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A Web-based machining process monitoring system for E-manufacturing implementation*

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Abstract: Recently, with the rapid growth of information technology, many studies have been performed to implement Web-based manufacturing system. Such technologies are expected to meet the need of many manufacturing industries who want to adopt E-manufacturing system for the construction of globalization, agility, and digitalization to cope with the rapid changing market requirements. In this research, a real-time Web-based machine tool and machining process monitoring system is developed as the first step for implementing E-manufacturing system. In this system, the current variations of the main spindle and feeding motors are measured using hall sensors. And the relationship between the cutting force and the spindle motor RMS (Root Mean Square) current at various spindle rotational speeds is obtained. Thermocouples are used to measure temperature variations of important heat sources of a machine tool. Also, a rule-based expert system is applied in order to decide the machining process and machine tool are in normal conditions. Finally, the effectiveness of the developed system is verified through a series of experiments.

Key words: E-manufacturing, Web-based system, Internet, Machining process monitoring, Expert system
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INTRODUCTION

Recently, the application of the information technology into manufacturing fields gets more and more importance on the whole manufacturing shop floors. Currently, many researches reflect the effectiveness of knowledge-based production system related to the exchange and management of various manufacturing information using information technology via the Internet in order to increase the competitive power of industries. This research suggests a Web-based machining process monitoring method to detect abnormal cutting situation and machine tool condition changes at remote sites through the Internet. Also, the developed system is designed to send required data to MES (Manufacturing Execution Systems), which is the lower level of E-manufacturing. The diagram of the E-manufacturing and MES is shown in Fig.1 (MESA—Manufacturing Enterprise Solutions Association, http://www.mesa.org, A MESA International White Paper Number 1, 2, 3, 4, 5, 6).

Several monitoring methods have been introduced so far for monitoring the processes on the machine tools; and many researches on the Web-based monitoring are performed for remote process control using information technology (Muto, 2003; Lee, 2003; Jung *et al*., 2001; Stein and Wang, 1990; Stein and Shin, 1986; Cheung and Lee, 2001; Park and Settineri, 1994; Kraiem, 2001; Jin *et al*., 2001; Ouyang *et al*., 2001; Yu *et al*., 2004).

In this research, a practical Web-based machining process monitoring system is developed and it is applicable inexpensively to shop floors. Hall sensors are used to obtain cutting force and feedrate variations for the machining process monitoring. The experi-

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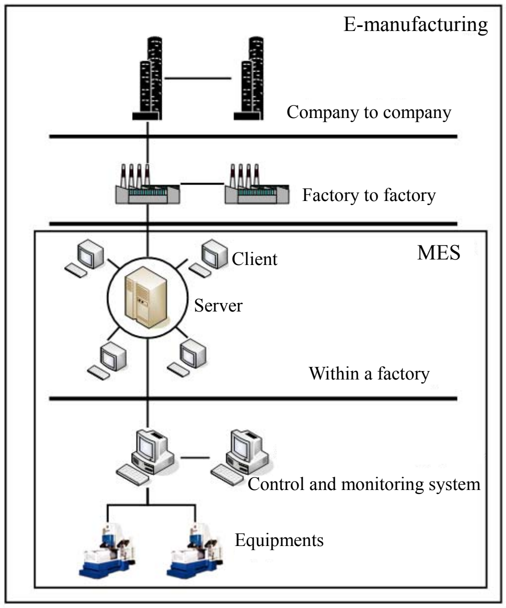


Fig.1 Diagram of E-manufacturing and MES

ments to compare and analyze the output of the tool dynamometer and the input of the spindle motor are carried out and an equation is derived to convert the current value of the driving motor of the main spindle to the cutting force. Thermocouples are used to measure temperature variations of important heat sources, such as main spindle, *x*- and *y*-axis bearings, of a machine tool. Also, a rule-based expert system is developed to decide whether the process and machine tool are in pre-defined normal ranges.

The developed system enables remote real-time monitoring on the Web by acquiring and dealing with the process data of the working machine tool. The system reports the information and the processing data of the parts on a machine tool for the monitoring of the manufacturing status. One-to-one socket communication is established for the realization of effective mutual communication. ActiveX control is used for the Web driver programming of the client. The interface for uploading and representing files of the manufacturing information and the process results on the Web are constructed. The concept of the developed monitoring system is depicted in Fig.2.

SENSOR INTEGRATION FOR CUTTING PROCESS MONITORING

In this research, a practical Web-based monitoring system is developed and it is applicable inexpensively to the shop floors. For effective real-time monitoring of the machining process, several sensors are integrated such as hall sensors, thermal sensors, etc. The hall sensors are used to monitor the motor current variations for main spindle and pulse rates for feeding system during manufacturing processes. Thermal sensors are used to detect temperature variations of important heat sources of machine tool. The sensor integration diagram is illustrated in Fig.3.

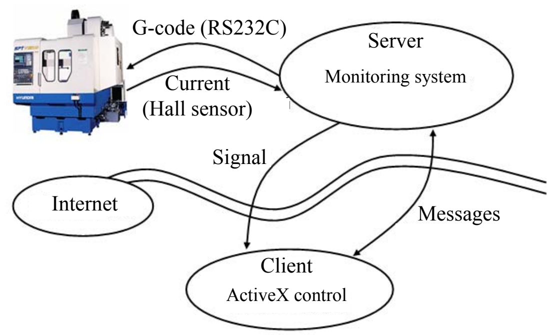


Fig.2 Basic structure of developed system

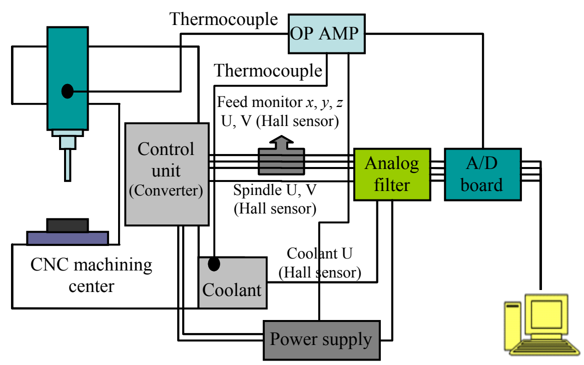


Fig.3 Developed process monitoring system diagram

Indirect cutting force measurement using hall sensor

Tool dynamometers can be used to measure cutting forces during machining process; however, it can be an expensive solution to install dynamometers to every machine tool if accurate cutting force values are not required, such as monitoring. Thus, in this study, inexpensive current hall sensors are used for cutting force measurement indirectly. The hall sensor can measure the cutting force indirectly by detecting the current values of the main spindle motor and the feeding motor during the machining process of a machine tool.

Generally, the cutting path in 2D milling can be approximated to an arc under the assumption that it is less than the tool radius. In this case, the cutting torque (T_c) can be calculated using tangential component of the cutting force (F_t) and the tool radius (R). Also, the motor torque (T_m) can be represented by current (I) and motor torque constant (K_t).

$$T_c=F_tR, \tag{1}$$

$$T_m=IK_t. \tag{2}$$

In the case of a 3-phase induction motor, the RMS (Root Mean Square) current values of the 3-phases are used to derive the equivalent direct-current in this study as the following equation:

$$I_{RMS}=\sqrt{\frac{I_U^2+I_V^2+I_W^2}{3}}, \tag{3}$$

Because the RMS conversion is a scalar product without information of the direction, measuring the rotation angle of the rotor is not necessary. Thus, when a synchronous motor is used, the machining is in the steady state. It is concluded that the current of the main spindle motor, the cutting torque, the motor torque, and the cutting force are proportional to each other (Kim and Chu, 1999; 2001; Kwon and Lee, 2001):

$$F_c \propto T_c \propto T_m \propto I_{RMS}. \tag{4}$$

An experiment was performed to measure the cutting force indirectly by measuring the current values of spindle motor and feeding motor. Fig.4 shows the installed locations of hall sensors in the control unit of a machine tool.

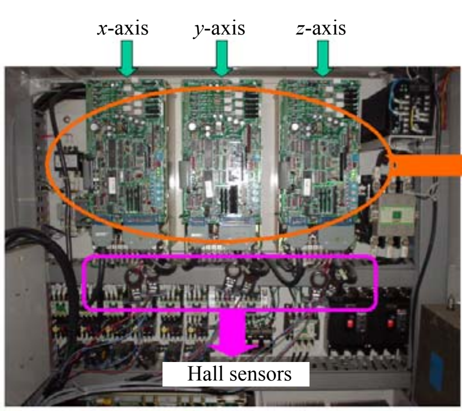


Fig.4 Locations of hall sensors in the control unit

In the experiment, the feedrate increased to 25 mm/min from 20 mm/min during which the cutting depth increased by 0.5 mm, and the cutting speed increased by 200 r/min. The current of the main spindle motor and the cutting force of the tool dynamometer were investigated at each machining condition. The result of the experiment is shown in Fig.5 as a graph. The correlation of the cutting force and the current is linear of 96.5% precision, and it is represented as Eq.(5):

$$F=143.70396M-790.15769. \tag{5}$$

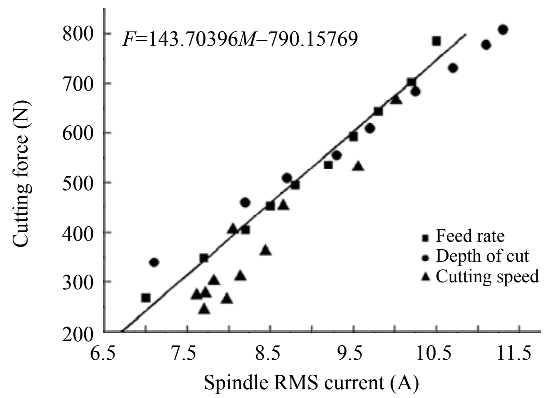


Fig.5 Spindle RMS current vs cutting force

Therefore, it is confirmed that the cutting force could be measured from the current value of the main spindle motor indirectly according to the linear relationship between the RMS current value of the motor and the tool dynamometer. To develop the system, the RMS current value is converted to the cutting force using the derived equation in real time. Its conversion process is depicted in Fig.6. Fig.7 shows the comparison between the measured cutting force using tool dynamometer and the converted values form current hall sensor signals.

Thus, it can be concluded that the RMS current is suitable to estimate the cutting force in spite of the time delay that is inevitable in real time monitoring.

Feedrate measurement

Generally, AC servo motors are used for x-, y- and z-directional feeding in a machine tool. An internal permanent magnet is connected with rotational axis, and it rotates by synchronizing with supplied alternative currents as shown in Fig.8.

The number of rotation of a 3-phase AC servo motor (N) has a relation with the frequency (f) of sup-

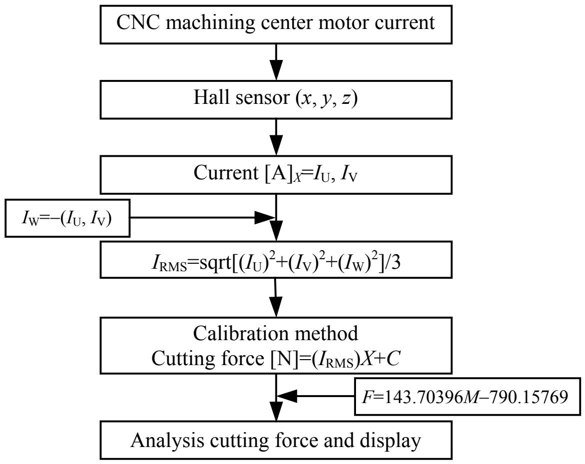


Fig.6 Conversion process of RMS current into cutting force. RMS: Root Mean Square; *X*: Multiplication factor; *C*: Shift factor

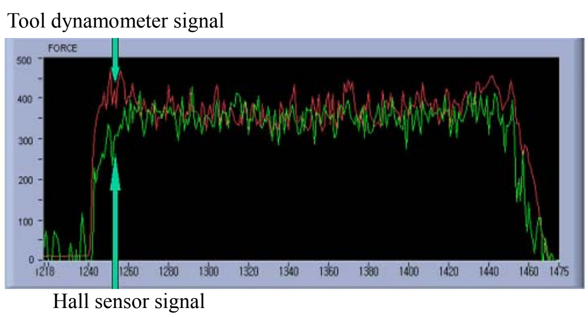


Fig.7 Experimental result of indirect cutting force measurement

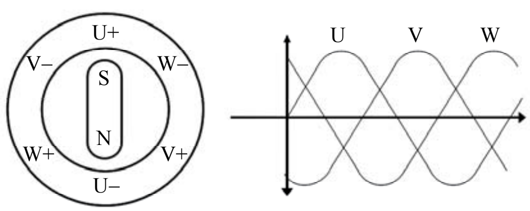


Fig.8 Brief structure of a 3-phase AC servo motor with 2-poles

plied current and the number of poles of the motor (P) as the following equation:

$$N=120f/P \text{ r/min.} \tag{6}$$

Thus, if the number of poles of an AC servo motor is fixed, the feeding speed can be controlled by changing the frequency of supplied current. In this research, for the experimental purpose, x- and y-directional feedrates were changed in 25~250 mm/min range, and the frequency of the supplied currents was measured using hall sensors. From the results of the experiments, it could be confirmed that the supplied current frequency and feedrate had a linear relation as shown in Fig.9. Thus, indirect measurements of federates of each axis were possible using the hall sensors.

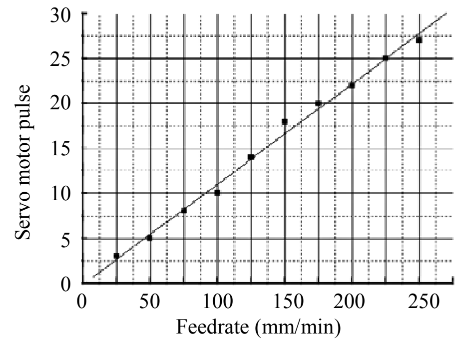


Fig.9 Servo motor pulse rate vs feedrate

Temperature measurement using thermocouples

Generally, machine tool temperature rises due to inevitable heat sources, such as main spindle motor, each directional feed motors, bearings, etc. Such heat sources cause thermal deformation of the machine tool and machining errors. Abnormal temperature rising can be an important signal to judge that the machine has serious problems.

In this research, temperature variations at selected locations of a machine tool were measured using thermocouples. To select dominant heat source locations of a machine tool, basic experiments were performed using 14 thermocouples. From the results, 4 important temperature measuring points were selected; x- and y-slide bearing, main spindle and motor were shown in Fig.10. Measured results are illustrated in Fig.11.

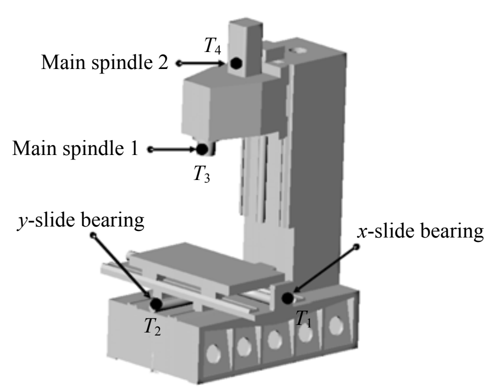


Fig.10 Thermocouple locations for temperature change monitoring

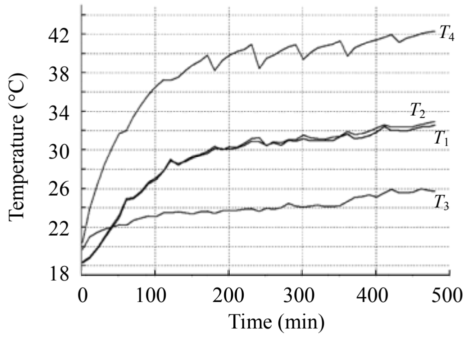


Fig.11 Measured temperature variations of a machine tool

Rule-based expert system

To decide the machining status using various sensor signals, a rule-based expert system was developed in (Seo and Kang, 1999). Input data of the expert system were cutting force, *x*-, *y*- and *z*-directional feedrates and main spindle temperature, etc. as shown in Fig.12. From the input data, sudden changes of cutting forces and temperature rising, etc. during machining process were monitored using the developed rules. Using the expert system, a tool failure, abnormal cutting action, coolant lack, main spindle problem, etc. could be obtained as outputs. Such data could be monitored in real-time at remote site through the Internet using developed program.

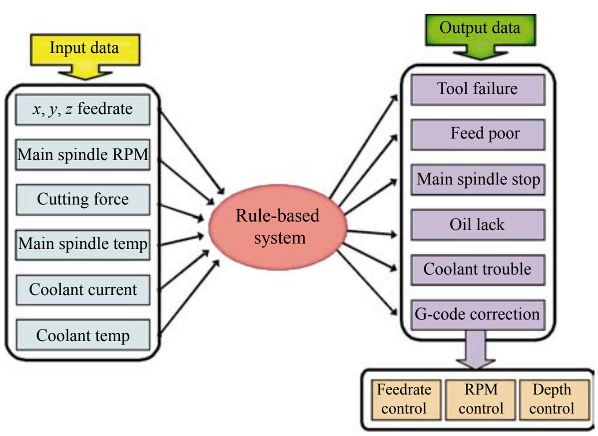


Fig.12 A rule-based expert system

DEVELOPMENT OF A MONITORING MODULE

System development

In this research, the sending and receiving of the messages between the server and the clients were implemented using socket communication. The software for the clients was programmed using Visual C++ and ActiveX control. It was downloaded automatically to the local computers of the clients through the Internet Explorer and it installed the exclusive viewer on them. The above method enabled the quick connection to the server and the mutual communication.

The overall operating flowchart of the developed system is shown in Fig.13. The remote client can easily send the required command to the server through the upload module. The monitoring signals are stored in the server during machining and they can be shown on the Web, then, the client can interpret the manufacturing result comprehensibly.

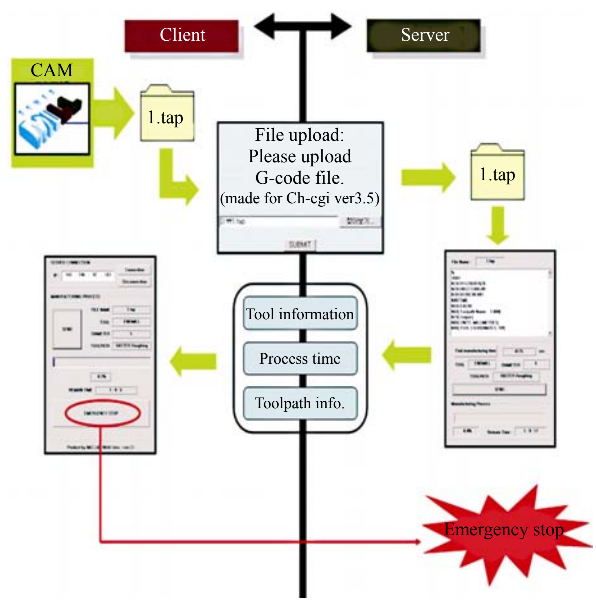


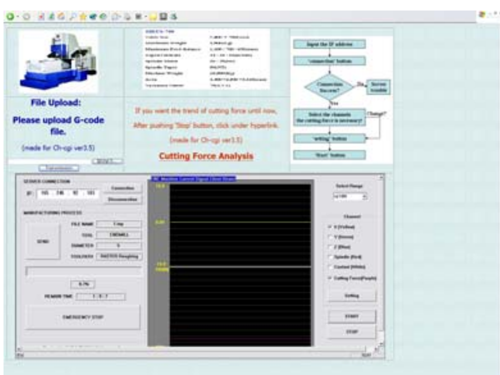
Fig.13 Process flow of Web based monitoring system

The system is developed under the environments of Table 1. IIS5.0 that is an element of Windows O/S and used to construct the Web server is easy to install and inexpensive. The developed system is composed of three modules: the machining process information module, the module for the process monitoring, and the module for the analysis of the process result. The process information module and the process result analysis module are made using one program of ActiveX control. When a client is connected to the server, the presently operating machining tool is selected and the corresponding Web page appears. The developed Web page is shown in Fig.14.

Table 1 Environment of system development

Items	Descriptions
OS	Windows 2000 Professional
Web server	IIS 5.0
Script language	HTML
Used language	Visual C++ 6.0 (ActiveX control)
Communication method	RS232C Serial Communication, Internet (TCP/IP)
PC	Pentium IV
A/D board	ADLINK PCI-9112, testing sample-rate: 1 kHz

(a)



(b)

Fig.14 Web pages of developed system. (a) Main Web page; (b) Example of a monitoring Web page

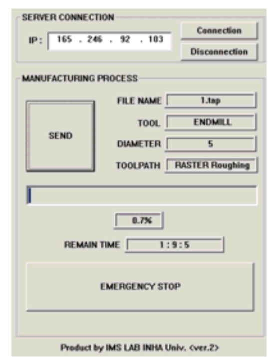
Process information and monitoring modules

The server sends the process status information for the machine tool and the cutting force value to the connected client, which is converted from the current value of the hall sensors attached to the equipment. Because the existing monitoring system simply monitors the signals from the sensors on the machine tool, only the present process status and the machine tool status can be known, but the detailed process information for the manufacturing process control cannot be known. The developed system removes the above shortage using the interfaces.

The system analyzes the command received from the remote client and delivers them to the client. After the client examines the files, it can directly control the starting of the process using the interfaces. The machining stage such as rough machining or finish machining, the machining time, the tool information, the abnormal status, etc. are informed to the remote client in order to investigate the manufacturing process from the beginning; then, the needs of the re-machining according to the machining errors and the inspection processes can be determined.

When an emergency situation occurs, the client can inform the worker on the shop floor. The interfaces for the server side and the client side of the monitoring program are shown in Figs.15 and 16. They were made using ActiveX control.

(a)



(b)

Fig.15 Process information viewer of developed system. (a) Server viewer; (b) Client viewer

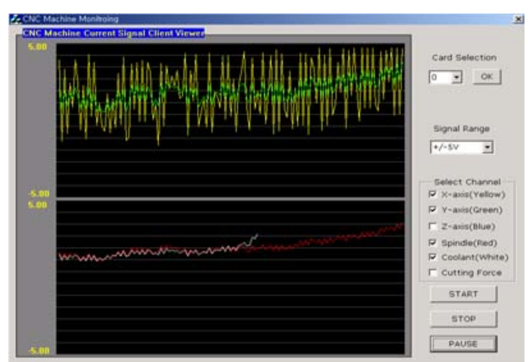


Fig.16 Monitoring program of developed system

Process result analysis module

This module takes the following roles. It stores the data acquired by the monitoring module in a file. When a stage of a process is finished or the client requires the information of the intermediate result of the present process, it plots the raw data and curve-fitted data on the Web page simultaneously. Then, the client can evaluate the machining process at every stage. By easy estimation of the variation in the cutting force, the finished process can be evaluated conveniently and the post-processes are planned flexibly.

CONCLUSION

In this research, a Web-based monitoring system is developed. The application of this system to the real manufacturing industry can make the basis adopt the information technology as follows:

(1) The developed system can be easily installed and applied on the existing machine tools inexpensively. The hall sensors are used to monitor the machining status without the interference to the machining process.

(2) An equation is derived to represent the RMS current value of the main spindle motor and the cutting force from the tool dynamometer by analyzing their variations.

(3) To monitor feedrate variations, supplied current pulse rates to AC servo motors are measured using hall sensors.

(4) Thermocouples are used to measure required temperature variations at selected locations of a machine tool.

(5) A rule-based expert system is developed to decide the status of machining operation and machine tools at remote site.

(6) The developed software system consists of the machining process information module, the module for the process monitoring, and the module for the analysis of the process result. Interfaces are also constructed for the flexible control and convenient.

References

Cheung, C.F., Lee, W.B., 2001. A framework of virtual machining and inspection system for diamond turning of precise optics. *Journal of Materials Processing Technology*, **119**(1-3):27-40. [doi:10.1016/S0924-0136(01)00893-7]

Jin, L., Oraifige, I.A., Lister, P.M., Frank, R.H., 2001. E-manufacturing in networked virtual environments. *IEEE*, **39**:1845-1849.

Jung, M.S., Kim, B.S., Park, H.S., 2001. Architecture of Web-based real-time monitoring systems. *Journal of Control, Automation, and System Engineering*, **7**:632-639.

Kim, G.D., Chu, C.N., 1999. Indirect cutting force measurement considering frictional behavior in a machining center using feed motor current. *The International Journal of Advanced Manufacturing Technology*, **15**(7):478-484. [doi:10.1007/s001700050092]

Kim, G.D., Chu, C.N., 2001. In process tool fracture monitoring in face milling using spindle motor current and tool fracture index. *The International Journal of Advanced Manufacturing Technology*, **18**(6):383-389. [doi:10.1007/s001700170047]

Kraiem, N., 2001. Virtual spaces and virtual manufacturing. *IEEE*, **6**:90-93.

Kwon, W.T., Lee, I.H., 2001. Development of torque monitoring system of induction spindle motor using graphic-programming. *Journal of the Korea Society of Precision Engineering*, **18**:184-193.

Lee, J., 2003. E-manufacturing-fundamental, tools, and transformation and inspection system for diamond turning of precise optics. *Journal of Materials Processing Technology*, **119**:501-507.

Muto, K., 2003. Advanced technology for manufacturing engineering development: XML technology on a system that enables user to view required information from the workshop through a Web brower. *JSAE Review*, **24**:303-312. [doi:10.1016/S0389-4304(03)00047-X]

Ouyang, C., Lin, J.S., Guan, T.Y., 2001. Developing a computer shop floor control model for a CIM system using object modeling techniques. *Computers in Industry*, **41**:218-238.

Park, J.J., Settineri, L., 1994. Cutting torque estimation using spindle power measurement. *Transaction of NAMRI of SME*, **24**:85-90.

Seo, D.K., Kang, M.J., 1999. Development of an expert system for diagnosing machine tool failures. *Journal of the Korea Society of Precision Engineering*, **16**:217-224.

Stein, J.L., Shin, K.C., 1986. Current monitoring of field controlled DC spindle drives. *ASME Journal of Dynamic Systems Measurement and Control*, **108**:289-295.

Stein, J.L., Wang, C.H., 1990. Analysis of power monitoring on AC induction drive system. *ASME Journal of Dynamic Systems Measurement and Control*, **112**:239-248.

Yu, Q.C., Chen, B., Cheng, H.H., 2004. Web-based control system design and analysis. *IEEE*, *Control System Magazine*, **24**(3):45-47. [doi:10.1109/MCS.2004.1299532]