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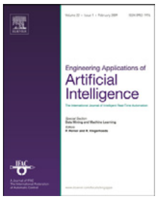

IMS 10—Validation of a co-evolving diagnostic algorithm for evolvable production systems ☆, ☆☆

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ABSTRACT

With the systematic implantation and acceptance of IT in the shop-floor a wide range of production paradigms, relying in open interoperable architectures, have been developed. Exploring these technological novelties, they promise to revolutionize the way current plant floors operate and react to emerging opportunities and disturbances. There is a high interest of module providers in the adoption of these open mechatronic architectures as they may provide a new business model where the automation solution can be easily tailored for each customer in due time and ships with a significant part of the control solution (high added value). Final customers on their side can contract operating hours rather than buying modules. Moreover, the automation solution can be swiftly modified to meet changing requirements.

The necessary increase in the number of distributed and autonomous components that interact in the execution of processes implies that new diagnostic approaches should be developed to tackle the network layer of these highly dynamic systems. In fact fault propagation events can be harder to understand and can affect the system in unpredictable and pervasive ways.

Following this rationale the paper presents a potential diagnostic solution that targets multiagent-based mechatronic systems where their components are highly decoupled from a control point of view. The diagnostic architecture presented tackles the problem of fault propagation while preserving the decoupled nature of the Mechatronic Agent concept. In this context the diagnostic system explores self-organization to enact an emergent response that denotes macro-level coherence. The system's response is the result of an individual probabilistic diagnostic inference based on Hidden Markov Models that capture the propagating nature of a failure.

The validation results of the proposed diagnostic approach are detailed for the system's response in simulation (highlighting the main variables that affect the performance of the system) and compared to the system applied to a pilot assembly cell. The simulation model and the performance metrics considered are detailed and discussed along with the main implementation details.

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1. Introduction

Modern control approaches already heavily rely in networking for the synchronization of production processes. With the pervasiveness and availability of affordable tiny computing devices it is anticipated that the overall complexity of industrial networks will increase quite substantially in incoming years.

Companies are not obviously introducing ad-hoc and purposeless complexity in their automation solutions. With a significant pressure towards achieving a more sustainable production environment it is fundamental to tight the system's regulatory mechanisms in order to avoid premature disposal of materials and other sources of energy waste.

The disposal of equipment, mostly motivated by the introduction of changes at shop floor level, is a significant threat to sustainability. The adoption of open automation architectures, as envisioned by a series of emerging production paradigms: Bionic Manufacturing Systems (BMS) (Ueda, 1992), Holonic Manufacturing Systems (HMS) (Babiceanu and Chen, 2006), Reconfigurable Manufacturing Systems (RMS) (Koren et al., 1999), Evolvable Assembly Systems (EAS) (Onori, 2002) and Evolvable Production Systems (EPS) (Barata et al., 2007a); while not relaxing the complexity issue provides an opportunity to tackle pressing

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complexity related events (failures, fault propagation, tracking, etc.) in an integrated and holistic approach.

This integrated approach is also interesting from a business point of view for module providers that could potentially add significant value to their modular systems by embedding part of the control solution.

Emergent control approaches have developed towards the Lego metaphor where self-contained and function-specific autonomous blocks are combined to implement a specific process. The metaphor itself has evolved starting with the notion of Flexibility whereby one of these constructs is able to perform many functions and can simultaneously take part in many processes mostly associated with the production of a specific product line. Becoming agile was the next paradigmatic step in competitiveness. Agility is different from Flexibility. The latter often refers to the ability of producing a range of products (typically predetermined). It is also different from being Lean (producing without waste). Agility implies understanding change as a normal process and incorporating the ability to adapt and profit from it. Agility covers different areas, from management to shop floor control and regulation aspects. It is a top down enterprise wide effort. The agile company needs to integrate design, engineering, and manufacturing with marketing and sales, which can only be achieved with the proper IT infrastructure (Kidd, 1994; Goldman et al., 1995; Goranson, 1999; Christopher, 2000; Christopher and Towill, 2001; Barata, 2003; Ribeiro et al., 2009). Sustainability is therefore the next step for agile companies which can be attained as these increasingly modular systems become adopted by industry.

The notion of Evolvable Production System (EPS) is consolidating in this context and can be envisioned as a broader umbrella for a wide range of design, architectural and technical considerations firstly explored under the framework of Evolvable Assembly Systems (EAS). The initial EAS concept dating from 2002 (Onori, 2002) was further developed under the FP6 EUPASS project. Current research includes the developments in the scope of the FP7 IDEAS project where the application of EPS concepts in networks of embedded tiny controllers is being pursuit. The essence of EAS/EPS resides not only in the ability of the system's components to adapt to the changing conditions of operation, but also to assist in its overall evolution in time so that processes become more robust.

In this context a system is a highly dynamic entity whose structure and processes evolve. From a diagnostic point of view it is somehow difficult to characterize and model such a system using conventional approaches as these have either been applied within the scope of specific devices or to entire installations with constraining degrees of freedom regarding evolution or adaptation. To a certain extent, diagnostic systems are one of a kind (tailored accordingly to the installation's peculiarities (Thybo and Izadi-Zamanabadi, 2004)).

Preserving the decoupled nature of modules is crucial for the robustness and prompt response of an EPS-based system. It is also the key to support system's evolution and adaptive response on the imminence of change. Hence, it is required a diagnostic system that captures the evolving nature of faults (exploring the network dimension of the system and complementing local/specific diagnostic methods) while ensuring that the system's components remain autonomous and decoupled units.

The self-organizing nature of EPS implies that the convergence of the system to macro-states and the events at module level are of probabilistic nature. In the proposed diagnostic approach self-organization and a local and probabilistic diagnostic model based on a Hidden Markov Model (HMM), which was designed to capture fault propagation events, are combined so that a global and consistent diagnostic consensus emerges. It is important to stress that the considered diagnostic approach envisions the subject of diagnosis from a systemic perspective essentially and evaluates how the system components, which may be other systems themselves, affect each other. The purpose of this paper is therefore twofold:

- To show that it is significant to consider this network/systemic dimension of the diagnostic problem detailing a fault simulation model that considers agent-based mechatronic networks of different complexity and whose components are more or less prone to fault propagation events while clarifying how small changes in parts of the system may influence the propagation of a fault.
- To demonstrate one solution to perform diagnosis at this level that consumes local network connectivity information as well as harmonized agent's sensorial data.

The decoupled, distributed and self-organizing nature of the diagnostic response is analysed for different operating conditions to shed light of the potential and limitations of this approach. Hence, the proposed approach does not perform diagnosis at component level, it concentrates on explaining how one of these component specific events may be abstracted and interpreted from a network perspective and used to diagnose pervasive failure scenarios.

This rationale reflects in the subsequent details that are organized as follows: Section 2 briefly presents the related literature, Section 3 depicts the system architecture, Section 4 presents the testing set-up and briefly addresses some implementation details, Section 5 details the main results, Section 6 discusses the main conclusions and points future research directions.

2. Related literature

2.1. Traditional diagnostic approaches

Fault diagnosis activities are fundamental to ensure the sustainability of systems and have taken many different forms and approaches throughout the years while accompanying the main technological and socio-economic challenges and opportunities.

One can relate the emergence of diagnosis practices with the beginning of machine instrumentation in the early industrial revolution whereby human operators were assigned the task of checking operational limits and performing minor maintenance tasks such as lubrication and part replacement.

In this period, essential dominated by breakdown maintenance, a process whereby assets are run until the eminence of failure or the failure event itself, labour costs were not a significant issue nor was the investment in spare parts. These maintenance practices were replaced by preventive maintenance approaches, still supported by human observation, whereby assets where maintained according to their failure tendency over time. Typically, the bath tub curve was considered to characterize the high failure tendency in early and later stages of the equipment's useful life.

Modern diagnostic approaches can be traced back to the advent of the microcomputer in the 1970s and they have opened the door to consider the maintenance of systems based in their operational conditions and wear given rise to the notions of condition based maintenance (CBM) (Jardine et al., 2006) and Predictive Maintenance (PM) (Mobley, 2002).

Majority voting with sensor redundancy was considered the most reliable approach then and CBM had inherently high costs due to the novelty and price of early electronic equipment.

Early efforts for improving the fault detection method's reliability are reported in the following surveys (Willsky, 1976;

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