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CONDITION MONITORING IN END-MILLING USING WIRELESS SENSOR NETWORKS (WSNs)

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KEYWORDS

Wireless Sensors, Machine Monitoring, MEMS-Accelerometers, Surface Finish

ABSTRACT

This paper focuses on the overall potential of wireless sensor nodes and networking in manufacturing environments. A specific case study is described that created the enabling infrastructure for MEMS-accelerometer based monitoring of machine tool vibrations. The focus of the case study was not on vibration analysis per se. Rather, experiments were carried out to show that wireless sensor networks, and their individual wireless sensor platforms, could provide new tools for research in predictive maintenance and condition-based monitoring of factory machinery in general, and for "open-architecture machining systems" in particular. In the tests of the case study, a linear relationship was demonstrated between surface finish, tool wear and vibrations of the machine tool. A MEMS-accelerometer based WSN platform, supported by the WSN, was thus shown to be an easily deployable "retrofit" technology for the identification of such correlations.

INTRODUCTION

Wireless sensor networks (WSNs) are *ad hoc* local area networks (LANs) created from small, inter-connected wireless platforms. Each platform carries sensors suitable for the desired industrial, residential, or civil application. Often, the small hardware platforms are colloquially referred to as *smart dust* and/or *motes* because of their miniature size. The research community has enthusiastically embraced WSNs—for example, see articles on *ambient intelligence* by Basten et al. 2003 and Mukherjee et al. 2006; and the well-known *Scientific American* article written by M. Weiser (1991) on *ubiquitous computing.* This enthusiasm has consequently spurred the commercial availability of the hardware platforms and system software, such as TinyOS (Hill and Culler 2002). New companies have been formed around the technology and successful prototype systems have been installed for low duty-cycle temperature monitoring in commercial buildings where radio transmission is relatively robust (see Conner 2006 for a list of commercial websites). Such 'early adopters' will hopefully create experience and know-how that will facilitate the wider adoption of wireless sensor networks. Even in non-manufacturing settings (for example, the energy monitoring in buildings) commercialization of wireless sensor networks has only occurred within the last five years, providing little time for design or implementation into manufacturing applications. Such experience and know-how will be important for an anticipated ‘second wave of adopters’ in the manufacturing area, where applications of wireless sensor networks are still in their infancy and most deployments described in the literature are for evaluation and product or process prototyping (Schneider 2005). Nonetheless, strategic manufacturing directions are directly emphasizing the advantages of wireless sensor networks for cost reductions resulting from increased automation and enhanced energy efficiency benefits since manufacturing accounts for approximately one third of the U.S. national primary energy consumption (EIA 2006).

Quite obviously, in a factory-floor setting, radio transmission and communication performance are more challenged by the presence of metallic machinery, which can reduce the signal strength of the wireless communication channel, create packet-losses within the data exchange, and require more robust protocols. Despite these challenges with radio frequency communication in a factory, there are many potential advantages that can result from deploying WSNs. The individual nodes can be mounted on various parts of a machine tool and monitored for early fault detection and analysis. The small size and autonomy of the individual wireless nodes enables their placement in locations that are usually difficult to access. In addition, it is also possible, with minimal changes to the machine configuration, to retrofit sensors onto machinery after it has been installed. The sensor nodes not only monitor their own output but also collaborate with neighboring nodes to determine the health of the overall machines and provide early warnings of potential failure. The paper discusses the potential uses of these networks and the issues that must be addressed for successful implementations. The case study in the last section correlates machine tool vibration with part surface-finish and was undertaken to show a specific, potential use.

INDUSTRIAL DEPLOYMENTS

Wireless sensor networks are being primarily piloted in non-critical industrial monitoring applications including *predictive maintenance* and *condition-based monitoring* to enable day-to-day *machinery monitoring* and automation of data collection, as shown in Figure 1. Predictive maintenance analyzes high-resolution sensor data using analytical models to estimate the condition of a component, machine, or process; whereas condition-based monitoring is an alarm-based methodology to monitor states of a machine. In fact, condition-based monitoring often supplements predictive maintenance by acting as an early warning system. Predictive maintenance applications benefit from automation of the traditional manual process for collecting machine condition data and more frequent sampling, while condition-based monitoring applications benefit from more sensing points.

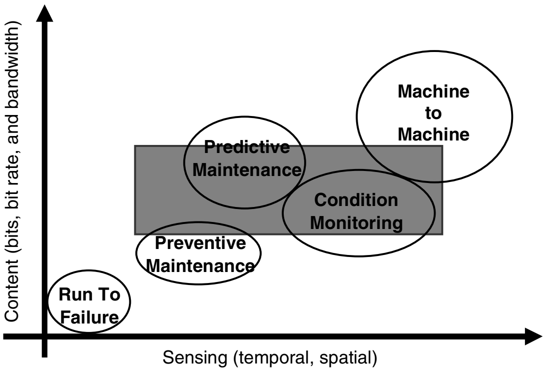

FIGURE 1. PROGRESSION IN MAINTENANCE TECHNOLOGY AND METHODOLOGIES. GRAY AREA DENOTES WHERE WIRELESS SENSOR NETWORKS CAN MAKE A SPECIAL IMPACT.

General cable replacement of wired sensors to reduce cost can be found for temperature sensors (Kevan 2005) and vibration sensors (Kevan 2006; Gbur et al., 2006; Krishnamurthy 2005). In these deployments, the sensors support predictive maintenance for machinery by sending sensor measurements to a central database that is later analyzed by an engineer.

Specific applications of wireless sensor networks include motor analysis and machine tool performance. Wireless sensor networks enable condition monitoring systems for small electric motors (Lu 2007) as well as wire replacement for traditional motor vibration monitoring sensors (Jagannath and Raman 2007). In addition, wireless sensor networks enable new in-situ motor analysis opportunities previously not possible with wired sensors

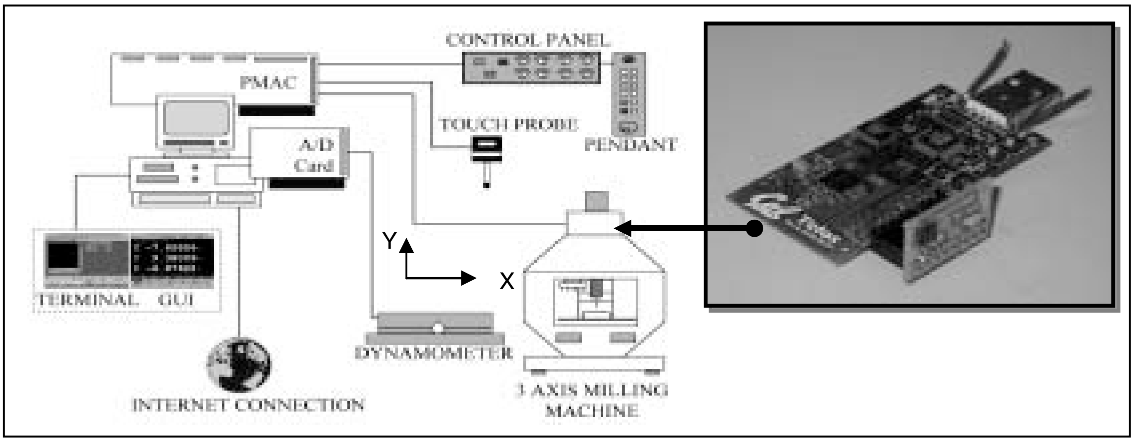

FIGURE 2. LEFT-SIDE SHOWS THE OPEN-ARCHITECTURE MACHINE TOOL ENVIRONMENT. RIGHT SIDE IS AN ENLARGEMENT OF THE WIRELESS PLATFORM CARRYING THE MEMS-ACCELEROMETER BOARD ON ITS SIDE. THE ARROW SHOWS THE MOUNTING POSITION. THE DEVICE WAS MOUNTED TO MEASURE VIBRATIONS IN THE X-DIRECTION (THE FEED DIRECTION).

including agent-based steady-state motor analysis (Sundararajan 2004) and onboard oil analysis (Wilson 1999). Applications to machine tool monitoring include temperature measurement sensors for end-mill inserts (Wright 2006) and vibration-based condition monitoring for tool breakage (Sundararajan 2005). In particular, vibrations in machine tools reduce tool life, are a result of dynamic loading, structural element flexibility, cutting conditions, and spindle characteristics, and are often characterized by stability lobes describing regions of "safe" machining with respect to chatter and surface finish (Altintas 1995). Wireless sensor networks enable new opportunities not possible with wired sensors such as multi-sensor data fusion methods to estimate tool wear using vibration monitoring of the spindle and/or workpiece. In addition, wireless sensing of current, voltage, and acoustic emission signals is also reported (Ghosh et al. 2007).

Wireless sensor networks also facilitate new applications that were previously not possible using wired sensors including more accurate multi-sensor condition monitoring techniques (Jardine et al. 2006) and a hybrid network of remote wireless machine condition monitoring sensors and radio frequency identification tags to enable secure access to a technician outfitted with a mobile computer (Ramamurthy et al. 2007).

To a lesser extent, wireless sensor networks are also augmenting control systems in process manufacturing (Koumpis et al. 2005) and discrete manufacturing (Korber et al. 2007). The general architectures consist of wireless sensors providing information to a wired control system that utilizes sensor information and dispatches controls signals to wired actuators, although prototype wireless actuators for low-latency process control exist (Johnstone et al, 2007).

Applying wireless sensors to industrial applications presents several challenges as well. Predictive maintenance applications often require high-resolution data sampling, especially vibration analysis, but the computationally constrained wireless sensor network hardware platforms do not readily support such data intensive sampling or provide sufficiently reliable end-to-end communication (Krishnamurthy 2005). Batch transmission and processing at a centralized computer with more processing power is an alternative, but such an architecture would strain the communication bandwidth limited low-data rate radios and limit the benefit from continuous monitoring by a wireless sensor network. Additionally, battery-powered sensors must provide a long lifetime to be cost effective and avoid manual maintenance to replace discharged batteries. However, industrial environments offer opportunities to scavenge ambient energy, such as through a vibration scavenging magnet and coil generator (James 2002).

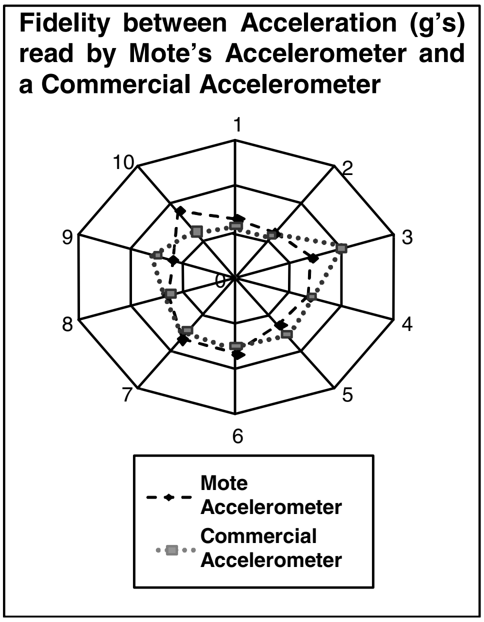

FIGURE 3: ACCELERATIONS (IN G'S) IN VARIOUS DIRECTIONS SHOWING GOOD CALIBRATION.

CASE STUDY

A wireless sensor network (WSN) was used to create the enabling infrastructure for MEMS-based accelerometer monitoring of machine tool vibrations. The case study's focus is not on vibration analysis per se. Rather, experiments have been carried out to show that wireless sensor networks, and their individual wireless sensor platforms, provide new tools for research in predictive maintenance and condition-based monitoring of factory machinery in general, and for "open architecture machining systems" in particular. The small-scale wireless sensor platforms bundle together the main essentials for laboratory studies in process manufacturing: USB programming capability, an IEEE 802.15.4 radio with integrated antenna, low power MCU with extended memory and an optional sensor suite. In the present experimental work, an accelerometer was mounted on the casing of the spindle head of a Haas VF-0 20HP CNC 3-axis milling machine. The output from the accelerometer was processed by the sensor node and then relayed through the WSN to a nearby base-station for additional processing and data logging. High-speed steel end milling tools were used to machine stainless steel work piece materials at various feed rates over the range 125-500 mm/min. Through these tests it was found that both surface finish and feed rate can be positively correlated to the machine's vibrations. The accelerometer-based WSN platform, supported by the WSN, was shown to be an easily deployable technology for the identification of such correlations. The use of the WSN to acquire data enabled an inexpensive retrofit of appropriate sensors to a standard CNC machine tool. In related work, the authors have shown the additional benefit of accessibility to rotating spindles that would normally be very hard or impossible to monitor with wired sensors.

EXPERIMENTAL WORK

Machining and Materials

End-milling of AISI 304 stainless steel was carried out with high speed steel M2 grade tools. The tools were 12.5mm in diameter. Slot end-milling was followed by surface finish measurements. The Talysurf profilometer data acquisition system v.1.2 using Talsurf 10 was used to collect the surface finish measurements. A minimum of 6 measurements were made on each cut. The depth of cut was held constant throughout the experiments at 2.5mm. Cutting speed was varied in the range 10 to 50 m/min and feed rate in the range 125 to 500 mm/min.

Sensor Platform and Accelerometer

The wireless sensor platforms (e.g. Figure 2) were supplied by the Sentilla company (www.sentilla.com). They employed a16-bit MSP430-F1611 microprocessor [from Texas Instruments] with eight 12-bit analog to digital converters (ADCs) and a 2.4 GHz RF transceiver [from Chipcon]. The mote transmitted at 0dBm. The communication used a CSMA medium access control protocol.

An ADXL 320 digital MEMS accelerometer [from Analog Devices] enabled a high sampling rate, low power consumption, appropriate sampling range, and small footprint.

A data-sampling rate of 1 kHz was used for the machining tests. The accelerometer itself was mounted to the flange of the spindle-head casing of the CNC milling machine, while cuts

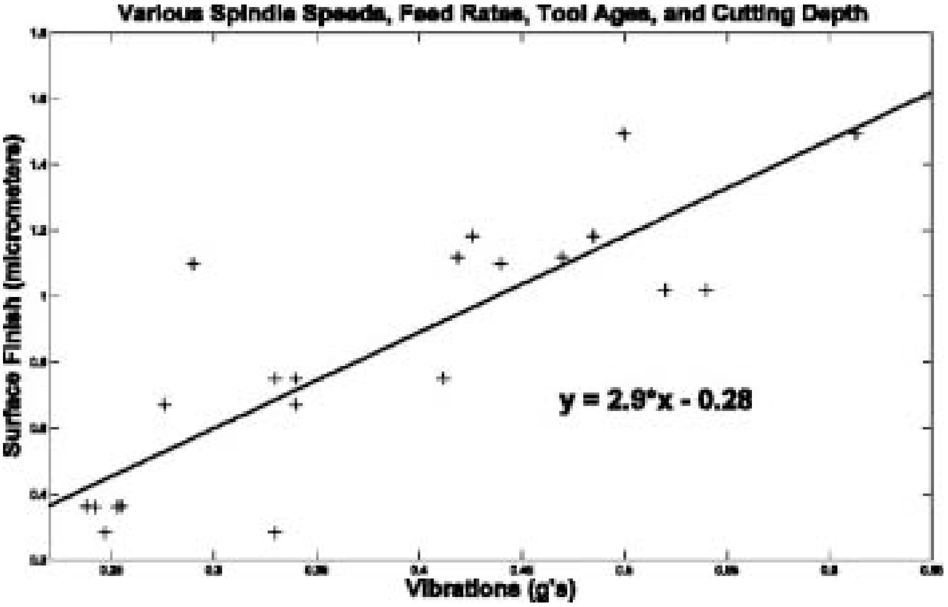

FIGURE 4. SURFACE FINISH IN RMS DETERIORATES WITH VIBRATIONS FROM INCREASED SPEED AND FEED.

were made at various feed rates. The combined sensor and wireless platform was then used to obtain the vibrations of the spindle-head casing in the vertical (z) and horizontal (y) directions.

A useful element of the wireless system was that the device in the top right of Figure 2 could quickly be re-deployed on other parts of the machine tool without having to worry about wiring and wire-routing.

Benchmarking Calibration of the MEMS Sensor

The MEMS, capacitance-based accelerometer on the wireless node (Figure 2) was first "benchmarked" against a commercial wired measurement system. Known forces in 10 different directions were applied to both the commercial system—a higher accuracy piezoelectric accelerometer [from PCB Piezotronics]—and the mote based system shown in Figure 2.

Figure 3 then shows readings in "g's" for the two kinds of accelerometers in the 10 different "x-y" directions. Good agreement is shown overall with some minor discrepancies in the "3" and "10" directions which correspond to the mounting points of the analog MEMS sensor itself within its packaging material.

RESULTS

Figure 4 is a plot of the surface finish on the machined specimens versus the measured vibration level from the accelerometer on the mote in Figure 2. Moving from left to right in Figure 4, corresponds to increased vibrations from higher rates of metal removal used (increased speed and feed). Increased tool wear, also created increased vibrations and a rougher surface finish as would be expected.

In Figure 5 for a feed rate of 250 mm/min (10in/min), surface finish data of the end-milled slots are plotted against tool wear. There was linear relationship between surface finish, tool wear and vibrations of the machine tool. Plots for other feeds, 125 to 500 mm/min showed the same trends.

CONCLUSIONS

1. The accelerometer-based WSN was shown to be an easily deployable technology for the identification of overall machine tool

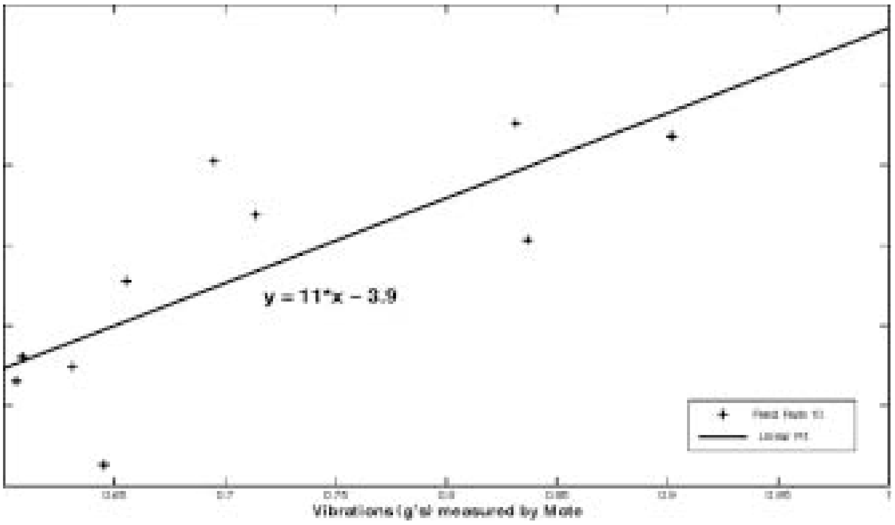

FIGURE 5. SURFACE FINISH IN RMS DETERIORATES WITH VIBRATIONS RESULTING FROM TOOL WEAR.

vibrations from issues such as tool wear and higher rates of metal removal as shown in Figure 4. Surface finish was also correlated with such vibration levels as shown in Figure 5. The use of the WSN to acquire such data allowed for an inexpensive retrofit of MEMS sensors to a standard machine.

2. Sensor-based, wireless sensor networks (WSNs) thus provide a useful tool for predictive maintenance and condition-based monitoring of factory machinery. In related work, we have also focused on ‘hostile’ industrial environments in order to show that wireless communications are not hampered by heavy metallic machinery, and random interference effects. Examples include aluminum smelting and copper refining (Schneider et al. 2006). Earlier, we also reported on the performance of wireless temperature sensors in rotational machine tool spindles where wired sensors are difficult to employ (Wright et al. 2006).

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