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Sensing for self-aware machine tools

Shashwat Kushwaha[1, 2], Jun Qian[1, 2], Dominiek Reynaerts[1, 2]

[1]*Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300, Leuven 3001, Belgium*
[2]*Member Flanders Make, Belgium*

shashwat.kushwaha@kuleuven.be

Abstract
Modern machine tools have a plethora of sensors that are used to operate machines' closed-loop motion control and safety. With these sensors, the state of the machine tool can easily measure or estimate motion variables, like position, motor current etc. This knowledge and control of machine motion can be termed as 'motion-awareness'. However, these sensors fail to provide the state of the process, like the actual position of the tool centre point with respect to the workpiece. Various influences like, limited stiffness of structure, thermal deformation, tool wear etc. result in error in estimating the TCP position and subsequent dimensional error on the workpiece. Newer predictive CAD-CAM simulations provide the option to consider machine behaviour (e.g. volumetric errors, compliance). However, they cannot estimate the random errors during the process, and thus fail to predict the state of the process accurately, or in other terms 'process-awareness'. Thus, most of the produced parts, especially in performance or safety-critical applications, pass through probing and CMM at various stages of production.
For processes like milling, cutting forces already hold key to number of models. Hence this study describes a force and acceleration sensing tool holder for milling machines to provide process-awareness and by extension the self-awareness of the machine tools. The tool holder enjoys wireless data and power transmission, thus allowing it to have a plug and play feature. The data is then received by an edge computer which also collects additional data from the machine tool controller. This data when processed with additional models makes the state of the machining process observable. At the current state of development, our models estimate in real-time the in-progress workpiece geometry and identify chatter. Additional dimensional analysis on the estimated part geometry reveals the quality of operation before the part is taken off the machine. With the help of additional sensors and models running in real-time, the modern machines can be imparted with an awareness of the process.

Self-aware machine tools; Process monitoring; Virtual metrology; Edge computing; Process parallel quality estimation; Digital shadow; Digital twin; Closed-loop manufacturing

1. Introduction

Before elaborating any details about the promised sensors stated above in the abstract, it is important to define self-awareness in the context of the machine tools. At a manufacturing facility, the value addition is achieved by converting the given workpiece blank to the desired part as described by its nominal geometry in form of CAD/manufacturing drawings. A trained human selects the appropriate operation and machines, investigates the fixture and clamping options, and with the help of the CAM package calculates the tool path (refer to **Figure *1***). Whereas the value in manufacturing is added only in the conversion of the raw workpiece to a more useful part, the various tools employed by the human are mere means of production and any additional expenditure here reduces the efficiency of the system. Although existing commercial CAM packages offer a great deal of automation for tool path calculation and collision detection, it is far from taking over the job of a trained technician, as it can't reliably optimize the cutting parameters for material removal rate and/or tool wear or chatter avoidance, while guaranteeing the expected tolerance.

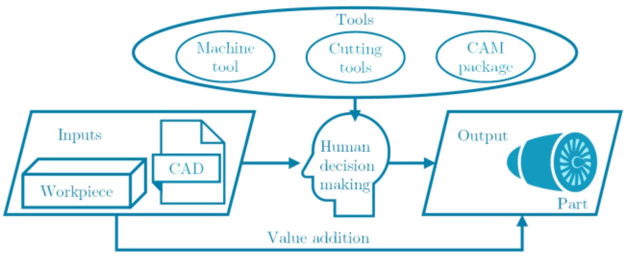

Figure 1. Value addition in manufacturing.

The machine tools can very well control their motion platform with very high positioning accuracy. The machines' ability to sense and control position and speed under no-load conditions can be called '*motion-awareness'*. However, the same motion platform and its controller can be employed for various manufacturing processes, without any knowledge of the type of operations performed on the machine. This interoperability of controllers ignores the '*process-awareness*' in the machine tools. The modern machine tools lack this '*process-awareness*' and by extension the '*self-awareness*'. As an example, they are aware and can control the axes position as seen by respective encoders, however, are blind to the process data and models like cutting force, tool wear etc.

This article aims to contribute to sensors and methods that can help modern machine tools achieve an awareness of the process. A self-aware machine tool will be able to perceive the effects of various influences based on the data made available from the existing and developed sensors. The awareness has two aspects: sensing and perceiving. Where sensing is about collection of raw data, perceiving is about converting this data into more meaningful abstraction.

The knowledge of process forces can already help model among others, tool deflection [1], workpiece deformation [2], tool wear [3], and chatter [4]. This makes process force a significant factor in modelling. Force estimation from motor current is an approach that does not require additional sensors on the machine tool as this information is readily available at the machine tool controller [5]. However, due to the inherent low-pass nature of the drive motor current in closed-loop, high bandwidth force information is not available.

Commercially available table top dynamometers are widely used force measurement systems however, the associated high cost and mounting restrictions make them difficult to use on end-user machines. Another location to measure force is at the tool holder. Here Kistler offers a rotary dynamometer, which can measure up to 5 kN with a natural frequency of 2 kHz and a mere 12 bit analog to digital conversion [6]. Pro-Micron GmbH, Germany has also showcased a tool holder with bending moment and torque measurement capabilities. However, the battery-operated system has a maximum sampling rate of 2.5 kHz [7]. Apart from force measurement, the commercial instrumented tool holder systems also provide vibration/acceleration measurement. Schunk's iTENDO2 tool holder can measure acceleration and transmit data wirelessly at 300 kb/s for 10 hours of continuous use [8]. Although accelerometers can be used for chatter detection, any further insight into the process would be difficult with such a tool holder.

Apart from the commercially available dynamometers and instrumented tool holders and spindles, many academic efforts have also been reported. Placing a force sensing element as close as possible to the workpiece-cutter engagement zone means that the force is not mechanically filtered in the transmission path. Adolfsson and Ståhl placed strain gauges between the cutting insert and tool holder, thereby absolutely minimising the force transmission path [9].

For solid carbide tools, it is not possible to measure the forces at the tool tip by sensors/gauges. In such cases, an instrumented tool holder presents an attractive alternative. Here the choice of sensing elements such as strain gauge or the piezo-electric sensors need not restrict the bandwidth of the system, it is rather the structural dynamics of the tool holder that presents a bottleneck. Often the strain gauge based systems exhibit a marginally lower bandwidth and lower dynamic stiffness of the structure due to the construction to achieve a high strain region for gauging. Nonetheless, these systems can be found anywhere between 0.5 kHz to almost 2 kHz. Gauges mounted on special purpose-designed structures are reported in [10, 11]. Since piezoresistive strain gauges offer very high sensitivity (~100 times more than metal wire based gauges), they can be directly mounted on the tool holder [12].

2. Sensing tool holder

2.1. Design

A sensing tool holder is made up of various building blocks, each block is meant to fulfil at least one function (refer **Figure 2**). Where physical measurements are carried out by sensing unit, data processing such as filtering, and scaling is performed on the processing unit. In the case of a sensing tool holder, it is also important that the data is transmitted wirelessly which requires additional capabilities from the transmission block. Otherwise, this data transfer can be carried out using machine's wired Fieldbus networks like EtherCAT® and ProfiNet®. The above-mentioned building blocks also require power, which is managed by a power unit.

The piezoelectric sensors and high-resolution displacement sensors are not only expensive, but their subsequent

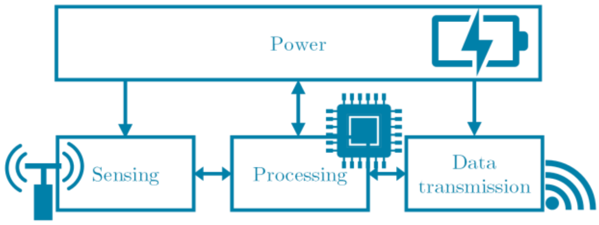

Figure 2. Function blocks of the sensing tool holder

instrumentation is also expensive. On the strain gauges end, the piezoresistive gauges offer high sensitivity and when resolved using high-resolution ADCs they provide unmatched benefits over other sensors. They are available in 0402 (0.4 mm×0.2 mm) package size with a gauge factor between 150 and 200.

For the prototype, an off-the-shelf HSK-A32 tool holder from Haimer is modified to receive instrumentation. The bending moment in two perpendicular directions and torque (moment along tool axis) is measured using the strain gauges glued on the body in a full-bridge configuration.

Three single axis MEMS accelerometers (ADXL 100x, -3 dB bandwidth: 21 kHz) are also mounted on the tool holder. Two of the accelerometers are mounted on an aluminium disc press-fitted onto the tool holder body. These accelerometers measure the motion in two normal directions. This placement avoids the measurement of radial acceleration, which can overwhelm the sensors at high spindle rotation speeds. Whereas a third accelerometer is directly mounted in the axial direction on the tool holder body. Modal analysis (FEM) shows that the out of plane bending modes of the mounting disc starts to show at around 15.5 kHz. However, the mode that affects the accelerometers' measurement direction is the torsion mode, it appears at a very high frequency (>38 kHz, refer ***Figure 3***).

The required bandwidth of the wireless data transmission depends on the sample rate and the resolution. It should be noted that the wireless transmission also results in extra data added in form of a header. Considering sampling of 6 channels (3 strain gauges and 3 accelerometers) at 16-bit resolution at a rate of 20 kSps, a throughput of 1.92 Mbps is required. ISM band in 2.45 GHz and 5 GHz offers many wireless protocols, where Bluetooth® and WiFi® offer this kind of throughput right out of the box.

The last part of the instrumentation is the power supply. Since the prototype tool holder is intended to be used with DMG US 20 milling machine, the inductive power is provided by the

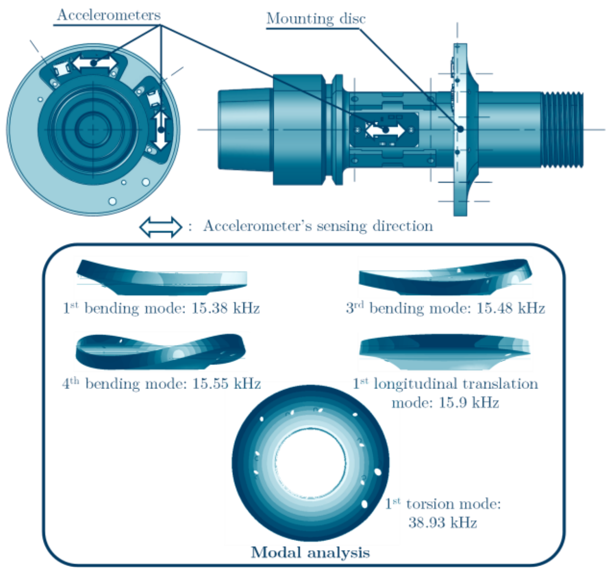

Figure 3. Mounting of accelerometers (top), mode shapes of the mounting disc

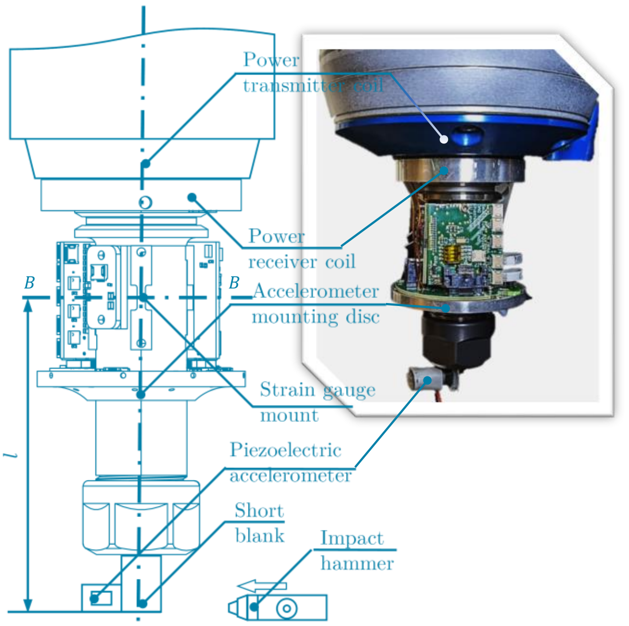

Figure 4. Schematic of the instrumented tool holder clamped in the machine spindle. Left: the strain gauges along BB axis measure the applied moment from instrumented hammer. A similar perpendicular AA axis is also measured simultaneously for cross-talk estimation. Right inset: Photograph of the setup.

machine's amplifier. The amplifier on the machine is designated for tool holders with ultrasonic vibration-assisted machining, where the power to the actuator in the tool holder body is inductively provided by a coil placed at the spindle nose. This coil at the spindle nose is utilised for the power transfer to the sensing tool holder (refer **Figure 4**).

2.2. Static and dynamic testing

The assembled instrumented tool holder is first calibrated for the sensitivity of the bending moment strain gauges. A simple setup to apply static load by making soft contact against a load cell is used, while the tool holder is clamped in the machine spindle. A static stepped load is applied at a known distance l from the strain gauges and the response from the bending gauges is recorded. A Moore-Penrose inverse gives a solution for the sensitivity by using applied bending moment $M = l \times F$ and the measured bridge output voltage $V_{o(o=A\ or\ B)}$ for V_{ex} = 5 V of excitation potential across the full-bridge:

$$\begin{pmatrix} V_A \\ V_B \end{pmatrix} [\mathrm{mV}] = \begin{pmatrix} 15.97 & 0.21 \\ 0.23 & 16.16 \end{pmatrix} [\mathrm{mV/Nm}] \begin{pmatrix} M_A \\ M_B \end{pmatrix} [\mathrm{Nm}] \qquad (1)$$

where, V_A and V_B are the output of strain gauge bridges measuring bending along axis AA and BB respectively, and M_A and M_B are moments applied along the axis perpendicular to the plane containing the tool axis and AA and tool axis and BB respectively. It can be seen that a small (<1.5%) cross-talk exists between the two directions.

The objective of the dynamic testing is to identify the frequency response of the structure and sensors. As the identified sensitivity is only valid for the quasi-static domain, any higher frequency cutting forces can't be estimated from that. To identify the frequency response of all the sensors (strain and accelerometers) an impact test is performed.

A modal testing impact hammer PCB086 with a hard metal tip is used to excite the end of a short blank clamped in the instrumented tool holder. The tests were performed for the main axis and cross talk. A miniature high bandwidth accelerometer PCB® 352C67 is also placed on the short tool blank to measure the collocated response.

The estimated FRFs of all the sensors is plotted in **Figure 5** It can be seen that all the sensors agree on the occurrence of the first

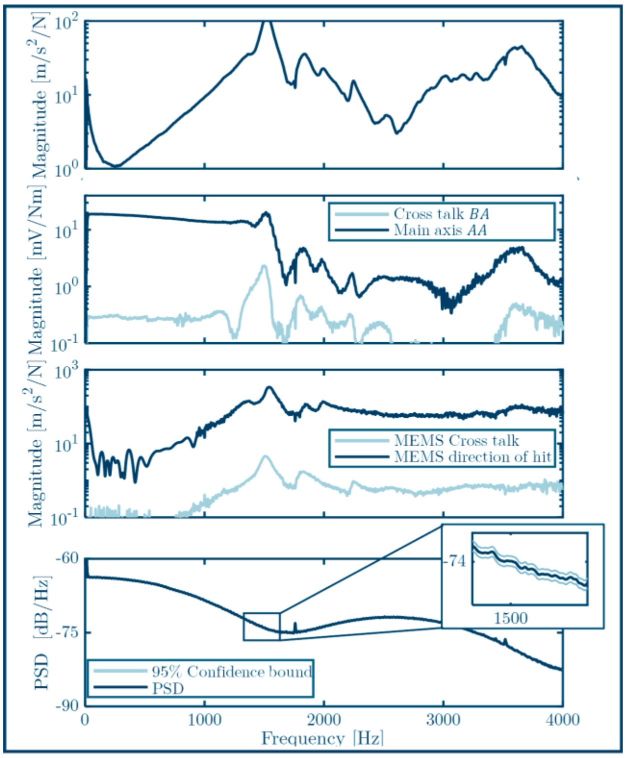

Figure 5. FRFs from top: piezoelectric accelerometer, strain gauges, MEMS accelerometers, and the power spectral density of the 10 hammer hits

mode to be beyond 1000 Hz. The power spectral density of the hammer's sensor reveals that the excitation energy drops beyond 3500 Hz, and data after that should be disregarded. Since the peaks of various sensors lie beyond 1000 Hz, it can be regarded as the uncompensated bandwidth of the instrumented tool holder.

As an example, a tool with 4 cutting edges (z=4) cutting at 12000 rpm would result in a tooth passing frequency of 800 Hz. Which is almost the limit of uncompensated bending moment estimation from the strain gauges. Also from FRFs of the strain gauges, it can be seen that the gap between the cross-talk and applied direction decreases at higher frequencies (increase in condition number).

2.3. Cutting test

A simple cutting test where a piece of titanium alloy is machined while measuring the cutting forces using a stationary

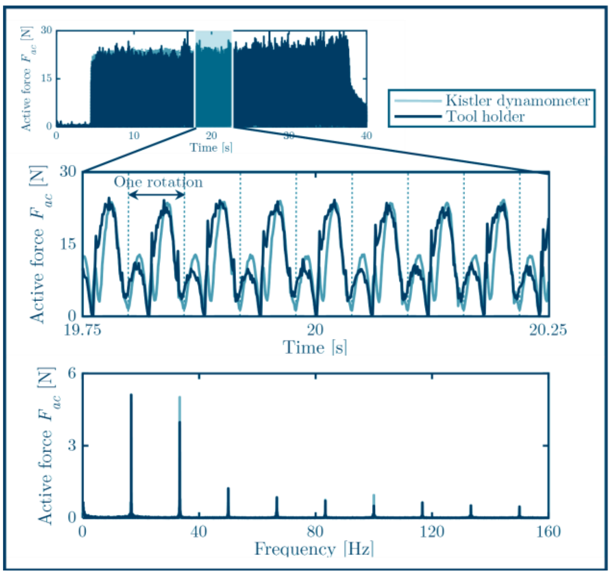

Figure 6. Active cutting force F_{ac}, cutting test performed with a used/worn out tool with two cutting edges (z=2), 6 mm at 1000 rpm.

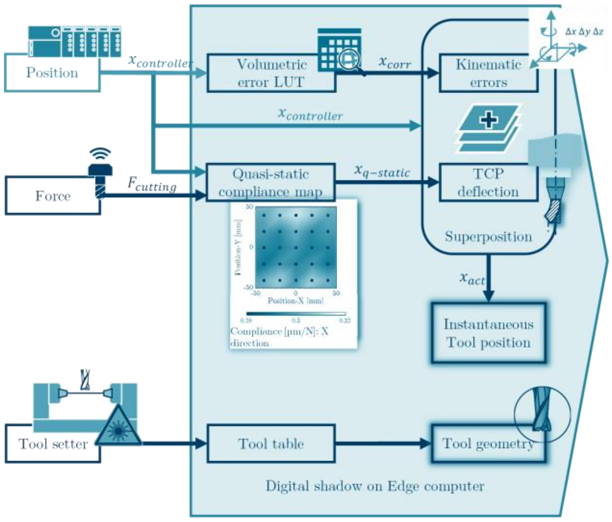

Figure 7. Left: employed workflow for TCP estimation; Right: estimated profile error while machining a gear plotted on the in-progress workpiece.

table type dynamometer Kistler® 911A1 is performed. From the measured bending moment M and the known length of the tool overhang, the active force F_{ac} can be calculated as:

$$F_A = M_{AA}/l \text{ and } F_B = M_{BB}/l$$
$$F_{ac} = \sqrt{F_A^2 + F_B^2} \quad (2)$$

A full immersion cut with two cutting edges in **Figure 6** shows the active force F_{ac} as measured from the instrumented tool holder and the stationary dynamometer. A good agreement between the two is found. The frequency content of the cut is also shown.

3. Applications

The knowledge of cutting force and TCP vibration can be employed to estimate the workpiece geometry with finer details. We have already showcased one such workflow at the Euspen ICE 2021. The presented tool holder in this article is integrated into the proposed workflow of the process-parallel quality estimation. For completeness and brevity **Figure 7** shows the workflow to estimate the TCP's position in real-time from the known cutting forces. A multi-dexel method then estimates the geometry of the workpiece in near real-time. For more information please refer [13].

Since the total estimated tool deviation from the programmed position is an indication of the quality of the machining operation. To provide quicker feedback to the machine operator the total measured TCP position error (δ_{tcp}; a sum of tool deflection due to process forces, geometric errors, and any control-related errors) is plotted on a low-resolution in-progress workpiece. **Figure 8** shows the TCP position error plotted on the gear profile measured during the operation. Since this indication is provided in real-time, it not only provides feedback to the operator, it can also provide an automated indication on control limits of the process.

Similarly, a chatter identification can also be carried out. The authors have presented a real-time chatter detection method and experimental validation [14]. With the help of accelerometers integrated into the tool holder and method to detect the chatter with the presented digital shadow workflow on Edge computer, chatter can not only be located in time but also spatially on the workpiece. A stainless steel 312 workpiece was cut with a 6 mm diameter tool with 50% immersion milling. At a corner where the effective width of cut increases the chatter is observed. **Figure 9** shows a photograph of the

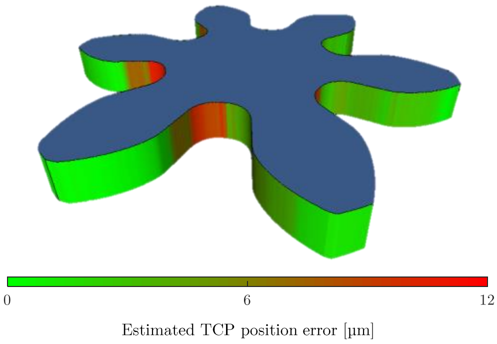

Figure 8. Estimated TCP deviation plotted on gear profile.

machined workpiece and the location of unstable machining on the virtual in-progress workpiece.

4. Conclusion

A workflow with additional sensors and models is presented. This workflow allows machine tools to obtain a knowledge of the state of the process. Along with motion-awareness (closed-loop control of the NC axes), the process-awareness takes the machines one step closer to the self-awareness. Such machine is able to self-report the quality of the part being produced.

On the sensors end, an instrumented tool holder with cutting force and vibration measurement is presented. It is integrated into the process-parallel quality estimation workflow developed at KU Leuven. At an application level the proposed methods are intended to reduce the resources spent in dimensional metrology of the parts produced on machine tools.

However, this machine can only self-report and cannot carry out corrective actions. Which is enough for self-aware system, and a conscious interventions and correction is reserved for future expansion.

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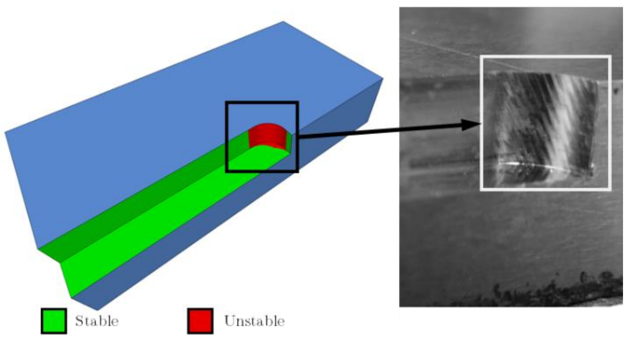

Figure 9. Left: Visualization of location of chatter, right: chatter marks seen on the workpiece