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A cloud-based cyber-physical system for adaptive shop-floor scheduling and condition-based maintenance

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ABSTRACT

Manufacturing, through the Industry 4.0 concept, is moving to the next phase; that of digitalization. Industry 4.0 enables the transition of traditional manufacturing systems to modern digitalized ones, generating significant economic opportunities by reshaping of industry. This procedure requires high-performance processes and flexible production systems. The adoption of the Internet of Things (IoT) in manufacturing will enable effective and adaptive planning and control of production systems. Towards that end, the proposed work presents a cloud-based cyber-physical system for adaptive shop-floor scheduling and condition-based maintenance. The proposed system demonstrated that it is possible to deploy a cost-effective and reliable real-time data collection, processing, and analysis from the shop floor. It also demonstrates that such collected data can be used in an adaptive decision making system, which includes a multi-criteria decision-making algorithm and a condition-based maintenance strategy aiming to improve factory performances when compared to traditional approaches. The proposed system consists of different modules (monitoring, adaptive scheduling, condition-based maintenance) interconnected through the cloud-based platform, enabled by communication protocols under the Industry 4.0 and IoT paradigms. The proposed system is applied and validated in a real-case study from a high-precision mold-making industry.

1. Introduction

Traditional manufacturing, through the fourth industrial revolution, is transformed into a digital ecosystem [1]. In this transformation, the Internet of Things (IoT) and the Cyber-Physical Systems (CPS) hold a major role. The advent of modern technologies such as cyber-physical systems, IoT, and the cloud technology open new horizons towards the industrial digitalisation by enabling automated procedures and communication by means that were not attainable in the past. Interconnected manufacturing systems and supply chains constitute an integrated whole that follows the System of Systems (SoS) paradigm [2]. In this context, the factory can be regarded as an ecosystem that is composed of interconnected entities that refer to the resources such as machine-tools and robots, the employees, the customers, the supply chain partners and other stakeholders of the value chain, following the idea of CPS [3].

Moreover, the integration of smart sensory systems, wireless sensor networks, as well as industrial communication protocols will support industries in adopting new ICT-based tools or to transform existing ICT-based production systems into adaptive ones. The interfacing of ICT-based systems with monitoring systems can provide the desired awareness of shop-floor condition, which is necessary for the realization of adaptive shop-floor planning and control. In parallel, the enabling technology of smart sensor networks can support in bridging the current gap in information distribution [4,5]. Web technologies, and especially cloud technology, can be used to establish integration interfaces in between disparate IT tools and enable a common data flow. Existing cloud-based applications in manufacturing have pointed out that the use of cloud technology enables the ubiquitous access to information and minimizes investment costs, among other key benefits that it offers [6].

To leverage the modern technologies towards the digitalisation of contemporary manufacturing systems, this paper presents a cloud-based cyber-physical system for shop-floor scheduling and control following the IoT and Industry 4.0 paradigms. The proposed system includes a monitoring system supported by a wireless sensor network. The monitoring system collects information from different sources (sensors, mobile devices, other IT systems) and analyses it through an information fusion technique [7] in order to derive meaningful information. Industrial communication protocols as well as security mechanisms are implemented. The storage of the gathered information is performed in a cloud server, along with the visualisation of the results

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to the end-user. The derived data are utilized as input in a scheduling algorithm in order to perform adaptive scheduling. In addition to that, the data is utilized as main input in a condition-based maintenance approach [8] which is developed within the proposed work. Exploiting cloud-based remote connectivity capabilities, the proposed system is delivered under the Software-as-a-Service (SaaS) model that can be applied in parallel in more than one manufacturers.

Modern manufacturing systems have to serve the increasing need for heavily customized products and deal with turbulences on their shop-floors which lead to increased complexity and difficulties during decision-making [9]. One of the main current challenges in production scheduling is the generation of efficient schedules under uncertainty factors [10]. Towards that, the proposed architecture aims to support adaptive scheduling taking into consideration not only monitoring data from shop-floor but also data related to maintenance.

The structure of the paper is organised as follows. Section 2 deals with the literature review on the technologies and the previous approaches related to the proposed cloud-based cyber-physical system. Section 3 describes the proposed method followed in this paper. Section 4 presents the hardware and the software developments. In Section 5, the case study where the cloud-based cyber physical system was evaluated is analysed. The results and the relevant discussion are presented in Section 6. Finally, Section 7 concludes the paper.

2. State of the art

CPSs have been defined as “the systems in which natural and human made systems (physical space) are tightly integrated with computation, communication and control systems (cyber space)”[11]. CPSs link the physical with the virtual world through flexible, cooperative, and interactive operation [12]. In the context of CPS, complex and heterogeneous large-scale systems are integrated through the service-oriented architecture (SOA), to deliver high performance and reliable operation [13]. In the digitalised era, the quality of services plays a crucially important role in meeting the emerging demands of customization and personalization. The adoption of CPS in industry is defined with the term Cyber-Physical Production Systems (CPPS) [3]. Towards the creation of Industry 4.0 factories, a stepwise approach is introduced for the design of CPS in manufacturing systems [14]. Moreover, the modelling of CPPS can be performed by following commonly accepted description frameworks such as the EAST-ADL modelling language. Apart from the connection with the tangible resources, the CPS can be extended with in-industry social media usage towards Social Manufacturing [15].

The physical entities enter the cyber world through microelectronic devices and internet communication protocols following the IoT paradigm [16]. Applications of Industrial IoT (IIoT) can empower the three pillars of the modern industry, i.e. the process optimization, the optimized resource consumption, and the creation of complex autonomous systems [17]. The robustness of the existing industrial networks makes them eligible candidates for several IIoT applications. Existing applications of IIoT have already demonstrated their potential in real-life case studies [18]. A key enabling technology for the digitalization of the modern industry is cloud manufacturing [19], as it enhances the integration of various industrial IT tools, and provides ubiquitous access to information and flexible licensing models [6]. Two major challenges that can decelerate the adoption of cloud manufacturing are the quality of services and the intellectual property protection [20]. Security is one of the main issues as different security protocols and standards should be developed and used, increasing data security and enabling companies to share their data.

The CPS paradigm suggests the use of monitoring devices under the IoT philosophy that goes beyond the traditional approaches for on-site data collection, processing, and visualisation. The main requirements for monitoring systems are to be robust, reconfigurable, reliable, intelligent and cost-efficient [4]. Various technologies of sensors can be employed for monitoring purposes. In the case of measuring energy-related operation characteristics, electrical current sensors are the most appropriate as they are cost-efficient and non-intrusive in nature [21]. A relatively new approach for monitoring, relevant to the resource awareness in the concept of CPS, is the machine-tool availability monitoring [22]. Despite the fact that various topologies for the communication of monitoring devices can be employed, in discrete manufacturing systems, the wireless sensor network topologies are the most eligible candidates as they offer flexibility and scalability, especially in environments such as the shop-floors [23][6]. A wireless sensor network consists of a large number of wireless-capable sensor devices, working collaboratively to achieve a common objective to increase or reduce production KPIs [24].

The use of various and heterogeneous types of sensors in monitoring systems requires specific manipulation of their output in order to extract meaningful information. This information extraction from various sources is realised through information fusion methodologies [7]. In 1988, concerning the topic of tool wear estimation in machining, [25] mentioned that the synthesis of system information can provide a number of benefits in process monitoring, such as maximum amount of information for making control decisions or reliable information during the process. The information fusion architectures are referred to as sensor level fusion, feature level fusion and decision level fusion [7]. In the decision level fusion, the Dempster-Shafer (DS) theory of evidence is mostly used, as in the work of [26], which aimed to identify the condition of a diesel engine. The Analytical Hierarchy Process (AHP) is coupled with the Dempster-Shafer theory in order to extract the corresponding weight for each source of information [21,27]. Several literature reviews have been performed regarding data fusion techniques. One of them is performed by Castenado in [28], explaining the different classification schemes for data fusion and reviewing the most common algorithms. The last years, most of the data fusion techniques were enhanced and enriched in order to deal with big data analysis. Zheng in [29] presented a review of data fusion methodologies, classifying them into different categories aiming to support the communities to find a solution for data fusion in big data projects. Another interesting review of Big Data analytics algorithms is presented by Ahmed et al., in [30], emphasizing on their role in Internet of Things and presenting several open challenges as future research directions.

Once the data are retrieved from the shop-floor, they are analyzed and meaningful information can be provided to the IT production systems, transforming them from isolated to adaptive. Several approaches have been reported in literature related to dynamic scheduling. Chryssolouris et al. in, [31] proposed a dynamic scheduling approach for manufacturing job shops using genetic algorithms and multiple criteria evaluation of alternative schedules. Michalos et al. [32] present a novel web-based tool for dynamic job rotation scheduling based on a multi-criteria intelligent search algorithm. The development of a multi-level adaptive control and scheduling solution for reconfigurable manufacturing environments from a real-time system automation perspective is proposed in [33]. Solution approaches for real-time control of manufacturing systems are also proposed by Monostori et al. in [34], where a scheduling system integrated with production monitoring subsystems is introduced to deal with common daily production disturbances. Furthermore, another dynamic scheduling approach is presented by Kumara et al. [35] by modelling dynamic scheduling systems as a virtual economy, where the “resource timeslots” are traded as goods.

During the last years, a number of research works have also introduced real-time scheduling. Subramanian et al. analyzed real-time scheduling algorithms for coordinated aggregation of deferrable loads and storage. In this study the authors compared three different scheduling policies and investigated their performance through simulations [36]. Buyurgan and Saygin proposed a multi-criteria decision-making algorithm for real-time scheduling and part routing solutions by implementing pairwise comparison of possible future states of a