bottleneck exists.

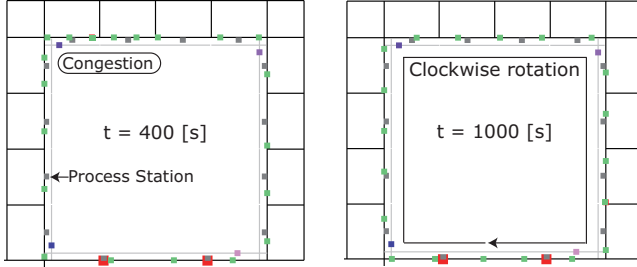
B. Effectiveness for a System with a Bottleneck

In this simulation experiment, the MHRs circulate in a system with different degrees of bottlenecks. That is to say, for each station, 1 \sim 12, shown in Fig. 1, a transport-production task is given in a random manner with a uniform probability; then, a series of tasks is listed as a recipe in one production batch. The total number of batches imposed on the MHRs is 200. In each recipe, a transport-production task for each station is given with a probability of 0.3, 0.6, and 0.9, in a random manner. The stations, 1 \sim 12, are located at intervals of 7.5 [m]. The discharging and cleaning stations are placed 15 [m] apart from each other. The number of MHRs is increased from 2 to 20 by two. Other settings regarding the MHR, system layout, and stickiness of the virtual damper are as described in VI-A.

The total operation times with the use of the previous and two proposed control methods are shown in Fig. 7. Although the proposed method was effective for a system



(a) Spontaneously occurring congestion of the circulating MHRs



(b) Eliminated congestion and circulating MHRs with an equal interval

Fig. 6. Snapshot of the Simulation with 20 Circulating MHRs

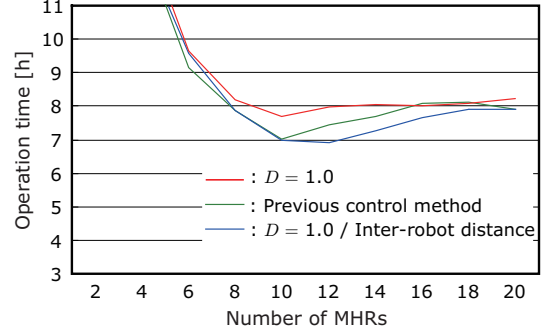
without a bottleneck regardless of stickiness D (see Fig. 5), for a system with a bottleneck, the proposed method with stickiness, $D = 1.0$, was the most time-consuming. On the other hand, the other proposed method, in which D was determined depending on the inter-robot distance to the stopping MHR, shortened the operation time as the number of MHRs increased, compared to the previous method. These results indicate that it is possible to improve the throughput for a system with a bottleneck by exerting a damping force on the moving MHR according to a suitable stickiness based on the inter-robot distance.

The reason of the different results for the two systems depending on D is that, in the system with a bottleneck, the MHR often had to stop and the congestion took place compared to the other system. The use of $D = 1.0$ indicates that a hard damper regardless of the distance between the stopping and moving MHRs is used, and $D = 1.0/\{\text{inter-robot distance}\}$ means that the inserted damper gradually becomes harder as the inter-robot distance decreases. Thus, an MHR reducing the velocity using a hard damper with $D = 1.0$ affected a large area.

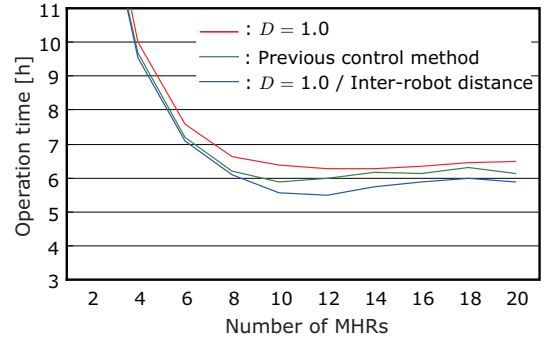
C. Result Analysis

We analyze the result described in VI-B on the basis of the MHRs' behavior controlled using the three methods. The average velocity of the MHRs, when the result listed in Fig. 7 was obtained, is shown in Fig. 8.

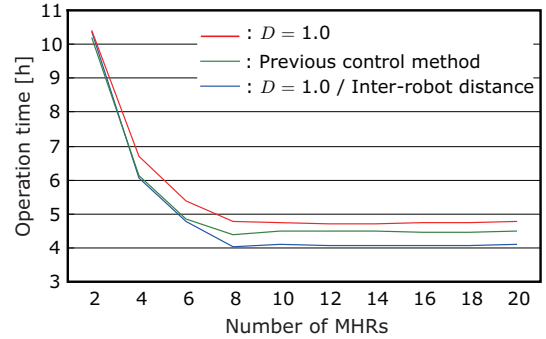
In each result, the average velocity is decreased due to the behavioral interference as the number of MHRs increases. In this regard, since the MHRs often had to stop at the stations due to a heavier bottleneck, the average velocities for the same number of MHRs were Fig. 8(a) < Fig. 8(b)



(a) A task is given with a probability 0.9 (heavy)



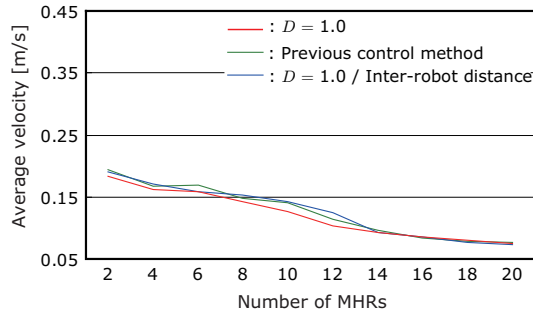
(b) A task is given with a probability 0.6 (medium)



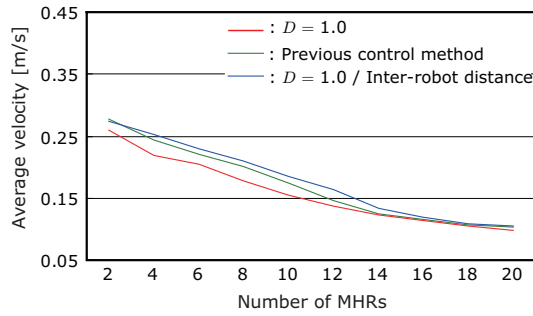
(c) A task is given with a probability 0.3 (light)

Fig. 7. Simulation Result of a System with a Bottleneck

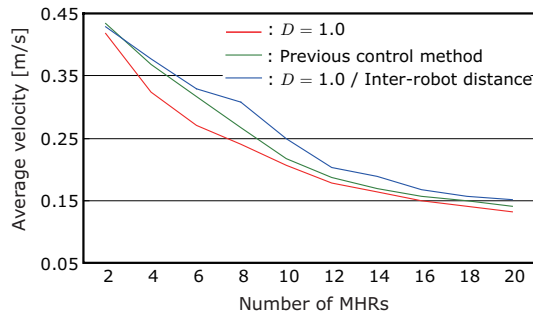
< Fig. 8(c). In addition, the average velocity affected the throughput; then, the operation times shown in Fig. 7 were Fig. 7(a) > Fig. 7(b) > Fig. 7(c), respectively. Moreover, in a comparison of the results of Fig. 8(a) and Fig. 8(b) with the result of Fig. 8(c), in Fig. 8(a) and Fig. 8(b), the average velocities using the three control methods were almost the same when the number of MHRs was over 14. The reason for this result is that the excess number of MHRs increased the behavioral interferences among the MHRs. For this reason, the operation times shown in Fig. 7(a) and Fig. 7(b) were increased when the number of MHRs was over 14. On the other hand, in Fig. 8(c), each average velocity obtained using each of the three control methods was different, and the



(a) Average velocity of the MHRs when Fig. 7(a)



(b) Average velocity of the MHRs when Fig. 7(b)



(c) Average velocity of the MHRs when Fig. 7(c)

Fig. 8. Analysis of the MHRs' Behavior in the System

average velocity using the proposed method was the fastest. Thus, in Fig. 7(c), the operation time was not increased but continued to be flat.

Compared to the results obtained when the number of MHRs was below 12, the average velocity obtained using the proposed method with stickiness, $D = 1.0$, was the slowest. This is because a strong external force always acted on the rearward moving MHR from the hard virtual damper in cases in which there were stopping and/or queuing MHR(s). On the other hand, by determining the stickiness of the virtual damper on the basis of the inter-robot distance, a small external force of the soft virtual damper acted on the MHR that was moving far from the stopping/queuing MHR(s), and the force was then gradually increased as the moving MHR approached; in this way, the MHRs were able to maintain an appropriate distance while reducing their

velocity in order not to become involved in the congestion. As a result, the average velocity using the proposed method was faster than the result of the previous control method. This result indicates that the proposed method was able to ease the congestion. Consequently, for the system with the bottleneck, the throughput was also improved; finally, the proposed control method resulted in the most efficient system, as shown in Fig. 7.

VII. CONCLUSION

In manufacturing systems, the occurrence of congestion that arises from a bottleneck is a serious concern. In a robotic manufacturing system, a bottleneck induces the congestion of MHRs. To overcome this issue, we proposed a behavior control method for the MHRs to eliminate or ease the congestion with the use of the virtual damper. Each robot adequately controlled the velocity on the basis of the damping force to keep the inter-robot distance in order not to become involved in the congestion. The simulation results showed that the proposed control method successfully improved the throughput of the system with a bottleneck by determining the stickiness of the damper according to the inter-robot distance and was effective for a more efficient system operation. This methodology could be useful not only for manufacturing systems but also for the AICCSs and intelligent transportation systems, ITSs, of vehicles.

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