Discrete-Event Control Theory for Flexible Manufacturing

Flexibility in Manufacturing

Flexibility in the manufacturing context refers to the ability of a manufacturing system to react to and accommodate changes. Changes may occur due to various causes: machine breakdown, system reconfiguration, and market demands. Correspondingly, flexibility is needed at different levels. For example, a machine may perform a variety of operations and a manufacturing cell may produce a range of products. Flexible manufacturing has been widely recognized as essential for reducing production costs, enhancing operational reliability, and adapting to variable needs in today's markets.

A flexible manufacturing system (Image courtesy of Cincinnati Milacron, Ohio)

Flexible Manufacturing Systems

In the past few decades, flexible manufacturing systems (FMSs) have attracted significant attention in industry as well as research communities. An FMS typically consists of a number of automatic machine tools linked by material handling/transportation elements (robotic manipulators, automated guided vehicles) and storage (buffers, inventories). Besides hardware, FMSs have sophisticated computer-control software that executes monitoring, scheduling, routing, and supervision tasks.

## Flexible Manufacturing Systems: Challenges

Despite the considerable advances in flexible manufacturing, today's state-of-the-art FMSs have several shortcomings:

- **Trial-and-error design and verification:** In current system and control design, behavioral requirements of FMSs are specified by experts/managers, and software is coded by software engineers. This frequently leads to coding-testing trial-and-error loops, making the design process inefficient, control software prone to error, and FMSs prohibitively difficult to expand in functionality and scale.

- **Limited scalability:** Many FMSs have a central controller that requires extensive communications for even moderate-scale systems. Such a control and communication architecture makes it difficult to increase system size and production capacity to meet rapid changes in market demand.

- **Poor fault tolerance:** Component failure in an FMS can cause cascading malfunctions; replacement of a component may require interruption of system operation. Efficient reconfiguration strategies are lacking that can allow unaffected parts of FMSs to continue to operate while recovering from a failure.

Why Discrete-Event Systems?

The dynamics of FMSs exhibit the typical characteristics of discrete-event systems (DESs). DESs are discrete in time and (usually) in state space; they are event-driven, with events occurring asynchronously; and they may be nondeterministic (i.e., capable of transitional choices by internal chance or other mechanisms not necessarily modeled by the system analyst). The theoretical machinery developed for DESs can help resolve outstanding issues with FMSs.

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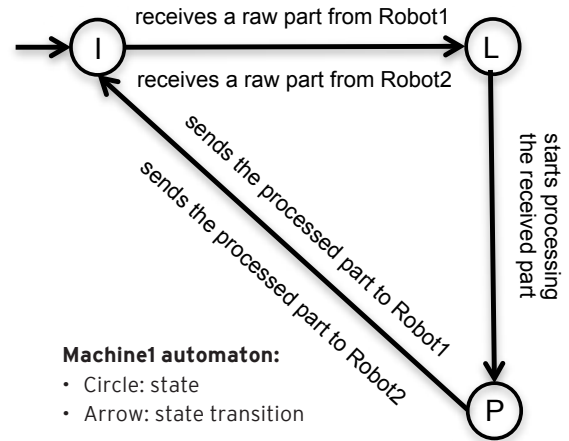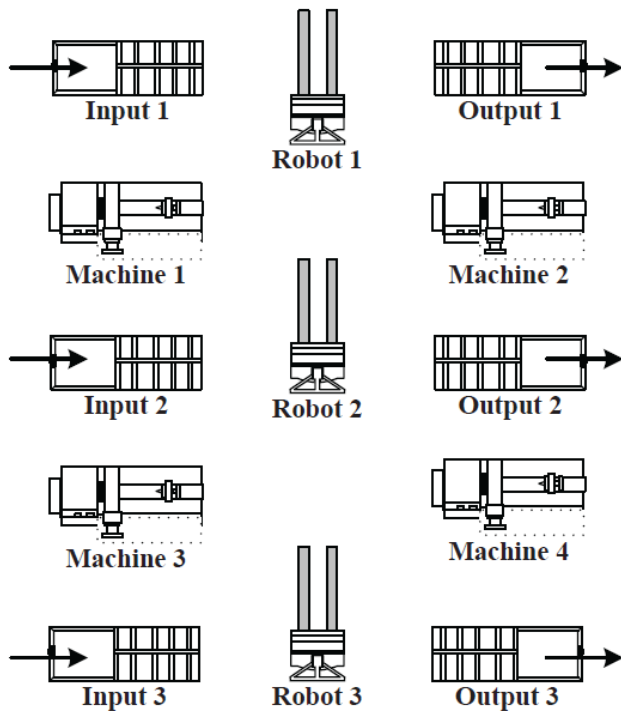
Left: An FMS consisting of machine tools, routing robots, and input and output conveyors. This FMS can produce three different products: the first uses machines 1 and 2, the second uses machines 3 and 4, and the third uses all four machines. (Image courtesy of W. Chao et al., Int. J. of Control, 86(1), 9-21, 2013)

Above: Automaton model of machine 1. The model has three states—"I" (idle), "L" (loaded), and "P" (processing)—with state transitions triggered by distinct events.

By modeling FMSs as automata, as shown here, formal supervisory control methods can be applied to address challenging control design problems in flexible manufacturing.

Why Supervisory Control Theory?

Supervisory control theory for DESs was proposed by P.J. Ramadge and W.M. Wonham in the 1980s. The theory employs finite automata for modeling and regular languages as analytic tools and has developed a compelling design methodology suitable for addressing the challenges faced by FMSs.

- **Formal models and correct-by-construction synthesis:**
  With uncontrolled FMS behavior and control requirements both modeled as finite automata, the theory automatically synthesizes supervisors that ensure safe, deadlock-free, and maximally permissive behavior. The synthesized supervisors are also finite automata, which can be translated into standard FMS control software such as for programmable logic controllers.

- **Modular control architecture and supervisor localization:**
  For large-scale DESs, the theory explores horizontal modularity (decentralized control), vertical modularity (hierarchical control), or a combination of both. Built on these modular control architectures, supervisor localization has recently been developed that decomposes modular supervisors into local control logics for individual distributed components. These techniques are useful for improving FMS modularity and scalability.

- **Automated diagnosis and reconfiguration:** Supervisory control theory provides diagnosis methods for efficient detection and isolation of failure events. Automatic reconfiguration approaches have also emerged that enable a DES to continue operation in reduced-performance modes. These methods will enhance the reconfigurability of manufacturing systems in response to failures.

Impact on Industry

We anticipate that research in the application of discrete-event supervisory control theory to flexible manufacturing systems will help companies at the forefront of this technology achieve numerous significant benefits that are critical for competitiveness in global markets:

- Improved flexibility of manufacturing with assurance of performance and safety

- Reduced delay and waste in manufacturing processes as a result of optimized controller designs

- Enhanced operational reliability against component and subsystem failure

- Improved scalability of production with modular designs

- Automatic and rapid reconfiguration of manufacturing lines in response to market changes