Modeling and information structures for supervisory control of flexible manufacturing systems

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Abstract

In this paper we discuss a new matrix-based modeling technique for flexible manufacturing systems (FMS). Four Task Plan Matrices can completely describe the job sequencing and resource assignment details of an FMS. The matrices come directly from plans generated by machine planners, or from the bill of materials and resource requirements matrix. Given the matrices, a rule-based supervisory controller operates in real-time to sequence jobs and assign resources depending on dynamic situational information about parts available, resources idle, and jobs completed. The function of the FMS can be quickly changed when new products are needed simply by changing the four matrices. By deriving explicit mathematical formulas for p-invariants and the resource requirement matrix for generalized reentrant flow lines, NP-complexity problems are avoided, which is often an issue in other modeling techniques.

Keywords

Manufacturing, discrete event systems, flexible manufacturing systems.

1 INTRODUCTION

For complex manufacturing processes it is very difficult to provide a mathematical model suitable for fast redesign of dispatching and routing controllers. In existing models (e.g. Petri nets) the functions of the workcell and of the rule-based controller are not separated, so that fast reconfiguration for changing goals and new products is not easy. Dealing with machine failures, changes in product mix, technological changes, changes in goals, etc., requires modifying the controller rules in real-time, which is difficult.

In Industrial Engineering there is a wide variety of techniques available for manufacturing scheduling such as the assembly tree [Wolter et al. 1992], bill of material (BOM) [Elsayed and Boucher 1994], resource requirement (RR) matrix [Kusiak 1992], and sequencing matrix [Steward 1981, Warfield 1973]. Unfortunately, these are treated as heuristic aids and cannot provide a rigorous mathematical framework as needed for computer analysis and control of manufacturing systems. Industrial Engineering approaches such as queuing methods [Kumar 1993], Operations Research (OR) approaches [Conway 1967, Graves 1984], etc., can provide rigorous analysis and are convenient for determining steady-state solutions. Transient analysis and analysis for large-scale systems is difficult.

Rigorous approaches for analysis of discrete event dynamical systems (DEDS) are emerging in Electrical Engineering and Computer Engineering. DEDS include communication networks, manufacturing systems, Intelligent Vehicle and Highway Systems, etc. Available analysis tools include Petri nets (PN) [Desrochers 1990, Krogh, 1991, Murata 1989, Peterson 1981, Zhou 1993], the max/plus algebra [Cohen 1985], perturbation analysis [Ho 1987, 1989], object oriented techniques [Glassey 1990], etc. Unfortunately, it is difficult to provide a mathematical model for a manufacturing system that can be used to guarantee deadlock-free performance, efficient shared-resource conflict resolution, and suitable part-routings. PN are difficult to construct. The max/plus equations cannot be written down unless a decision-free PN is available. Finally, computational complexity associated with these techniques very often leads to intractability [Garey and Johnson 1979].

This paper discusses an analytic matrix framework for discrete event manufacturing systems modeling, analysis and control. By taking advantage of this matrix model, explicit formulae are provided for some useful information structures used in analysis and design, thereby correcting the prime deficiency of Petri net and other modeling concepts – the inability to provide efficient computational techniques.

2 INTELLIGENT MANUFACTURING

With the development of automation technology its supporting systems - planning, scheduling, and control - have gained importance. Fast response to market demands and flexibility involves sophisticated control architectures in

manufacturing systems. The hybrid nature of FMS and flexibility issues increase the role of multi-layer architectures with enhanced sensing, modeling, and execution capabilities. All of these concepts are captured by the so-called intelligent control (IC) architectures that have been studied extensively in the last decade [Antsaklis and Passino 1992, Kusiak 1992, Saridis 1996].

Figure 1 Three-level intelligent control architecture.

A general IC architecture based on work by Saridis is given in Figure 1, which illustrates the principle of decreasing precision with increasing abstraction. In this figure, the organization level is considered to be the highest level of decision-making where the Production Plan (PP), Master Production Schedule (MPS), and Material Requirements Planning (MRP) is developed through information provided by the marketing department forecasts and upper management plans. This level has a role of a manager that schedules and assigns tasks, performs task decomposition and planning, and determines for each task a required partial ordering of jobs. The coordination level performs the exact job sequencing, coordinating the workcell agents or resources. In addition, in the case of shared resources it must execute dispatching and conflict-resolution decisions. The agents or resources might include automated machine tools, robot manipulators, material handling, storage systems and computer hardware for planning, data acquisition and decision-making. The execution level contains a closed-loop controller for each agent that is responsible for its real-time performance.

It is shown [Harris et al. 1997] that a task plan produced in the organization level is equivalent to four matrices; two of them capturing the information on job sequencing and two others describing the assignment and release of resources that are needed to perform the jobs. The matrices are passed to a supervisory controller in the Coordination level for real-time execution of the plan.

Based upon the matrix model of discrete event systems [Lewis et al.1993] it is easy to design the intelligent rule-based workcell controller. The objective of designing the controller is to provide two main functions: (1) job sequencing, (2) resource allocation and conflict resolution. The controller design is based upon a matrix model of discrete manufacturing systems that is fully consistent with the IC

architecture described above. In the next section, the matrix model of discrete event manufacturing systems [DEMS] will be discussed in more detail.

3 MATRIX MODEL FOR DISCRETE EVENT MANUFACTURING SYSTEMS

A new rule-based DEMS matrix model [Lewis et al. 1993] is now described that provides a framework for rigorous analysis of discrete event manufacturing systems. The matrix discrete model is described by the following equations:

Logical matrix state equation

$$\bar{x} = F_v \bar{v}_c + F_r \bar{r}_c + F_u \bar{u} + F_D \bar{u}_D . \quad (1)$$

Job start equation

$$v_s = S_v x . \quad (2)$$

Resource release equation

$$r_s = S_r x . \quad (3)$$

Product output equation

$$y = S_y x . \quad (4)$$

PN transition equation

$$m(k+1) = m(k) + W^T x(k+1) . \quad (5)$$

The matrix state equation is a set of rules, so that it is formally a rule base. Entries of 1 in v_c and r_c respectively indicate jobs complete and resources idle. A computed entry $x_i = 1$ of logical state vector x indicates that all the conditions required to fire rule i are met. Entries of 1 in v_s , r_s respectively indicate the jobs to be started or resources to be released. The overbar in equation (1) denotes logical negation. (Given a natural number vector a , its negation $\bar{a}$ is such that $\bar{a}(i) = 0$ if $a(i) > 0$, and 1 otherwise; for instance, job complete is shown by $\bar{0}$. Overbar notation is used similarly throughout the paper). Finally, all matrix operations are defined to be in and/or algebra where multiplication is replaced by 'and' and addition by 'or'.

These equations are easy to write down: F_v is Steward's job sequencing matrix (JSM) [Steward 1962], and can be determined from the *Bill of Materials* (BOM) [Elsayed and Boucher, 1994] or the assembly tree [Chakrabarty and Tsao, 1992].

$F_v(i,j) = 1$ if job j is required as an immediate precursor to job i (equivalently, in the BOM, if subassembly j is required to produce subassembly i). F_r is the resource requirements matrix of Kusiak (1992), which is assigned by the shop-floor engineer, with $F_r(i,j) = 1$ if resource j is required for job i . The job sequencing matrix F_v and the resource requirements matrix F_r have long been used as heuristic design aids by industrial engineers, with some possibility for limited analysis (as discussed e.g. by Warfield (1973) in the case of F_v and Kusiak (1992) in the case of F_r). The logical matrix model elevates these design tools to formal computation elements.

The job start matrix S_v and the resource release matrix S_r are additional matrices that must be introduced to complete the description of the controller, and they are equally direct to write down for a specific DEMS. $S_v(i,j) = 1$ if job i is to be started when all the requirements of logical component x_j of the decision rule vector $\mathbf{x}$ are satisfied (i.e., x_j is set high). When there are no routings in the system this matrix has a diagonal of 1's. In the more general job shop case, it has multiple ones in columns, which correspond to job routing decisions. $S_r(i,j) = 1$ if resource i to be released when logical state component x_j is set high.

Input $\mathbf{u}$ and output $\mathbf{y}$ represents, respectively, raw parts entering and finished products leaving the cell. Input $\mathbf{u}_p$ is a conflict resolution input that selects the jobs to be initiated when there are simultaneous requests involving shared resources, a situation which may occur when the resource requirements matrix F_r has multiple 1's in the same column. To resolve such potential conflict and turn the controller into a 'decision-free' graph [Cofer and Garg, 1992], it is therefore necessary to add the extra dispatching control input $\mathbf{u}_p$, which is allowed to have only one of its entries of a given column high at any given instant.

It is exactly in the selection of the dispatching control input $\mathbf{u}_p$ that the dispatching rules available in the industrial engineering literature [Panwalker and Iskander 1977; Elsayed and Boucher 1994] can be used.

It is important to label the jobs causally in the formulation of the controller so as to obtain F_v and S_v in lower triangular form [Warfield 1977]. A causal ordering is important also in proving the results on the computation of deadlock analysis structures. The components of the rule vector $\mathbf{x}$ should then be ordered in accordance with the jobs they initiate. This procedure corresponds to numbering the jobs from bottom to top in an assembly tree.

The transition equation (5) together with matrix state equation (1) provide complete dynamical description of the system where

$$m(k) = \begin{bmatrix} v_c(k) \\ r_c(k) \end{bmatrix}, \quad (6)$$

represents the PN marking vector at discrete event iteration k , and

$$W = [S_v^T - F_v \quad S_r^T - F_r], \quad (7)$$

represents the PN incidence matrix.

4 INTELLIGENT RULE-BASED CONTROLLER DESIGN

Control of discrete event manufacturing systems (DEMS) [Lewis et al. 1993] is examined from a system theory perspective which makes an explicit distinction between the plant or workcell (comprised of machines and resources to be controlled) and the controller (representing a real-time decision-making scheduler in the coordination level which implements a rule base). This rigorous point of view is able to provide a design algorithm for discrete event control systems that afford a very convenient approach to the design of DEMS. The controller has an intelligent rule-based structure and consists of inner loops, where no conflict resolution is needed and outer loops, where logic is needed to resolve shared-resource conflicts. The DEMS matrix controller design will be illustrated through the example.

Figure 2a depicts an assembly tree, which shows the required sequence of actions (jobs) to produce a product. This assembly tree contains information analogous to the BOM; it does not include any resource information.

Figure 2a Assembly tree.

Figure 2b Subassembly tree.

To build a dispatching controller for shop-floor installation to perform this particular assembly task, the resources available must be added. Figure 2b shows a subassembly tree for the assembly task, which includes the resource requirement information.

Referring to Figure 2a, define the job vector as $\mathbf{v} = [R1P1 \ BP \ M1P \ R1P2 \ R1P3 \ M2P1 \ R1P4 \ M3P \ M2P2]^T$, the input vector $\mathbf{u} = [PI1 \ PU2]^T$, and the output vector $\mathbf{y} = [PO1 \ PO2]$. The job vector $\mathbf{v}$ has two interpretations: as a status output of the workcell, it denotes completed jobs; in this role it is denoted as $\mathbf{v}_c$. On the other hand, as an input of the workcell, it represents the job start command vector; in which case it is denoted by $\mathbf{v}_s$. Define the controller state vector $\mathbf{x}$, each

component corresponding to a unique component of vectors $\mathbf{v}$ or $\mathbf{y}$, thus representing the initiation rule for the latter. Then, the job start equation and the part output equations are:

$$\mathbf{v}_s = \begin{bmatrix} 10000000000 \\ 01000000000 \\ 00100000000 \\ 00010000000 \\ 00000100000 \\ 00000010000 \\ 00000001000 \\ 00000000100 \\ 00000000010 \\ 00000000001 \end{bmatrix} \begin{bmatrix} x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \\ x_{15} \\ x_{21} \\ x_{22} \\ x_{23} \\ x_{24} \\ x_{25} \\ x_{26} \end{bmatrix} \equiv \mathbf{S}_v \mathbf{x} \quad (8)$$

$$\mathbf{PO} = \begin{bmatrix} \mathbf{PO1} \\ \mathbf{PO2} \end{bmatrix} = \begin{bmatrix} 00001000000 \\ 00000000001 \end{bmatrix} \mathbf{x} \equiv \mathbf{S}_y \mathbf{x} \quad (9)$$

Referring to Figure 2b, define the resource vector $\mathbf{r}$ as $\mathbf{r} = [\mathbf{M1A} \ \mathbf{M2A} \ \mathbf{M3A} \ \mathbf{BA} \ \mathbf{R1A} \ \mathbf{PA1A} \ \mathbf{PA2A}]^T$, where 'A' stands for 'available'. Vector $\mathbf{r}$ accounts for all the resources and pallets in the flowline. Now, by inspection of the subassembly tree, write down $\mathbf{F}_v$, $\mathbf{F}_r$ and $\mathbf{F}_u$, and obtain the controller state equation

$$\bar{\mathbf{x}} \equiv \begin{bmatrix} x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \\ x_{15} \\ x_{21} \\ x_{22} \\ x_{23} \\ x_{24} \\ x_{25} \\ x_{26} \end{bmatrix} = \begin{bmatrix} 000000000 \\ 100000000 \\ 010000000 \\ 001000000 \\ 000100000 \\ 000000000 \\ 000010000 \\ 000001000 \\ 000000100 \\ 000000010 \\ 000000001 \end{bmatrix} \begin{bmatrix} \mathbf{R1P1} \\ \mathbf{BP} \\ \mathbf{M1P} \\ \mathbf{R1P2} \\ \mathbf{R1P3} \\ \mathbf{M2P1} \\ \mathbf{R1P4} \\ \mathbf{M3P} \\ \mathbf{M2P2} \end{bmatrix} + \begin{bmatrix} 0000110 \\ 0001000 \\ 1000000 \\ 0000100 \\ 0000000 \\ 0000101 \\ 0100000 \\ 0000000 \\ 0010000 \\ 0100000 \\ 0000000 \end{bmatrix} \begin{bmatrix} \mathbf{M1A} \\ \mathbf{M2A} \\ \mathbf{M3A} \\ \mathbf{BA} \\ \mathbf{R1A} \\ \mathbf{PA1} \\ \mathbf{PA2} \end{bmatrix} + \begin{bmatrix} 10 \\ 00 \\ 00 \\ 00 \\ 00 \\ 01 \\ 00 \\ 00 \\ 00 \\ 00 \\ 00 \end{bmatrix} \begin{bmatrix} \mathbf{PI1} \\ \mathbf{PI2} \end{bmatrix} + \begin{bmatrix} 100000 \\ 000000 \\ 000000 \\ 010000 \\ 000000 \\ 001000 \\ 000100 \\ 000010 \\ 000000 \\ 000001 \\ 000000 \end{bmatrix} \begin{bmatrix} u_{d1} \\ u_{d2} \\ u_{d3} \\ u_{d4} \\ u_{d5} \\ u_{d6} \end{bmatrix} \quad (10)$$

In this equation, row 7, for instance, indicates that component x_{22} is set high if job R1P3 is done and resource M2 is available. To verify this one can formally work out the logical operations using deMorgan's rules.

The last issue to be resolved in this design is that of resource and pallet release. Thus, using industrial engineering experience and Figure 2b, obtain the resource and pallet release matrix S_r and write down the resource release equation

$$\mathbf{r}_s = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \\ x_{15} \\ x_{21} \\ x_{22} \\ x_{23} \\ x_{24} \\ x_{25} \\ x_{26} \end{bmatrix} \equiv S_r \mathbf{x}, \quad (11)$$

where subscript 's' denotes a command to the workcell to start resource release.

It should be emphasized that F_v and S_v depend only on job sequencing information, while all the resource information is contained in F_r and S_r . Note that rows containing multiple ones in S_r correspond to columns having multiple ones in F_r . The dispatching input, u_d , is needed as a control decision input, since F_r has multiple 1's in its 2nd and 6th columns, indicating that machine M2 and robot R1 are shared resources.

Figure 3 Petri net representation of the workcell with shared resources.

It is straightforward to derive the Petri net description of a manufacturing system from the matrix model equations (1)-(4). This allows all the Petri net analyses tools to be used for DEMS within the matrix model framework. Figure 3, depicts the

Petri net model with an initial marking reflecting the number of resources available in the workcell (system idle).

DEMS structure analysis and associated computational complexity issues are addressed in the next section. Taking advantage of the matrix model, explicit formulas are provided for some useful information structures used in analysis and design, thereby correcting the prime deficiency of Petri net and other modeling concepts – the inability to provide efficient computational techniques.

5 MATRIX FRAMEWORK AND COMPUTATIONAL COMPLEXITY

There are many distinct analysis and design problems to be solved in FMS, including scheduling with optimality, computation of PN p-invariants to determine resource loops, analysis of deadlocks and circular waits, design and implementation of deadlock avoidance strategies, and design/selection of dispatching and routing algorithms. These problems have varying degrees of complexity, which depends on whether one has a flow line, assembly line, or general job shop structure.

The theory of NP-completeness [Garey and Johnson 1979] potentially provides a comprehensive approach for analysis of computational complexity in FMS. Many traditional scheduling and sequencing problems have been found to be in NP so that significant increase in computing power do not significantly improve computational capabilities. Thus it has been necessary to develop heuristics or approximate methods for analysis and solution.

Petri Nets have been extensively used in the analysis of manufacturing systems with quite variable results. The PN incidence matrix has been used to study structural properties of FMS, including determination of the siphons [Boer 1994] and deadlock avoidance [Lewis et al. 1996]. However PN applications have not fully exploited the matrix nature of the system structure and lead to computational intractability.

The new DE matrix model overcomes one of the prime deficiencies of PN theory - it provides rigorous computational techniques for DE systems. As an example we select the representative problem of determining the p-invariants for the very general class of reentrant flow lines with assembly that allow more than one resource to be assigned to job, as well as to assign a resource to more than one job in the sequence. The p-invariants have been extensively studied in work by [Desrochers 1990], [Jeng and DiCesare 1993], [Zhou 1993] and elsewhere. They provide the basis for several FMS control techniques that involve dispatching of shared resources. The Matrix model allows p-invariants to be given by an explicit matrix formula.

Using Petri net terminology, a p-invariant can be defined as a place vector $\mathbf{p}$ having elements of zeros and ones that is in the nullspace of incidence matrix W , that is

$$W \cdot p = \underline{0}. \quad (12)$$

Where W is given by (7) and place vector can be partitioned by vector of job places v and vector of resource places r . Now (12) becomes

$$[W_v \ W_r] \begin{bmatrix} v \\ r \end{bmatrix} = \underline{0}, \quad (13)$$

which is equivalent with

$$W_v \cdot v = - W_r \cdot r. \quad (14)$$

To find v vectors, multiply (12) by W_v^T to get the square term on the left side and than take its inverse getting

$$v = -(W_v^T \cdot W_v)^{-1} \cdot W_r \cdot r. \quad (15)$$

Now for each particular resource, set the r vector by putting the 1 in appropriate row and vector v will give us the set of jobs contained in the corresponding resource loop. Make note that v vectors form a resource requirement matrix (RR) [Kusiak 1992] that provides the basis for dispatching of shared resources (MDR rule). To obtain the (RR) matrix set $r = I$, the identity resulting in

$$F_k = -(W_v^T \cdot W_v)^{-1} \cdot W_r. \quad (16)$$

Every conservative system (very broad class of manufacturing systems have this property) has one and only one set of jobs that together with corresponding resource form a p-invariant vector. Therefore in these systems, matrix $(W_v^T \cdot W_v)$ is always invertible.

The complete set of p-invariants is given by the columns of the matrix,

$$P = \begin{bmatrix} F_k \\ I \end{bmatrix}, \quad (17)$$

where F_k is the resource requirement matrix, and I , the identity matrix.

To illustrate the formula (17), consider the example in Figure 4. This example belongs to the very general class of reentrant flow lines with assembly that allow more than one resource to be assigned to job, as well as to assign a resource to more than one job in the sequence.

Figure 4 Example of generalized reentrant flow line with assembly.

From (7),

$$W = [W_v \quad W_r] = \begin{bmatrix} p_1 & p_2 & p_3 & p_4 & p_5 & r_1 & r_2 & r_3 & r_4 \\ t_1 & -1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ t_2 & 1 & -1 & 0 & 0 & 1 & -1 & 1 & 0 & -1 \\ t_3 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & -1 & 0 \\ t_4 & 0 & 0 & 1 & -1 & 0 & 0 & -1 & 1 & 0 \\ t_5 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 \\ t_6 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (18)$$

Employing now (17) one obtains p-invariants as the columns of:

$$P = \begin{bmatrix} F_k \\ I \end{bmatrix} = \begin{bmatrix} p_1 & p_2 & p_3 & p_4 & p_5 \\ r_1 & r_2 & r_3 & r_4 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (19)$$

Using the formulas (16) and (17) allows one to compute mathematically p-invariants and resource requirement matrix for generalized class of flow lines where it is very difficult to obtain any results by inspection.

6 CONCLUSION

A new rule-based DEMS matrix model is adopted that provide a framework for rigorous analysis and control design of discrete event manufacturing systems. The matrices in the matrix model description come directly from industrial engineering tools such as the bill-of-materials, assembly tree, and resource requirements matrix. By deriving explicit mathematical formulas for p-invariants and the resource requirement matrix for generalized reentrant flow lines, NP-complexity problems are avoided, which is often an issue in other modeling techniques.

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