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Distributed Supervisory Control Synthesis For Discrete Manufacturing Systems

Y. Qamsane*. A. Tajer*. A. Philippot**

** LGECoS Laboratory, ENSA-University of Cadi Ayyad BP 575, 40000 Marrakech, Morocco*
qamsaneyassine@gmail.com, a.tajer@uca.ma
*** CReSTIC, Reims University, Moulin de la Housse, BP 1039, 51687 Reims – France,*
alexandre.philippot@univ-reims.fr

Abstract: A formal approach to distributed supervisory control synthesis for automated manufacturing systems is presented in this paper. The discrete manufacturing system (plant) is modeled with automata in a modular way and local control specifications are defined for each local subsystem by means of logical equations in order to construct local supervisors. To establish global control, global specifications are defined as logical combinations to ensure coordination and interaction between the different subsystems. Formal algorithms for the intersection between local controllers and global constraints are proposed. We refer to the resultant controllers as Distributed Controllers (DCs). The formulation of the problem and the control synthesis algorithms are applied to an experimental manufacturing system.

Keywords: Discrete Event Systems, Supervisory Control, manufacturing, Control Synthesis, PLC.

1. INTRODUCTION

Engineers and designers over the past few decades have dealt with increasingly complex technical systems. Such systems found in a variety of application areas such as communication networks, automated manufacturing systems, air traffic systems, control systems in automobiles, transportation systems and so on, are viewed as Discrete Event Systems (DES). Dynamics of DES are characterized by asynchronous occurrences of discrete events (Cassandras and Lafortune, 2008).

The work presented in this paper is interested in Automated Manufacturing Systems (AMS), which are a class of DES used to produce quality products faster and more efficiently or to perform services. To help the designer with analysis, design, validation, implementation, control and optimization of AMSs, two types of methods are used: Verification and Validation (V&V), and Synthesis. V&V methods consist of checking that an AMS meets the requirements and specifications and that it achieves its envisioned purpose. These methods implement the automatic demonstration or model-checking (Baier and Katoen, 2008; Biallas et al., 2011). Synthesis methods (Ramadge and Wonham, 1987; Hietter et al., 2008) consist of constructing models of the system together with the expected properties in order to obtain a control model which meets the specified properties. Among synthesis methods, the Supervisory Control Theory (SCT) initiated by Ramadge and Wonham (Ramadge and Wonham, 1987) has been the one considerably enhancing results in the DES domain. It provides formal control architectures based on properties such as controllability, observability, safety, liveness, and ultimately, diagnosability. The objective of the SCT is to define (synthesize) a supervisor that disables the occurrence of a set of events in such a way that the supervised DES behaves in accordance with the considered specifications. It is basically supported by automata and formal language models (Hopcroft et al, 2006). Two main problems compete against its applicability in the industrial world. The first one yielding the state-space explosion, i.e. the computation of real system models becomes challenging given their large size. The second one is the models interpretation, i.e. supposing the computation is a success, the understanding of large models remains strenuous.

In this paper, we propose a distributed synthesis approach that avoids composition between modular components. It eliminates the problem of combinatorial explosion of the state space and reduces the size of supervisors. The proposed distributed supervisory control architecture shown in (Fig.1) is divided into two parts: (a) the supervisory control of a DES according to the SCT and (b) the offline distributed control synthesis and implementation approach. The supervisory control of a DES part is constituted of the discrete event system (Plant) to be controlled, the control system, the sensor signals considered as outputs from the DES and as inputs to the control system, and the control actions, considered as outputs from the control system and as inputs to the DES. The second part (the offline distributed control synthesis and implementation approach) is based on three main steps: (i) the local control synthesis, (ii) the global control synthesis and (iii) the interpretation of the synthesized control into Grafcet (IEC, 2013) for implementation purposes. The first step aims toward synthesizing local modular controllers from the plant and the behavioral specifications models. In this step, the entire operation physically realizable by the system is modeled in a modular way according to its mechanical characteristics (sensors/actuators). Local safety and liveness constraints are expressed as logical equations in Boolean algebra. The intersection of local safety and liveness constraints with the corresponding local PEs is carried out by

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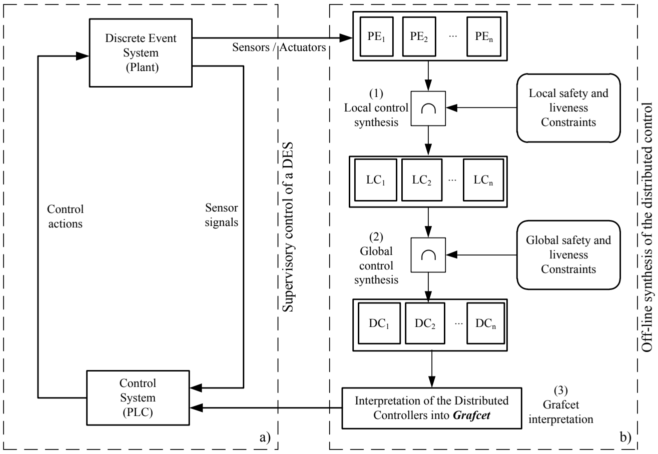

Fig. 1. The proposed distributed supervisory control architecture.

means of the local synthesis algorithm proposed in (Tajer et al., 2013). The second step proposes novel algorithms of global distributed control synthesis. These algorithms consider the local controllers (LCs) of the corresponding Plant Elements (PEs) and a set of global constraints in order to build Distributed Controllers (DCs). The third step provides an interpretation method consisting of translating the synthesized DCs into Grafcet (IEC, 2013).

The remainder of the paper is organized as follows. In Section 2, mathematical preliminaries about the SCT are explained together with some basic important concepts that must be known to grasp the essence of this work. In Section 3, we detail the concepts of the global control synthesis approach and we provide two algorithms for computing the DCs. This approach is then applied to an experimental manufacturing system in Section 4. Finally, Section 5 summarizes the results of the paper and gives conclusions and some perspectives.

2. PRELIMINARIES

2.1 Supervisory control theory

The main objective of the SCT initiated by Ramadge and Wonham (RW) (Ramadge and Wonham, 1987) was to extend control theory concepts and notions for continuous systems to the DES. The originality of the RW model lies in the separation of the free behavior of the system modeling the entire operation physically realizable by the process (open loop operation) and the desired behavior (closed loop operation). In SCT, a system is assumed to evolve spontaneously. It executes sequences of events which describe its behavior, and engenders a language constructed by the alphabet of events. Events are divided into two disjoint sets, the controllable events and uncontrollable events. The SCT aims to synthesize supervisor(s) whose purpose is to disable the occurrence of controllable events in such a way to impose the supervised system to behave according to certain specifications. It provides formal methods and algorithms for the automatic synthesis of supervisory controllers from given specifications. The basic model of the unsupervised DES is an automaton called generator describing all possible evolutions of the process. Formally, a DES is represented by the quintuple $G = (Q, \Sigma, \delta, Q_m, q_0)$ where Q is a finite set of *states*, with $q_0 \in Q$ as the *initial state* and $Q_m \in Q$ as the set of *marked states*; Σ is a finite set of events called an *alphabet*; and finally δ is a *transition function* $\delta\colon Q\times\Sigma \rightarrow Q$. In some DES applications, several independent processes can be considered simultaneously. To combine two DES (A and B) into one single more complex DES, i.e. C = A||B, a procedure called synchronous product is used. In the resulting automaton, common events occur synchronously, while the other events occur asynchronously.

As mentioned before, the set of events Σ is divided into two disjoint sets, the set of controllable events Σ_c and the set of uncontrollable events Σ_{uc}. The supervisor can disable only controllable events and has no effect on uncontrollable events. The existence of a supervisor is guaranteed if the specified language satisfies the following controllability condition: $\overline{K}\cdot\Sigma_{uc} \cap L(G) \subseteq \overline{K}$; where $L(G)$ is the physically possible behavior and K is a desired behavior. This condition denotes that K is controllable, if for any sequence of events w that starts from a sequence that is already a prefix of K ($w \in K$), the occurrence of an uncontrollable event does not lead the sequence out of the desired behavior K.

2.2 Local synthesis approach

In (Tajer et al., 2013), we have proposed a local supervisory control synthesis algorithm that considers local models for the plant modeling and logical Boolean equations for the constraints modeling. The algorithm allows the application of local logical constraints to their corresponding local PEs automata in order to obtain LCs. The local synthesis approach defines the PEs as event-driven models and uses the Balemi's interpretation (Balemi et al., 1993), i.e. the set of controllable events $\Sigma_c \subseteq \Sigma$ represents the set of control outputs (actuators) and the set of uncontrollable events $\Sigma_{uc} \subseteq \Sigma$ represents the set of control inputs (sensors). It considers also that the either rising "↑" and the falling edge "↓" associated with an event are the changes of its value from 0 to 1 and from 1 to 0 respectively. According to this interpretation we consider that the set of controllable events corresponds either to the activation orders "$\uparrow Z$ " or to the deactivation orders "$\downarrow Z$ " of the control part and the set of uncontrollable events is associated with the rising edges "$\uparrow E$ " or with the falling edges "$\downarrow E$ " of the input variables of the control part. The sets Σ_c and Σ_{uc} are then written $\Sigma_c = \uparrow Z \cup \downarrow Z$ and $\Sigma_{uc} = \uparrow E \cup \downarrow E$.

In the plant modeling stage, the approach consists of dividing the plant into several modular plant elements (PEs) that present all possible situations without taking into account any constraint coming from the control part. A practical construction of detailed and enriched PE model was introduced in (Philippot, 2006). The model of each PE is an automaton $G^{(PEi)}=(Q^{(PEi)}, \Sigma^{(PEi)}, \delta^{(PEi)}, q_0^{(PEi)})$ where $Q^{(PEi)}$ is the set of states, $\Sigma^{(PEi)}$ is the alphabet of events, $\delta^{(PEi)}\colon Q^{(PEi)} \times \Sigma^{(PEi)} \rightarrow Q^{(PEi)}$ is a transition function and $q_0^{(PEi)}$ is the initial state.