TopKontrol: a Monitoring and Quality Control System for the Packaging Production

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Abstract

Industry 4.0 refers to the last revolution involving the manufacturing domain. Particularly, it is characterized by the introduction of innovative technologies and systems able to establish a high level of digitization. The adoption of these technologies is crucial to the development of more intelligent manufacturing processes. These processes should be able to independently exchange information, trigger actions and control each other, enabling an intelligent manufacturing environment. By creating manufacturing systems where machines are enhanced with sensors and IoT devices, the productivity and quality of the production will increase. In this paper we explore the TopKontrol project's objectives and results in the context of the packaging production line.

Keywords

Industry 4.0, smart manufacturing, monitoring system, packaging industry

1. Introduction

The concept of *Industry 4.0 (I4.0)* [1], also known as the fourth industrial revolution, is, today, a result of the emergence and distribution of new technologies, such as digital and internet technologies, which allow for the development of fully automated production processes. These processes involve only physical objects that interact without human interventions [2].

Smart Manufacturing is a term that is commonly associated with Industry 4.0. It aims to improve manufacturing processes in order to increase productivity and quality, ease workers' lives, and create new business opportunities. This is made possible by leveraging innovative

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technologies such as Artificial Intelligence (AI), big data analytics and Business Decision Support Systems (BDSS).

Digital Twin (DT) is a key technology used in the industrial context to achieve such goals. Authors in [3] propose a consolidated and generalized definition for a Digital Twin as a virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual world. Interestingly, several other definitions of DT can be found in the literature [4]. The application of DT can impact the way products are designed, manufactured, and maintained. On a high level, the DT can evaluate production decisions, access product performance, command and reconfigure machines remotely, handle troubleshoot equipment remotely, and connect systems/processes to improve monitoring and optimize their control [5, 6].

Quality control is another crucial aspect of manufacturing, and Industry 4.0 offers new opportunities for improving quality control processes. With the help of Industry 4.0 key enabling technologies, including Internet of Things (IoT) and Industrial IoT (IIoT) concepts, it is possible to collect vast amounts of data on the manufacturing process. This data can be analyzed in real-time allowing to identify and address quality issues as soon as they arise, minimizing waste and improving overall efficiency. Digital Twin can also play a significant role in quality control. By employing DTs simulation techniques manufacturers can test the impact of design and production choices on product quality. This allows manufacturers to identify potential quality issues before they occur in the physical world, reducing the need for costly and time-consuming testing and rework and implementing, therefore, Zero-Defect Manufacturing (ZDM) [7]. Furthermore, DTs enable the implementation of proper maintenance techniques, e.g., predictive and prescriptive maintenance, that can let production processes operating at peak efficiency [8]. By leveraging on IoT sensors and AI algorithms, manufacturing equipment are monitored to identify potential issues before they lead to downtime or quality problems.

This paper presents TopKontrol, an industrial project that focuses on the packaging domain. By utilizing various data devices and sources, including Bluetooth Low Energy (BLE) beacons and industrial cameras, TopKontrol aims at the development of a monitoring and quality control system for cardboard production. This system will serve two main purposes: first, it will monitor the die cutter, which is responsible for cutting the cardboard, by predicting its health and ensuring a timely replacement before it wears down. Second, the system will also detects errors on individual cardboards to avoid further waste of resources and time. Overall, the final purpose of the TopKontrol project is to improve the efficiency of the cardboard production process by identifying potential problems before they occur.

The paper is organized as follows: Section 2 provides a summary of the TopKontrol project, Section 3 and Section 4 respectively outline the expected and current project results. Finally, in Section 5 conclusions and future works are outlined.

2. Summary of the project and objectives

In 2018, TopKontrol was initiated as an industrial project with the purpose of creating a smart die cutter to monitor and improve the cardboard production process. The project has been supported by Italian entrepreneurship special funds, which leads to the creation of the private company spin-off iKarton. The consortium includes Sapienza Università di Roma as research unit, iKarton as the company commercially exploiting the system, A Come Azienda and SA.EL. as product certification experts. The first version of the TopKontrol system has been released in March 2023 and a first set of three industrial installations will be completed by the end of 2023. Die machines, also known as a die cutting machines, represent the key equipment used in such process. A die machine is composed of two heavy rollers, one of which has a die cutter attached to it. A die cutter consists a wooden board equipped with a set of blades and rubber blades in a specific design. The design of the die cutter is usually based on a drawing of the desired shape, which is created using Computer Aided Design (CAD) software. The CAD file serves as a blueprint for the die cutter, guiding the placement and shape of the blades and rubber blades to ensure that the final product is precisely cut to meet the required specifications. There are two primary types of die cutters: rotary and plane. Specialized blades attached to the die cutter can create cuts or folds in the cardboard. These blades have different names, including cut blade, crease blade, cut-crease blade, and perforating blade. In the manufacturing process of cardboard, it is common to use rotary die cutters over plane ones as they work faster. The process, depicted in Figure 2, begins with a conveyor belt that transport each raw cardboard from a stack and position it between the two rollers of the die machine. The roller with the die cutter applies pressure to the cardboard, producing cuts and folds according to the design. After the cardboard has been cut and folded to the desired shape, it is stacked and packaged for shipment to various customers. Die machines are capable of producing high-quality cardboard at high speeds, with the motorized roller typically set between 1 to 10 rotations per second. Thus, these equipment can produce a number of cardboard that ranges from a minimum of 3,600 pieces per hour, up to a maximum of 36,000 pieces per hour. Over time, die cutters can deteriorate and produce faulty cardboard sheets, leading factories to halt production and request a new or repaired die cutter. Typically, packaging factories avoid storing duplicate die cutters due to their size, as spare parts require twice the inventory space. Unfortunately, this approach can lead to inefficiencies and disruptions in production, causing delivery delays and wasted resources. To mitigate these problems, the TopKontrol project aims to develop a system prototype capable of tracking and monitoring essential features of the packaging production line, including rotations, speed, temperature, humidity, and cardboard defects. The monitoring system will enable prompt maintenance actions, reducing delays and costs, and ensuring seamless production processes.

The project is relevant for the information system community as the amount of data generated by every single installation is so high to require a careful design of the architecture in order to provide real-time guarantees for the operators and a satisfying experience for the management of the company.

3. Expected results

As a final outcome, the TopKontrol project is going to be composed of a set of interconnected software components processing data coming from IoT devices.

More in detail, there will be a component able to collect Bluetooth Low Energy (BLE) packets coming from sensors associated to the die cutters. Additionally, a vision-based software component will deal with the real-time analysis of produced cardboard. Production process-related

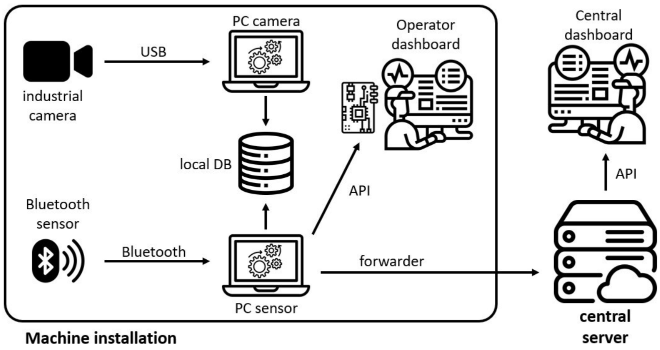

Figure 1: The deployed architecture

information will produce a production quality assessment. Finally, dashboards are going to be developed to provide end-users, i.e., operators and manager, easy access to information related to productions.

The final system is expected to improve the overall production quality from the perspectives of both die cutter and cardboard manufacturers. In particular, the die cutter manufacturer will be able to optimize the die cutter production according to the data gathered by the system and the simulated ones according to a Digital Twin (DT) model, focusing on the parts more prone to damaging with usage, increasing their products' useful life and reducing maintenance costs. From the perspective of the cardboard manufacturer, the benefits of the presented product would be various:

- Production operator may have live feedback for each individual cardboard.
- Every batch of cardboard sheets can be associated with a quality certificate.
- Realize an accurate custom Digital Twin model of the die cutter.
- Feedback on the Remaining Useful Life (RUL) of every die cutter, based on the Digital Twin and Machine Learning techniques (including, but not limited to, deep convolutional neural networks for anomaly detection) [9], will be provided in order to avoid any major interruption to the production caused by a malfunctioning.
- Optimization of the production based on current environmental conditions, i. e. temperature and humidity can vastly influence the outcome of a certain cardboard batch.
- Extract from data various Key Performance Indicators (KPI) of the ongoing and past production.

4. Current project results

We divide the discussion of the current results in two parts. In the first part we will describe the current system prototype and each component within the system in more details. Then, in the second part we will present a preliminary and ongoing work about designing and implementing a DT model of a die cutter.

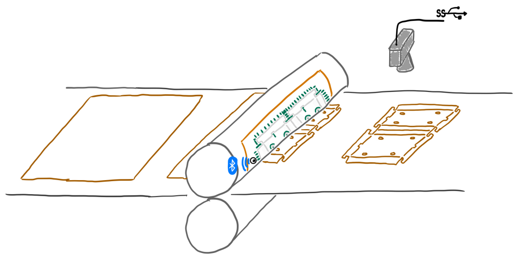

Figure 2: Cardboard manufacturing process and die machine setting

4.1. Architecture

Figure 1 presents the architecture of the experimental prototype of the system, where the machine installation block components are located close to a die machine and the remaining components are cloud-deployed software components.

The machine installation block includes two primary data sources, a BLE sensor and an industrial camera. The BLE sensor is directly attached to the die cutter, while the industrial camera points to the cardboard coming out of the die machine (see Figure 2). The data collected by these sources is then stored in a local database through two distinct PCs and subsequently sent to a cloud server.

Figure 1 also displays two dashboards: the operator dashboard, which presents data from local storage, and the central dashboard, which provides a comprehensive overview of data gathered from multiple die machines.

It is worth noting that the system prototype described in this section has been patented, so its specific design and capabilities are protected under patent law [10].

4.1.1. Monitoring process

The monitoring process is a crucial element of the TopKontrol project. To make the die cutter smart, an Industrial IoT (IIoT) BLE programmable chip is mounted on it, and its unique MAC address is used to identify the smart die cutter when broadcasting packets via Bluetooth.

The BLE chip collects data on the die cutter's revolution speed per second, as well as the temperature and humidity of the surrounding environment. The chip's firmware has been customized to compute some of this data, and a heuristic has been implemented to conserve the chip's battery life. The chip only turns on and starts data streaming when the smart die cutter is installed on the die machine during the effective cardboard manufacturing production process. This results in a more efficient and sustainable chip for tracking.

Data from the smart die cutters is collected by monitoring software running on a specific PC (referred to as PC sensor in Figure 1). The main function of this software is to collect die cutter usage data from the BLE chip, which is then stored in the local database and used by other components of the system for further analysis.

4.1.2. Quality control process

Another crucial component of the TopKontrol project is the one related to the quality control process. An industrial video camera is mounted alongside the production line with light projectors that enhance the lightning conditions and highlight cardboard surface. The camera acquires high quality frames of the cardboard sheets that pass underneath it at high speed. Such frames are processed by an inspection process running in a specific PC (dubbed PC camera in Figure 1) that applies image processing techniques in order to identify the cardboard features and compare them to the CAD model of the cardboard. CAD models, or engineering drawings, are an essential element for quality control of the manufactured product. Indeed, CAD models represent the depictions of products that include geometric as well as textual information such as measurements [11]. These information represents the quality requirements that the manufactured product need to meet. The developed inspection process first parses the CAD model to extract the relevant features of the cardboard which will be compared with the cardboard frame captured by the camera. Cardboard defects detected by the inspection software ranges from missing cuts in the cardboard to size errors (e.g. width or height). These defects are then stored to the local database and shown both in the Operator dashboard and in the Central dashboard.

4.1.3. Dashboards

The *Operator Dashboard* is a user-friendly tool that consists of a touchscreen interface and provides the worker with a summary of critical information during a production session. Typically, the BLE chip is responsible for automatically signaling the start and end of a production session, and the dashboard receives this information to begin showing data. The Operator dashboard enables the worker to manually indicate the start and end of the production session if needed, thus providing full control over the data collection process. The dashboard also presents a summary of the data collected during the production session, such as the number and type of errors detected by the system. In addition, the dashboard displays sample images of cardboard with defects, which can help the operator identify and address issues in the production process. Finally, the dashboard operates in real-time, thus providing the worker with timely information to intervene promptly and avoid any potential production issues.

The *Central dashboard* is an administrative tool that displays data from various die cutters and die machines. It provides a centralized location where data on each machine's history, monitoring, and quality-related data can be viewed. In the future, important KPIs will also be displayed. The dashboard is designed to benefit both packaging factory employees and die cutter manufacturers. On one hand, packaging factory employees can remotely monitor the productivity of their die cutters and identify any issues with the cardboard being produced. They can access a list of their die cutters, which allows them to easily track each machine's output and identify which machines are underperforming. By having access to this information, they can take appropriate action to address issues and ensure that the production process runs smoothly. On the other hand, die cutter manufacturers can use the dashboard to gain insight into their machines' usage patterns and identify areas for improvement. By analyzing the data on the dashboard, they can identify trends, such as which die cutters are being used more frequently, and which ones are producing the most errors. This information can help them design better die cutters that meet the needs of their customers and improve the overall quality of their products.

4.2. Towards a Die-cutter DT

As part of this project, we are also working on developing a custom die cutter DT using the work proposed by [12] and the data sources mentioned in the previous section, with the final goal of having a model that is capable of both processing real sensor data and and creating simulated ones to improve overall quality control performances of our system. Although there are several pre-existing frameworks for DT, their effectiveness might be limited in certain scenarios, as emphasized by prior works such as [13]. On the other hand, custom DT solutions such as [6] usually focus on simulation aspect of the DT. We intend to devise a custom solution that can handle real-time data streams without relying only on simulated data (e.g. to update the model's internal state). Our approach is especially relevant as we are dealing with machines that are over 40 years old and cannot be retrofitted with Industry 4.0 technologies. Therefore, we need to devise a solution that does not interfere with the original machines, treating them as *black boxes*. Put differently, we are using a *wrapper* approach, similar to the one used for legacy information systems over 20 years ago with distributed object technologies, as discussed in [14]. Having a custom DT solution could also potentially provide us the full control of the model and a direct interaction with the die cutter, allowing us to fine-tune its performance and monitor its health in real time. As theorized by [12], our DT will expose support for both *synchronous* and *asynchronous* Application Programming Interfaces (APIs), taking all necessary data from the database of current and past aggregated production data. Using the synchronous API, it would be possible to access the internal status of the twin, e.g., if the die-cutter is currently mounted to the die machine or not, its current real time cutting performances and its RUL. On the other hand, the asynchronous API would be used by the DT of the die cutter to trigger alarms that are displayed in real time to the operator dashboard if a noticeable amount of production errors is detected or if the simulation part of the model predicts a short amount of RUL. These functionalities will be used in the future by the operator dashboard, in order to display to the die-machine operator relevant data for the current production, or by the control dashboard to show historical performances of a die-cutter and its RUL.

5. Concluding remarks

In this paper, we presented the TopKontrol project, a system that aims to improve the overall production quality in the cardboard industry by collecting usage data from die cutters and analyzing the produced cardboard using image processing techniques. The system is composed of a set of interconnected software components, including a BLE beacon that is directly attached to the die cutter, a vision-based software component for real-time analysis of produced cardboard, and dashboards to access production-related information. The proposed system is expected to bring several benefits to die cutter and cardboard manufacturers, such as the optimization of die cutter production, certification of cardboard quality, and avoidance of major production interruptions caused by malfunctioning die cutters. Future work will focus on the development and implementation of advanced ML algorithms to enhance the quality assessment of cardboard and provide more accurate predictions of the RUL of die cutters. Another potential future work of the TopKontrol project is the integration with the Computer Numerical Control (CNC) systems of the equipment in the factory. By leveraging the data collected from the sensors and the analysis of the cardboard defects, the system could provide feedback to the CNC systems to adjust the cutting parameters and improve the quality of the cardboard produced, leading to further improvements in the quality and cost of the final product.

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