MACHINE TOOL HEALTH AND USAGE MONITORING SYSTEM: AN INTITIAL ANALYSES

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In order to be competitive on a present-day machine tool market, it is needed to produce a high quality, highly reliable systems with low operating and overall lifecycle costs. Health and usage monitoring systems are one of the promising technologies which are being developed to support this effort. The health and usage monitoring systems have been widely employed in the aerospace branch where the condition based maintenance can save maintenance costs and provide higher reliability. In the field of machine tools it is becoming increasingly important because the maintenance costs often exceed 30% of the overall operating costs. The main aim of this paper is a methodical introduction of the health and usage monitoring systems to the machine tools branch. This process has to start with in-depth analyses of machine tool functions and components. Consequently, the review of relevant standards is provided.

KEYWORDS

machine tools, health monitoring, usage monitoring, HUMS, sensors, reliability, industry 4.0

1 INTRODUCTION

In order to be competitive on a present-day machine tool market, it is needed to produce a high quality, highly reliable systems with low operating and overall lifecycle costs. Health and usage monitoring systems are one of the promising technologies which are being developed to support this effort.

The health and usage monitoring system is capable of providing the information about a current state of the engineering object – it means the technical health, lifetime, abnormal wear, etc. Moreover, with the introduction of prognostics methods a so-called product health management system can be deployed. Thus the history (usage), present (health) and expected future (prognostics) statuses of the engineering object are covered. On the basis of these information, the preventive or proactive maintenance actions based on an actual condition of the technical object can be performed. This approach results in a final decrease of lifecycle costs.

The health and usage monitoring system have been widely employed in the aerospace branch, mainly on helicopters [Land 2001] where the condition based maintenance can save maintenance costs and provide higher helicopter reliability. The reduction of maintenance costs is also becoming increasingly important in field of machine tools. The maintenance costs often exceed 30% of the operating costs [Efthymiou 2012]. Based on a precise cost-benefits analyses, maintenance guided by health and usage monitoring system which make an advice for the preventive maintenance intervention can significantly reduce this share.

The present machine tools do not provide a systematic and structured way of modelling and integrating early failures in the associated maintenance activities. For this reason the newly developed machine tools have to integrate monitoring systems and measured data could be used with mathematical models for determination of health and lifetime of a machine tool or its subassembly. The sensing and monitoring of machine tools follow current development in this branch where factory and machines are connected as a collaborative community. This phenomenon is labelled as Industry 4.0 [Lee 2014].

Machine tools operate in specific conditions, whereas a number of similar or identical machines is exposed to completely different operating conditions. Their operating conditions are dependent on their manufacturing program. The disparity in the operating conditions leads to the differences in machine operating loads [Lee 2014]. Thus a predictive maintenance plan based on health and usage monitoring system is beneficial.

Beside the condition-based maintenance, the health and usage monitoring system can be applied within the machine tool CNC control algorithm to adopt the manufacturing process for the actual operating conditions. This feature can increase the machining precision which is critical to isolate the non-conforming parts from the process.

2 HEALTH AND USAGE MONITORING SYSTEMS (HUMS)

The health and usage monitoring system (HUMS) is an auxiliary system deployed on a monitored machine to assess its usage history, current health and potentially a future performance, based on the measurement of characteristic variables.

The acronym "HUMS" can be based on [Land 2001] and tailored to the field of machine tools described as:

- H (Health) – is a measure of the machine tool capability to produce a high quality workpiece;
- U (Usage) – is a measure of machine tool operational loads history;
- M (Monitoring) – is a process how the information about the machine tool is acquired;
- S (System) – emphasizes that a capability for a machine tool monitoring is a complex task which will be distributed among many sub-systems to achieve a common objective.

Generally, the functional requirements given for the health and usage monitoring system include but are not limited to [Cheng 2010]:

- providing advance warning of system failures;
- optimizing the maintenance costs (minimizing unscheduled maintenance, extending maintenance cycles, minimization of the waste of remaining system useful life);
- ensuring the transition from preventive and corrective to predictive and proactive maintenance;
- reducing system downtime;
- providing of the operation data and customer behaviour data for the future systems design development;
- providing the operational history data when solving a complaints procedure demands with customer.

All the above-mentioned requirements will be reflected in the desired reduction of lifecycle costs.

3 PERSPECTIVE APPLICATIONS

A motivation for a deployment of HUMS for machine tools can be taken an example from aerospace industry [Land 2001]. One of the biggest helicopter operators are linking the oil platforms in the Nord see with mainland. Due to helicopter accidents, the United Kingdom Civil Aviation Authority released in 1984 a recommendation to deploy a monitoring devices or systems onboard of a helicopter. This recommendation was conducted by a need to trace a usage history of helicopters in the Nord see fleet. These helicopters are very often exposed to harsh environmental conditions which thus affects negatively the system health and requiring a higher demands on maintenance. The most suffering component of a helicopter is the drive system. Failures in the drive system are almost always caused by unexpected levels of wear in its components. The flight safety, rotorcraft availability, maintainability are improved which consequently leads to the reduction of helicopter life cycle costs.

The most important function covered by the HUMS developed for Nord See fleet is a monitoring of the helicopter dynamic system represented by engines, shafts, gearboxes, rotors, and bearings. System implementation of such functions is ensured by various sensors which measure physical variables such as vibrations, temperatures, pressures, flow rates, and electrical quantities.

It is evident, that based on the above-mentioned motivation from aviation industry, the implementation of health and usage monitoring system to the newly developed machine tools might be a great asset.

3.1 Health and Usage Monitoring of Machine Tool

The major benefits for the machine tool stakeholders can be observed in the reduced amount of scheduled and unscheduled maintenance, increased safety and above all reduced extra costs for unneeded maintenance connected with preventive maintenance plans.

Maintenance plans of large fleets of autonomously operating machine tools in various conditions can be easily tailored base on exact health and usage of the machine rather than under the preventive/corrective maintenance plans and actions. This approach is mainly promising in the Industry 4.0 era connected with smart cyber-physical systems deployed in machine tools environment. The actual state of the machine tool can be fed back to the machine control algorithm for further on-line correction enabling a longer service-free operation of the machine fleet [Lee 2014].

A very important benefit of the health and usage monitoring systems consists of the precise knowledge of the machine operational history. Thanks to the usage features of the system the exact behaviour of the customer is known and can be further considered in a future machine tool development process.

The characteristics covered by the health monitoring system in the tool region include the process conditions, cutting tool fracture, tool wear state, chip form acceptability, work material properties, or workpiece surface integrity [Ostasevicius 2015]. When considering the whole machine tool structure, various bearing failures, shaft unbalances and wear of machine tool driveline can be monitored [Verl 2009]. The exact parameters to be monitored for a various types of machines are reported in [ISO 13380:2002].

4 NORMATIVE STANDARDS

Normative standards for a machine health and usage monitoring and prognostics can be generally divided among five categories [Vogl 2014]:

- overview standards (general guidelines and vocabulary)
- dependability analysis (business vs. research and development)
- measurement techniques (sensors, physical principles and metrology)
- diagnostics and prognostics (rulemaking)
- data management (consistence of systems to each another)

The International Organization for Standardization (ISO) has established subcommittee SC 5 “Condition monitoring and diagnostics of machines”. The mission of SC5 is a standardization of the condition monitoring of machines and structures using multidisciplinary approaches. This subcommittee is organized under the framework of Technical Committee ISO/TC 108 “Mechanical vibration and shock”. The SC 5 has prepared and keeps the following portfolio of health monitoring- and prognostics- related standards:

- ISO 17 359 “Condition monitoring and diagnostics of machines – General guidelines”
- ISO 13 380 “Condition monitoring and diagnostics of machines – General guidelines on using performance parameters” (revised by ISO 17 359)
- ISO 13 374 “Condition monitoring and diagnostics of machines – Data processing, communication and presentation”
- ISO 13 372 “Condition monitoring and diagnostics of machines – Vocabulary”
- ISO 13 379 “Condition monitoring and diagnostics of machines – Data interpretation and diagnostics techniques”

The above-mentioned ISO standards cover the system-level development process for the condition monitoring and diagnostics of machines.

The [ISO 17359:2011] is an umbrella document for the condition-based maintenance and health and usage monitoring. It covers the generic flowchart for the HUM system development and outlines the basic methodologies for the acquired data evaluation as [ISO 13380:2002]. The [ISO 13372:2012] standard defines the essential nomenclature connected with the field of health monitoring and diagnostics of machines. The document has mainly definitional character.

The [ISO 13381:2004], [ISO 13379:2015], and [ISO 13374:2012] are standards defining the data processing, representation, and interpretation.

There are also a number of existing standards which are intended to use in different industries – e.g. Aerospace Recommended Practices (ARPs) prepared by the Society of Automotive Engineers, or ADS-79C-HDBK from the US Army, both dedicated to the field of aerospace engineering.

A comprehensive overview of over 50 existing standards published by the Air Transport Association (ATA), International Electrotechnical Commission (IEC), International Organization for Standardization (ISO), Society of Automotive Engineers (SAE), and the US Army, related to health and usage monitoring can be found in [Vogl 2014].

5 FUNCTIONAL DESCRIPTION OF HUMS

The essential subsystems of the health and usage monitoring system are shown in the Figure 1.

The most important part of HUMS are the sensors which measure the variables related to the health and usage history of a machine tool. The sensors are deployed on the monitored component or process. Sensors suitable for the application on machine tools are furtherly discussed in section 5.1.

The signal processing unit is subsequently applied to tailor the raw signal from sensors for the input requirements of the diagnostic unit. The diagnostic unit compares the data currently being measured with pattern obtained from a model or operational history data. The prognostics of a future behaviour can be also performed at this stage. The result of prognostics is usually the information about the remaining useful life of the machine.

The data acquired by the health and usage monitoring system can be classified into two main categories – event data and condition data. The event data deals with events which occurred on the monitored platform in the past, e.g. single shut-down event or crashes. The condition data are physical quantities which are somehow related to the platform health, e.g. temperatures in drive bearings. [Efthymiou 2012]

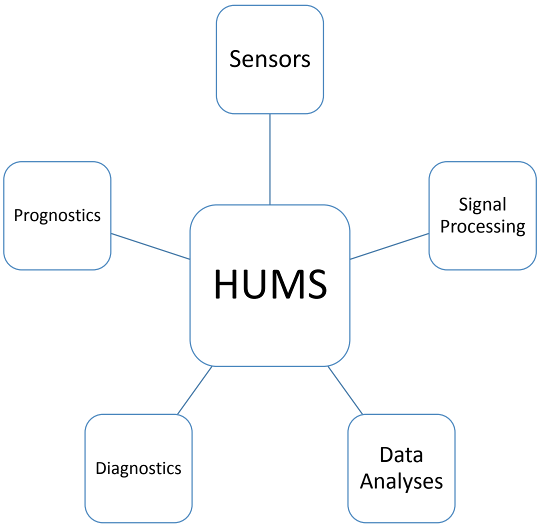

Figure 1. Sub-systems of a typical HUMS

There are two fundamental approaches for the prediction of the remaining useful life – a data-driven approach and model-based approach [Cheng 2010].

The data-driven approach is based on the statistical pattern recognition and artificial intelligence which are applied to the operational history data of the machine tool. This approach does not require a proper knowledge of the failure processes physics. All the information required for the decision about the machine tool health and future behaviour are based on finding the patterns of failure precursors in operational data gathered by sensors. This approach can be so-called as "black-box". The implementation is usually performed using the fuzzy systems and neural networks.

The model-based approach requires a deep understanding of failure processes physics and features. The data acquired form the sensors deployed on a machine tool are used as inputs to the physics-of-failure mathematical model. This model estimates the health and future behaviour of the machine tool based on mathematic function describing the war and failure processes of all the components of the machine tool. This approach can be so-called as "white-box". This approach is very often called as first principles or rule-based.

5.1 Sensors

The implementation of health and usage monitoring system can be either sensor or sensor-less. The desired data can be very often acquired form the already deployed sensors which are included in the machine tool control system. This approach does not negatively affect the wiring harness, sensor system complexity, and overall system costs [Verl 2009]. The sensor approach is useful in the situation where a quantity required as an input to the health monitoring algorithm cannot be obtained from the machine tool control computer. Combination of both above-mentioned approaches is also possible. Indeed, that the sensor-less approach is more cost-effective. Compared to that, the sensor approach generally provides more flexibility in sensor selection. The HUMS developer can select an appropriate solution in the terms of measurement and dynamic range, accuracy, sensitivity repeatability, resolution, linearity, sampling rate, frequency response, etc. A comprehensive overview of sensors useful for health and usage monitoring systems was reported by [Cheng 2010].

A survey targeting to the sensors for tool condition monitoring was done by [Byrne 1995]. Force, power and acoustic emission sensors are the most common sensors in machine tools deployments.

[Byrne 1995] also conducted a survey of current sensor systems deployed on machine tools. These sensors are most commonly based on acoustic emission sensors (27 %), followed by strain (22 %), force (17 %), current (17 %), and other (17 %) principles. The survey was carried out among 26 machine tool manufacturers.

Finally, [Byrne 1995] also summed up the implementation of such sensors. Their application is mostly to monitor tool wear (28 %), collision (22 %) and breakage (50 %).

Drilling (45 %), turning (38 %), milling (8 %), grinding (3 %), and others (6 %) are the tool condition monitoring deployments in the terms of manufacturing processes.

As an evolution of traditional sensors can be considered energy-autonomous sensor nodes supplied by energy harvesting. The energy-autonomous approach is useful for reducing the wiring harness in large machine tool deployments. Energy is acquired from the sensors' surrounding environment. Feasibility study of the energy harvesting in machine tool environment was presented by [Hadas 2014]. The practical demonstration and evaluation of the energy-autonomous sensor node supplied by the vibrations from cutting tool was done by [Ostasevicius 2015]. The developed energy-autonomous sensor was capable of indicate the limitary threshold when the cutting tool started to manufacturing parts in insufficient quality. The information about such event was send autonomously for the distance of 20 meters which is an advantageous approach in large machine tool environments.

Generally in the field of machine tools, the data acquisition of discrete state variables can lead to the detection of operation and control system faults (unfinished motion/operation), while faults in the equipment, process or caused due to the abnormal operating conditions can be determined by the measurement of continuous-state variables [Zhou 2000].

Another challenges have arisen with the implementation of sensor system to the machine tool environment. These challenges include the defects in machine interfaces or operating errors in setup of operation of the monitoring system. [Byrne 1995]

6 HUMS DEVELOPMENT FLOWCHART

The generic health and usage monitoring system development flowchart applicable in the machine tools industry is defined within the scope of ISO 17 359 "Condition monitoring and diagnostics of machines – General guidelines" [ISO 17359:2011]. This process is shown in Figure 2.

The HUMS development is started with a deep analyses of the system (machine tool) under consideration for HUMS deployment. The dependability and afterwards a cost-benefits analyses are introduced as initial studies to determine the items of a machine suitable for the monitoring. This stage of development is in overall called the equipment audit. The equipment audit is usually performed on the basis of a deep assessment of machine tool documentation, technical drawings, maintenance and operational history.

The next step in the development process is a reliability/criticality audit. This kind of assessment consists of various top-down or bottom-up methods. A typical example of the bottom-up method is the Failure Modes Effects and Criticality Analyses (FMECA), while the bottom-up approach is e.g. the Fault Tree Analyses (FTA).

After the equipment audit and reliability/criticality audit, the functions and equipment to be covered by the health

monitoring functions are identified. As a reference for the requirements specification in the development of a health and usage monitoring system can be, beside relevant ISO standards, used paper written by [Saxena 2010].
The next step in the development process is the selection of appropriate maintenance tasks. This step primarily consists of a check whether or not all the considered failure modes are covered by the health and usage monitoring system. If the failure modes cannot be covered by the health and usage monitoring, the implementation of conventional corrective or preventive maintenance strategies, or redesign of such component is required.
The following step is the selection of measurement method with all its specifications – including measurement (sensor) location, and measurement technique.
For all the data acquired from the machine tool by the selected measurement techniques are subsequently developed the data collection and data analyses algorithms used for the system diagnostics and prognostics. Note that the whole HUMS development process is iterative. A review of selected measurement and maintenance strategies based on the operational experience with such HUMS is essential.

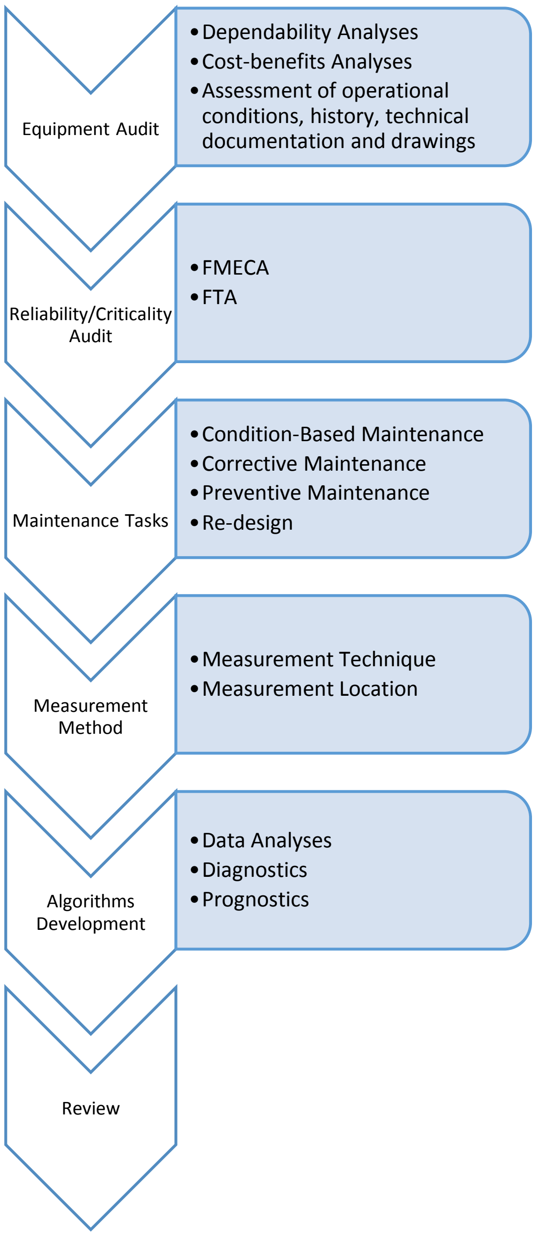

Figure 2. Generic flowchart of the HUMS development process

7 COST-BENEFITS ANALYSES

The concrete business case is usually a crucial aspect when considering an implementation of a HUMS system [Feldman 2008]. The Return On Investment (ROI) is the most common metrics deciding on the implementation costs to benefits ration. The so-called analytic process is the cost-benefits analysis. This analysis are application-specific processes, thus should be performed uniquely for every machine tool and its typical operating conditions. The cost-benefits analysis has an estimative character given by uncertainty of its critical inputs – e.g. customer behaviour, operating conditions, etc.
The return on investment is, in general, the ratio of gain to investment. The return on investment as a product of cost-benefits analysis includes all the HUMS implementation costs, cost avoidance and lifecycle cost model. The implementation costs include the costs for HUMS implementation including but not limited to costs for development, testing and manufacture of the HUMS system with all its hardware and components. The cost avoidance is the amount of lifecycle costs which are eliminated by the HUMS deployment – e.g. saved maintenance costs, failure avoidance, minimization of remaining useful life, costs for the avoided non-conforming parts. The lifecycle cost model is based on the previous evidence of typical customer behaviour and machine tool operating data.
The Return On Investment is not always the most meaningful value when considering a HUMS implementation. The nonfinancial benefits – such as knowledge of operational history useful for further research and development – can be taken into an account [Feldman 2008].
The cost-benefits analyses very often reveals the inadequate costs for the health and usage monitoring system which are not well-balanced by the utility value of the newly-deployed monitoring feature. There are still a lot of applications where the preventive maintenance, corrective maintenance or component re-design are the appropriate solutions.

8 CONCLUSIONS

The main aim of this paper is an introduction of health and usage monitoring systems to the machine tools branch. The sensing and monitoring of machine tools is in accordance with idea of the machine transformation toward to the 4th Generation Industrial Revolution (Industry 4.0) based on Cyber-Physical System-enabled manufacturing and service innovation. The innovative health and usage monitoring system leads to higher reliability of machine tools and furthermore it provides savings of maintenance and operation costs. The development process of new machine tools should be carried out together with analysis and integration of the innovative health and usage monitoring system.

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