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A Hybrid Control Architecture Applied to Flexible Manufacturing Systems

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Abstract: The introduction of advanced information systems and machinery with communication capability and operational versatility provide the manufacturing systems with the capacity of material modification and transport, changes in material processing routes, different product insertion in the production line and plant layout reconfiguration. These characteristics give the production process great flexibility. Supervisory Control Theory (SCT) and Colored Petri Nets provide a formal tool for developing controllers for Discrete Event Systems, e.g., Flexible Manufacturing Systems (FMS). One of the problems for implementing this approach is the difficulty that the modeling of the subsystems and specifications represent in today's modern manufacturing systems. In Flexible Manufacturing Systems the transport mechanism is identified as the subsystem that provides these functionalities. This paper describes the modeling of the subsystems and specifications for a large Flexible Manufacturing System using a hybrid integrated framework.

1. INTRODUCTION

The introduction of advanced information systems and machinery with communication capability and operational versatility provide the manufacturing systems with a high degree of flexibility. This characteristics results in the possibility of material modification and transport, changes in material processing routes, different product insertion in the production line and plant layout reconfiguration. These characteristics give the production process a greater flexibility. Giving their complex characteristics, the project of a control structure for these systems requires formal tools for its implementation.

The Supervisory Control Theory (SCT) (Ramadge & Wonham, 1989) was developed to provide a formal methodology for the automatic synthesis of controllers for Discrete Event Systems (DES). The theory makes a clear definition and distinction between the system to be controlled, called plant and the entity that controls it, called supervisor. Considering that the system to be controlled is composed of several subsystems, the plant model reflects the physically possible behavior of the subsystems, which means, every possible action that they are capable of performing in the absence of any control and restrictive action. The SCT`s role is, executing a control and restrictive action on the subsystems so that they behave in accordance with a desired set of specifications.

The SCT has been successfully applied in automated manufacturing system, where security, operational, sequencing constraints amongst other are part of the control restrictions. However, implementing a SCT based control structure results in some implementation problems (Cury et al., 2002).

One of the problems is related to the spontaneous event generation, which is an intrinsic aspect of SCT (Fabian and Hellgren, 1998). In the case that simultaneous controllable events are enabled (events which the supervisor may execute disabling actions), the theory does not predict which one of the events will in fact occur. This problem is resolved in the implementation, as it is established during coding which event will be generated first. This issue becomes particularly important when is required to choose, in accordance to certain criteria, which event should in fact occur (within the permitted ones).

In this context, this paper proposes an extension to the SCT structure proposed by Queiroz and Cury (2002), including one layer for event generation decisions. For example, if in a determined state, two controllable events are enabled to be executed by the supervisor, the decision layer generates a disable signal for one of the events. Naturally, the global control system will conduct the plant through a determined sequence of events, in accordance to certain criteria. This paper proposes to use Colored Petri Nets (CPN) (Jensen, 1992) for modeling the decision level described.

Colored Petri Nets have been applied for modeling dynamic behavior of determined systems (Jensen, 1992). Particularly, papers can be found describing industrial applications and implementation schemas for control structures based on CPN (Bernd et al., 1997; Dotoli and Fanti, 2005; Uzam and Wonham, 2006; Daene et al., 1997, Cardec and Prunet, 1996; Belabas and Berruet, 2004; Ey et al., 2000; Zimmerman 1994). In general, CPN are used for creating more complex control structures, where the necessity for a larger quantity, representation and manipulation of information is required.

The proposed control structure is based on two formalisms: Supervisory Control Theory and Colored Petri Nets. This structure is used in the control of a didactic manufacturing system, where routing changes are required depending on the production planning. Supervisory Control Theory is used for taking care of security, interlocking and sequencing constraints. CPN introduce determinism in the SCT based structure, as it will take decisions on particular events.

The paper is structured as it follows: The conceived control structure is presented in section 2; the Advanced Integrated Manufacturing System (AIM) used for modeling is presented in section 3; in section 4 the SCT subsystems' models where routing and product based decisions are required are presented; section 5 presents the Colored Petri Net (CPN) model for the routing coordinator and section 6 presents the conclusions of this paper.

2. HYBRID MODELING

Due to the complexity of flexible manufacturing systems, the used control structure is divided in hierarchical layers. The control structure presented by Queiroz and Cury (2002) based in modular approach (Queiroz and Cury, 2000) and using SCT (Ramadge & Wonham, 1989) is extended to include upper layers of control, which was implemented using CPN (Jensen, 1992) being responsible for routing decisions and for including determinism in the model when needed. The conceived structure is presented in Figure 1.

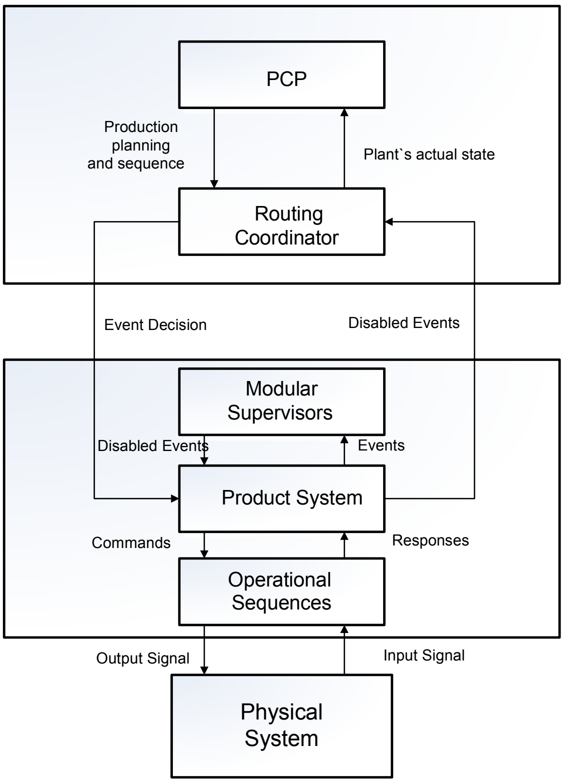

Fig 1. Hybrid Control Structure

The presented structure can be applied to discrete production systems, where routing or product related decisions are required. The operational sequences, product system and modular supervisors take care of security constraints, correct sequence of events, interlocking and that the system's specified behavior is respected.

Supervisory control theory does not specify generation of events (Cardec and Prunet, 1996), according to the theory they are spontaneously generated. Control actions are imposed exclusively by event disabling, which is done by the synthesized supervisors.

The routing coordinator layer is implemented using a colored Petri net model; the layer uses constantly updated information of enabled/disabled events by the SCT supervisors and information provided by the production planning and control layers to take routing and task execution decisions. Each model's variables are constantly updated and the product's evolution throughout the plant is available at all times for any required modifications from the planning layer.

Following modular approach proposed by Queiroz and Cury (2000), the system to be modeled is divided into sub-systems. These sub-systems are chosen in a way to facilitate modeling and synthesis. The abstraction level for representing the model must include relevant events for routing decisions and manufacturing operations. Once the models for the sub-systems are designed, the specifications models must be developed. With that, the product system is obtained and modular supervisors synthesized. For the routing coordinator, a modeling layout similar to the physical system is implemented, where conditional transitions or guards are implemented in the CPN model, in the cases of manufacturing stations and possible route changes.

As the implementation has to be in synchrony with SCT, the routing coordinator layer communicates with the product system layer, generating disabling signals for decision making.

3. ADVANCED INTEGRATED MANUFACURING SYSTEM

The Advanced Integrated Manufacturing (AIM) platform is a system which reproduces every aspect of an automated manufacturing process, providing the academic environment, tools for evaluation and experimentation of discrete event system, production engineering and control engineering theories and techniques. This system is composed of several devices and software packages, which, when integrated make the AIM platform capable of performing a completely planned, automated and flexible manufacturing process.

Physically the AIM platform occupies a 50 square meter area, and it is main components are: Conveyor Belt Transport System; AS/RS (Automatic Storage/Retrieval system); Assembly station; Flexible Welding Station; Lathe Machining Station; Milling Machine Station. The existing layout provides the platform with ease of expansion, alternative routing capabilities and workstation isolation. According to figure 2, the AIM platform is made up of five cells interlinked by a transport system. However, in this work, the modeling will be introduced considering only two of the five existing cells.

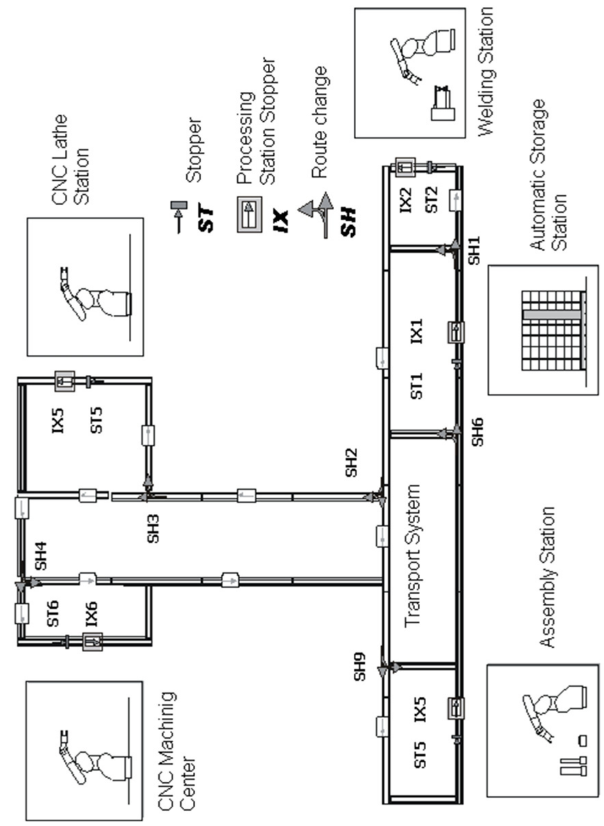

Fig 2. AIM platform Layout.

3.1. Transport System Details

The transport system is consisted of constant direction conveyors belts, where the product's pallets are transported; the pallets´ route and direction is determined by a series of devices located in the conveyor system which stop or change the pallets´ direction. This characteristic provides AIM`s transport system with routing flexibility, which is a desired characteristic in a manufacturing system. The system can perform several production routes and control actions based on the defined specifications. For example, if a product's process route determines that the product has to be welded and lathed, not necessarily in this order, to be finally stored, the pallet can change direction and perform the lathing process first if the welding station in occupied at the time of its arrival. When then lathing process is finished, the pallet can come back to the welding workstation, and finally be directed to the automatic storage station.

For analysis and modeling convenience, the transport system is divided into segments. A segment is defined by two successive stopping devices, which can be stoppers, shunts or clampers. Each one of these devices is described in detail as follows. For each transporter system segment, the stopper (ST), illustrated in figure 3, is the device which halts the pallets once they arrive. The arrival of a pallet is detected by a material detection sensor (represented by the symbol PS1); by default, every pallet that arrives at a stopper is always halted by a pneumatic pin (represented by the symbol PP1). After the security, routing and control specification checking is done, the supervision determines if this pallet must or must not be released.

For each workstation (Welding, AS/RS, Assembling and Machining), there is a Clamping device (IX), illustrated in figure 4. It has the functionality of securely pressing and holding the pallet for each workstation manipulators. Besides clamping, it has the same characteristics as a stopper.

The shunt devices (SH), illustrated in figure 5, are responsible for route changes on the transport system; they are composed of a stopper and an actuator (represented by the symbol AC) which directs the pallets, according to product routing or safety specification to the available paths.

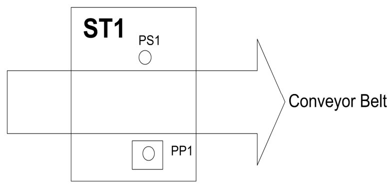

Fig 3. Stopping Device

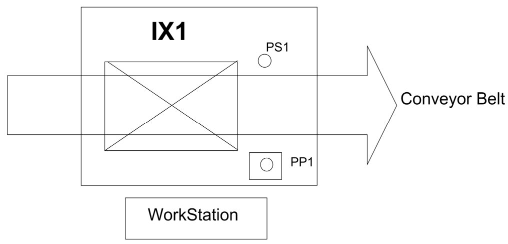

Fig 4. Clamping Device

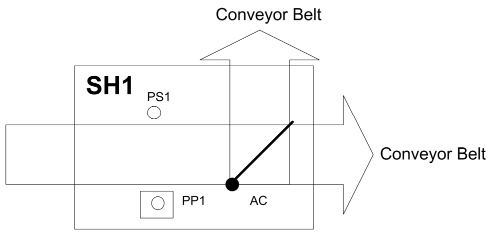

Fig 5. Shunting Device

These devices represent the main components of the transport system, and their configurations are replicated throughout the whole platform.

4. SUPERVISOY CONTROL THEORY MODELS

The constructed models and synthesized supervisors were designed and synthesized by using the local modular control approach (Queiroz and Cury, 2000). The AIM system was modeled dividing it into segments and workstations, where supervisors are synthesized for each segment and machine. As the paper's focus is to present the interaction between the SCT models and CPN, only the models where deterministic decisions are required are presented. A partial and more detailed view of the system is shown in Figure 6.

According to the modular approach, the several subsystems' open-loop behaviors (with no control) may be modeled with a set of asynchronous automata (with no common events). This way, Queiroz and Cury (2000) states that it is feasible to obtain a representation by Product System (Wonham and Ramadge, 1988), according to what was discussed in the previous section.

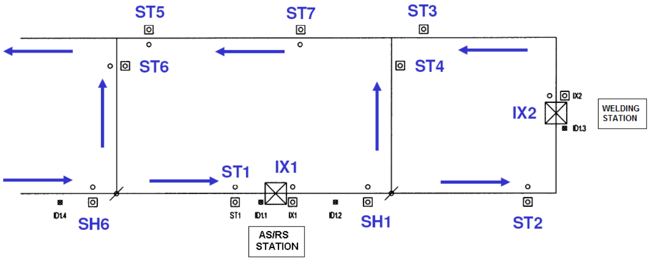

Fig 6. Partial View of the Transport System

For the transport system, four kinds of asynchronous subsystems were identified; the first one composed by segment limiting devices, the second one by a clamping device and a machine, the third one composed by a shunt device and the two stopping devices immediately following it (2 segments), and finally the fourth subsystem which is composed by three stopping devices that together form a transport system joint. For didactic purposes only the supervisors where product related decisions are made are shown.

The Shunt (represented in Figure 6 by SHx, where x is the number of the device), is the device where is decided whether or not a pallet should change its path; this segment is composed by three devices: One Shunt device and two Stoppers (represented in Figure 6 by STx, where x is the number of the device). In the SH1 device the decision whether the arriving pallet must continue to the welding station, or skip that station and continue its path to the other parts of the system. This is decided by the routing coordinator layer. It is in the Workstations that product modification actions effectively take place. Each workstation has the capacity to perform at least two different material modification actions.

The second model is the resulting supervisor for the welding machine, capable of performing two different types of welds. The station is composed by a clamping device to keep the pallet in place and the machine itself. The synthesized supervisors for the shunting segment and the welding machine are presented in Figure 7. The event nomenclature used for creating the models and supervisor synthesis is described:

Events alx/arx: Controllable Event describing the pallet release and routing by a shunt device, where l means left, and r means right

Event Ux: Non-controllable event describing a pallet release, characterized by the lack of presence sensed in the device.

Event Kx: Controllable Event describing a clamping event.

Event Rx: Controllable event describing a clamp release.

Event Rqx: Controllable event describing the request for a resource.

Event Rpx: Non-Controllable event describing a resource report (action finished by a workstation) .

The reduced synthesized supervisors basically ensures that collision between pallets within the shunt sub system (Figure 7A) doesn't occur and, for the WorkStation (Figure 7B) that no request for service is done until the pallet is properly secured, also verifying the end of every requested service.

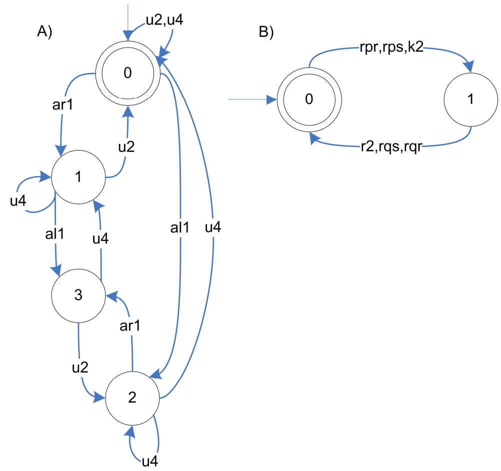

Fig 7. (a) Shunt Supervior. (b) Machine Supervisor.

As presented by the resulting supervisors, two controllable events are available for execution. For the Shunt the pallet release left/right (al1,ar1); and for the machine two different request resource events (rqr,rqs). These exact events require decision making, and for that the Routing Coordinator CPN model is used.

5. ROUTING COORDINATOR MODELING

The AIM platform is capable of processing several types of products; to exemplify the approach implemented in the plant only two types of products and a segment of the plant are shown in the model. Our approach is implemented to include the interaction between the SCT models previously presented which control security and interlock throughout the system and the necessary routing and product related decisions. For modeling the routing coordinator was chosen CPN Tools, a package developed by the "CPN Group" at the University of Aarhus which allows editing, simulation and analysis of Colored Petri Nets.

The fist stage of the modeling process establishes the environment variable definitions required for the implementation of the net. The definitions used for the manufacturing system are:

colset ROUTE = list STRING; color set defined for representing the production sequence that each product must follow. Production cell names are used for defining the sequence, e.g: {"M1", "M2"} indicates that the product must pass through machines one and two, in that specific order.

colset zero = int 0..i; color set defined for representing the production stages of each product. After passing through a production cell or machine, this index is updated.

colset PIECES = product ROUTE x zero; color set that defines a product. Defines the tokens traveling through the net.

The communication schema used between the CPN model (routing coordinator) and the SCT model is presented in Figure 8. The interface uses the Comms/CPN libary (Gallasch e Kirstensen, 2001), which is used for interfacing a model developed for CPN Tools with an external process. The base protocol used for implementation is TCP/IP, which is a widely known and used protocol with the advantage that almost every operational system, industrial control device or software package, offers an implemented TCP/IP layer ready to be used.

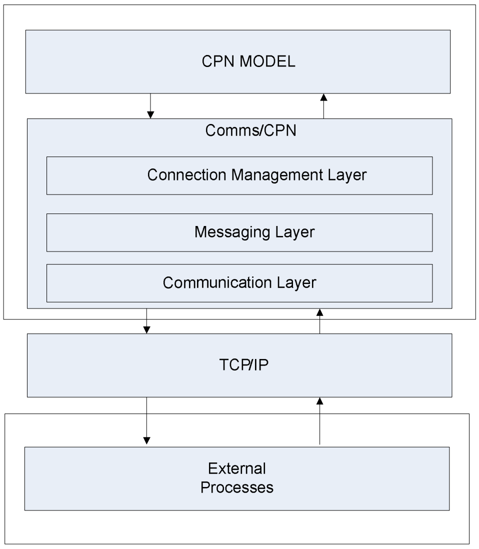

Fig 8. Communication Interface.

In Figures 9 the model for the net initialization is presented. The model contains the net's interface with the PCP level, from where the production sequence and planning is received. The sequence is received in a predefined file structure that contains every product details regarding cell processing sequence and number of products to enter the process.

Input.txt =

M1;M3;M4;M5
M2:M3:M2

After passing through the initialization phase, the file with the production order is read, the TCP/IP connection with the SCT supervision is established and the tokens representing the production sequence are ready for circulating the network. Every token is initialized with its production sequence index zeroed, representing that a new, non processed product has entered the network. The partial model of the production plant is presented in Figures 10 and 11.

The figures represent the basic structures used throughout the entire Routing Coordinator model. For route checking, resources of the used tool (CPN Tools) are implemented. Places *Int* and *SH1* are identified as places previous to routing or processing decisions. Immediately following these places, transitions with *guards* are used, which evaluate to *true* or *false,* deciding this way which events must be disabled in the supervision level.

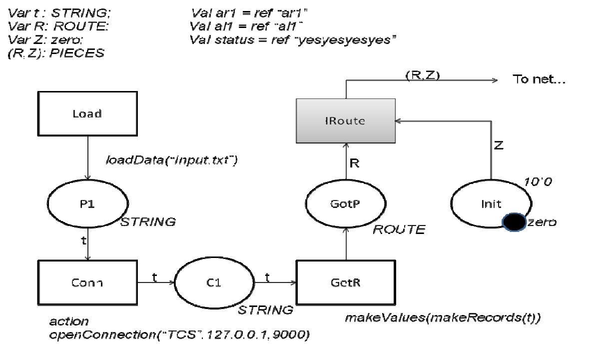

Fig 9. Initialization of Routing Coordinator.

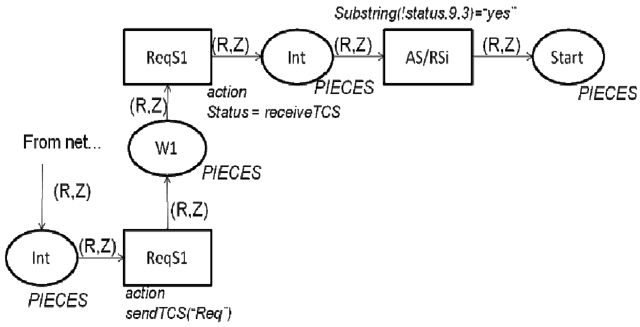

Fig 10. Initial stage of Routing Coordinator.

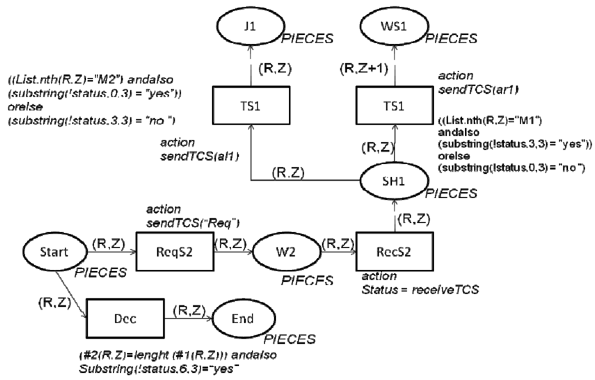

Fig 11. CPN Model of routing coordinator. SH1 decision modeling.

For constructing the *guards* the CPN Tools function *List.nth(R,Z)* is used. The function receives as parameters an element list (representing the product's production sequence) and the number that indicates which member of the list is desired, which represents the index of the product in its production sequence. Once the actual processing stage of the product is obtained, it is compared to the name of the corresponding cell or machine to identify which processing must the product undergo. In the previous example (Figure 11) are shown stations M1, for which the product would proceed to place WS1 and M2, for which the product would proceed to place J1.

Once the route has been verified, the logic includes the actual state of the events received from the supervision level to verify if, for security constraints for example, the product must not proceed to a determined station. The information of each of the plant's events is extracted using an unique *STRING (var : status),* together with the function *substring,* which extracts a part of the event string corresponding to a desired, previously defined event. For each event are reserved three consecutive characters inside the string, thus extracting any event is easily accomplished.

Finally, with the product state and supervision info, one *guard* will evaluate to *true* and its transition will be enabled. In the event of the transition firing, occurs the update of the supervision level. The routing coordinator informs which event must take place, sending the disabling signal to the supervision level. If the route takes a product to a workstation, which is the case or the arc TS1-WS1, the increment of the production index occur with the transition firing. This ensures the in the next guard, the product will have its state updated to reflect its current state.

6. CONCLUSIONS

In this paper it is presented how a hybrid approach for designing a control environment for flexible manufacturing systems could result in a solid and formal based solution, taking advantage of the best characteristics and features that SCT and CPN theories have to offer. The proposed control structure can be conceived, expanded and replicated for enhancing a manufacturing system's flexibility by facilitating the design or re-implementation of its control structure. As manufacturing systems' complexity and performance requirements increase, becomes imperative that their control structures design and implementation are created formally based and less intuitively. By researching and expanding existing formal theories and methodologies, and by creating new control structures, manufacturing systems will increasingly become more reliable and offer better performance and flexibility.

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