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Developing a hierarchical decomposition methodology to increase manufacturing process and equipment health awareness

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ABSTRACT

Manufacturing systems are becoming increasingly complex as more advanced and emerging technologies are integrated into the factory floor to yield new processes or increase the efficiency of existing processes. As greater complexity is formed across the factory, new relationships are often generated that can lead to advanced capabilities, yet produce unforeseen faults and failures. Industrial robot arm work cells within the manufacturing environment present increasing complexity, emergent technologies, new relationships, and unpredicted faults/failures. To maintain required levels of productivity, process quality, and asset availability, manufacturers must reconcile this complexity to understand how the health degradation of constituent physical elements and functional tasks impact one another through the monitoring of critical informative measures and metrics. This article presents the initial efforts in developing a novel hierarchical decomposition methodology. The innovation in this method is that it provides the manufacturer with sufficient discretion to physically deconstruct their system and functionally decompose their process to user-defined levels based upon desired monitoring, maintenance, and control levels. This enables the manufacturer to specify relationships within and across the physical, functional, and information domains to identify impactful health degradations without having to know all possible failure modes. The hierarchical decomposition methodology will advance the state of the art in terms of improving machine health by highlighting how health degradations propagate through the relationship network prior to a piece of equipment compromising the productivity or quality of a process. The first two steps of the methodology, physical decomposition and functional decomposition, are defined in detail and applied to a multi-robot work cell use case.

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1. Introduction

Manufacturing processes, and the corresponding physical systems that enable them, can be complex. This complexity has grown substantially due to the integration of advanced technologies and reconfigurable systems. Maintaining a factory's operational efficiency requires clear maintenance and control strategies [1,2]. Manufacturers are turning towards Smart Manufacturing (or Industry 4.0) practices to support these strategies [3–5]. Smart Manufacturing aims to integrate hardware, software, and data to increase operational efficiency, asset availability, and quality while lowering scrap and unscheduled downtime. Successful integration of these elements and acceptable, continued operational performance of the resultant system should provide manufacturers with the intelligence to minimize unscheduled process and equipment downtime; and flexibility to meet changing consumer demand and supply chain volatility.

The manufacturing evolution is being advanced by emergent, disruptive technologies (i.e., additive processes, collaborative robotic systems) and an abundance of more affordable sensing and visualization technologies [6]. Greater sensing, monitoring, and control capabilities have supported the development of new approaches to better manage complex manufacturing systems. For example, some of these approaches leverage energy consumption and efficiency metrics to promote smarter maintenance and control strategies across diverse platforms from the manufacturing floor down to machine tools and robot systems [7–9].

Complexity can be readily viewed in many robot systems that are currently operating on factory floors. Robot systems can be configured to perform numerous tasks in many manufacturing environments including aerospace [10–12], automotive [13–15],

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consumer packaged goods [16], and electronics [17,18]. Smart Manufacturing is elevating the capabilities of these robot systems through the integration of diverse end-effectors, sensors, and supporting automation (e.g., conveyor systems, linear rails) in concert with advanced data analytics and information visualization tools. In turn, these robot systems are becoming more adept to complete a range of tasks under changing conditions and parameters. These additional features and capabilities lead to increased complexity at the system, sub-system, component, etc. level of the overall work cell.

Another result of the added complexities is an increased potential for elements within the process or the system to experience faults or failures. Faults and failures typically create asset downtime leading to lost productivity and increased maintenance which leads to increased costs and decreased profits. Currently, the manufacturing community ranges from taking a 'react and repair' approach to taking a 'predict and prevent' approach to their maintenance [2,19]. Most manufacturers practice a combination of 'react, repair, and prevent' which is usually driven by a documented maintenance plan (the quality of documentation varies across the manufacturing community). Some innovative manufacturers are taking a 'predict and prevent' approach, yet they still succumb to 'react and repair' when faced with unexpected failures, albeit these unexpected failures are usually reduced in frequency and/or severity.

Manufacturers can only survive for so long on a strict 'react and repair' approach, especially if competition emerges and takes a 'predict and prevent' approach to process and equipment health. 'React and repair' typically involves greater maintenance costs (both in labor and materials) and has a more substantial impact on production since reactive maintenance is unplanned where both have a negative impact on costs and profits [2,3,19]. A benefit of adopting a 'predict and prevent' approach is that it will support evolving manufacturing process configurations as new technologies are integrated on the factory floor.

In addition to the intricacy presented by robot systems on the factory floor, other key technologies exist within manufacturing that increase complexity. Machine tools and additive manufacturing are two such technologies that are inherently complex. These technologies are currently being integrated with robot systems (e.g., industrial robot arms being used in machine tending operations) thereby creating greater complexity [20]. This complexity manifests itself as many relationships between a system's physical elements, functional tasks, and the metrics/measures necessary to characterize system performance and health. Manufacturers are challenged in accurately and appropriately defining these relationships to understand how equipment and process health degradation propagate through the manufacturing system; the manufacturing community would like to see the development of a means of defining and organizing these relationships to support the design and implementation of their maintenance strategies [4,6].

The U.S. National Institute of Standards and Technology (NIST) is performing research to support the manufacturing community in the design, deployment, verification, and validation of advanced monitoring, diagnostic, and prognostic (collectively known as Prognostics and Health Management (PHM)) technologies to enhance maintenance and control strategies [21]. One research effort in this area is the development of a hierarchical decomposition methodology that will enable manufacturers to articulate the relationships across and between physical elements, functional tasks, and the metrics/measures so a manufacturer can make informed and strategic decisions on where and what PHM technologies should be deployed in their manufacturing operations. The innovation in this method is that it provides the manufacturer with sufficient discretion to physically deconstruct their system and functionally decompose their process to user-defined levels based upon desired monitoring, maintenance, and control levels; and enables the manufacturer to develop relationships within and across the physical, functional, and information domains to identify impactful health degradations without having to know all possible failure modes. The hierarchical decomposition methodology will advance the state of the art in terms of improving machine health by highlighting how health degradations propagate through the relationship network prior to a piece of equipment compromising the productivity or quality of a process. This paper presents the latest efforts in developing this methodology. Section 2 presents background on this effort including PHM within manufacturing. Section 3 discusses the hierarchical decomposition methodology. Section 4 details the initial application of the methodology to an in-house multi-robot use case. Section 5 discusses the findings of this effort and the next steps in developing the hierarchical decomposition methodology. Finally, Section 6 concludes the paper.

2. Background

2.1. Manufacturing work cells

Work cells are a critical unit of factory operations. These units vary in terms of size, scope, hardware, and software necessary to enable a cell's operation. Collectively, work cells are capable of many operations including welding, stamping, assembling, and machining [22–24]. These operations are enabled by a combination of industrial robot systems (e.g., robot arms, automatic/automated ground vehicles), machine tools, 3D-printers, and other automation (e.g., conveyor systems, linear rails) working together to turn raw material (or a part) into a part (or a more finished part).

Work cells present multiple layers of complexity to the overall manufacturing enterprise. They have their inherent complexity in that they can be construed as their own systems made up of subsystems, and components that work together to yield a process. Likewise, work cells may also be elements of the larger process occurring within a factory; the health of work cell elements influence both the health of the overall work cell and the higher-level systems in which the work cell is connected. Work cell health also influences the quality of its output parts. In turn, compromised part quality from a work cell can impact the health of higher-level systems and/or work cells downstream in the manufacturing process. Overall, this complexity makes it more difficult to ensure that a work cell's health is not compromised to the point where its availability, productivity, and quality (of the work cell-enabled process and/or output part) are not impacted. All three of these elements form the universal metric of Overall Equipment Effectiveness (OEE); a metric in which many manufacturers assess their operations [25]. A negative impact on any of OEE's constituent measures (availability, productivity, quality) will typically call a manufacturer to action; manufacturers are thus adopting PHM technologies to minimize (ideally, avoid) negative events.

2.2. Prognostics and health management

PHM refers to the field of monitoring, diagnostics, and prognostics aimed at enhancing maintenance and/or control strategies [26]. PHM has been applied to monitor, diagnose, and predict faults and failures in products across numerous industries including automotive, defense, earth-moving, and electronics [27–30]. PHM enhances maintenance and control by offering greater intelligence and awareness of the health of the specific process or product. To varying extents, PHM supports the numerous maintenance strategies available [2,3]:

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