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Study of sensing technologies for machine tools

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ABSTRACT

Technologies for machine tools have been rapidly developed in recent years. Innovative technologies are expected to be developed in the electronics and information fields with the trend of industry 4.0 or IoT, which will significantly contribute to the development of control technologies for machine tools. This paper describes approaches to sensing technologies which can be practically used on machine tools. The sensing system used in this study was developed to obtain a huge volume of sensing data about cutting conditions. By this system, we are studying innovative technologies of machine tools to improve cutting efficiency and sensing technologies for coolant level using machine learning.

Introduction

Machine tools have been equipped with a variety of sensors. High-precision and high-resolution motor encoders and linear scales are used to achieve machining accuracy at the submicron level. Some of the latest high-performance laser scales with pico-resolution capacity are used in ultrahigh-accuracy machining and studies on them are on-going [1,2]. A more recently developed three-dimensional linear encoder [3] will be used on machine tools in the future. Temperature sensors for thermal displacement compensation are used on high-precision machine tools as studies of thermal issue advance [4,5].

Recently, many sensors have been effectively used in various fields such as consumer appliances, health care, transportation, businesses, etc. Numerous sensors made functions once inconceivable reality. Consequently, the production volume of sensors increased, while production costs per unit decreased. According to the 2013 TSensors Summit, the volume in the mobile sensor market grew exponentially, exceeding annual increases of 200% between 2007 and 2012. Visionary organizations foresee the growth in sensor demand push past the billions of 2012 to trillions within the next decade [6].

The number of high-functionality sensors used on machine tools will soon increase significantly. A huge volume of sensing data will be gathered toward applications seeking to improve machining accuracy, shorten machining time, lower energy consumption, and reduce downtime through preventive maintenance [7]. Information technology including artificial intelligence (AI) must assist such sensing data applications.

Fig. 1 shows potential sensing applications. Sensing data are collected through the sensing network and monitored on operation screens. While some applications are already developed, others are still being refined. To further improve sensing applications, a huge volume of data from more sensors is required.

As many sensors are used for machine tools, sensing applications are developed in 4 stages, namely the monitoring, controlling, optimization, and the autonomous stage. More specifically, sensing data are collected and displayed on an operation screen to monitor the machine's condition. The feedback is then controlled using sensors. The monitoring and controlling stages are already in practical use. Sensing technologies in the optimization stage are now being studied. For example, cutting parameters can be determined to optimize for higher cutting efficiency based on motor power, spindle speed, values measured by the vibration sensor, etc. Various studies on chatter vibration have been concluded [8–12] but many practical challenges still remain such as a spindle stiffness change due to cutting conditions [13]. Once these challenges are overcome, machine tools with AI will be able to autonomously perform optimum cutting operations.

Sensing technology research requires machine tools with many sensors to produce an enormous amount of sensing data, which affords the development of state-of-the-art applications. To that end, a storage system capable of saving big data volumes had to be developed.

Members of CIRP have been studying various types of monitoring technology by using sensors [14,15]. Some of the

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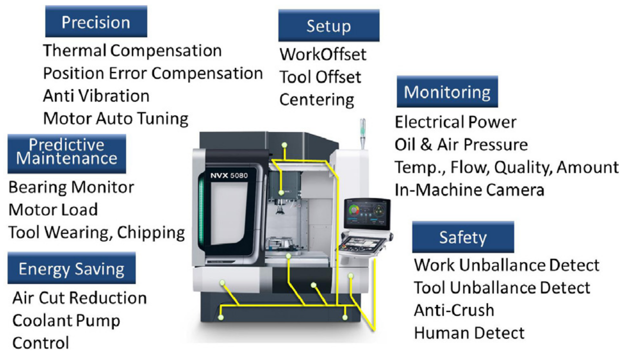


Fig. 1. Sensing application territory (NVX 5080 vertical machining center).

technologies will be effective, if they are put into practice. The goal of this study is, hence, to develop a test machine with various sensors and practical applications in the industry by applying past studies of sensing technologies.

System architecture

To develop sensing data applications for machine tools, the test machine in this study is equipped with more sensors than commercially available machines. The base machine, the NVX 5080 Vertical Machining Center, has 24 additional sensors shown in Table 1.

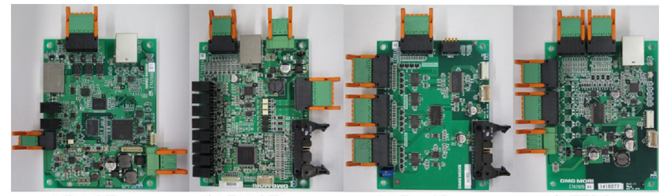
Acceleration sensors embedded in the spindle unit were used to measure chatter vibration, collision impact, and unusual bearing vibration; additional sensors embedded in the work table measured work vibration. A coolant level sensor, developed for this study, provided cost advantage and superior performance; additional detail on this sensor is provided. Load cells were embedded in the adjustable legs to verify load at level adjustment. Electric current and voltage sensors were used to measure energy consumption of the entire machine tool. Temperature sensors were embedded in the spindle unit and the work table to compensate for thermal displacement or diagnose spindle bearings. A camera records all experiments and a Kistler dynamometer was used as a cutting force sensor. Motor power and spindle speed obtained from the NC unit were recorded as well.

Machine tool input–output (I/O) signal lines are usually connected to the programmable logic controller (PLC). I/O signals are mostly digital binary at DC24V. Analog signals can be received by the PLC, but a generic PLC is not suitable to receive high-speed analog signals in sensing technology studies. The sampling rate required for acceleration sensors exceeds several kHz, which is several fold of chatter vibration frequency. Since generic PLC control cycles commonly perform only in the millisecond range, we developed a platform that allows machine tool manufacturers to utilize sensor data without PLC or NC unit limitations.

The operation panel computer of the test machine can also collect sensing data. However, an external computer for data

Table 1
Sensor categories for the experimental system.

Sensor	Num.	Purpose
Acceleration	6	Spindle and table *x y z* directions
Coolant level	2	Level Sensor for coolant tank
Load cell	8	Level adjustment
Electric current	1	Power supply 3 phase
Voltage	1	Power supply 3 phase
Temperature	3	Spindle and table
Cutting force	3	Kistler dynamometer *x y z* directions
Camera unit	1	Movie & sound in machine



(a) DAQF (b) DAQT (c) DAQL (d) EPM

Fig. 2. Sensor interface boards.

storage was added to enable large-scale data analysis. It was, therefore, possible to monitor sensing data on the operation screen while obtained data write to the external computer.

The backbone route of the sensing network was structured with 100BASE-TX Ethernet. Because sensors cannot be connected to Ethernet directly, we developed 4-type interface boards with sensor signal inputs and Ethernet outputs, shown in Fig. 2. These interface boards have CPU chips and memory.

The data acquisition FFT board (DAQF) has three acceleration sensor interfaces and two temperature sensor interfaces. In addition, the real time FFT function is embedded in this circuit board.

The data acquisition temperature board (DAQT) is a general A/D converter board with voltage input terminal and a thermistor interface.

The data acquisition load cell board (DAQL) is added to the DAQT, providing an interface for a load cell to the DAQT.

The electrical power monitor board (EPM) is connected to electrical current sensors and voltage sensors, which were placed at three phase power supply lines of the machine tool. Aside from calculating electrical power consumption, this function monitors power supply quality. The EPM is also connected to the coolant level sensor.

Table 2 lists the specifications of sensor interface boards. The collected data were transferred to the external computer through Ethernet and stored to the hard disk drive.

The structure of the sensing data storage system (SDSS) is shown in Fig. 3, including all 24 sensors, 3 in-machine video cameras, and the sensing data storage unit (SDSU) with its 20 interface boards.

At the study stage of sensing technologies, sensing data ought to be stored without being processed, since data mining technology can readily analyze enormous volumes of raw data.

The processing algorithm emerging from such studies will be installed in the interface board. The interface board will be smaller

Table 2
Sensor interface board function.

Board/sensor function	Channel	Specification
DAQF data acquisition FFT board (high speed FFT function board)		
Acceleration sensor	3	16 kHz, raw wave data or FFT data
Temperature sensor	2	0.5 Hz, for thermistor
DAQT data acquisition temperature board (general A/D converter board)		
Temperature sensor	8	0.5 Hz, for thermistor
Pressure sensor	8	0.5 Hz, for voltage
Linear position sensor	3	For voltage
DAQL data acquisition load cell board (additional board to DAQT)		
Load cell	8	For load cell of jack screw
EPM electrical power meter board		
Voltage sensor	4	Two 3-phase power lines
Current sensor	4	Can be measured
Hydraulic unit interface	1	RS422 can get power consumption, etc.
Oil cooler unit interface	1	RS422 can get temperature, etc.
Coolant level sensor	2	RS485, max sensor number: 255