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Zero defect manufacturing strategies for reduction of scrap and inspection effort in multi-stage production systems

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Abstract

Multi-stage production systems offer a huge potential for defect compensation and defect propagation avoidance on system level, in contrast to current single-stage solutions, in order to reduce scrap and to minimize time-consuming and cost-intensive quality control. Integration of additional sensor systems and sophisticated analysis of the acquired signals enable strategies in the field of downstream compensation, inline rework and enhanced process control without including additional process and inspection stages. The presented strategies are validated in three emerging European industrial sectors (aerospace, railway and medical) yielding a universal solution for zero defect manufacturing in multi-stage production systems.

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Keywords: Zero-defect manufacturing; Effect elimination; Multi-stage; Production system

1. Introduction

Increasing volatility in the global and local economies, shortening product life cycles and increasing degree of product customization call for production systems that comply with these changing demands in all their basic functions, including quality and production control. Current Zero Defect Manufacturing (ZDM) approaches are local solutions focused on single production stages. They are also static and sequential, in the sense that when a problem is analyzed and solved at a specific stage, the company considers the process as 'frozen' and moves the attention to a new critical stage. This sequential strategy prevents the company from quickly adapting its production operations to changing production targets, thus undermining its competitiveness on the global market. In order to achieve this, the goal is to develop ZDM strategies that reduce the generation of scrap parts and prevent defect propagation in multi-stage production systems.

End-of-line quality testing is usually applied to assess the product functionality at the end of the process chain [1]. However, this approach does not support the in-line prevention and correction of defects. Emerging Key Enabling Technologies (KETs), such as in-line data gathering solutions, data storage and communication standards, data analytics tools and digital manufacturing technologies offer new opportunities for ZDM. These technologies are increasingly becoming integral part of modern production systems [2]. If these technologies are properly integrated with a cross-KETs approach, new cyber-physical systems (CPSs) can be designed and implemented at shop floor level, to support systemic ZDM solutions [2,3]. CPSs are usually defined as systems integrating computation and physical actuation capabilities [4]. In CPSs, embedded computers and networks

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monitor and control physical processes, usually with feedback loops, where physical processes affect computations and vice versa. The economic and social potential of CPSs is vastly greater than what has been realized yet, and major investments are being made worldwide to develop these solutions in response to emerging industrial problems (Industry 4.0) [5]. This potential in connectivity and computational power in manufacturing can be exploited to support the implementation of efficient in-line quality-oriented production solutions.

Successful projects in the 4ZDM cluster supported by the European Union such as MUPROD, IFACOM [6], MEGAFIT and MIDEMMA demonstrate how to achieve near zero defect level in different manufacturing systems. The focus was to reduce the number of defects in manufacturing of complex high-precision and high value parts by in-line measurement, process control, or enhanced quality control. In MUPROD, an innovative quality control system was developed on lab scale for in-process multi-stage defect reduction [7–9]. MEGAFIT and MIDEMMA were focused on micro-manufacturing processes, including multi-stage micro forming [10–12].

The new research project ForZDM within the 4ZDM cluster aims at developing and demonstrating a next generation ZDM strategy capable of dynamically achieving the production and quality targets grounding on an integrated quality and production control solution for multi-stage systems. In both large volume and small batch production contexts, this solution will allow companies to rapidly deploy a cost-effective line monitoring and control system that will reduce expensive off-line measure-rework-assess loops and avoid the delivery of defective items at the end of the line. The ultimate goal is to reduce the system operational costs and materials wasted in scraps, thus increasing the competitiveness and sustainability of European companies in the global market.

This paper is structured as follows. Section 2 introduces the overall ZDM solution concept and the reference architecture. Section 3 outlines the different data gathering systems while section 4 investigates online defect prevention and defect propagation mitigation solutions. The focus in section 5 lies on system-level ZDM solutions followed by section 6, which highlights the integration in production and equipment control systems. In section 7, the validation in industrial production systems is presented. Finally, a conclusion and outlook is given in section 8.

2. Zero defect manufacturing solution for high value adding multi-stage manufacturing systems

The multi-stage ZDM solution proposed is developed on three different production lines, namely, for jet engine shafts, medical microcatheters and railway axles. These lines provide a basis to deploy the specific contents of the solution and serve as pilot cases to demonstrate the applicability of the solution to very different multi-stage lines.

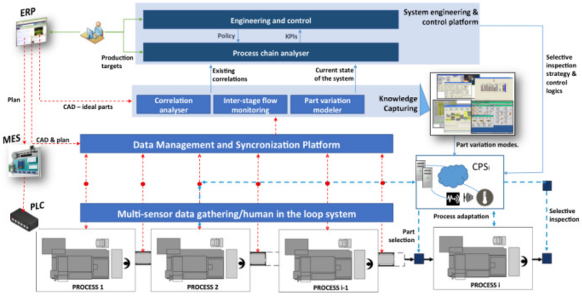

Fig. 1. Reference architecture of the ForZDM solution.

2.1. Zero defect manufacturing system architecture

The reference architecture for multi-stage systems on which the solution proposed by ForZDM is based is represented in Figure 1. The proposed architecture grounds on five major pillars, which are described in the following. The first pillar consists in a comprehensive *Data Acquisition System*, able to collect and synchronize data gathered from different, heterogeneous, multi-resolution and multi-scale data sources distributed in the production line. These data include (i) workpiece quality data, gathered by inspection technologies, (ii) process data, gathered from in-process sensors, (iii) machine state data, gathered by the production monitoring system, (iv) product flow related data, gathered by tracking solutions, and (v) codified feedback, gathered by production line operators. This new integrated data-acquisition system will feed a *Data Management Platform* that will store and update the acquired data in a structured and formalized way. This platform will be enriched with data management, extraction and aggregation features in order to support the knowledge-based analysis of the relevant inter-stage correlations. Overall, this solution will make it possible to achieve observability of the product, process and resource states, throughout the system stages. Connected to the aforementioned data management platform, a suite of *Data Correlation, Error Budgeting and Root Cause Analysis* tools, based on advanced data analytics and artificial intelligence techniques, is included to characterize the significant defect correlations among product, process and resource data, at different stages. This tool will be supported by an HMI to allow the user to model existing correlations via “knowledge-based” and “learning-based” methods.

At zero defect generation level, Cyber Physical Systems (CPS) make it possible to proactively adjust the process parameters, the fixture, and the reference locators before each critical process stage. The information about the incoming part history in the previous stages is used to issue alarms on the specific variation mode of the part, before the process. With these inputs, a model-based approach is used to adjust the controllable variables at the next correlated stage to avoid the generation of defects while processing the part under the identified variation mode. To reduce complexity, a pre-defined discrete set of alternative process parameter sets will be designed and validated for each part variation mode combination. After the processing, if one or more product key quality characteristics is outside the specification limits