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Procedia CIRP 41 (2016) 655 – 660

www.elsevier.com/locate/procedia

48th CIRP Conference on MANUFACTURING SYSTEMS - CIRP CMS 2015

A cloud-based approach for maintenance of machine tools and equipment based on shop-floor monitoring

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Abstract

Maintenance and its cost continue, over the years, to draw the attention of production management since the unplanned failures decrease the reliability of the system and also the return of investments. Advanced maintenance techniques that capture and process shop-floor information can reduce costs and increase the sustainability of an enterprise. This paper presents a condition-based preventive maintenance approach integrated into a machine monitoring framework. The latter acquires data from shop-floor machine tools and analyses them through an information fusion technique to support the condition-based preventive maintenance operations. The proposed approach is developed into a software service, deployed on a Cloud environment. The service gathers and processes data, such as their actual processing time and machining time per tool, related to the operation of machine tools and equipment and calculates the expected remaining useful life of components. Moreover, it provides notifications to machine tool operators and maintenance departments, as well as it enables the communication among them using mobile technology. The framework is applied to a case study with data obtained from a machining SME.

Peer-review under responsibility of the scientific committee of 48th CIRP Conference on MANUFACTURING SYSTEMS - CIRP CMS 2015

Keywords: Monitoring; Maintenance; Cloud manufacturing

1. Introduction

Maintenance is a core activity of the production lifecycle since it accounts for as much as 60 to 70% of its total costs [1]. More specifically, industrial studies have revealed that the cost of replacing worn-out components may be as high as 70% of the total maintenance cost [2]. Although the cost of maintenance is extremely high, the existing industrial maintenance solutions are used in isolation without considering the real condition of the machine tools and equipment [3]. Failures of the machine tools, easily lead to supplying bottlenecks in the subsequent value-added processes of the company and its customers, due to the interlinked production systems [4,5]. Advanced manufacturing systems have introduced the use of monitoring techniques for maintenance purposes in order to gain awareness of equipment condition and to identify failures ahead of time [6]. However, the actual link between maintenance solutions and monitoring techniques is still missing [7].

Real-time monitoring of machine tools and equipment together with visualization and data analysis, under the umbrella of collaboration between the two systems, can lead to condition-based maintenance techniques. In addition, condition-based maintenance utilises condition measurements to schedule appropriately maintenance activities without interrupting normal machine operations [8]. Condition–based preventive maintenance (CBPM) represents the preventive maintenance approach supported by sensor measurements [8, 9]. The collaboration between various IT tools can be enabled and facilitated through the mobile technology and communication [10]. Thus, manufacturing systems are more and more perceived as social structures, built up of employees that act as social machines [11] that process data and information and distribute it among the different IT tools.

Towards that end, this research work presents an approach for condition-based preventive maintenance of machine tools and cutting tools, based on real-time shop floor monitoring

Peer-review under responsibility of the scientific committee of 48th CIRP Conference on MANUFACTURING SYSTEMS - CIRP CMS 2015
doi:10.1016/j.procir.2015.12.069

and enhances the collaboration between the maintenance department and the operators of the machine tools both through the Cloud and the mobile technology.

2. State of the Art

The customers' satisfaction is inseparable from the quality of the products, produced by a manufacturing enterprise [12]. Quality, however, heavily depends on the condition of the equipment. Thus, their maintenance is a matter of great importance to preserving their performance as close to the "like new" standard as possible [13]. However, advanced maintenance techniques that increase the sustainability of production systems have not been well implemented in industry yet [7].

Preventive maintenance, as a maintenance approach, is introduced to inhibit the equipment failure before it actually occurs [14]. In this direction, a computer-aided maintenance resource planning framework for preventive maintenance has been proposed in [13]. The major factor that determines the need for preventive maintenance is the degradation state of the equipment. For the tool degradation, a well-referred modelling method is the Taylor's tool life model that has been extended in [15]. Another factor that is considered during preventive maintenance is the Mean Time Between Failures (MTBF). Chryssolouris, in [10], has presented MTBF as the reciprocal of the failure rate λ of a component and referring to it as a reliability requirement. Moreover, Kumar et al., [16] has introduced a new reliability requirement called maintenance free operating period (MFOP).

The importance of real-time monitoring of machine tools in maintenance planning has been extensively stressed in literature [10, 17]. Monitoring systems have been employed in a number of occasions; to identify the tool wear in [18] and to provide the availability of the machine in [19, 20]. Various sensors among others vibration, acoustic, and temperature have been used in monitoring applications [17]. Current transducers as current sensors have the benefit of being easily installed and giving accurate results in terms of machines status [19].

As the different and heterogeneous sources of data increase, information fusion techniques have been applied to provide meaningful information about a system [21]. The information fusion techniques can be categorised as sensor level fusion, feature level fusion, and decision level fusion [22]. In the subject of decision level fusion, the Dempster-Shafer theory of evidence (DS) is mostly used [23].

The usage of web technologies in manufacturing enhances the data handling and enables automated approaches for procedures such as maintenance. The term of e-maintenance has emerged since early 2000 and is now common in maintenance-related literature. Mori Seiki and Fujishima proposed a product-service system with monitoring services that provide preventive remote maintenance through automatic notifications via email [6, 14]. In an enhanced version of the previous framework, the communication with the controller of the machine has been performed via the open and royalty free industrial communication protocol MTConnect [24]. In addition to this approach, Zhang et al. consider that e-maintenance is a combination of the web service and agent technology, which provides the means of realizing intelligent features for the industrial systems [25]. Manufacturing systems require intelligence in collaboration, and adaptability to dynamic changes. The application of Cloud technology to manufacturing will act as enabler for data exchange between IT tools and the ubiquitous access by multiple users and IT tools to information [26], by introducing the e-maintenance approach. Another recent study [26] presented the key benefits of manufacturing brought about by the adoption of Cloud technology, such as scalability to business size and needs, and ubiquitous network access.

The literature review makes apparent that although the advanced maintenance systems are built with near real-time monitoring capabilities, the collected data are not fully utilized in terms of predictive maintenance actions. The benefits from the combination of monitoring and maintenance techniques, under the umbrella of Cloud and mobile communication, have not been sufficiently exploited yet. In this study, a framework for the CBPM approach, exploiting the information of a real-time monitoring service, is proposed. The monitoring service provides the total operating hours of the machine tool and the equipment, through an information fusion technique that utilises the Dempster-Shafer theory of evidence. The operators of the machine tools and the maintenance experts are kept in the loop through mobile communication technologies. The system is developed on Cloud under the Infrastructure-as-a-service (IAAS) philosophy.

3. Architecture and design of the proposed framework

This paper proposes a CBPM approach integrated into a machine monitoring framework (Fig. 1). This framework gathers data from machine tools using two data sources, namely the multi-sensory system and the machine tool operator input. The sensory system consists of the necessary hardware to monitor the currents of all motor drives and the revolutions per minute (RPMs) of the spindle head. The operator reports through mobile devices the status of the machine tool (i.e. available, busy, down), the currently running task, the cutting-tool availability, and the failures occurred. Combining the input derived from the machine tool operator and the sensory system, the actual machining time of the machine tools and the cutting tools is calculated.

Once the data are captured, they are processed for the calculation of the remaining operating time (ROT) of the machine tool and the actual machining time of the cutting tools. The monitoring data are processed through an information fusion technique in order for the status of the machine tool to be derived and consequently, its actual machining time.

The information fusion technique consists of the DS theory of evidence [23] which is used in order for the evidence,

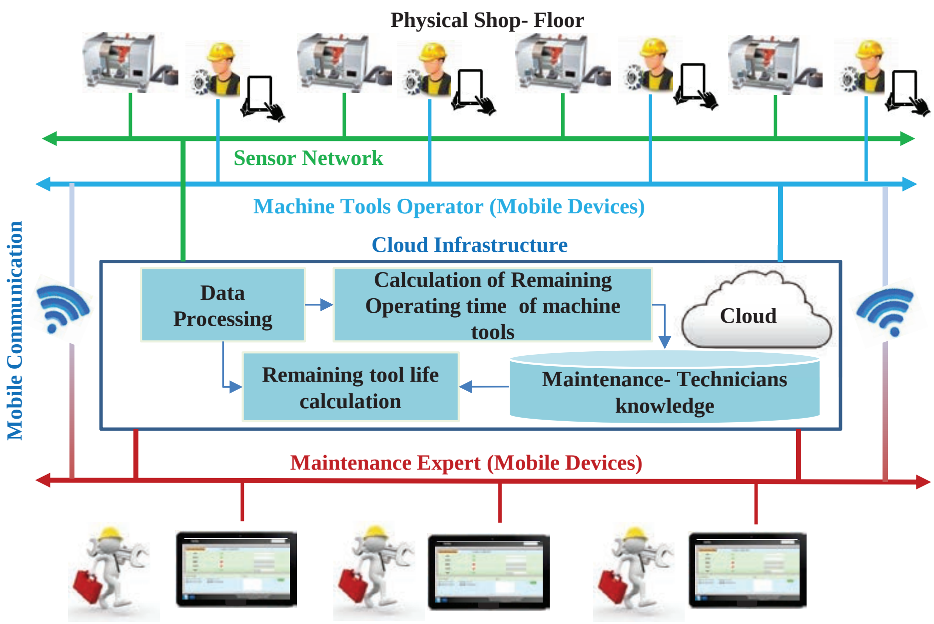

Fig. 1. Overall architecture of the proposed framework.

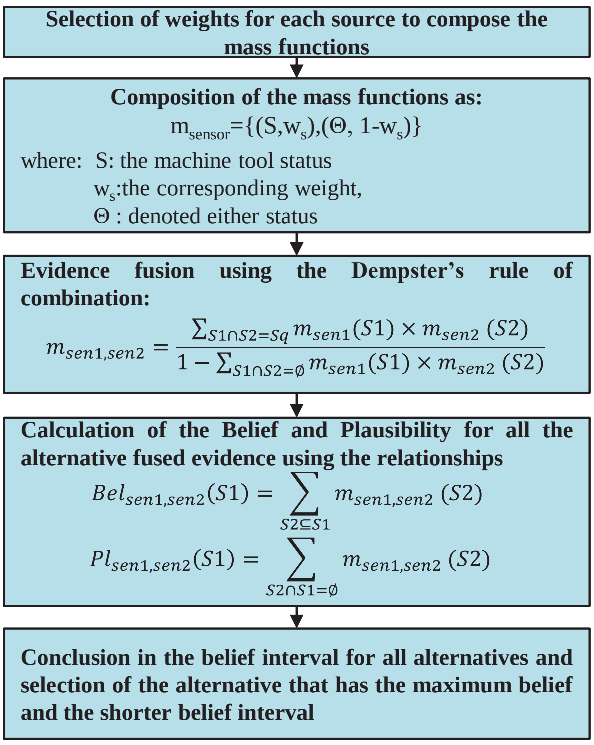

Fig. 2 Dempster-Shafer methodology.

provided by the different sources to be combined in two levels of fusion (Fig. 2). The first level, includes the identification of the status of the spindle and the axes. The second level comprises the identification of machine tool status. The weights assigned, reflect the capabilities of each source to indicate the status of the machine tool, based on the source type and environment. The fusion of the two sensors associated with the spindle, influence the actual machining time of the cutting tool. In addition, the results of the high level fusion influence the actual machining time of the machine tool for maintenance purposes. In the implemented Cloud framework, the total life of the machine tools and the equipment as well as the remaining life of them are calculated. The cutting tool remaining life is calculated through the extended Taylor's equation [15], having obtained the values of the parameters, including the cutting speed, the feed rate, and the properties of the tool material and the workpiece through the process plan and the data from [28]. The machine tool MTBF is based on the machine tools' specifications and on the maintenance department's experience and knowledge.

The proposed framework, having as main inputs the data of the maintenance department and the machine tools' specifications is capable of calculating the time remaining until the next maintenance task. Specifically, it calculates the remaining operating time (ROT) as a subtraction of the actual machining time from the MTBF of the machine tool (Eq.1).

$$ROT = MTBF - AMT \quad (1)$$

where:

- ROT= Remaining Operating Time of each machine tool
- MTBF= Mean Time Between Failure of each machine tool
- AMT= Actual Machining Time of each machine tool

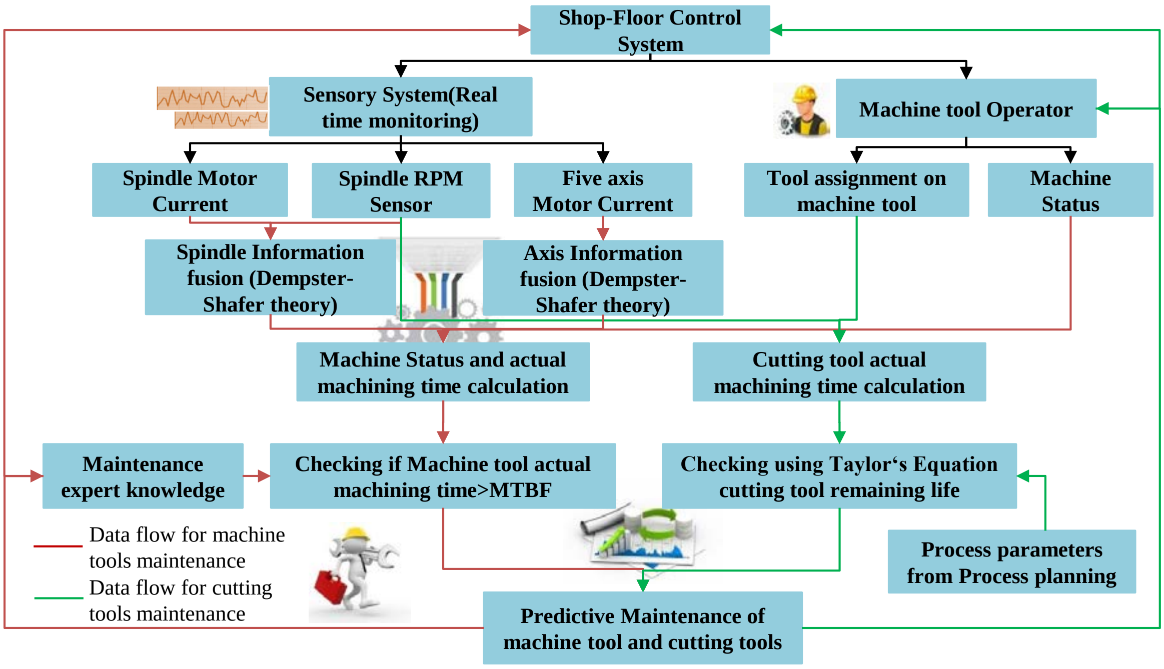

Fig. 3. Detailed workflow of the proposed framework.

As a result, the proposed maintenance approach is capable of identifying the potential failures of the machine tools and the cutting tools. Informed of the remaining operating time of the machine tools and the frequency of the failures, the maintenance department is aware of the shop-floor condition. Subsequently, the maintenance department is capable of performing quick and efficient maintenance of the machine tools. In addition to that, the proposed framework provides notifications to the operator and the maintenance department, informing them of the failure events during production time. The operator is informed of the total machining time of the cutting tools and the maintenance department is notified on the machine tool's remaining operating time (Fig. 3). Direct communication between the operator and the maintenance department is accomplished through the usage of mobile technology. Through this communication, solutions to negligible failures are reported directly from the operator to the maintenance experts in the form of a tele-maintenance service. All the failure events and the proposed solutions are captured in the system's database for being reused quickly and efficiently when new machine tool failures occur.

4. Software development

Modern manufacturing systems under the umbrella of Cloud environment utilize a new business model, capable of managing the growth in the amount of the collected data, by incorporating Internet of Things, and mobile computing. Thus, a Cloud-based system is implemented in order to satisfy the needs of the proposed work.

The specific framework is implemented as a Web Application, developed on top of a Cloud Service. This application conforms to the Representational State Transfer (REST) architectural pattern, which is based on simple Hyper Text Transfer Protocol (HTTP). The cloud-based platform is deployed on an Infrastructure as a Service (IaaS) virtual machine, running a Linux based operating system and includes an Apache HTTP server, a Ruby on Rails (R.o.R) framework, and a MongoDB database. In addition, graphical user interfaces (GUIS) are developed for data entry and visualization of the results.

The developed framework enables the communication between the machine tool operator and the maintenance department on issues related to machine tool failures. The maintenance department is continuously notified of the frequency and the type of the machine tool failures and as a result, it is capable of supporting the operator directly through the mobile communication (Fig. 4). Thus, the maintenance department supports and encourages the operator to deal with negligible machine failures, by increasing the system's efficiency and adaptability. A main concern, regarding the cloud-based monitoring systems, is that of security. The security of the monitoring service is divided into three main layers, namely the shop floor layer, the web application layer, and the Cloud service operating system layer. In these layers, the most important counter measurements against threats are, among others, the encryption on data transfers, the identification of clients through Secure Sockets Layer/Transport Layer Security (SSL/TLS) protocol used in parallel with a secure database authentication system, and Virtual Private Network technology.

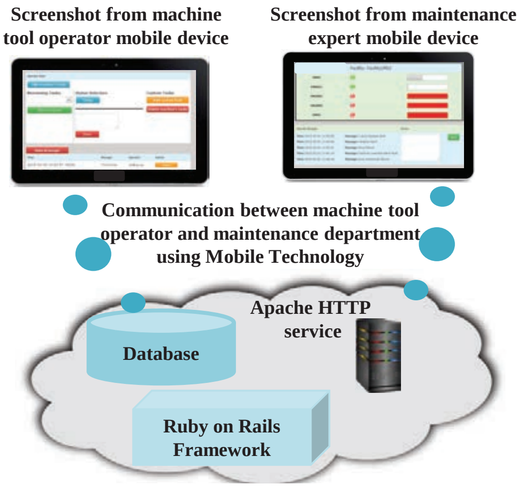

Fig. 4. Architecture and screenshots of the developed framework.

5. Case study and Results

Whenever a problem occurs in machine tools, the customer contacts the maintenance department through the system developed and requests for a service. As a result, the maintenance department is informed of the machine tools problems only when one takes place. In most industries, and specifically in the mould-making ones, numerous machine tool failures occur during the production time.

The proposed monitoring and maintenance framework is validated in a mould-making industry. In this case, five milling machines have been considered in the shop floor with various values of MTBF and Mean Time to Repair (MTTR) as shown in Table 1, including real life data, obtained from the machine specifications and the knowledge of the maintenance department. The monitoring system is installed in these five milling machines and the sensor measurements are transferred to the Cloud, through a sensor board and a gateway. Moreover, having considered the data entry from the maintenance department and the real machining time retrieved from the monitoring system, the proposed framework calculates the ROT according to Eq. 1 and informs directly the maintenance department about the current condition of the machine tools. The monitoring system provides information to the maintenance department about the condition of the machine tools indicated by their current status and their remaining operating time (Fig. 5). In addition to that, the machine tool operator is furnished with the actual machining time of the cutting tools (Fig. 6). This knowledge enables the maintenance department to schedule its tasks according to the actual wear of the equipment, in contrast with the conventional way of scheduling maintenance tasks in fixed intervals.

As described in section 4, one the main functionalities implemented in the proposed framework is the communication between the machine tools operator and the maintenance department via mobile devices. In this case study, mobile devices have been given to both and in a one-month period, 20 negligible problems have been reported from the machine tools operators to the maintenance experts.

Fig. 5 Screenshot from maintenance expert mobile device.

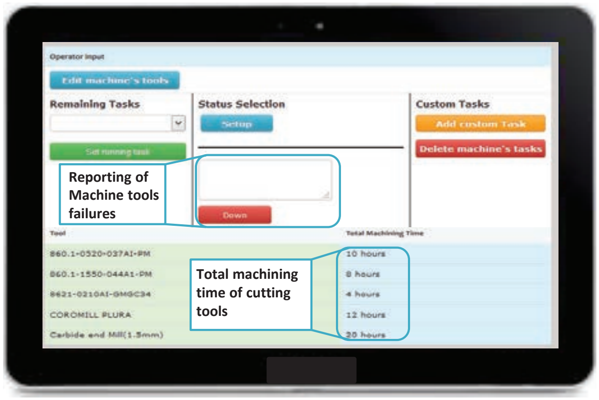

Fig. 6 Screenshot from machine tools operator mobile device.

Table 1. Real life values of MTBF and MTTR of machine tools according to machine specifications and maintenance department information.

Machine Tools	MTBF (h)	MTTR(h)
Milling machine 1	2160	1.5
Milling machine 2	1600	1
Milling machine 3	1800	1.5
Milling machine 4	1800	1.5
Milling machine 5	1700	1

These reported problems according to the maintenance department would have taken otherwise over 10 man hours to be fixed. Using the mobile communication and information on the current state of the machine tools according to the monitoring system, the reported failures have been resolved in 4 man hours. As a result, the mould-making industry has gained over 50% of the maintenance time, required in case of negligible failures. The study presented in this paper, facilitates the direct communication between the machine tools operators and the maintenance experts. Moreover, it provides a near real-time reporting from the monitoring system on the machine tools remaining operating time, which leads to a maintenance model, capable of providing industry with time and cost efficient solutions.

6. Conclusions

This paper proposes an approach of machine tools and equipment maintenance, based on a monitoring system. Among the main advantages of this approach is the distribution of the real-time information, related to machine tools and cutting tools condition to the maintenance department and the operators. The near real-time reporting of the machine tools failures to the maintenance department and the capability of the latter to respond directly and support the operators without having to be in the shop-floor, leads to the reduction of the required maintenance time and the increase of the production rate of the shop-floor. The use of advanced monitoring techniques, capable of identifying in near real-time, the status of the machine tools and their actual operating time, characterizes this maintenance approach. Furthermore, the proposed framework utilizing the mobile technology enhances the collaboration among the different departments and enables the shop-floor operators and the maintenance experts to have an overview of the maintenance analysis results in a timely and efficient way.

In a future study, a further validation of the proposed system, focusing on the extension of functionalities related to the remaining life of the cutting tools, will be performed. In addition, this study will be enhanced with maintenance planning, according to the shop-floor condition, provided by the monitoring system.

Acknowledgements

The work presented in this paper is partially supported by the EU funded research project “Collaborative and Adaptive Process Planning for Sustainable Manufacturing Environments − CAPP4SMEs” (314024).

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