Monitoring System Architecture for Long-Term Resilience in Manufacturing

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Abstract. In a volatile environment, the resilience of a manufacturing system is an element of high importance to avoid collapse and find a way to recover after disruptive events. In such an environment, having flexibility and adaptability are of higher long-term value than the attempt to maintain equilibrium or short-term stability at any sacrifice. Resilience is an intangible characteristic that cannot be measured directly, but its assessment requires the combination of measurable and probabilistic inputs. The aim of this work is to develop an architecture for resilience-aware monitoring and more knowledgeable management and control of manufacturing processes. The developed architecture combines the retrieval of real-time and event log data from the manufacturing shop floor and databases to allow the simulation of various manufacturing scenarios and data analytics for better decision-making. A modular real-time monitoring system creates the bases for higher predictability of internal disruptions. Therefore, four main groups of real-time and event log data were considered as input for process simulation and analytics: the status of machinery, workers and production orders; machinery and transportation system condition monitoring and in-process assessment of workpieces compliance; safety equipment usage and; items location and quantity tracing. The architecture was modeled to be applied on a cyber-physical demonstrator consisting of an assembly transfer line equipped with transport shuttles, workstations, a warehouse, a decision support system with analytics and simulation by creating an Industrial Internet of Things network. The developed resilience-aware architecture allows to optimize production and maintenance strategies execution for increased long-term resilience in cyber-physical production systems.

INTRODUCTION

While in the era of Industry 4.0 mostly productivity was the main concern of manufacturing, Industry 5.0 has a wider perspective integrating also resilience. Also, the European technology platform Manufuture emphasizes that innovative technologies must support manufacturing resilience [1]. Productivity and resilience are basically two sides of the same instance. Productivity characterizes the performance of the shop floor until the present moment. The productivity in further periods can be accurately predicted in a highly stable and reliable environment only. In counterweight, resilience considers the environment naturally being non-stable and full of various potential disruptions. As last years have presented, the external environment has gone through several severe disruptions as the pandemic, peaking inflation, supply chain bottlenecks at the international level, and energy crises. Many of the root causes continue to be present and further fluctuations in the external environment are anticipated that implicate effects on manufacturing shop floors' internal processes.

Monitoring system execution becomes a prerequisite for Cyber-Physical Production Systems (CPPS) and their purposeful operation that allows real-time information-based simulation of various manufacturing scenarios, data analytics for decision-making, and non-disruptive changes in the production process and system itself. For the longer-term efficiency of the system, the increased resilience should be considered as a central component to achieving. Therefore, the architecture of a modular monitoring system can be planned from the manufacturing system resilience perspective. Herewith, our research question is formulated. RQ: How to organize monitoring modules from a manufacturing system resilience perspective?

The aim of this work is to design a resilience-aware approach for monitoring architecture to enhance knowledge-based management and control of manufacturing processes. In the context of this study, resilience-aware means focusing on the subsystem (monitoring system) design to enhance resilience at a higher system level (workstation and manufacturing station). The monitoring architecture focuses on human-in-the-loop CPPS [2] [3] that must become capable of digital twin applications. This research covers only monitoring modularization in the shop floor from the perspective of internal disruptions. It does not cover means of communication and data handling processes.

This work is organized as follows: in the second section we introduce a practically usable resilience metric and existing monitoring approaches, in the third section we develop a resilience-aware approach for monitoring architecture design, in the fourth section we bring an example of how we applied the resilience-aware monitoring architecture approach to the cyber-physical system, and in the fifth section we conclude the developed architecture and point out further research need.

LITERATURE REVIEW

Several quantitative resilience metrics have been proposed to measure engineering system resilience [4] [5] [6], but none of them has become the industry standard. Even so, the resilience metric Penalty of Change (POC) [7] is outstanding for its practical usability in CPPS. According to the POC, resilience has two main components, probability of changes and penalty of changes. Changes are considered system responses to disruptions. These can be internal such as machine breakdown and quality flaws [8], or external such as cyber-attacks, pandemics, natural disasters, and shortage of materials and parts [9] [10]. The POC is calculated as follows [11]:

$$POC = \sum_{i=1}^{D} Pn(X_i)\Pr(X_i) \tag{1}$$

where D is the number of potential changes, X_i is the i-th potential change, $Pn(X_i)$ is the penalty (cost) of the i-th potential change and, $Pr(X_i)$ is the probability of the i-th potential change to occur.

As seen from equation 1, resilience is an engineering system property that cannot be measured directly. Therefore, a monitoring system for resilience-related data collection and processing is essential. Such monitoring systems often have a modular architecture, containing modules as machinery condition monitoring [12] for predictive maintenance, in-process quality monitoring for quality assurance [13], status monitoring with pause identification [14] for improved planning and delay detection, etc. Modularity allows its step-by-step implementation [15]. In turn, prioritization requires knowledge about the module's long-term effect to the whole system. Resilient monitoring systems [16] consider the resilience of the monitoring system itself and not the resilience of the overall workstation or manufacturing system.

Complexity in monitoring system setup has increased as automatic systems and human related activities must be approached differently. Human behavior can be unpredictable and unsystematic in certain conditions [17], such as tiredness, stress, fear, and monotony. In addition, human privacy must be protected also during working time [18]. During the heavy automation period in last decade, it has been understood that human skills and flexibility are often not replaceable with robots and therefore human in the loop and flexible automation is needed for CPPS [19]. Such systems are also called cyber-human systems [20] to emphasize human importance in CPPS. While automatic tasks and control logic generate tracking data of items and processes into reliable event log database, then human-related processes are often open for unsystematic errors.

Although, the monitoring system is a key element for knowledgeable resilience management in manufacturing, CPPS monitoring architecture in resilience perspective has not been in research focus and can be considered as research gap. As researchers have lately proposed an outstanding resilience metric POC to assess manufacturing systems, its structure can be taken as a source for resilience-aware monitoring system design.

RESILIENCE-AWARE MONITORING ARCHITECTURE

The resilience-aware approach for modular monitoring architecture for CPPS was developed. The approach aims at inspiring further work in resilience-aware monitoring system design, rather than presenting final validated results. The resilience metric POC was taken as the main knowledgebase for the approach. Additionally, differences between manual and automated work processes were considered.

Event log data tracking and monitoring are reliable in an automated environment. If the human is included in the loop, continuous monitoring is a more reliable solution. For instance, counting the number of finished products can be time-consuming for a human if the items are bulk positioned. Often, workers count at least twice to be sure of their correctness. Also, it cannot be guaranteed that the input and output quantities are equal in manual workstations as human-related operations are open for various unsystematic movements, such as losing or forgetting the parts. While machining errors are systematic and better trackable. Therefore, human-related processes require continuous monitoring, which we call real-time monitoring as opposed to event log data capturing.

Common industry practice is monitoring and tracking processes and items around to the human worker, instead of direct monitoring of a worker. First, ethics must be considered in human tracking in workplaces. Secondly, the quality of the work could decrease due to the stress regarding highly intrusive monitoring solutions.

According to POC, resilience can be characterized based on two components: cost of change and probability of change. Relevant costs are for instance equipment investment cost, workers training, decreased productivity, opportunity cost, and reprogramming cost. Additionally, resilience can be evaluated in temporal term by prognosing the time of change instead of cost if cost information lacks.

Probability of change aims to minimize the occurrence of change (disturbance) until avoiding it. Thus, avoidance of disruptions requires recommendatory pre-process or latest in-process detection of nonconformity and actions to absorb the aberration. Additionally, it contributes to the availability of machines and workers. Therefore, the probability layer in resilience can be called "avoidance of disruptions" in monitoring aspect.

Cost (time) of change is influenced by preparedness for potential changes. Preparation means ability for rapid and anticipated changes. Prerequisite for replanning of processes or activities and implementation of sudden changes are discovery of disruptions and awareness of status of the system entities and location of its components. This monitoring layer can be called "situation awareness and preparedness". This layer contributes to the planning at the time of disruptions as well as at regular daily manufacturing.

For the avoidance of disruptive events, real-time monitoring is needed as it requires collecting and processing of datasets and is in some monitoring modules time critical to take fast actions. While situation awareness and preparedness stands for knowledge about the system state (including machines, humans, components/products, and production orders). The difference between the two monitoring layers for resilience perspective (Fig. 1) can be distinguished by asking the question: can we execute actions in the system based on monitoring information to maintain the nominal productivity level? For instance, machinery condition monitoring helps to plan the replacement of components at a suitable time to ensure the availability of machinery. Safety equipment usage monitoring benefits for the availability and continued vitality of a worker. In-process quality monitoring works as a quality assurance by enabling the control system or worker to act in time to improve output quality, which is opposite to quality control after production. Additionally, tracking and tracing the state and/or location of machinery, workers, components/products, and purchase orders creates the basis for fast decisions and rescheduling if the system change (adaptation to a new state) is needed.

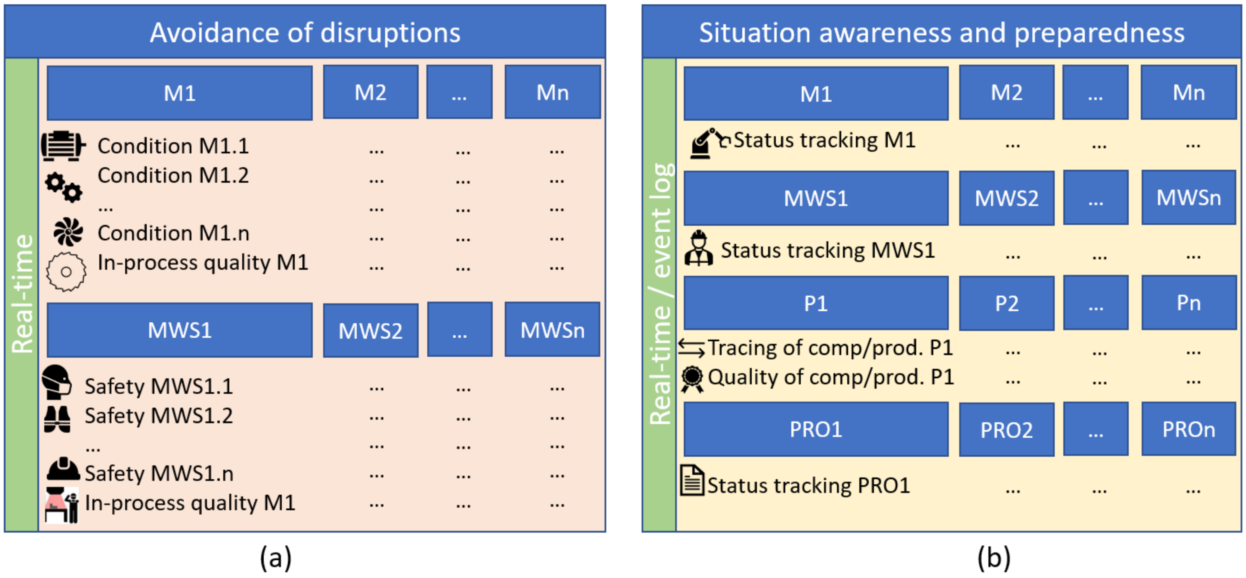

FIGURE 1. Two-layer resilience-aware modular monitoring architecture. a) Layer 1 – avoidance of disruptions. b) Layer 2 – situation awareness and preparedness. M – machine, MWS – manual workstation, P – component/product, PRO – production order.

We are calling these two components as monitoring layers for resilience in CPPS. The layer Avoidance of disruptions covers machinery condition monitoring, in-process quality monitoring in machining and in manual processing, and safety modules. Safety and condition monitoring often have more than one module to cover critical machinery components and safety risks. The layer Situation awareness and preparedness covers machinery, workers and purchase orders status tracking, post-processing quality control and tracing of items quantity and locations.

APPLICATION USE CASE: MONITORING SYSTEM DESIGN FOR CYBER-PHYSICAL DEMOMNSTRATOR

The developed resilience-aware approach was applied on the design of a cyber-physical demonstrator's monitoring system. The realization of the demonstrator's physical monitoring system was in process and the results could not be measured and evaluated during this study. Still, the use case example illustrates the approach in real life situation.

The CPPS demonstrator will be executed in the learning factory 'Smart Mini Factory' at the Free University of Bozen-Bolzano. The monitoring architecture of the demonstrator was designed to increase the awareness on resilience of the manufacturing system by avoidance and preparedness for potential disruptions. The demonstrator consists of the following physical entities: a Montrac transfer line with three shuttles for transportation; a warehouse rack; a Universal Robot UR10 collaborative robotic arm for loading components and products from warehouse to shuttles and manual workstation; a 3D-printer; a manual workstation with digital assistance system; and an Omron Adept Quattro fixed robot for servicing the 3D-printer (Figure 2). The human worker in the manual workstation is in the loop of a production process. Nevertheless, manual workstation servicing processes will be executed automatically (servicing with physical components and providing step-by-step digital work instructions). The transfer line allows to add of up to seven workstations, which makes the demonstrator extendable.

Sensor's selection and allocation with measuring type and feedback actions in CPPS were defined to create bases for digital twin execution (Table 1). According to the resilience-aware approach, the sensors were divided into two groups in resilience perspective: avoidance of disruptions, and situation awareness and preparedness. The idea of the demonstrator is to cover various monitoring types and to present the possibilities and solutions for resilient CPPS. Therefore, in the monitoring system design, each module was covered at least once. For instance, condition monitoring was allocated for a shuttle, but not for other machining modules.

TABLE 1. Sensor allocation for data collection in the cyber-physical demonstrator

Monitoring parameter	Measured parameter	Sensor/ input type	Sensor placement	Measu-ring type	Feedback actions	Sensing point no.
Avoidance of disruptions						
Condition of a shuttle motor	Vibrations	Accelero-meter	Under the bottom of the shuttle	Real-time	Scheduling of shuttle maintenance	1
In-process quality of assembling operation	Shape, color	Multi-sensory camera	Above the assembling area	Real-time	Noncompliance with a quality alert (reassembly needed)	2
Personal safety equipment usage	RFID tag presence	RFID reader	Under the manual WS working table	Real-time	Missing safety equipment alert / suspension of operation	3
In-process 3D-printed part quality monitoring	Shape correctness	Set of temperature sensors	Near the printer nozzle and near the edge of bottom plate	Real-time	In-process adjustment of the filament temperature of the running program	4-5
Component placement in a blister	Position and orientation	3D-camera	Above the shuttle	Real-time	Command to the robot to replace the component	6
Situation awareness and preparedness for potential disruptions						
Quality of product	Shape and color	3D camera	Above the shuttle	Real-time	Bring the item to the manual quality control	6
Manual WS input quantity	Weight	Strain gauge	Under the bin of the main component in manual WS	Real-time	Missing parts alert / reason request for worker	7
Manual WS output quantity (finished goods and scrap)	Weight	Strain gauges	Under the bin of finished goods and scrap in manual WS	Real-time	Production orders and scrap reporting	8-9
Status of production order	No of linked finished products	Link between product and production order	Enterprise resource planning	Event log data	Send to final packaging / delay alert	10

Status of automatic machine/robot/ shuttle	Program start/stop	Status of program	Relational database	Event log data	Scheduling of a new operation/task	11
Status of worker	Progress of a digital assistance system program	Digital assistance system program workflow	Above manual WS working area	Event log data	Asking for pause reason reporting	12
Location of components/ products	Control system logic	Robot/shuttle program	Enterprise resource planning	Event log data	Input for (re)scheduling	13
Internal logistics fault detection	Bin presence and state	Photo-resistors	On top of the shuttle	Real-time	Blister disappearance alert for manual check	14

Figure 2 illustrates the sensors physical allocation according to monitoring layers. It can be seen that (i) system knowledge (cloud databases) benefits for situation awareness and preparedness, (ii) automated machining processes mainly need sensors for avoidance of disruptions and (iii) manual workstation is covered with both types of sensors.

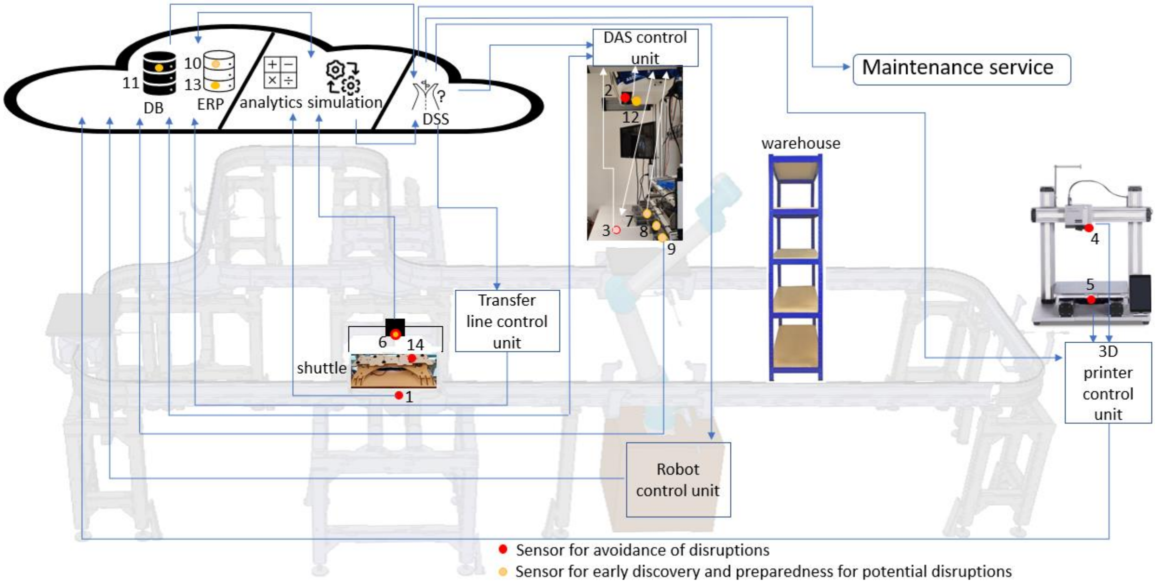

FIGURE 2. Resilience aware monitoring architecture for cyber-physical demonstrator. DB – database; ERP – Enterprise Resource Planning; DSS – Decision Support System; DAS – Digital Assistance System; WS - workstation. The numbers 1-14 indicate the sensing points listed in table 1.

CONCLUSION

The research provided first steps on resilience-aware approach for CPPS monitoring system architecture. The research question is answered in Figure 1. Shop floor monitoring information was organized into two layers from manufacturing system resilience aspect. One layer stands for avoidance of disruptions, which means collecting the in-process information during machining, manual working and internal logistics. This enables actions to be taken before losing in productivity. The second monitoring layer, situation awareness and preparedness, focuses to the current manufacturing system status (machinery, workers, components, production orders) information to enable knowledgeable changes. This architecture was applied as use case in cyber-physical demonstrator monitoring system design.

Such classification enables prioritization and knowledgeable analysis in planning of monitoring modules. It has practical value in facilitating the selection of the monitoring methods. In theory, decreasing one of the POC components until zero, would bring the resilience into maximum level. In practice, disturbances cannot and should not be totally avoided as manufacturing companies are part of global economy and the occurrence of external disruptions is out of their control. Rather, balance between avoidance and preparedness must be found.

Next step in our research is execution of the monitoring system modules and integration for digital twin realization. It requires detailed configuration of communication hardware, common protocol over various field entities, and control logic. Additionally, preferred manufacturing scenarios can change in time based on disturbances, electricity price or additional customer orders. Therefore, research in digital twin scenarios simulation in CPPS is further needed.

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