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A STUDY ON REAL-TIME SCHEDULING METHODS IN HOLONIC MANUFACTURING SYSTEMS

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Abstract: Recently, new architectures of manufacturing systems have been proposed to realize flexible control structures of the manufacturing systems, which can cope with the dynamic changes in the volume and the variety of the products and also the unforeseen disruptions, such as failures of manufacturing resources and interruptions by high priority jobs. They are so called as the autonomous distributed manufacturing system, the biological manufacturing system and the holonic manufacturing system. Rule-based scheduling methods were proposed and applied to the real-time production scheduling problems of the HMS (Holonic Manufacturing System) in the previous report. However, there are still remaining problems from the viewpoint of the optimization of the whole production schedules. New procedures are proposed, in the present paper, to select the production schedules, aimed at generating effective production schedules in real-time. The proposed methods enable the individual holons to select suitable machining operations to be carried out in the next time period. Coordination process among the holons is also proposed to carry out the coordination based on the effectiveness values of the individual holons.

Key words: Manufacturing system, Holonic Manufacturing system, Real-time scheduling system, coordination

1. INTRODUCTION

Recently, automation of manufacturing systems in batch productions has been much developed aimed at realizing flexible small volume batch productions. The control structures of the manufacturing systems developed, such as FMS (Flexible Manufacturing System) and FMC (Flexible Manufacturing

Cell), are generally hierarchical. The hierarchical control structure is suitable for economical and efficient batch productions in steady state, but not adaptable to very small batch productions with dynamic changes in the volumes and the varieties of the products.

Computer systems and manufacturing cell controllers have recently made much progress, and individual computers and controllers are now able to share the decision-making capabilities in the manufacturing systems. The network architectures are widely utilized for the information exchange in the design and the manufacturing, and some standardized models, such as STEP [1] and CNC data model [2], have been developed for the information exchange through the information networks for the design and the manufacturing.

New distributed architectures of manufacturing systems are therefore proposed, in order to realize more flexible control structures of the manufacturing systems, in order to cope with the dynamic changes in the volume and the variety of the products and also the unforeseen disruptions, such as failure of manufacturing equipment and interruptions by high priority jobs. They are so called as autonomous distributed manufacturing system, biological manufacturing system, and holonic manufacturing system [3]-[13]

The objective of the research is to develop holonic control architecture of the manufacturing systems. This research is now being carried out as a part of an international cooperative research organized as a HMS (Holonic Manufacturing System) consortium. HMS consortium has defined holon as an autonomous and cooperative building block of a manufacturing system for transforming, transporting, storing and/or validating information and physical objects. The present paper deals mainly with the following issues.

(1) Procedures for the real-time scheduling in HMS,
(2) Real-time selection of suitable machining operations to be carried out in the next time period,
(3) Coordination methods among the selected machining operations by the individual holons, and
(4) Case studies for the real-time scheduling by the proposed methods.

2. REAL-TIME SCHEDULING PROCEDURE IN HMS

2.1 Scheduling Procedure of Existing System

One of the important objectives of the HMS is to provide the system components with the flexible and robust capability against the unforeseen disturbances of the manufacturing systems, such as failure of machining equipment and interruptions by high priority jobs. A real-time production scheduling system has therefore been proposed to control of the components of the HMS. The real-time scheduling means that the production schedules of the workpieces and the machining equipment are determined dynamically only when the status of the manufacturing system and its components are changed due to some events occur in the manufacturing system. Therefore, the scheduling system only determines the schedules of the workpieces and machining equipment in the next time period. The time period means the period between the time when one event occurs and one when another successive event occurs.

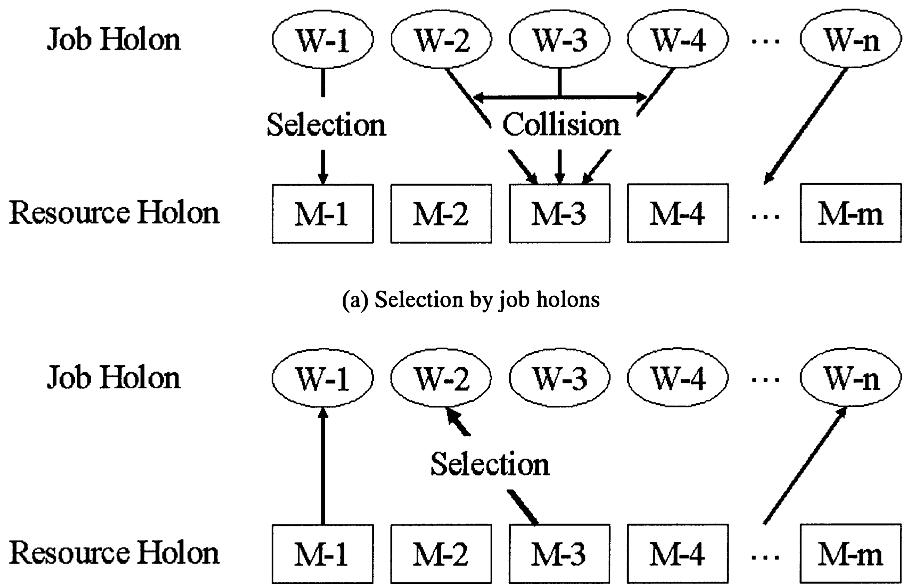
The scheduling system consists of a set of holonic components named job holons and resource holons, which represent the workpieces to be manufactured and the machining equipment, respectively. A distributed real-time scheduling method has been proposed, in the previous paper [13], to determine suitable production schedules dynamically, based on the decision-makings of the individual holons. The procedure to determine the schedule is summarized in the followings.

The individual holons in the HMS firstly modify their status, if one of the following events occurs. The status of the resource holons and the job holons are represented by 'operating' or 'idling'.

(1) a machining process of a job holon is finished,
(2) a new job holon is inputted to the HMS,
(3) a resource holon is broken down, or is recovered, and
(4) a status of a job holon is changed from normal one to high priority one.

In the second step, all the job holons which are 'idling' at that time select suitable resource holons, which are 'idle' and can carry out their machining processes in the next time period. Some collisions may occur among the selections of the job holons. For example, more than one job holons select a same resource holon for their next machining processes, as shown in Fig. 1 (a). If a resource holon is selected by more than one job holons, the resource holon selects a most suitable job holon, as shown in Fig. 1 (b), in order to avoid the collisions, in the third step. The job holons and the resource holons select most suitable ones by applying their own decision rules.

The procedure mentioned above provide the holons with an effective distributed scheduling system, however, the individual holons make decisions based on only their own decision-rules, which do not reflect the objectives of the whole HMS. Therefore, a new scheduling procedure is proposed, in the present paper, to determine a suitable combination between the job



(a) Selection by job holons

(b) Selection by resource holons

Figure 1. Rule-based real-time scheduling process [13]

holons and the resource holons from the viewpoint of coordination among all the holons.

2.2 New Scheduling Procedure

It is assumed here that the individual job holons have the following technological information representing the machining process of the jobs.

M_{ik}: k-th machining process of the job holon i. $(i = 1,..,a)$, $(k = 1,..,\beta)$.
A_{ik}: Required machining accuracy of machining process M_{ik}. It is assumed that the machining accuracy is represented by the levels of accuracy indicated by 1, 2, and 3, which mean rough, medium high, and high accuracy, individually.
R_{ikm}: m-th candidate of resource holon, which can carry out the machining process M_{ik}. $(m = 1,...,\gamma)$.
T_{ikm}: Machining time in the case where the resource holon R_{ikm} carries out the machining process M_{ik}.

The individual resource holons have the following technological information representing the machining capability of the resources for the machining process M_{ik}.

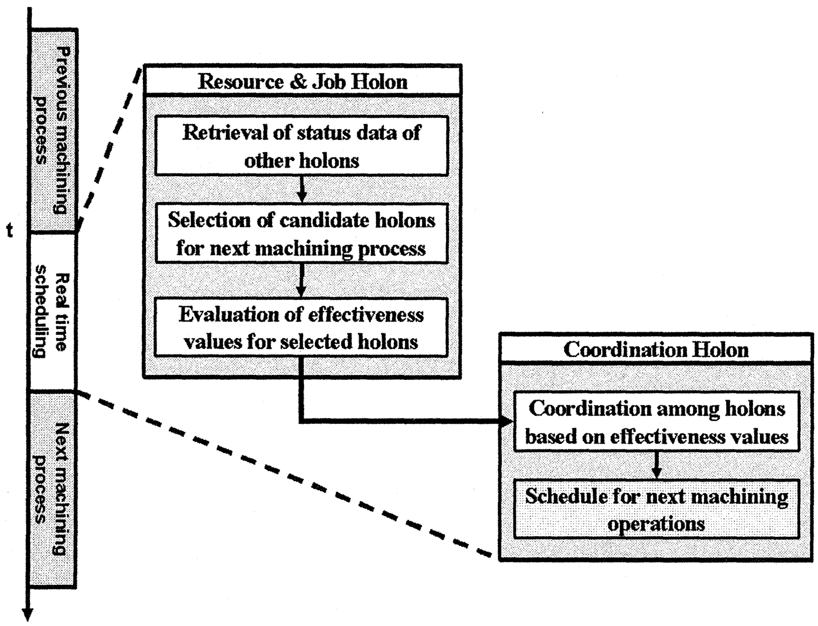


Figure 2. Real-time scheduling process proposed

MA_{ikm}: Machining accuracy in the case where the resource holon R_{ikm} carries out the machining process M_{ik}. MA_{ikm} is also represented by the level of 1, 2 and 3.
MC_{ikm}: Machining cost /unit time in the case where the resource holon R_{ikm} carries out the machining process M_{ik}.

Based on the information above mentioned, a procedure shown in Fig. 2 is proposed, in the present research, to select a suitable combination between the job holons and the resource holons which carries out the machining process in the next time period.

In the figure, t shows a time when some machining process are finished, and some resource holons and job holons change their status from 'machining' to 'idling'. At the time t, all the 'idling' holons have to select their machining schedules in the next time period. The following procedure is newly proposed for the individual holons to select their machining schedules.

(1) Retrieval of Status Data

The individual 'idling' holons firstly get the status data from the other holons which are 'operating' or 'idling'. The 'idling' holons can start the machining operation in the next time period.

(2) Selection of Candidate Holons

The individual 'idling' holons select all the candidate holons for the machining operations in the next time period. For instances, the job holon i selects the resource holons which can carry out the next machining process M_{ik}. On the other hand, the resource holon j select all the candidate job holons which can be machined by the resource holon j.

(3) Determination of Effectiveness Values

The individual holons determine the effectiveness values for the individual candidates selected in the second step. For example, the job holon determines the effectiveness values, based on its own criteria for all the candidate resource holons which can carry out the next machining process. The effectiveness values are given as follows.

JVEi(j) ($0 \leq$ JVEi(j) ≤ 1): Effectiveness value of the candidate resource j for the job holon i.
RVEj(i) ($0 \leq$ RVEj(i) ≤ 1): Effectiveness value of the candidate job i for the resource holon j.

(4) Coordination

All the 'idling' holons send the selected candidates and the effectiveness values of the candidates to the coordination holon. The coordination holon determine a suitable combination of 'idling' job holons and 'idling' resource holons which carry out the next machining processes in the next time period, based on the effectiveness values. The decision-criteria of the coordinate holon is to maximize the total effectiveness values of all the 'idling' holons.

3. EFFECTIVENESS VALUES AND COORDINATION

3.1 Effectiveness Values

The effectiveness values are evaluated based on the criteria of the individual holons, and various criteria are considered for the holons. Therefore, it is assumed that the individual holons have one of the objective functions shown in Table 1 for evaluating the effectiveness values, in the present research. They are:

(1) Availability factors of resource holons: ME

ME is the ratio of the total operating time of a resource holon and the total time after the resource holon starts the operations. The total time

Table 1. Objective functions of holons

Objective		Objective Functions
Resource Holon	Availability Factor	Σ Machining Time / Total Time
	Machining Accuracy	Σ (Machining Accuracy of Resources – Required Machining Accuracy of Jobs)
Job Holon	Total Processing Time	Σ (Machining Time + Idling Time)
	Machining Cost	Σ (Machining Cost of Resources)

includes both the operating time and the idling time of the resource holon.

(2) Machining accuracy of resource holons: MC
MC is the difference between the level of machining accuracy of the resources and the required level of accuracy of the machining process.

(3) Total processing time of job holons: JT
JT is the total time after the job is inputted to the HMS. JT includes the operating time and the idling time of the job.

(4) Machining cost of job holons: JC
JC is the sum of the machining cost of the job holon, which are obtained from the machining costs of the resource holons.

The following procedures are provided for the resource holons to evaluate the effectiveness values.

Let us consider a resource holon j at a time t. The total time after the resource holon j starts its operations, the availability factor, and the evaluated value of machining accuracy of the resource holon j are assumed to equal to $TT_{j.t}$, $ME_{j.t}$, and $MC_{j.t}$, respectively. If the resource holon j selects a candidate job holon i for carrying out the machining process M_{ik}, the availability factor and the evaluated value of the machining accuracy are estimated by the following equations.

$$ME_{j.t+1}(i) = (ME_{j.t} \cdot TT_{j.t} + T_{ikm})/(TT_{j.t} + T_{ikm}) \tag{1}$$

$$MC_{j.t+1}(i) = MC_{j.t} + (MA_{ikm} - A_{ik}) \tag{2}$$

Where, the resource holon j can carry out the machining process M_{ik} of job holon i. ($j = R_{ikm}$)

As regards the job holons, the following equations are applied to evaluate the total processing time and the machining costs, for the case where a job holon i selects a candidate resource holon j ($= R_{ikm}$) for carrying out the machining process M_{ik}. It is assumed that the total time after the job holon i is inputted to the HMS and the machining cost equal to $JT_{i.t}$ and $JC_{i.t}$, respectively.

$$JT_{i.t+1}(j) = JT_{i.t} + T_{ikm} \quad (3)$$

$$JC_{i.t+1}(j) = JC_{i.t} + MC_{ikm} \quad (4)$$

The objective functions mentioned above have different units. Some of them shall be maximized and others shall be minimized. Therefore, the effectiveness values are normalized from 0 to 1, by applying the following equations.

(1) Availability factors of resource holons:

$$RVE_j(i) = 1-(max(ME_{j.t+1}(i))-ME_{j.t+1}(i))/(max(ME_{j.t+1}(i))-min(ME_{j.t+1}(i))) \quad (5)$$

(2) Machining accuracy of resource holons:

$$RVE_j(i) = (max(MC_{j.t+1}(i))-MC_{j.t+1}(i))/(max(MC_{j.t+1}(i))-min(MC_{j.t+1}(i))) \quad (6)$$

(3) Total processing time of job holons:

$$JVE_i(j) = (max(JT_{i.t+1}(j))-JT_{i.t+1}(j))/(max(JT_{i.t+1}(j))-min(JT_{i.t+1}(j))) \quad (7)$$

(4) Machining cost of job holons:

$$JVE_i(j) = (max(JC_{i.t+1}(j))-JC_{i.t+1}(j))/(max(JC_{i.t+1}(j))-min(JC_{i.t+1}(j))) \quad (8)$$

Where, *max*(f(k)) and *min*(f(k)) give the maximum value and the minimum value of f(x) evaluated for all candidates k, respectively.

3.2 Coordination Process

After evaluating the effectiveness values, all the 'idling' holons send all the candidates and their effectiveness values to the coordination holon, and the coordination holon select a most suitable combination of the resource holons and the job holons, which execute the machining processes in the next time period. The coordination process is summarized in the following, for the case where the coordination holon determine a suitable combination of the job holon Job-i ($i = 1,2,..,\alpha$) and the resource holons Resource-j ($j=1,2,..,\gamma$).

The effectiveness value δ_{ij} of the combination of Job-i and Resource-j is given by the following equation, as shown in Table 2.

$$\delta_{ij} = RVE_i(j) + JVE_j(i) \quad (9)$$

The problem to be solved by the coordination holon is to select a combination of job holons and resource holons which maximize the total of the effectiveness value, as shown in the following equation.

Table 2. Effectiveness values of holons

	Resource-1	Resource-2	···	Resource- γ
Job-1	δ_{11}	δ_{12}	···	$\delta_{1\gamma}$
Job-2	δ_{21}	δ_{22}	···	$\delta_{2\gamma}$
···	···	···	···	···
Job- α	$\delta_{\alpha 1}$	$\delta_{\alpha 2}$	···	$\delta_{\alpha\gamma}$

Table 3. Combination of resource and job holons

	Resource-1	Resource-2	···	Resource- γ
Job-1	a_{11}	a_{12}	···	$a_{1\gamma}$
Job-2	a_{21}	a_{22}	···	$a_{2\gamma}$
···	···	···	···	···
Job- α	$a_{\alpha 1}$	$a_{\alpha 2}$	···	$a_{\alpha\gamma}$

$$\max\left(\sum_{i=1}^{\alpha}\sum_{j=1}^{\gamma} a_{ij} * \delta_{ij}\right) \tag{10}$$

where, a_{ij} (= 0 or 1) are the decision parameters, as shown in Table 3. If a_{ij} =1, the job holon i is machined by the resource holon j in the next time period. Otherwise, job holon i is not machined by the resource holon j. Only one job holon is machined by one resource holon, therefore, the following equation shall be satisfied.

$$\sum_{i=1}^{\alpha} a_{ij} \le 1,\ \sum_{j=1}^{\gamma} a_{ij} \le 1 \tag{11}$$

The branch-and-bound method is applied to determine the decision parameters a_{ij}, which maximize Eq. (10) under the constraints given by Eq. (11).

4. CASE STUDY

A prototype of real-time scheduling system for HMS has been developed based on the proposed methods to evaluate the effectiveness values and to carry out the coordination. Some case studies have been carried out to verify the proposed methods.

A holonic manufacturing system model consisting of 10 machining centers (MC) is considered for the case study. The machining centers are classified into 4 types, which have different machining functions, capacities and accuracy. The individual machining center holons have different objectives to evaluate the effectiveness values. The characteristics of the

Table 4. Combination of resource and job holons

Machine Tool Holon	Objective		Machine Type
	Case A	Case B	
MC1	Availability	Accuracy	Type1
MC2	Accuracy	Availability	
MC3	Availability	Accuracy	
MC4	Accuracy	Availability	Type2
MC5	Availability	Accuracy	
MC6	Accuracy	Availability	
MC7	Availability	Accuracy	Type3
MC8	Accuracy	Availability	
MC9	Availability	Accuracy	Type4
MC10	Accuracy	Availability	

Table 5. Objectives and machining processes of products

Job ID	objective	Processes	
		Case 1	Case 2
Job 1	Time	Type2→Type1→Type3→ Type4	Type3→Type1→Type4→ Type2
Job 2	Cost		
Job 3	Time	Type1→Type3→Type2→ Type4	Type1→Type4→Type2→ Type3
Job 4	Cost		
Job 5	Time	Type3→Type2→Type1→ Type4	Type4→Type2→Type3→ Type1
Job 6	Cost		
Job 7	Time	Type2→Type3→Type1	Type2→Type3→Type1
Job 8	Cost		
Job 9	Time	Type1→Type2→Type3	Type1→Type2→Type3
Job 10	Cost		
Job 11	Time	Type3→Type1→Type2	Type3→Type1→Type2
Job 12	Cost		

machining centers are summarized in Table 4. Cases A and B, in the table, mean that tow cases are considered for the case study from the viewpoints of the objectives of the machining center holons. As regards the job holons, the characteristics of the individual job holons are given in Table 5. The table gives the objectives to calculate the effectiveness values and the machining process of the jobs. Two cases are also considered from the viewpoints of the machining processes, as shown in the table.

An example of the machining schedules obtained in the case study is shown in Fig. 3. The obtained results were compared with the results determined by the rule-based method proposed in the previous paper [13], from the viewpoints of the objectives of the individual holons. Figure 4 summarizes the comparison of the proposed method and the previous method. In the figure, horizontal axis gives the objective functions of the individual holons, and the vertical axis shows the number of holons, the objective functions of which are improved by the proposed methods. As shown in the figure, the proposed methods improve the objective functions of the individual holons.

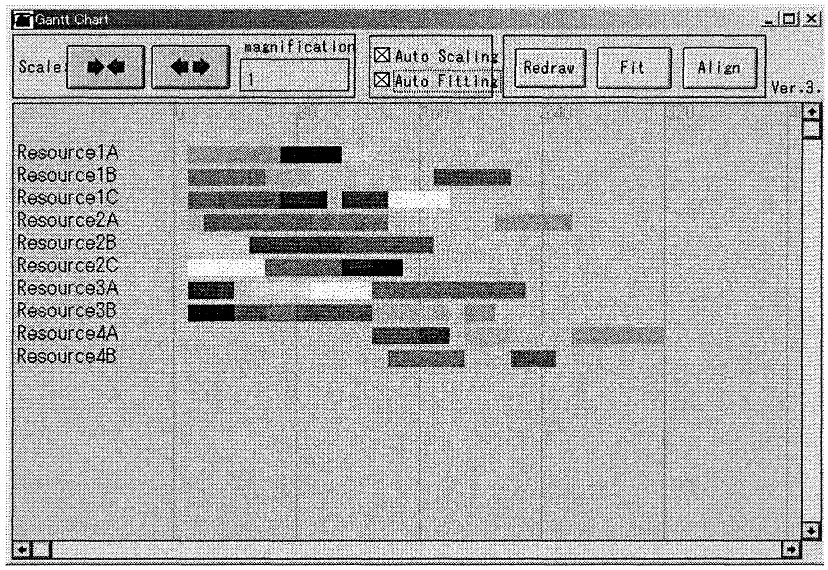


Figure 3. Machining schedules obtained

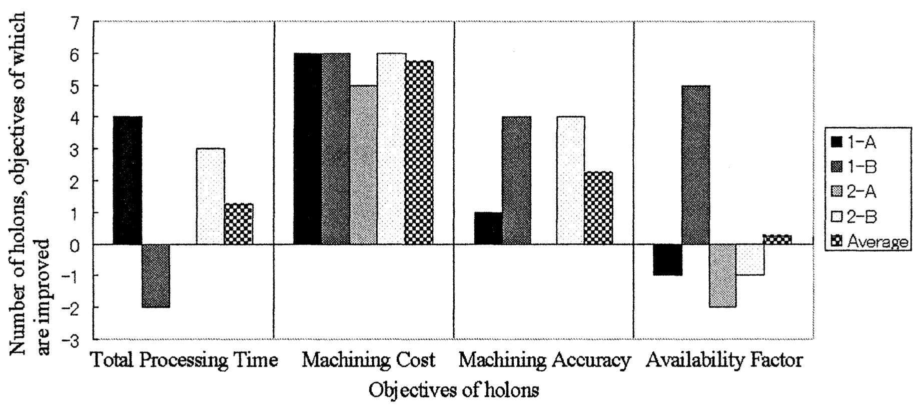


Figure 4. Comparison of proposed method and rule-based method

5. CONCLUSIONS

New real-time scheduling methods are proposed to select a suitable combination of the resource holons and job holons which carry out the machining process. The following remarks are concluded.

(1) A distributed decision-making procedure is proposed to select a suitable combinations of the resource holons and the job holons for the next machining processes, based on the effectiveness values for the candidates.
(2) A systematic method is proposed for the resource holons and the job holons to calculate the effectiveness values of the candidate holons. A coordination method is also developed for the coordination holon to determine a suitable combination of the resource holons and the job holons based on the effectiveness values of the individual holons.
(3) Some case studies of the real-time scheduling have been carried out to verify the proposed methods in comparison with the previous method. It was shown, through case studies, that the proposed methods are effective to improve the objective functions of the individual holons.

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