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Modeling and analysis of fault-tolerant systems for machining operations based on Petri nets

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Abstract

This paper introduces a methodology for modeling and analyzing fault-tolerant manufacturing systems that not only optimizes normal productive processes, but also performs detection and treatment of faults. This approach is based on the hierarchical and modular integration of Petri nets. The modularity provides the integration of three types of processes: those representing the productive process, fault detection, and fault treatment. The hierarchical aspect of the approach allows us to consider processes on different levels of detail (i.e., factory, manufacturing cell, or machine). Case studies considering detection and treatment of faults are presented, and a simulation tool is applied to verify the models.

Keywords: Detection and treatment of faults; Manufacturing systems; Fault-tolerance; Petri nets

1. Introduction

Despite advances in automation technology, faults are events that cannot be ignored in a real manufacturing system. However, most reports in technical publications consider only the description and optimization of processes under normal conditions (Zhou & DiCesare, 1993). Thus, the development of a methodology that considers not only normal processes but also the detection and treatment of faults is essential for improving the flexibility and autonomy in manufacturing systems.

According to technical norms, a fault (Jalote, 1994) is in general defined as an interruption in the ability of an item to perform a specific function. In this paper, we adopt a more generic definition; i.e., the term fault is synonymous of failures, errors, mistakes, or disturbances that lead to undesirable or intolerable equipment behavior.

Manufacturing systems are composed of different elements (such as machines, feeders, controllers, etc.); the interaction among these elements can be characterized as discrete, asynchronous, and sequential. Therefore, the process synchronization, deadlock avoidance, choice solution, etc. should be considered as the main issues in both normal and abnormal cases (Ho, 1992). An approach using discrete event dynamic systems (DEDS) allows us to consider these characteristics on the analysis and control of manufacturing systems. From this point of view, Petri net (PN) is employed as uniform techniques for modeling manufacturing activities (Zurawski & Zhou, 1994).

This paper initially presents an overview of the main concepts related to detection and treatment of faults in manufacturing systems. In Section 3, a methodology that considers the detection and treatment of faults in manufacturing systems based on PN is introduced. In Section 4, case studies are presented in which the detection and treatment of faults in different hierarchical levels are modeled and analyzed. Finally, in Section 5, the conclusions are presented.

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2. Faults in manufacturing systems

The improvement of productivity in the field of manufacturing requires the automation of tasks and integration of techniques such as CAD and CAM. However, events such as start-up, maintenance, and faults cannot be treated completely automatically. In general, supervision by human operators is necessary, because the knowledge, experience, and skills for working with unexpected situations are very difficult to structure or to reproduce. In addition, several reports confirm that totally automated machines are very expensive, and that appropriate combination of automated machines and human supervision is more effective for the operation of manufacturing systems when considering features such as fault-tolerance (Riascos & Miyagi, 2001; Miyagi & Riascos, 2002; Riascos, Moscato, & Miyagi, 2004). Thus, in the automated manufacturing systems context, the *balanced automation* approach considering an appropriate level of automation is more effective than either totally automated machines or anthropocentric systems (Camarinha-Matos, 1996).

Manufacturing systems can be considered as distributed systems formed by several sub-systems, and can be organized according to a hierarchical structure (Fig. 1):

- The factory level: composed of production lines or manufacturing cells.
- The manufacturing cell level: composed of machines.
- The equipment level: composed of specific devices forming machines on the shop floor.

Both top–down and bottom–up approaches can associate the treatment of specific types of faults on different levels in a manufacturing system (Zhou & DiCesare, 1993).

2.1. Detection and treatment of faults

We are interested in the early detection of incipient faults, because it provides the means to schedule repairs before an actual fault takes place (in contrast to corrective maintenance). The proposed methodology considers fault detection only on the equipment level while their treatment is executed on the most appropriated level.

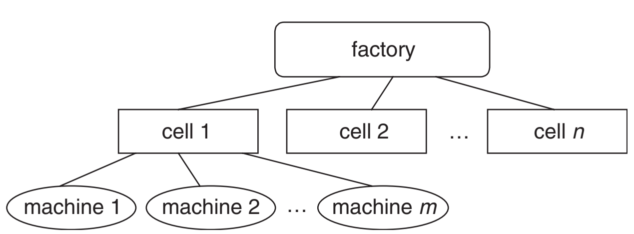

Fig. 1. Hierarchical structure of a distributed manufacturing system.

Based on the automation degree of a manufacturing system, two types of fault detection on the equipment level can be considered (Frank, 1992):

- Faults detected by monitoring a specific device parameter. For example, a leak of lubricant oil can be detected by installing a sensor, which monitors this parameter. In this case, a diagnosis is not necessary.
- Faults that cannot be detected directly on the monitoring stage. Such faults that need some type of diagnosis.

This work focuses on faults of the second type.

In general, fault detection methods can be grouped into three categories (Frank, 1992):

- Model-based: the actual and the expected behavior (from a mathematical model) are compared to identify a fault.
- Knowledge-based: qualitative models are associated with heuristic symptoms for reasoning about fault causes.
- Signal-based: such as spectral analysis that does not incorporate any model.

From a theoretical point of view, the model-based approach has reached a higher degree of maturity, particularly for controlling linear systems with small uncertainties. The challenge of designing a robust, model-based fault detection system is to generate measures insensitive to sources of uncertainties, but sensitive to actual faults. In the case of modeling with large uncertainties, a more suitable strategy is the knowledge-based approach. In fact, knowledge-based approaches have been applied successfully to fault detection (Frank, 1992).

In a knowledge-based approach, the detection and treatment of faults should consider several steps (Umeda, Tomiyama, & Yoshikawa, 1999).

i. Detection
  i1. Data acquisition of operational parameters by sensors.
  i2. Identification of the operational state (i.e., normal or abnormal).
  i3. Diagnosis of fault causes.
ii. Treatment
  ii1. Proposition of a repair plan.
  ii2. Fault recovery or execution of a repair plan.

2.2. Fault detection

The data extraction stage involves the machine's instrumentation, to measure a physical phenomenon (if possible, without interfering with it). In general, the data