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PHYSICAL RESOURCE COORDINATION IN MANUFACTURING SYSTEMS

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Abstract: This paper focuses on the physical resource coordination problem for reconfigurable manufacturing systems. It establishes requirements for physical resource coordination to support highly reconfigurable manufacturing systems, and uses two illustrative examples to illustrate critical issues that must be considered. Finally, an approach to part of the physical resource coordination mechanism for reconfigurable systems is presented.

Keywords: manufacturing, manufacturing system, co-ordination, simulation, requirement analysis

1. INTRODUCTION

Manufacturing practices in the future will have to cope with customers demanding low cost products whose needs are likely to change quickly. Hence, the manufacturing operations will have to be organized differently and be more effective in responding. Traditional centralized manufacturing planning, scheduling and control mechanisms have been found incapable of supporting changing production methods or highly dynamic variations in product requirements (Leitao, 2002). Because of this, much research effort (e.g. Leitao, 2002; Koren et. al., 1999) is being devoted to developing manufacturing systems which are able react to changes rapidly and cost-effectively. One of the key properties of the manufacturing system which can react to changes rapidly and cost effectively is reconfigurability. The term reconfigurability can be defined as the ability of a manufacturing system to be simply altered in a timely and cost effective manner (Garcia-Herreros et al., 1994). This paper examines the implications of the requirement for reconfigurability in manufacturing control systems. It does so by looking at two typical manufacturing control problems.

A manufacturing system can be considered as a functional hierarchy (Phelan et al., 2003). Its fundamental function is to transform material to product. As shown in figure 1, a manufacturing system can be layered into shop floor, cell, machine and element level.

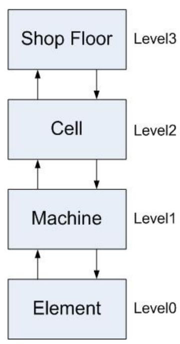

Fig. 1 Manufacturing system functional hierarchy (Phelan et al., 2003)

Each level has a number of control actions associated with it. In particular, one of the key requirements at the cell level is that of physical resource coordination in which interactions between resources are managed. A formal definition of the physical resource coordination problem is given below:

Definition 1.1 *(The Physical Resource Coordination Problem)*: *The physical resource coordination problem refers to the requirement for the reliable and efficient prevention of collision between two physical resources or between a physical resource and a static object in the manufacturing environment.*

In order to support reconfigurable manufacturing systems, Koren, et al. (1999) suggested that the structure of the manufacturing system and the associated hardware and control software in the manufacturing system must be reconfigurable. He also mentioned that machines should be easily integrated together to build a manufacturing system. In the context of the management of the physical resources, this implies that it must be easy and cost effective to add, remove or modify the machines in a manufacturing system. Further, since the workspaces of some machines in the manufacturing system overlap, these machines can collide with each other. Hence, in order to support a reconfigurable manufacturing system, a solution is required to the physical resource coordination problem that is easy to establish and also to modify when the layout of the manufacturing system is changed.

The aim of this paper is to establish the need for a physical resource coordination strategy that supports highly reconfigurable manufacturing systems and to propose the typical characteristics of such a strategy. The previous work in this area is reviewed in section 2. Section 3 proposes a framework that may be used to create and assess different physical coordination strategies to support reconfigurable systems. In Section 4, two case examples are presented to illustrate the features of the physical resource coordination problem and the way that they can be managed. Finally, section 5 summarizes the paper.

2. BACKGROUND

This section gives a brief review of the previous work relating to the physical resource coordination problem outlined in definition 1.1. The features and disadvantages of each previous approach in the context of supporting reconfigurability will be discussed. Based on these disadvantages the characteristics of the desired physical resource coordination mechanism are suggested in section 3 and a framework for developing such a strategy is proposed.

Physical resource coordination—or collision avoidance—can be viewed as a process of establishing, predicting or detecting potential *trajectories* of each resource, identifying potential intersections and adjusting the trajectories accordingly. Informally, it is noted that in order for such a strategy to readily support reconfigurability, it must require minimal *a priori* planning and be readily executed in the case of a new configuration.

This review begins by proposing that collision avoidance strategies can be categorized into five types which are:

S1: Those which create trajectories online during operation.
S2: Those which create a library of many trajectories off line and then select a suitable trajectory to avoid collision.
S3: Those which create a single fixed trajectory and then adapt this with manoeuvre protocol.
S4: Those which create trajectories and schedule all movements off line in advance.
S5: Those which create trajectories in advance off line and use reactive collision avoidance strategy without changing trajectories.

In S1, trajectories for physical entities are created online. The trajectories are changed (in real-time) if there is an obstacle(s) along the path. This method is suitable for a physical entity operating in unknown environment, for example, sub-sea vehicle path planning (e.g. Wang et al., 1997).

For S2, many trajectories are defined in advance. When an object needs to move from one point to another point, the most suitable path from all available paths is selected. This method is quite similar to those used in routing for road traffic (Papageorgiou, 2004).

In S3, a manoeuvre protocol approach is used, and the object moves along a pre-defined trajectory. If it is predicted that an object will collide with other object both objects will perform the manoeuvre protocol (a pre-defined action to guarantee that there will be no collision). After executing the manoeuvre protocol, both objects will continue to move along their old (or slightly changed) trajectories. An example of an application using this strategy is collision avoidance in air traffic control. The manoeuvre protocol called roundabout policy (Tomlin et al., 1998; Massink et al., 2001) is shown in figure 2.

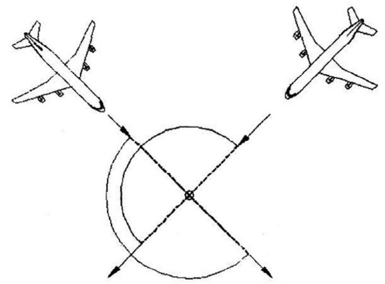

Fig. 2 The *roundabout* policy for air traffic collision avoidance (Massink et al., 2001)

Table 1 Comparison of Coordination Strategies

	S.1	S.2	S.3	S.4	S.5
Computationally Expensive	×				
Extra space required for executing collision avoidance strategy			×		
Not Flexible				×	
Application is limited		×			
Allows deadlock					×

In the fourth class of strategy (S4) all trajectories are created in advance. The allowed start time for each object to move along the predefined path is already specified. Hence, there will be no collision provided all objects start executing their operations at these predefined times. Some examples of previous work using this method include Akella's (2002) work in which this strategy is used to coordinate the motion of multiple robots and Spensiri (2003) who also uses this strategy in his work to provide collision avoidance in multiple robot welding cell.

In the final approach (S5) trajectories are also created offline but the start times for executing operations are not defined in advance. When objects or resources need to access shared space, they have to reserve that space (or check that the space is available) before they can gain access to it. S5 is used for example, in Zone logic (Cirocco et al., 1999), which is an approach to prevent collision between physical resources in manufacturing systems. All allowed states of each machine are defined in a mechanism table and an interference table. The machine can perform an operation if and only if it is permitted in both the mechanism table and the interference table. In a related approach called Control Logic (Matson et al., 2000), a machine must ask for permission from a "space manager" and must be granted this before it can get access to the shared space.

Table 1 provides a comparison between the five different classes of physical coordination strategy. In each case, particular shortcomings of the strategy that may limit its effectiveness in dealing with highly reconfigurable manufacturing systems are identified. The shortcomings considered are computational cost, space required for executing the strategy, flexibility and deadlock.

Note that the information in table 1 is intended to be indicative only as a guide to an effective approach for reconfigurable systems coordination. Nevertheless, table 1 indicates that currently available strategies must be improved before they can be used to solve the physical resource coordination problem.

Based on the review in this section, the next section proposes criteria for developing a physical resource coordination strategy to support reconfigurability. A framework for achieving this coordination strategy is also presented.

3. FRAMEWORK FOR PHYSICAL RESOURCE COORDINATION FOR RECONFIGURABLE MANUFACTURING SYSTEMS

It is mentioned in section 2 that available strategies need to be improved before they can be used to solve physical resource coordination problem in the context of a reconfigurable manufacturing system. The criteria for developing reconfigurable physical resource coordination are proposed in table 2.

Table 2 Criteria for developing a physical resource coordination strategy

Requirements	Sub requirements
1. Reliable	1.1 Practical
	1.2 Deadlock free
	1.3 Fault tolerance
2. Efficient	2.1 Resolvable in finite time
	2.2 Least restrictive
3. Reconfigurable	3.1 Modular
	3.2 Scalable
	3.3 Can be modified easily
	3.4 Can be integrated easily
	3.5 Diagnosable

As given in table 2, there are three fundamental requirements for a physical resource coordination strategy. The first requirement, reliability, ensures that the strategy is feasible, usable and robust. The second requirement, efficiency, is concerned with the processing power required and the performance of the mechanism. The final requirement, reconfigurability, implies that the physical resource coordination strategy must itself be easily reconfigured when a manufacturing system is to be set up, modified or extended. Sub-requirements shown in table 2 are key properties that will support these fundamental requirements.

From an examination of the different strategies in section 2, it is proposed here that the process of developing a physical resource coordination strategy comprises three main steps, which are *trajectory creation*, *collision prediction*, and *collision avoidance strategy creation.* These steps will be used as a guideline to develop a reconfigurable physical resource coordination strategy. Nevertheless, each step must be modified so that the reconfigurability requirements shown in table 2 can also be met. A brief explanation about the three steps is presented next.

Trajectory creation: Trajectory creation is a process of establishing potential trajectories for the resource from initial position to destination. Physical resources moving along these trajectories must not collide with static obstacles.

Collision prediction: Collision prediction can be performed once the trajectories have been created. It is a process of predicting whether a physical resource, moving along its trajectories, could potentially collide with other moving objects.

Collision avoidance strategy creation: This involves avoiding collision with other moving objects according to the chosen strategy. A strategy can be rules that are defined in advance, directions from a dynamically calculated collision avoidance algorithm, or may take some other forms. The collision avoidance process is initiated when it is predicted that physical resources have a potential to collide with other objects.

This section has proposed a framework for developing a physical resource coordination mechanism. This framework will be demonstrated in the next section.

4. CASE EXAMPLE

This section presents two examples of physical resource coordination problems. The first example demonstrates that reliability, efficiency and reconfigurability are desirable in a reconfigurable physical resource coordination mechanism. The second example investigates an approach that has the potential to be used as a part of a physical resource coordination solution.

4.1 Case study one: The two slide problem

The aim of this case study is to examine the desired properties of the physical resource coordination mechanism that is to be used in the reconfigurable manufacturing system. Three coordination strategies from class S5 in section 2 are implemented and the performance of these three coordination strategies is compared.

The layout of a simple manufacturing cell, which will be used for this example, is shown in figure 3. There are four slides in this manufacturing cell. The slides are used to transfer material from start point (current position of the slide) to destination (the opposite side to the start point). Limit switches (depicted by lines in figure 3) are used to detect the positions of the slides. The aim of this example is to examine the performance of a set of the strategies in terms of the criteria in Table 2.

This physical resource coordination problem is now examined using the framework presented in section 3.

Trajectory creation: In this example, the trajectories for the slides are defined offline. Each slide will move along a straight line (its trajectory) between its start point and destination.

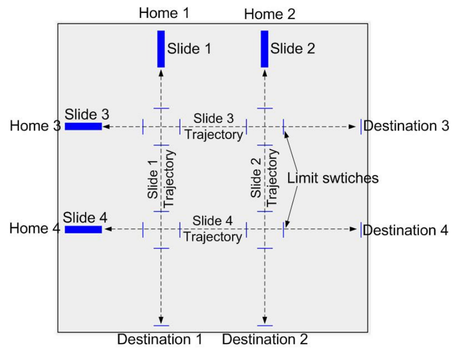

Fig. 3. Layout of the manufacturing cell for the two slide problem

Collision prediction: Based on the defined trajectory for each slide, collision prediction is performed by identifying the zones in which there is a potential for collision. This is found by identifying overlapping trajectories for any two slides. Limit switches are placed around these shared spaces. They are used to represent the size of the shared spaces recognized by each slide. Note that it is not necessary for the limit switches to be placed exactly at the border of the real physical shared spaces. They can be placed outward from the border of the real physical shared spaces which will increase the size of the shared space recognize by the associated slide. The distance between the border of the real physical shared space and a limit switch is referred to here as *extra shared space*. In this example, all extra shared spaces are equal. The central controller uses information from the limit switches to control access to the shared spaces.

Collision avoidance strategy creation: Three coordination strategies are implemented in this example. They are described below.

- Strategy A: Only one slide that desires access to the same shared space can move at a time.
- Strategy B: A slide has to book the shared space before it can access that shared space.
- Strategy C: A slide has to book all shared spaces along its entire path before it can access any one of these shared spaces.

To evaluate the performance for each strategy, all slides are expected to perform 20 tasks. For each task, the slide has to move from its start point to its destination and return to its start point. When all slides finish their tasks, the average throughput (per 1000 time unit) is calculated by using the equation below.

$$\text{Average throughput} = \frac{1000n}{\sum_{i=1}^{n} \frac{TS_i}{T_i}}$$

Where n is the number of the slides, TS_i is the total time required to finish all tasks for slide i and T_i is the number of the task assigned to slide i. After the average throughput had been calculated, the position of the limit switches around shared spaces was changed to increase the size of the shared spaces and the simulation was repeated. The above procedure was repeated for all coordination strategies. It is assumed that zero time is required to load and unload material from the slides. Results from the simulation are shown in Figure 4.

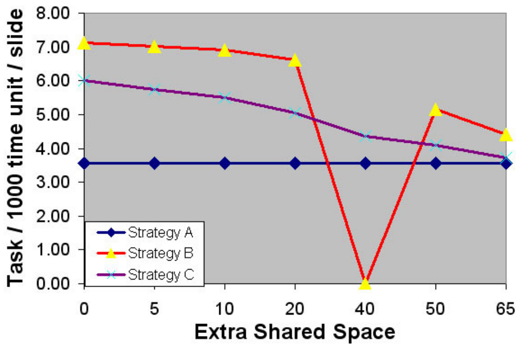

Fig. 4. Average Throughput of the manufacturing cell using different strategies.

From the simulation results, it is clear that the least restrictive strategy (strategy B) gives the best throughput performance in most cases. This strategy is not reliable, however since it is not guaranteed to be deadlock-free (average throughput = 0 at extra shared space size = 40). A deadlock-free strategy is usually achieved by introducing a more conservative strategy (A or C). Such a strategy is more restrictive and the performance is decreased.

From the results, it is seen that an efficient coordination strategy might be desired, since it allows better performance. A reliable strategy is also desired, since it guarantees that all tasks required will be finished. Finally, if an additional slide is to be added to the system, it is desired that minimal effort and time is needed to modify the physical resource coordination mechanism. Thus, the mechanism should also be reconfigurable.

4.2 Case study 2: The packing cell

This second case study presents an approach for gathering the information required to create a physical resource coordination mechanism. This approach tries to minimize the need for a priori knowledge about factory layout and interaction between resources in the early stage of strategy development. Information about each resource is gathered individually and information about other resources will be needed only when all resources are integrated to build a manufacturing system. Hence, this approach is potentially well suited to reconfigurable manufacturing environments.

The layout of the manufacturing cell for this example is shown in figure 5. There are three resources in this manufacturing cell, labeled robot1, robot2 and shuttle. A physical resource coordination mechanism is required to prevent collision between these resources. It is assumed that these resources have the ability to communicate with other resources, since communication is required when all resources are integrated to form a manufacturing cell (described later in this section). To simplify the problem, it is assumed that the links of both robots will not collide with any other object nor themselves. Hence, the only part of the robot which can collide with other objects is its end effector.

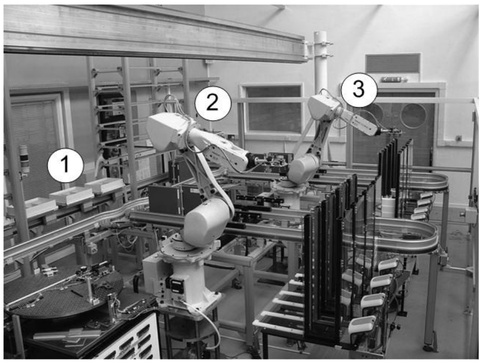

Fig. 5. Layout of the manufacturing cell; showing shuttles (1), robot 2 (2) and robot 1 (3)

To examine the requirements for the physical resource coordination mechanism, the framework proposed in section 3 is used.

Trajectory Creation: First, trajectories for each resource must be created individually. The created trajectories ensure that the resource will not collide with static (non-moving) objects within its work space. Note that the information about other resources is not needed in this step. The swept volume and the different trajectories for Robot 1 are given in Figure 6 as an example.

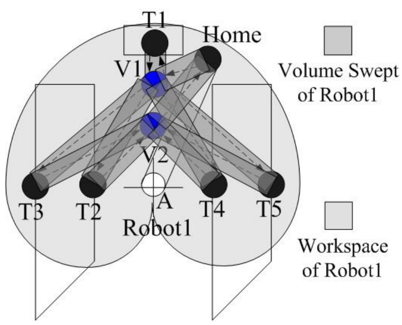

Fig. 6. Swept volume and trajectory of robot 1

Collision prediction: Collision prediction starts with calculating the swept volume required by each resource. Since other resources are not considered at this stage, there will be no collision with other resources. The collision prediction process can be completed only when all resources are integrated to create a manufacturing cell. When the resources are integrated, it is possible to detect whether one resource's swept volume overlaps with another resources' swept volume. If an overlapping swept volume is detected, then an interference zone is defined for each overlap. An interference zone represents the volume in which the collisions between resources may occur. Figure 7 illustrates the interference zone arising between Robot 1, Robot 2 and the shuttle. With specific reference to reconfigurability, note that it is possible to perform this step in a relatively distributed manner, such that each resource is responsible for its own workspace and trajectory information. Then, when the resources are integrated, each resource communicates its workspace to the other resources and this is reciprocated. Each then detects whether there is another resource's workspace that overlaps with its workspace. If an overlapping workspace is detected, it then establishes a communication link with the resource associated with that workspace.

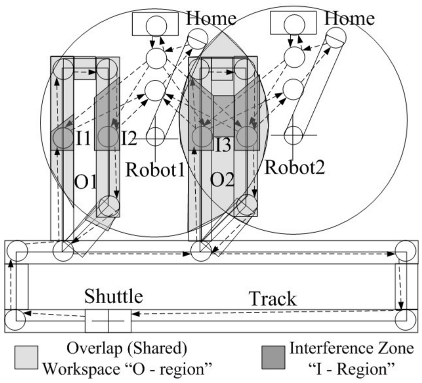

Fig. 7. Overlapping Interference zones

This provides a potential method to gather the required information for creating physical resource coordination mechanisms *without* requiring a priori knowledge of other resources before all resources are integrated. Future work will identify collision avoidance strategies compatible with this type of distributed approach to collision information management.

5. CONCLUSION

This paper introduces a physical resource coordination problem in manufacturing system. The criteria for developing the coordination mechanism are also suggested. Two case studies are presented in this paper. The first example demonstrates that reliable, efficient and reconfigurable are desired in**?** physical resource coordination mechanism for reconfigurable manufacturing system. The second example investigates an approach that has the potential to be used as a part of a physical resource coordination solution. Nevertheless, a complete solution for the resource coordination problem which supports reconfigurability is not yet achieved. It is believed that developing a distributed collision avoidance strategy is the key to the solution of the reconfigurable physical resource coordination problem.

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