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Starting with the specification of each resource and the whole structure of a flexible production system, in this approach a special kind of coloured Petri nets is used for performing the modelling and the validation of the coordination control structure of the systems. In a second phase, it is proposed to modify the first models to synchronised Petri net schemas to facilitate the supervision and the interaction of the coordination model with the physical components of the system as well as the development and maintainability of the discrete-event control structures. The final result is a formal specification of coloured Petri net based coordination control of resources of the system, and logic control structures for control sequencing based on the use of synchronised subPetri net structures derived from the first one by refining transitions, i.e., their occurrence. Based on the proposed approach, the coordination control model of resources and a first skeleton of the logic control structures of a flexible assembly cell located at the Institute of Manufacturing Automation and Production Systems at the University of Erlangen-Nuremberg, Germany is elaborated and then the correctness of the obtained models with regard to material flow and control sequence specifications is validated by means of the structural analysis of the coloured Petri net-based models.

Keywords: Coloured Petri nets; Discrete-event control systems; Flexible production systems; Modelling; Validation

1. Introduction

A flexible production system (FPS) is made up of a number of machining centres and handling systems, physically and logically interconnected to each other. The task of the system is to carry out a production plan consisting of a list of parts to be processed with regard to a predefined work routing.

The degree of flexibility of a flexible production system depends not only on the flexibility of the single components and the layout of the system, but also on the structure of the embedded control system, which is usually built up in a hierarchical manner [1].

Because of their dynamic behaviour, flexible production systems can be classified as discrete-event systems (DES). As many authors have pointed out, modelling, formal specification and validation problems emerge as main issues for a more effective design of a real-time control structure of such systems [2–7].

Owing to the steadily increasing complexity of industrial production systems, Petri nets (PN) are a suitable modelling, analysis and implementation tools for the design of FPSs and their logic control structures [8–19]. Petri nets are based on a well-founded mathematical theory, which allows validation of the specifications of the modelled flexible production system by means of a qualitative analysis of the net properties before the implementation is performed. However, when modelling industrial applications, Petri net models become highly complex and are difficult to handle. In this situation, the use of high-level Petri nets (e.g. coloured Petri nets-CPN) has made it possible to create a compact representation of the modelled systems [8].

After giving a presentation of the essential features of a flexible production system (e.g. material flow and control objectives) and based on our recent research developments, this work proposes the synthesis, formal specification and validation of an universal reconfigurable and hierarchical discrete-event control structure for FPSs using a unique approach. This is based on the use of a special kind of coloured Petri net tailored for control purposes, i.e. ordered coloured Petri nets [22–25], and the basic concepts of both mutual exclusion and structural theories [18,26]. The functional steps of the proposed methodology are highlighted in Fig. 1.

The paper is organised as follows: Section 1 presents the introduction of the work. Section 2 recalls the basic definitions and concepts related to coloured Petri nets. In Section 3 the main steps to be performed for modelling flexible production systems with coloured Petri nets are presented. In Section 4 a methodology for performing the formal validation of material flow specifications of the modelled flexible production systems is described. Section 5 presents a modelling methodology for formally specifying a logic control structure of an FMS based
on synchronised Petri nets. Section 6 summarises this work and gives a brief outlook.

2. Coloured Petri Nets – General Definitions

It is assumed that the reader is familiar with Petri net and coloured Petri net concepts and the basic terminology in both fields. Nevertheless, for a better understanding of the subjects and mathematical fundamentals, references [15,20,27] can be consulted.

Let us recall here, the definition of coloured Petri nets (CPN) [20], the firing rule of transitions, the incidence matrix and the rules of the dynamical evolution of the kind of coloured Petri nets used in this work [22,25].

Definition 1. A CPN is a 7-tuple CPN = \(<P, T, C, I', I, G, M_0>\) satisfying the following requirements:

- \(P = \{p_1, p_2, \ldots, p_n\}\) is a finite set of places.
- \(T = \{t_1, t_2, \ldots, t_m\}\) is a finite set of transitions.
- \(C\) is the colour function defined from \(P \times T\) into \(\Sigma\), where \(\Sigma\) is a set of finite and not empty sets. \(C\) attaches to each place a set of possible token colours \(C(p)\) and to each transition a set of possible occurrence colours (firing modes) \(C(t)\).
- \(I' (I')\) are, respectively, the input matrix and the output matrix defined on \(P \times T\), such that \(I'(p,t)\) is a function from \(C(t)\) to \(\mathbb{N}\) (set of non-negative integers). Elements of \(I' (I')\) are denoted, \(I'(p,(t,c))\), where \(c\) belongs to \(C(t)\).

Remark. The incidence matrix \(I\) of a CPN is defined by \(I = I' - F\). The elements of the incidence matrix can be interpreted as functions from \(C(p) \times C(t)\) into \(\mathbb{Z}\) (set of integers).

\(G\) is a guard function, defined from \(T\) into Boolean expressions, (i.e. a predicate). A standard form of a guard is described below:

\[ \forall t \in T \land \forall c_i, c_j, c_k \in C(t) \Rightarrow G&(t) = (c_i \land c_j \land (\neg c_k) \land \ldots), i \neq j \neq k; \text{ where } \neg c_k \text{ is the complement of the Boolean variable } c_k; \neg c_k = 1 \text{ exactly when } s_k = 0 \]

Then, each \(G&(t)\) is a Boolean function of occurrence colours, related to the transition \(t\).

\(M_0\) is the initial marking of the net. It is a function defined on \(P\), where \(m_0(p)\) is a function from \(C(p)\) to \(\mathbb{N}\). \(m(p)\) and \(m_0(p)\), respectively, give the number of tokens of each colour in the place “p” for the current and the initial marking. \(M(p)\) and \(M(p)\) can be seen as a vector whose dimensions (cardinality) corresponds to the number of places of the CPN.

Definition 2. A transition \(t\) is marking-enabled in a marking \(M(p)\) for the occurrence colour \(c_i \in C(t)\) if and only if the following condition is satisfied: \(\forall p \in P: (\Sigma I(p,(t,c))) \leq M(p)\)

Definition 3. A transition \(t\) is enabled in a marking \(M(p)\) if \(t\) is marking-enabled and the corresponding guard \(G&(t)\) is true.

Definition 4. Two or more occurrence colours in a transition \(t\) are concurrently enabled if their corresponding \(G&(t)\) are true.

Definition 5. The firing of transition \(t\) for a marking \(M(p)\) and a colour \(c_i \in C(t)\) results in a new marking \(M'(p)\) defined by:

\[ M'(p) = M(p) + I(p,(t,c)); \quad \Sigma, \forall p \in P \quad (1) \]