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Abstract

The on-going digitisation in the machine tool field is opening up new possibilities for intelligent manufacturing and more efficient production. The access to the machine state allows tracking the evolution of the key production variables to optimise the machining processes. High frequency and low-frequency data are needed to combine information from slowly changing variables (tool parameters, spindle speed, program line number…) and from high dynamics variables (acceleration, spindle power). This article presents the implementation of a monitoring and analytics platform that allows analysing production data at three levels: production planning level, part program level and program line level. A large milling machine in production is used to present the results.

1. Introduction

The advances in the Information and Communication Technology (ICT) are revolutionizing our everyday life. However, the manufacturing industry has not taken complete advantage of this huge potential yet. In the trend to industry 4.0, the Cyber-Physical Systems empowered by Cloud technologies can allow to have a digital twin of the real machine that operates in the cloud platform and to simulate the process with an integrated knowledge from both data-driven analytical algorithms as well as other available physical knowledge [1]. The concepts behind the big data revolution for machine tools have been well defined [2] but there is still a lack of clear and practical implementations that can generate a significant added value on the shop floor. Large companies such as Siemens, DMG and Schaeffler are now providing solutions like the DMG CELOS® app-based control interface for operating the machine tools and realising machine condition and process monitoring. However, even if promising results have been demonstrated, it is still too early to have a clear view of the potential of those new technologies.

The objective of this article is to present an implementation of a monitoring and analytics platform and its first benefits for the analysis of the production of a large milling machine running long and repetitive programs. First, the task of data acquisition and preparation is described as well as the architecture for the data processing. Then, a dataset of one month is processed with an increasing level of details to present potential applications of the data analysis for machine tools.

2. Data acquisition architecture

The CNC is the brain of the machine tool and is a crucial component that should be integrated into the Cyber-Physical System developed around the machine. Indeed, the CNC gives access to the information measured by all the internal machine sensors, and it performs the closed loop controls. CNCs are composed of a Programmable Logic Controller (PLC) in charge of the sequential control of the machine and of a Numerical Control Kernel (NCK) in charge of the trajectory interpolation and axes control. Both PLC and NCK variables are measured to capture the machine state. However, acquisition frequency is often limited to avoid overloading the CNC with data exchange. To obtain additional and high-frequency information on the manufacturing process additional sensors are connected to a real-time controller able to treat the signals. Acceleration sensors have high sensitivity and can be used for chatter detection, condition monitoring or collision detection. Hence, two accelerometers are located as close as possible to the cutting point to monitor the vibration level with a sampling frequency of 4 kHz. Transferring all this high-frequency data to the cloud platform would be burdensome and costly, so local processing of the acceleration signals is performed to extract the most meaningful information. The Fast Fourier Transform is used to obtain the frequency spectrum of the vibration, and only the ten highest peaks are transferred to the cloud platform, the vibration severity is also computed for different frequency ranges. Hence, the vibration level can be well reflected with a limited amount of data thus increasing the ratio between data and information.

A Savvy Smart Box [3] connected to the CNC retrieves PLC and NCK internal variables every second. In parallel, the real-time controller measures and treats locally the high-frequency acceleration data to perform chatter detection and process monitoring. A cloud platform is continuously collecting those data so that to use the historical data to accumulate process knowledge. Indeed, in this study, the analyses are
focusing on repetitive productions. The Qlik analytics platform® [4] is used to provide interactive visual data analysis tools. This robust platform allows filtering the data in real time to go from global production visualisations to detail performance evaluation of a given machining operation. Further analyses, performed with Matlab or R, allow getting insight into the acceptable process variability so that to detect when the process is out of the acceptable bounds. In that case, the process can be modified using the actuation means of the machine (activation of active dampers, continuous variation of the spindle speed, modification of the spindle speed or feedrate). These modifications can be implemented automatically by an expert system or can be collected in a process improvement report that will then be analysed by the machine operator. The monitoring and analytics infrastructure that has been setup allows getting the required information to feed the needs that new products or services will have in the near future.

3. Data analysis at production planning level

From a production planning point of view, the monitoring system allows having a real-time view of the current production status of all the machines in the plant. For example, Figure 1 shows the machine activity for a given day on the left and a summary of the activity of the previous week on the right. In this figure, the active state represented in green is defined by the fact that the machine is moving. Considering that the machine is operated on two shifts of 8 hours per day, the maximum activity level that can be reached is 66%. Hence, the visualisations of Figure 1 provide a rapid tool to evaluate the use of the plant assets. It is also possible to visualise the time required to unload and load the workpiece between two programs. Further analyses of the variability of the machine use from (60% to 51%) could help finding the causes of production stops.

To have more details about the production of that machine, Figure 2 shows the Gantt diagram of the four machining programs that have been executed during one month. At a lower level, it is also possible to obtain the Gantt diagram presenting the sequential use of the cutting tools for each part program. These Gantt diagrams help the production planner analysing the organisation of the shop floor assets, and the Manufacturing Execution System can be feed with measured data instead of estimations.

Treemapping is a method for displaying hierarchical data using nested figures, usually rectangles. In the application considered here, Figure 2 presents a treemap on which each rectangle has an area proportional to the time spent. Treemaps are ideal for displaying large amounts of hierarchically structured data. Here, the treemaps give a different visualisation of the data presented in the Gantt diagrams. A quick look allows understanding that the program OP113 is taking more than half of the production time of this machine. Moreover, the regularity of the area of each rectangle representing a program execution shows that there is a low variability in the machining time of each workpiece. Finally, the treemap allows adding a colour coded information representing, in this case, the average spindle power consumed by each tool. As for the Gantt diagram, it is also possible to dig into the data and select a specific execution of the program OP113 and to have a visual representation of the time of use of each cutting tool. This analysis permits to focus the process optimisation efforts on the program OP113 and the tools Milling D20, Milling D40 and Milling D100 as they represent the biggest share of the machining time.

![Daily use and Weekly use](image)

**Figure 1: Daily and weekly machine use.**
Figure 2: Gantt diagrams and treemaps of the program and tool executions.

4. Program execution time analysis

Based on all the observed executions of a given program, it is possible to estimate the remaining machining time of the current process within a specific confidence interval. Figure 3 shows the remaining machining time as a function of the block number. In the use-case considered here, it takes several hours to machine a workpiece and the machining time can vary due to unplanned events such as tool breakage, machine error, missing operator… The exploration of the measured data indicates that the best execution of the program without any interruption or feed override reduction would take around 20 minutes less than the fastest execution that has been seen. This potential machining time reduction gives an idea of the time that could be saved by increasing the process reliability and automatization. The analytics platform also provides details about the number of tools that have been used for the selected program. At this point, it is possible to know that the tool change time represents between 4 to 6% of the machining time. A detailed analysis of the tool change sequence showed that tiny improvement could be made and that the global impact of the production would not be significant. Hence, based on the previous analyses, it seems relevant to try increasing the process reliability for the previously identified program and tools.

Figure 3: Observed machining time and estimation of the remaining machining time.
Based on the acquired data, a program execution pattern can be generated to detect anomalies in the production process. The time spent by NC program line is lower than 3 seconds so the synchronisation of the production pattern with the program line is sufficient for this application. In Figure 4, the superposition of 12 executions of the program OP113 shows the spindle power and vibration pattern of the process. Using this pattern, it can be seen that one of the execution presents a higher vibration that could damage the tool or workpiece. One of the aims of the data analytics is to provide early detection of those process anomalies so that the machine operator could act preventively before tool breakage occurs. On the right-hand side of Figure 4, it can be seen that chatter vibrations have been detected for all the measured executions. The real-time controller proposes automatically a chatter suppression method based on the cutting conditions and chatter frequency [5], [6]. In that case, the modification of the spindle speed could avoid machining for more than 40 minutes with chatter vibrations. An active damping system could be activated for other situations for which low-frequency structural chatter has been detected [7], [8]. The monitoring and analytics platform is an interesting tool for diagnostics and remote expert assistance.

6. Conclusions
This article presented a monitoring platform that allows capturing data from a CNC machine and from external sensors to analyse the machine tool production. Different level of analysis have been presented from production scheduling to vibration and power pattern of a program. The potential applications of the monitoring and analytics architecture are still largely unexplored. Further work will extend the use of the data to provide added value to the machine customers.

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