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Automatic multiple sensor data acquisition system in a real-time production environment

Jonathan Downey[a,c,]*, Sebastian Bombiński[b], Mirosław Nejman[b] Krzysztof Jemielniak[b]

[a]*Schivo Precision Limited, Cork Road, Waterford, Ireland.*
[b]*Faculty of Production Engineering, Warsaw University of Technology, Poland.*
[b]*Waterford Institute of Technology, Cork Road, Waterford, Ireland*

* Corresponding author. Tel.+353857081773; *E-mail address*: jdowney@schivogroup.com

Abstract

This paper presents a multiple sensor automatic data acquisition system deployed on a CNC turning center in a real-time production environment at Schivo Precision, Waterford, Ireland. The machine has been fitted with a variety of sensors measuring acoustic emission, cutting force & vibration installed at the turret of the machine, coupled with an automatic image acquisition system monitoring the wear on the tools in real time after each operation. The combination of sensors and data acquisition is novel in that it brings together all the currently popular sensoring techniques in the field of tool condition monitoring and tests the validity of these techniques in a live production environment. The sensor data acquisition and optical tool wear measurements are controlled by a computer automatically with no intervention from the machine tool operator in normal production on a variety of component geometries, materials and cutting inserts. All the acquired data is available on-line for the research partners in the various countries. Independent operator feedback on the performance of the process in terms of both product dimensional stability and machined surface stability is used for evaluation of the acquired data applicability for tool condition monitoring.

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1. Introduction

In Precision Engineering, and in particular in the modern high accuracy CNC machining industry where product tolerances are required to be maintained within the single figure micron wavelength, there is much focus on the use of technology for the post manufacture inspection of the products, for example through the use of CMM machines. This expectation has been driven through the accuracy of modern CNC machines and their use in the production of products for the medical, diagnostic and nano-technology sectors.

However there is a significant commercial disadvantage when a product discrepancy is detected during a final inspection as opposed to failure detection during the manufacturing process on the machine. Significant resources have been allocated to the manufacture of the product, and detection of an issue at this point is costly due to machine time, material, and lead time to the customer.

There is currently no reliable method whereby the operation of a CNC operation can be scientifically measured within a true production environment that will give a reliable analysis of the production process.

There has been many years of research undertaken within the CIRP community to determine a methodology whereby the efficiency and effectiveness of the various material removal processes in modern manufacturing can be monitored and evaluated. Such has been the degree of activity in the area that down through the years a number of state of the art reviews have outlined the progress thus far.

The most recent was the keynote paper presented by Teti. *et al* [1] in 2010 which provided a broad ranging review of the most recent developments in the art and the technology under development and this paper provided an excellent snapshot of from where the research had come, and where the research was going.

When read in chronological order the previous reviews that had been undertaken, by Byrne *et al* [2] in

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1995, by Tonshoff *et al* [3] in 1988, by Tlusty & Andrews [4] in 1983, and by Micheletti *et al* [5] in 1976, demonstrated the pace at which the understanding of the various material removal processes have developed, and also serve to illustrate the rate at which the associated technological deployment has been enhanced.

The literature shows that a number of variables within the process have been evaluated and experimentation has served to both discount variables and prove the merit of the variable depending on the approach taken by the researchers.

The CNC machining process variables that have been examined include motor power and currents [6], machine vibrations, temperature [7,8], force and torque analysis [9,10], ultrasonic evaluation [11], workpiece irradiation [12], audible sound energy [13,14] and acoustic emissions [15,16]. In each instance it can be argued from the evidence in the literature that each of these examined variables has worthwhile information, but there is also evidence to discredit each of these elements on a standalone basis.

Increasingly the research community has evaluated approaches to this problem that uses the application of multiple sensors [17,18], and also has increasingly investigated smarter methods of signal conditioning and computational analysis of the sensor signals employed during experimentation.

To do this requires intensive knowledge of various process conditions, and the experimentation that will be further outlined in this paper aims to add to the research and the industrial communities understanding of these variables.

The research has shown that among the most promising variables within the CNC machining operation that provide information on the performance of the operation are force sensing, acoustic emissions, and vibration.

The combination of acoustic emissions and vibrations has been examined in detail, Al-Ghamd & Mba [19] demonstrated that the use of AE, combined with vibration analysis, was shown to be beneficial in the identification and estimation of defect size in bearings. Augereau *et al* [20] examined the use of acoustics to determine damage levels in 304L SS subjected to various treatments.

Otman & Jemielniak [22] examined catastrophic tool failure (CTF) and concluded that the AE bursts detected during the experimentation may not be reliable measures of catastrophic tool failures. Among other research into the use of AE to predict CTF, there is evidence to support the premise that ongoing continuous monitoring of the process will pre-empt catastrophic failure, such as outlined by Holroyd [23].

A number of detailed studies have been undertaken to determine the worth of the acoustic emission signal from a specific machining operation. The theoretical effectiveness of AE has been examined for fracture detection by Rao [24], in drilling by Gomez *et al* [25], in turning by Li [16] and Reddy [26] and in micro milling by Jemielniak & Arrazola [27].

A large body of research has been undertaken into associated signal pre- and post-conditioning methodologies by Jemielniak [28], Wilkinson & Reuben [29], who examined tool wear prediction using multiple sensors and artificial neural networks.

In recent years there have been a number of collaborative projects between industry and academia investigating the control of the material removal and forming processes. In 1996 a project was undertaken by Lazarus [21] which was sponsored by Allied Signal and undertaken in conjunction with the US department of energy where a correlation was determined between the state of tool wear and the level of acoustic emissions (AE) and audible sound energy from the process. Although the project methodology did not have the level of sophistication available to today's researchers, it concluded that the premise was fundamentally sound.

More recently there has been considerable activity through EU funded projects. ADACOM [30] investigated a modular platform to allow the metal cutting process to self-adapt to changes in performance. IFaCOM [31] has been working on intelligent fault correction and self-optimising systems and has been investigating the usefulness of sensoring in the monitoring of high precision processes.

The research that will be outlined in this paper is also being undertaken as part of a funded research project. REALISM [32] is a two year project that has been funded under the EU's FP7 "Research for the benefit of SME's" programme. The project comprises consortium partners from a number of EU countries, as is detailed in table 1 below.

Country	Type	REALISM participant name
Poland	RTD	Warsaw University of technology
Ireland	SME	Schivo Group
Ireland	RTD	Waterford Institute of Technology
Italy	RTD	The University of Naples Federico
Italy	SME	Tulino SRL
Norway	SME	IDT Technologies
Norway	RTD	University of Gjøvic

Table 1

The objective of the REALISM project is the development of a multi-sensor system whereby the CNC machining operation can be effectively monitored and the process performance fed back in simple terms to the process operator, in real time. The experimentation that is outlined in this paper is the initial trials of the REALISM project.

2. Development of automatic multisensory data acquisition system

The objective at this stage of the REALISM project is to develop a system of automatic acquisition of vibration, force and acoustic emission signals and visual tool condition registration in a real time production environment. The system should be controlled by the CNC controller on the machine and work without any intervention of the machine tool operator. This makes this approach different from the methodologies historically applied, where experimentation is undertaken in laboratory conditions or under the direct supervision of a researcher. Additionally, all the collected data in this experimentation must be accessible to all the consortium partners in their various countries allowing them to verify and comment on the obtained results. The illustrative, logical structure of the entire system developed is outlined in Figure 1.

The CNC machining centre chosen for the deployment of the system is a Mazak Quick Turn Nexus 250-II MS, which is situated in the lathe section of Schivo precision's main factory floor in Waterford, Ireland. The machining centre is less than 5 years old.

As has been described in section 1 above, the best configuration of a tool condition monitoring system is now known to be through a combination of measurements from several sensors, analysing a number of process variables. The quality of information gleaned from the chosen sensors is very dependent on the choice of location within the machine for sensor installation.

The sensors should be located near to the cutting zone but a limitation of this can be protection of the sensors from moving parts of the machine. The machining bay is illustrated is Fig 2. The force sensor (A) was mounted under the tool head. Accelerometer (B) and AERMS sensor (C) were installed on the tool head. The sensors deployed, and their locations, are outlined in Table 2 below.

Sensor type	Sensor Description	Location
Force	KISTLER 9017C with charge amplifier	A
Accelerometer	50g Ceramic Shear Triaxial KISTLER 8763B050AB	B
Acoustic emission	Piezoceramic AE Sensor KISTLER 8152C0050000 – (50-400kHz)	C

Table 2

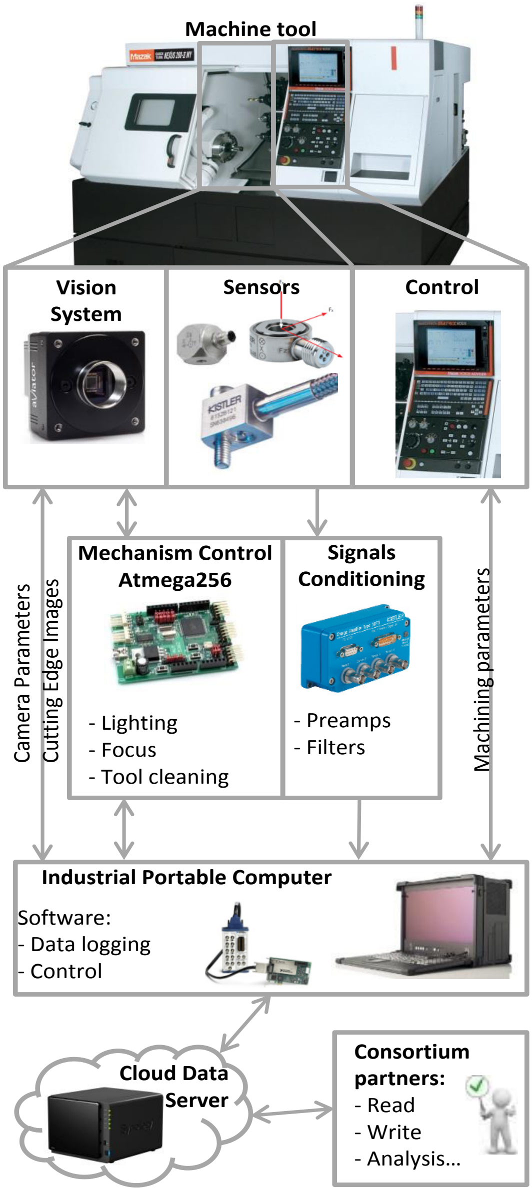

Figure 1

As the measured signals will be used for development of a tool condition monitoring system, this condition must be monitored objectively, independently from the signal measures and automatically. This was achieved through the use of a vision system installed inside the work space of the machine tool. After each operation high resolution pictures of the flank and rank face of the cutting tool/insert were taken automatically. The tool was illuminated during this image acquisition step by monochromatic light of an appropriate intensity. As the surface of the cutting edge is of a limited area, typically of the order of 2 mm, pictures of the tools with the cutting edge not perpendicular to the optical axis of the camera must be taken several times with a different point of focus. This allows for reconstruction of the sharp cutting edge picture by the superposition of the previously known sharp parts within every picture.

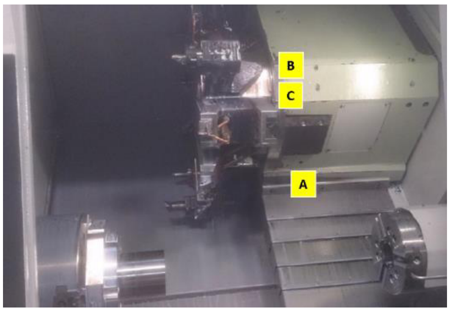

Figure 2

The optical system obviously is exposed to a harsh environment containing cutting fluids and chips during machining; therefore the vision system must be enclosed in a protective waterproof casing. The front glass of the camera was automatically covered during cutting operations and uncovered before acquiring images with a mechanical cover and an air curtain. In addition to this, there is the likelihood that after each machining operation the tool cutting interface could also be concealed from the cameras view by loose chips and/or cutting fluid.

The best method for removal of this contamination before analysis is through a burst of compressed air. The vision system employed consists of high speed CCD camera Basler Aviator avA2300-25gm equipped with Schneider Apo-Componon 4.0/60 lens and auxiliary system support devices such as stepper motors for automatic focus adjustment, cover movement and an LED lighting system.

The auxiliary system support equipment is controlled by the microcontroller ATMEGA 256 which is also enclosed in a watertight housing for protection during the experimentation. Communication with the computer recording the data is realised via the USB port 2.0 (ATMEGA) and the LAN (camera). The photos of the cutting interfaces are saved in the PNG format, and the software that triggers the vision system is a subprogram of data acquisition program. It is activated when the tool is in the required position for the capture of the tool images. This information is conveyed through the digital line "working feed" which specifies the tool number. The automatic registration of images required a modification of the production CNC programs by adding an operation to allow indexing the tool to the required location after an operation to allow image acquisition.

All the analogue signals from the sensors are collected through a data acquisition system based on an industrial portable computer installed with a National Instruments PCIe-6351 card and data logging software developed in LabVIEW as a VI. Ultimately, the diagnostic system is processing the data in real-time. The frequency contents of the signals generated during machining do not exceed some 2-3 kHz. Therefore the applied sampling rate was 10kS/s per channel.

As the entire data acquisition system operates in an automatic mode, it is necessary to continuously monitor the status of the machine tool such as the tool holder position of the actual working tool, a digital trigger (start/stop) of operation and indication (start/stop) of working feed. These signals are created by the machine controller as digital signals (logic 1 or 0). Each start of a new operation (high level, logic 1 of appropriate digital signal) activates data recording to a new file – all digital and analogue signals are sampled simultaneously and saved to the same file. The end of operation (low level, logic 0 of the digital signal) stopped data recording and closed the file.

In addition to the above outlined sensor and operational information, there is other information that can be taken from the CNC machine in terms of the operational parameters, such as the spindle speed , program block number and similar data. It is important to note at this point that a PROFIBUS or LAN standard communication connection is required to include this information in the analysis, however for the outline being presented in this paper of the progress of the REALISM project, inclusion of these data variables at this stage is outside the scope.

As the data analysis was being undertaken in a different country to the data collection the files were synchronized to the cloud file server. This allowed for very quick verification of the accuracy of recorded data by all the project participants.

An overview of the communication between the industrial portable computer and rest of the system is presented in figure 3 below.

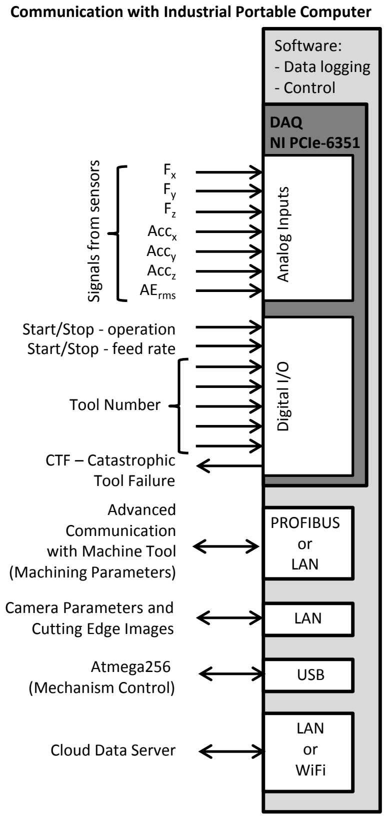

Fig 3

3. Results

The machining centre, as described, was utilised in normal production operations throughout the duration of the experimentation. The operations being undertaken by the machining centre during this experimentation included roughing and finishing of materials including 6082 aluminium and 3 & 4 series stainless steel using a variety of cutting inserts and tool geometries.

During the data collection, which took place over a two week period in normal production, across a three shift cycle, the data from the sensors was collected by the computer system and uploaded to the Fionn supercomputer in the Waterford Institute of Technology. In addition to the electronic data being collected by the sensors, the operators of the machine kept logs of the operations being undertaken on the machine in terms of the Schivo job numbers (which offers the material and machine operation being undertaken at a point in time). This allowed the researchers to correlate the sensor data from the machine with the actual machine operation across a period totalling 160 hours across multiple machining configurations and operations.

The data collected from the visual images, collated against the sensor signals obtained thus far in the experimentation, is at this point indicating that this portion of the research should continue. The initial results being obtained are very encouraging with strong correlation between the sensor signals and the detected tool wear as observed by the camera system.

4. Continued research

As outlined, this paper provides an overview of the initial experimentation that has been undertaken as part of the EU FP7 REALISM project. The experimentation described within this work is the first deployment of sensoring within the real time production environment and is the initial trial run of the configuration outlined, and the next step of the project is the deployment of this technology on machines in the other consortium partners in Norway and Italy.

This paper has described our initial results from sensor deployment on machines and once the sensor systems described above have been deployed on the machines at the manufacturing facilities in Norway and Italy there will be collation of sensor data across three sites within the EU. All the data from the three sites will be uploaded through the Fionn supercomputer at Waterford Institute of Technology for analysis during one of the later work packages within the project.

The later work packages within the REALISM project intend bringing the data obtained in the early and intermediate stages to a stage where this huge volume of data is mined and interpreted to a stage whereby this will provide the platform for the development of an intelligent system to allow the monitoring of the CNC machining operation within a real time production environment.

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