Electrospindle 4.0: Towards Zero Defect Manufacturing of Spindles

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Abstract

Industry 4.0 represents the last evolution of manufacturing. With respect to Industry 3.0, which introduced the digital interconnection of machinery with monitoring and control systems, the fourth industrial revolution extends this concept to sensors, products and any kind of object or actor (thing) involved in the process. The tremendous amount of data produced is intended to be analyzed by applying methods from artificial intelligence, machine learning and data mining. One of the objectives of such analysis is Zero Defect Manufacturing, i.e., a manufacturing process where acquired data during the entire life cycle of products are used to continuously improve the product design in order to provide customers with unprecedented quality guarantees. In this paper, we discuss the goals of the Electrospindle 4.0 project, which aims at applying Zero Defect Manufacturing principles to the production of spindles.

Keywords

Industry 4.0, Zero Defect Manufacturing, Design for X, Artificial Intelligence

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1. Introduction

Industry 4.0 represents the last evolution of manufacturing. With respect to Industry 3.0, which introduced the digital interconnection of machinery with monitoring and control systems, the fourth industrial revolution extends this concept to sensors, products and any kind of object or actor, i.e., *thing*, involved in the process. Internet-of-Things (IoT) enters in the manufacturing sector. The tremendous amount of data produced is intended to be analyzed by applying methods from artificial intelligence, machine learning and data mining.

One of the objectives of such analysis is Zero Defect Manufacturing [1], i.e., a manufacturing process where acquired data during the entire life cycle of products is used to continuously improve the product design in order to provide customers with unprecedented quality guarantees. The achievement of such an objective also requires to rethink the entire manufacturing process and the entire supply chain, in order to consider every single phase of the product life cycle.

In this paper, we discuss the goals of the Electrospindle 4.0 project, which aims at applying Zero Defect Manufacturing principles to the production of spindles.

A spindle is a rotating motor device employed in manufacturing for machining different types of material, by applying different possible tools. Such machine undergoes severe functioning conditions in terms of vibrations and shocks, thus reliability is a fundamental feature for customers, which do not want to sustain inactivity periods due to maintenance operations.

HSD is an Italian company and one of the international leading companies in the production of spindles for manufacturing customers. The Electrospindle 4.0 project has started in June 2021 and has a duration of three years. Its objectives are coherent with some of the lines of action proposed by the Italian Cluster "Fabbrica Intelligente" (CFI), which clearly identifies HSD as a *Light House Plant* for *Zero Defects Manufacturing*, i.e., a national reference point for what concerns technological innovation. The identified lines of action are: *(i)* production systems for a personalized production, *(ii)* efficient production systems and *(iii)* adaptive and evolutionary production systems; that are also coherent with the European strategies for the development of a resilient country in the manufacturing sector.

The nationally funded Electrospindle 4.0 project should sustain the effort of HSD in the development of a new family of spindles respondent to the principle of Zero Defect Manufacturing.

The new family of spindles will be equipped with special sensors that will enable them to independently transmit data related to their status and working conditions while performing their functions on the machine tool on which they are installed. Such devices will be the result of the application of several techniques, including cloud computing, machine learning (ML), artificial intelligence (AI), digital twins (DT) [2] and Design for X [3]. The new manufacturing process will promote a continuous improvement of design and manufacturing processes, with the goal of creating more reliable and efficient products.

The paper is organized as follows. Section 2 summarizes the project organization, Section 3 outlines the objectives and Section 4 presents the current status of the project.

2. Summary of the project

The project involves four partners specialized in various aspects of the project. HSD (https://www.hsd.it/) and EN4 (https://en4.it/) are the industrial partners of the project. HSD, already introduced in Section 1, is the project leader that will develop the new spindle family, the use cases and the Zero Defect pilot production process. EN4 is a leading company in the production of automated test systems and will devise new Industry 4.0 compliant smart testers. Sapienza Università di Roma and Università Politecnica delle Marche (UnivPM in short) are the academic partners of the project and will provide technological transfer from research to practice. UnivPM will focus, in particular, on the technological solutions needed for the design and production processes, whereas Sapienza will focus on software solutions to manage and elaborate the big amount of data of the entire production process.

The project aims at applying innovative technologies to realize a family of Zero Defects products (X-CORE spindles), produced through a Zero Defects Manufacturing process. Two distinct and strictly connected results have been identified. The first one is the development of the new *product line*, whereas the second one is the definition of an innovative Zero Defects production process (*process line*). See Section 3 for further details about these objectives.

The X-CORE spindle will be a highly digitized product intended to be part of the HSD Industry 4.0 ecosystem. The integrated sensors and the interconnectivity features will allow a complete control of the spindle, and to collect data during the entire product life cycle allowing to evaluate the performance with respect to actual employment conditions. This will, in turn, allow to improve the manufacturing and design processes.

The Zero Defects production process will be the result of a continuous improvement thanks to the analysis of data acquired from multiple sources including raw materials and components provided by suppliers, machines and humans on the manufacturing line, design phase projects, maintenance information, and of course data coming from the new X-CORE spindle. This will allow to make the production process iteratively more and more reliable and responsive.

3. Objectives and expected tangible results

The project is organized into eleven workpackages (WPs). The first five WPs (WP1-WP5) have industrial research objectives, whereas the last six (WP6-WP11) represent prototype development activities. In particular, the WP6-WP11 temporally comes at the end of WP1-WP5, representing their implementation phases. In the following, we show how these workpackages contribute to the two objectives defined in Section 2.

The X-CORE devices are the evolution of the E-CORE spindles, patented by HSD in 2007, which are intelligent devices able to self-monitor their status and conditions. E-CORE spindles are examples of devices for the Industrial Internet of Things (IIoT) and the X-CORE family will improve the functions, performances, duration and reliability of the product. Innovative sensors will be added and the spindle will be able to communicate with an Edge/Cloud architecture able to manipulate the huge amount of produced data for different purposes, including predictive and preventive maintenance strategies. The design and development of the new X-CORE family are the goals of WP1 and WP6 respectively.

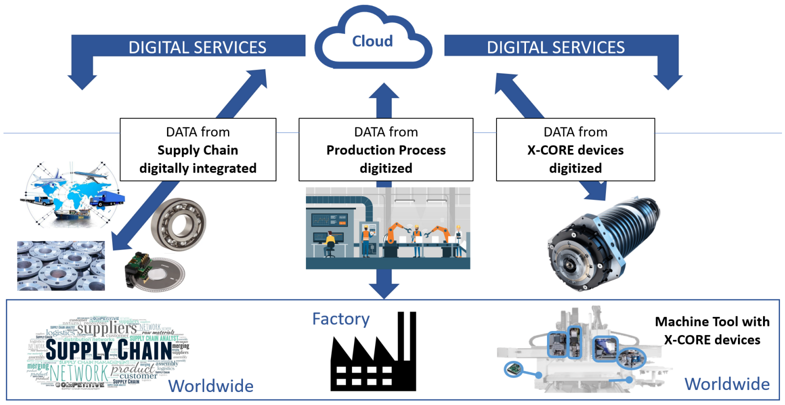

Figure 1: End-to-End production chain data flow

A new end-to-end manufacturing process will be developed with the purpose of *(i)* turning the process from reactive to proactive, *(ii)* designing a new logistic for raw materials and components, *(iii)* studying the possibility of applying augmented reality to production, and *(iv)* studying the functionalities of the new Manufacturing Execution System (MES). All of these objectives are the goal of WP2 and WP7.

As can be seen from Figure 1, in the new process data will come from the suppliers, from the HSD factory and from the customers. These data will be used to establish a circular feedback to improve the design and manufacturing processes. The new production strategies will be defined to guarantee real-time monitoring, reduce products defects, decrease costs and reduce downtime.

The definition of a new family of spindles will be coupled with a new family of testers (called *smart testers*), which will support the new features introduced by the X-CORE spindles. These new testers will be additionally integrated with the cloud infrastructure defined for the project. The design and development of smart testers are the goals of WP3 and WP8 respectively.

The novel manufacturing process will follow the product throughout the entire life cycle. This means also to consider what to do with the product at the end of its life. In particular, WP4 and WP9 will take care of so called Design-for-X, where X can be in the Electrospindle 4.0 product End-Of-Life (EoL) or environmental sustainability. The following objectives must be considered during the design phase: costs, defects, maintainability, energy saving, product sustainability, EoL management. A system will be developed to assist the designer in the identification of product's critical points and the alternative technical solutions to cover, e.g. optimization of the high added value components disassembly suitable for De/Re-manufacturing strategies [4]. The same WPs will also define the new services offered by HSD to its customers thanks to the newly developed product line.

The data gathered in the context of the project must be analyzed by using appropriate facilities. WP5 and WP10 have as main goal the definition of a cloud/edge architecture allowing to develop a multidimensional analysis including data mining, pattern analysis and visual analytics. WP5 and WP10 are also in charge of defining dashboard and visual analytics tools.

An important role in the project will be played by so called Digital Twins (DTs). The term is used in the project with a double meaning [2]. DTs will be employed in WP1 and WP6 for simulation purposes. In addition, DTs for monitoring, retrieving data and perform predictive and prescriptive maintenance tasks will be defined in the context of WP5 and WP10 [5].

Finally, WP11 is the integration WP, where results obtained in the other WPs are combined and evaluated.

4. Current project results

The Electrospindle 4.0 project started in June 2021. So far, only industrial research activities have been performed. In particular:

- The main characteristics of the new X-CORE family in terms of sensors and interesting measures have been chosen. In particular, these focus on three main components of the spindle: bearings, docking system and drive unit. Accordingly, several sensors were identified to measure temperature, vibration, speed, rotation, electromagnetic field, tie-rod position and impacts. The X-CORE circuit board will compute additional parameters that can be derived from the collected measurements. Finally, testing parameters, such as mechanical and electrical safety parameters, were also identified to contribute to Zero Defects Manufacturing. Also, networking hardware has been defined in order to ensure the necessary bandwidth to transmit all the obtained information.

- The AS-IS production process has been analyzed through different techniques to find the main characteristics that are needed to reach the Zero Defect Manufacturing. The Value Stream Analysis (VSA) [6] method was used to define the production process's Key Performance Indicators (KPIs), e.g., stocks, total process space, transportation, cycle time, set-up time. Next to the KPIs, the product and process sources of error were determined by performing the Failure Mode and Effects Analysis (FMEA) [7]. Another important analysis made was about the value stream of each product, that identified the value-added activities, the non-value-added necessary activities and the non-value-added unnecessary activities. Finally, the Critical-To-Quality (CTQ) value (perceived by the customers) was defined, by following the Lean Six Sigma [8] principles, to improve the products and services qualities.

- A cloud system and a dashboard were devised to collect Smart Tester data in real time with the purpose of monitoring and visualizing the test performances. The architecture is deployed on an AWS virtual machine where Docker containers instantiate the PostgreSQL database to store data, the MQTT broker to receive messages from the tester and the REST API to communicate with the implemented dashboard. The developed system results to be highly scalable allowing to integrate Smart Testers in the Zero Defect production.

- The Design for X tool was defined to support the designer in the development phase. CAD models, data stored in the central database and additional details defined by the user are analyzed with the goal to improve the product recyclability and re-manufacturing and to optimize its assembly and disassembly. The analysis produces KPIs and design rules validations that are used to improve the design.

- The solution will be based on a mix of edge, public cloud and private cloud computing [9]. In the context of the project:
  - Machine learning (both training and evaluation) and data mining tasks will be executed using resources from the public cloud (e.g., Azure Machine Learning). Identified tasks fall in the categories of descriptive, predictive (e.g., Remaining Useful Life [10]) and prescriptive maintenance. In addition, correlation techniques will be employed in order to correlate online data with design choices and constructive features of materials used for manufacturing. Process mining will be also used to analyze the end-to-end process [11].
  - The private cloud will be used to store data from HSD own information systems. These systems include the ERP, the CRM and the MES, which is one of the intended outcomes of WP2.
  - Data from X-CORE spindles will be stored in a public cloud. This public cloud is already available and called MyHSD.
  - Part of the models will be trained in the public cloud and will be evaluated directly on the spindle using edge computing [12]. To this aim, the X-CORE family will be equipped with computing capabilities.

5. Concluding remarks

In this paper, we have introduced the Electrospindle 4.0 project, whose aim is to design a completely new family of spindles together with their production process towards Zero Defect Manufacturing. The project is in an initial phase where only industrial research WPs have already started. Nonetheless important practical challenges have already been identified.

First of all, one of the technical challenge consists in the collection of a dataset big enough to allow for machine (deep) learning training. Unfortunately, the available data could be severely unbalanced. High resolution spindle data will be likely available only in certain phases of the life cycle, namely manufacturing and maintenance, whereas the data coming from the customer will be at a lower resolution (i.e., one measurement every 10 seconds), making it difficult to detect short term phenomenon. This is due to the necessity of reducing the data transmitted by customers for their installed spindle. This challenge could be addressed, in principle, by adding a fog layer to the architecture, but during the analysis phase the consortium decided that placing an additional infrastructure at the customer side is not feasible for security reasons.

Runtime data is needed first of all for predictive and prescriptive maintenance tasks, but it also important to help the designers to find correlations between issues detected at the spindle and characteristics of the raw materials and semi-product employed during the manufacturing phase. This last task must be feasible either using (semi-)automatic techniques or by providing suitable graphical user interfaces for visual analytics.

Another challenge under study, is how to track the product during shipping and installation operations, when no power source is available. Certain events during shipping (e.g., impacts) may indeed tamper the integrity of the spindles, thus influencing the life expectation. To this aim, a possible solution would be the employment of low energy, battery powered, solutions.

A last challenge worthy to be mentioned is the safe interaction between the HSD private cloud and the public cloud solutions that will be used for training purposes. In order to preserve the confidentiality of company's data, data transfer flow must be designed in order to keep the data in the public cloud only at training time. Also, the cost of the public cloud solutions is an important aspect for the sustainability of the project in the future.

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