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Internet of Things and industrial applications for precision machining

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Abstract. The Internet of Things (IoT) can be regarded as an attempt to bring together the physical and the digital world by using devices for seamlessly exchanging and processing information that can be used anywhere, anytime. For industrial automation and manufacturing, the Industrial Internet of Things (IIoT) is regarded as the next step of industrial revolution that promises a step-change in productivity and operational efficiency.

Precision machining is a field that has received a lot of research interest as it deals with phenomena and underlying mechanisms that are very complex and highly interacting. As the requirements and demand for products of high quality and tolerances that must be produced with shorter lead times are increasing, innovative approaches and methodologies need to be developed to compensate and IIoT offers an appropriate platform. This paper aims to present an overview of IIoT, investigate potential industrial applications for precision machining and predict future trends.

Introduction

The basic concept behind Internet of Things (IoT) was first introduced in 1985 to describe the integration of people, processes and technology with connectable devices and sensors to enable remote monitoring, status, manipulation and evaluation of trends of such devices [1]. It took almost 30 years and a combination of factors including technological advancements (such as low cost semiconductors, ubiquitous wireless networking, web-based computing, artificial intelligence), cultural shifts (such as digitalisation, move from product-centric to customer-centric markets, customisation) and strategic initiatives (such as Industrie 4.0) for IoT's potential to be realized and to gain significant adoption. To distinguish between consumer and industrial oriented applications the term Industrial Internet of Things (IIoT) was introduced in 2012 [2] denoting, among other sectors, the use of IoT technologies for manufacturing. While networking and remote data access are familiar concepts in manufacturing, the most typical implementations involve point-to-point connections such as machine-to-machine communications. Instead, IIoT promises a horizontal integration between equipment, data analytics, enterprise applications as well as people to a much larger scale.

Precision machining involves the use of material removal processes to create products of very high tolerances for a wide range of applications found in consumer goods, optics, automotive, aerospace, defense and other industrial sectors. Achieving such high tolerances is a highly complex problem due to the number and nature of the processes required, the properties of the often hard to machine materials and the properties of the equipment (machine tool, cutting tool, fixturing devices). The strong interactions between these factors result in a problem that is very difficult to understand and model, let alone to control to achieve a consistently reproducible result. Even after part production, there are considerable metrological difficulties to validate part quality through measurement and analysis of the machined surface characteristics.

This paper aims to present an overview of IIoT and identify any direct or indirect applications for precision machining. The paper is organized so that Section 2 presents the enabling technologies and associated challenges for IIoT while Section 3 lists common research approaches and problems around precision machining. Section 4 presents the identified IIoT applications for machining and finally Section 5 summarises the main findings and presents the relevant conclusions.

Industrial Internet of Things

IIoT enabling technologies. The IIoT revolves around six categories of enabling technologies to achieve its full potential and functionality as a platform (Fig. 1). These are i) identification, ii) sensing, iii) communication, iv) computation, v) services and vi) semantics [3].

Figure 1. IIoT categories of enabling technologies.

Identification methods are responsible for matching every connected object with a unique address within the communications network. Identification is very important as this is the only way to trace without ambiguity where and when data were generated. Normally, identification is implemented based on a client-server model and the Internet protocol version 4 (IPv4) to assign the required address. However, with current predictions estimating that tens of billions of devices are going to be connected to the Internet by 2020 [4], and with IPv4 having already exhausted the available number of addresses, a new protocol was needed and thus IPv6 was created. IPv6 does not merely increase the available address space but also provides enhanced security features such as end-to-end encryption and network layer security [5]. It is to be noted that the two protocols are not designed to be interoperable.

Sensing refers to the actual data collection from the connected objects (typically sensors and other instrumentation, actuators and machine tools) and to subsequent data storage in an online server database, which is called the cloud. IIoT's contribution to sensing comes in many forms; by using smart and/or embedded sensors, by deploying and managing Wireless Sensor Networks (WSNs), by making the data available anytime, anywhere, to anyone and by providing the capability to process the vast amount of generated data either close to the originating source (edge computing) or to centralized nodes (cloud computing).

Communication technologies include both software and hardware elements required to enable networking [6]. Software elements mostly refer to the necessary communication standards, protocols and security considerations. For close proximity communication, Radio-Frequency Identification (RFID), Near Field Communication (NFC) and Bluetooth or Bluetooth Low Energy

(BLE) are typically used. Wider coverage is enabled through Ethernet, WiFi, GSM and LTE standards for wired, wireless and cellular based implementations. Special security considerations that deal with user control, intrusion detection and prevention, logging and reporting etc., therefore determining how, when and by whom the collected data can be accessed are also part of the communication technologies. Finally, hardware elements include the physical network infrastructure (cables, antennas, switches, gateways, servers etc.).

Computation can also be considered in terms of software and hardware. Software is distinguished between real-time operating systems (for example Contiki [7], TinyOS [8], LiteOS [9]) and cloud based frameworks tasked with data exchange, storage and analysis. Several free and commercially available cloud platforms have been developed and comparisons of their features and functionalities can be found in [10, 11]. Hardware refers to the actual processing units tasked with performing the required computations at embedded device level. These are either in the form of microcontrollers or System-On-Chips (SOCs) with some popular development kits including Arduino, Raspberry PI and Intel Galileo among others.

Services can be categorised between simple data collection/storage and complex data processing for pattern identification and determination of appropriate actions to be taken [12]. The latter case is described by the term big data analytics and various techniques are used to achieve this goal. Among the more popular ones, statistical programming, time series analysis, machine learning and predictive modeling can be identified depending on the exact application.

Finally, semantics attempt to describe the meaning of the data that move around the network. Specific standards for capturing and communicating in unambiguous ways the information have been developed as well as for semantics integration like the Ontology Definition Metamodel (ODM) and the Model-Driven Message Interoperability (MDMI) standards.

IIoT challenges. Despite the fact that considerable progress has been achieved in each of the enabling technologies mentioned above, there are still significant challenges that have to be addressed [13]. These refer to technological, standardisation and even societal issues and the most important ones are security and data privacy, incompatibility of already deployed systems and equipment, lack of uniform legislation for data governance between different countries and job displacement.

In terms of security, system vulnerabilities and cyberattacks are the biggest concerns as both involve the risk of unauthorised access to sensitive data and in a worst case scenario the possibility to disrupt normal operation of production equipment. A number of research projects (for example IETF SOLACE, BUTLER) have already tried to address different security aspects of IIoT and several relevant publications can also be found in the literature [14, 15, 16, 17].

The incompatibilities of existing systems are due to the fact that manufacturing lines are typically commissioned independently and based on the level of technology at the time of design and development. Since manufacturing equipment exhibits long service life, the end result is a heterogeneous environment with equipment that has different levels of automation and communication capabilities. The direct consequence is that legacy equipment has to be evaluated before appropriate upgrade to overcome these interoperability issues, which requires a significant amount of resources and financial justification.

Precision Machining

Precision machining has received a great deal of research interest as there has always been a need for products with high tolerances and excellent surface quality. This need has become even more intensive in recent years as specific industrial sectors set requirements that are continuously harder to meet. Precision machining is a unique field as there is a variety of involved processes with significantly different characteristics. Based on the primary material removal mechanism, the most commonly used processes can be classified as shown in Fig. 2.

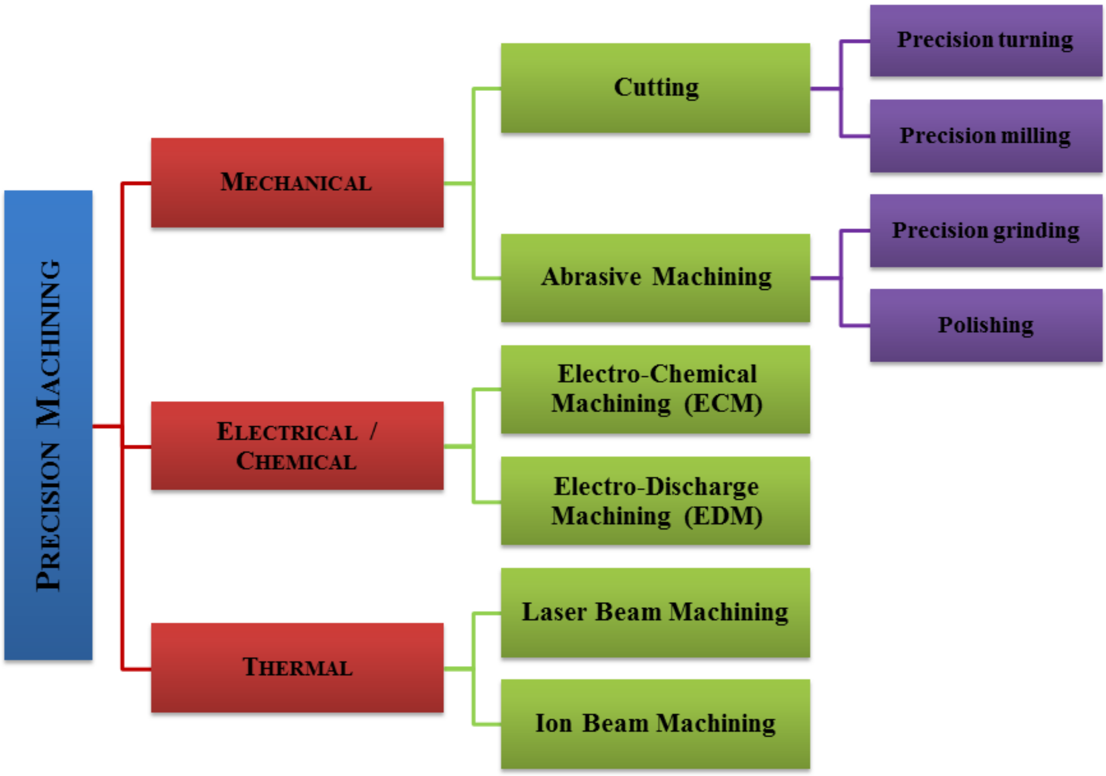

Figure 2. Precision machining process classification.

Research approaches and challenges. Several approaches have been proposed to address the goal of consistent part production that conforms to tight specifications, with each approach focusing on different aspects of the involved equipment, processes and materials system. Typically, extensive experimental studies are considered as inefficient as they require expensive materials and equipment, both for machining and post-process metrological analysis. Therefore, modelling is generally considered a better strategy and various methodologies are employed ranging from Finite Element Analysis (FEA), Artificial Intelligence (AI) inspired techniques to molecular dynamics simulations and coupled analyses are also frequently performed. Some of the most investigated factors include cutting conditions, cutting tool geometry and wear, material properties, machine tool vibrations and heat transfer while the most investigated quality criterion is surface topography in general and the Ra value of surface roughness in particular. Given the number of processes and adopted approaches, a detailed description of each is out of scope of this paper but [18, 19, 20, 21, 22, 23, 24] can be used for reference.

However, modelling presents several distinct drawbacks; as the underlying phenomena are highly complex some assumptions have to be made to simplify the investigated problem; it is also common for these models to include coefficients that must be experimentally determined and validated; finally, while the theoretical models are able to provide insight about key parameters (for example temperature, stress, strain and resulting deformation etc.) they are not often applicable on the production floor. These drawbacks make them less industrially relevant as the parameters that are modelled cannot always be controlled during machining. To overcome this problem, there is a need for further development of process-specific hybrid models that can combine analytical with empirical and/or numerical formulations in areas such as prediction of dimensional deviations, cutting tool wear, real time control and compensation of process parameters.

IIoT Applications in Machining

Macroscopically, the main benefits that IIoT is expected to provide for machining are increased productivity, operational efficiency and quality. Of course, there are more than one ways that these can be achieved, so this section presents some specific areas where IIoT can be applied to realise the above benefits. As can be seen, most of the identified implementations target automation, process monitoring and control and predictive maintenance (Fig. 3).

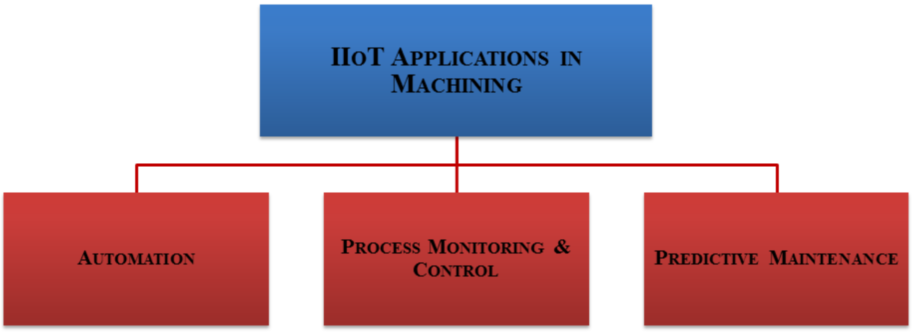

Figure 3. Common IIoT application areas in machining.

In a report published by the Finnish Funding Agency for Innovation (Tekes) [25], the impact of IIoT in automation and industrial robotics is discussed along with examples on the transformation of shop floors. The most typical applications are identified to be process monitoring and control and these will be implemented at product rather than system level. Through the use of embedded sensors and robust intelligent algorithms, the deviations from nominal values are recorded in real-time and appropriate corrective actions are taken in real time. As it is stated "Process and device will be inseparable; the work flow ceases to exist as an independent logistical layer; it is integrated in the hardware". A similar application is presented in [26], for a new type of PC-based controller that integrates precise motion control, machine vision, monitoring and gateway capabilities for application in increasing machining precision. The argument is that current industrial controllers need to communicate with and coordinate several control nodes (machine tool, material handling system, inspection system etc.), which limits their capabilities for in-process compensation. By integrating these functionalities at hardware level, there is a decrease in loss of data and the correlation of system variables for identification of trends becomes much faster. This enables more complex logic to be executed at controller level with positive effects on product quality.

A web-based approach for machine availability monitoring and machining process planning is presented in [27]. The approach is based on three distinct modules that are able to identify the machining features in a part and determine an appropriate machining sequence (supervisory planning module), monitor machine availability in real-time and dynamically schedule and dispatch machining jobs (execution control module) and deal with tool path planning, cutting tool selection and cutting parameters assignment during machining (operation planning module). The approach is implemented as a Cloud provided service and is able to run through a standard web browser for monitoring purposes, while the distinct modules reside in dedicated application servers. A similar approach, in terms of being web and real-time enabled, can be found in [28]. In this case, real-time inspection results characterizing the manufactured parts are collected directly from the controller of a hybrid CNC/CMM machine carrying out the measurements with which the system is able to automatically generate quality reports about the product and provide feedback on any required corrective actions.

Increased machining performance can also be accomplished through equipment prognostics and health management [29]. The goal is to use the data that are collected through sensors installed in the machine tool to continuously evaluate the status of key individual components (axes motors, spindle bearings, cutting tool etc.) and predict the occurrence of failures that lead to reduced performance or even downtimes. The terms predictive maintenance and condition based monitoring describe the same goal. Another relevant example of this approach can also be found in [30] where a digital twin of the real machine tool is developed in a cloud platform containing information both from the actual operation but also from data and system information that were determined during the machine tool design phase. The last set of data are used to establish a reference state of what is considered as nominal operation so that any other operational state can be compared to that. That reference state can also be modified in case of regular maintenance and/or any upgrades carried out.

Based on the above it can be concluded that in its core, IIoT is based on the premise that given sufficient amount of data new insights on processes and systems can be gained that will lead to a better understanding about how they can be improved. Equally, it is crucial to minimize the cycle time between data collection, trend identification and decision making so that the compensatory actions can be taken as quickly as possible. It is therefore the processing of the collected data and the attempt to discover the underlying trends and associate them with specific decisions/actions that is the breakthrough that IIoT envisions towards achieving the expected befits of increased productivity and operational efficiency. Data analytics is, in this aspect, the key enabling technology mainly responsible for this breakthrough.

Conclusions

It is evident that the manufacturing industry is undergoing a major paradigm shift; the ability to outfit machine tools, or processes in general, with a multitude of sensors that generate large amounts of unstructured data allows for data driven modelling and control approaches to increasingly become more accurate in addressing complex phenomena compared to analytical formulations that are based on assumptions and/or experimentally determined coefficients. Subsequently, there is a clear trend towards developing methodologies that are able to efficiently process these data in an attempt to determine correlations and patterns and due to this trend, data analytics in general and AI techniques in particular have become highly popular research areas again. Furthermore, the added advantages of remote access for system monitoring and troubleshooting and the integration with existing manufacturing execution systems (MES) provide tangible benefits to industry that justify the adoption of IIoT. At the same time, there are certain technical challenges around the transition to IIoT that have to be overcome; retrofitting and/or upgrading legacy equipment, interoperability between equipment that use different communication protocols and data security are the most important ones.

Although no scientific published papers could be found to report direct applications of IIoT in precision machining, there are available white papers and case studies that show that this is a field that is currently being investigated. Additionally, key IIoT enabling technologies can help in dealing with typical problems faced by precision machining researchers and manufacturers alike and more specifically sensing and data analytics offer the best opportunities for exploitation. Therefore it is expected that an increased number of applications will be realised in a short to medium term horizon. It remains to be seen whether the developed approaches will remain strictly data-centric or evolve into hybrid approaches combining the insight of data analytics with theoretically developed models for precision machining.

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