Ubiquitous-Based Mobile Control and Monitoring of CNC Machines for Development of u-Machine

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This study was an attempt to control and monitor Computerized Numerical Controller (CNC) machines anywhere and anytime for the development of a ubiquitous machine (u-machine). With a Personal Digital Assistant (PDA) phone, the machine status and machining data of CNC machines can be monitored in wired and wireless environments, including the environments of IMT2000 and Wireless LAN. Moreover, CNC machines can be controlled anywhere and anytime. The concept of the anywhere-anytime controlling and monitoring of a manufacturing system was implemented in this study for the purpose of u-manufacturing and u-machines. In this concept, the communication between the CNC controller and the PDA phone was successfully performed anywhere and anytime for the real-time monitoring and control of CNC machines. In addition, the interface between the CNC controller and the developed application module was implemented by Object linking and embedding for Process Control (OPC) and shared CNC memory. For communication, the design of a server contents module within the target CNC was based on a TCP/IP. Furthermore, the client contents module within the PDA phone was designed with the aid of embedded c++ programming for mobile communication. For the interface, the monitoring data, such as the machine status, the machine running state, the name of the Numerical Control (NC) program, the alarm and the position of the stage axes, were acquired in real time from real machines with the aid of the OPC method and by sharing the CNC memory. The control data, such as the start, hold, emergency stop, reserved start and reserved stop, were also applied to the CNC domain of the real machine. CNC machines can therefore be controlled and monitored in real time, anywhere and anytime. Moreover, prompt notification from CNC machines to mobile phones, including cellular phones and PDA phones, can be automatically realized in emergencies.

Key Words : CNC, Ubiquitous Machine, Anywhere-Anytime, Mobile Control and Monitoring

1. Introduction

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In recent years, there has been in increase in demand for a convenient environment in which users can achieve their purposes anywhere and anytime (Kim et al., 2005). Such demands have also been made with respect to manufacturing systems and machine tools (Kim et al., 2005;

Kim, 2004 ; Lee et al., 2004 ; Tahk and Shin, 2002). In particular, machine tools with open CNC architecture have been the motivation for active research on methods for the control and monitoring of CNC machines (Erol et al., 2000 ; Lee et al., 2003 ; Oldknow and Yelloeley, 2001 ; Rober and Shin, 1995). This research has spawned numerous studies on remote monitoring and controlling (Kim et al., 1999 ; 2000 ; Wright, 1995 ; Yellowley and Pottier, 1994), which are vital functions in a wireless environment (Kim, 2004).

Conventional controlling and monitoring of machine tools focuses on the machine itself or on the relationship between CNC machines and peripheral equipment (Kim et al., 2000 ; Wright, 1995 ; Yellowley and Pottier, 1994). Recently, however, the widespread use of computers and the Internet have led to a proliferation of studies on the remote controlling, monitoring and diagnosis of CNC machines for distributed global management in manufacturing systems (Kim et al., 2005 ; Ong et al., 2001). Most of these studies are based on the client-server local domain in a wired LAN, and, recently, Web-based control and monitoring has actually been realized (Kim et al., 2005 ; Jung et al., 2001). The circumstances mentioned above, which are due to the inferior field environment, are exacerbated by the difficulty of merging machine technology with IT. These two types of technology are now being applied together in manufacturing systems. However, although this merger is possible in a wired network environment, it has not yet been fully realized in a ubiquitous-based wireless and mobile environment (Kim, 2004).

Therefore an attempt was made to develop a solution for the mobile controlling and monitoring of CNC machines in a wireless environment. By finding a method of remotely controlling and monitoring CNC machines, and by enabling various functions to be controlled and monitored anywhere and anytime, it will be possible to lay the foundation for the development of u-machines. For this, the interface between the CNC controller and developed application modules was implemented by accessing the shared CNC

memory and the parametric values for the interface were mutually referred by the OPC.

2. The Scheme of the Approach Method for Implementation

The goal was to enable the controlling and monitoring between a CNC machine and a PDA phone to be implemented anywhere and anytime. For such implementation, a server contents module based on the TCP/IP was designed within the CNC of the machine. In addition, client contents module was designed using embedded c++ programming, for mobile communication, into a PDA phone.

Then the OPC method was used and CNC memory was shared for a real-time interface between the developed application modules and the CNC domain in order to acquire data on the machine status, the machine running state, the NC program information, the alarm information and the position of the stage axes of real machines. Another reason for adopting this approach was to apply the control data, such as data on the start, hold, emergency stop, reserved start and reserved stop.

To ensure the remote controlling and monitoring of systems anywhere and anytime in a wireless environment, the following process were used :

- A PDA phone was used as a mobile terminal.
- The contents of a mobile terminal was programmed with embedded visual c++ for operation in the WinCE.Net operating system.
- The server contents module of the CNC machine communicated with the client contents module that operated in the mobile terminal. Through the communication medium, the data for control and monitoring were transferred between the two modules.
- To control and monitor a real CNC machine, the interface between the server contents module and the CNC was performed with the OPC method and by sharing CNC memory.

3. System Configuration

The system was configured as follows: First, the system functions were divided into two developed modules: the client mobile contents module and the server contents module. The server contents module was programmed with standard visual c++, and the developed agent program was executed in the CNC domain.

Next, for the client mobile contents module, the developed agent program, which was programmed with the aid of embedded visual c++ was used for execution in a WinCE.Net 4.2 operating system. This module was designed to operate on a PDA phone (Nexio S155). An IMT2000 (CDMA2000) network and a wireless LAN was used for the communication between the server contents module and the client contents module.

For the next step, the server contents module was used to obtain the monitoring data, such as the machine status, the alarm information, the NC information, the position of the axes, the CNC screen image, and Universal Serial Bus (USB) camera images. The server contents module was also used to communicate with the client contents module. On the other hand, the client contents module was used to receive the monitoring data from the server and to show the data on the screen of the PDA phone. In addition, the client contents module was used to transfer the control data to the server contents module; for example, data on the machine start, hold, emergency stop, reserved start and reserved stop.

Figure 1, which illustrates the communication between the two contents modules, shows that the client contents module operates on a PDA phone, and that the communication is performed with a base station through the CDMA2000 network. The base station sends the data transferred by the CDMA2000 network to the Internet. The server contents module, which is connected to the Internet, operates the CNC machine and transfers the monitoring data, such as the machine status, to the base station through the Internet. The architecture of the server contents and client contents, using CDMA2000 and wireless LAN, is as follows.

3.1 Server contents

In Fig. 2, which shows the structure of the OPC program in the server contents, there are two server contents models. The models are classified in terms of the process they use to interface with
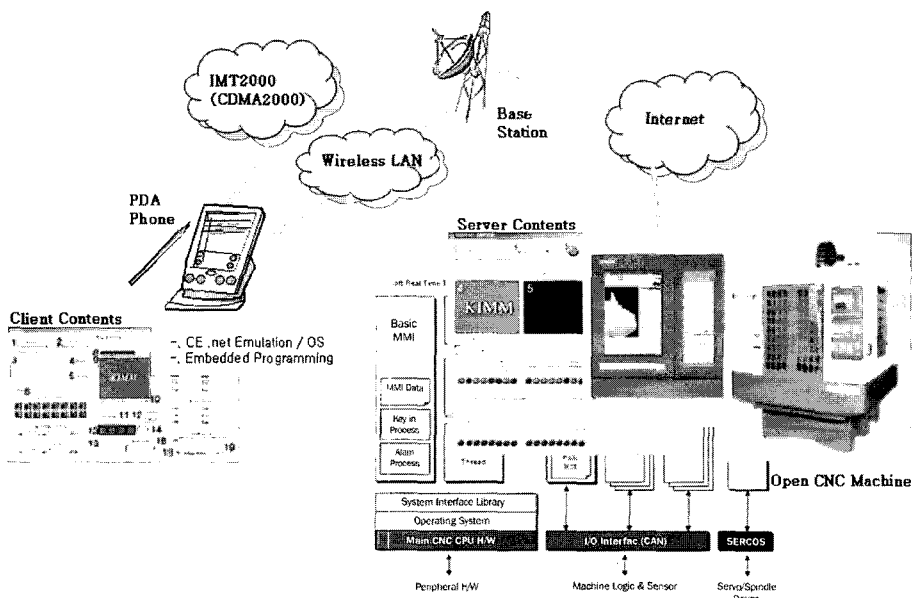

Fig. 1 The system scheme and the communication between two contents modules

the CNC machine : that is, either the OPC method or the method of sharing the CNC memory map.

The explanation of Fig. 2 is as follows.

- Object Linking and Embedding (OLE) dynamic linking library initialization : The OLE initialization is used for the OLE process.

- Variable initialization : The variables used in the program are initialized. In detail, the basic variables and icons used in the graphic user interface are initialized, as well as the variables for the OLE and communication.

- Network setting : The status for communication is set up in the server contents module. To solve network congestion, the packet size is controlled and over-sized packets are avoided. The port number is also set up. The settings for the parameters are saved in static memory to ensure the parameter values can be restored in the program initialization.

- OPC initialization : The OPC process is initialized with the aid of the OLE to interface with the machine controller. The variables used in the OPC process are initialized and the required

classes are created.

- USB camera initialization : The USB camera is initialized and the initial frame is displayed on the screen.

- Wait event : The event of the user's command is checked. The command includes the server contents of Server_Start, CNC_Start, CNC_Hold, CNC_Stop, Self Test, Close.

- Server start : The communication part of the server side is executed, and the wait data requests a query from the client side. The server contents module, which creates a new class, charges the created class with the communication process. The created class communicates with the client contents through a predefined protocol.

- CNC_Start : The start command of the CNC machine is applied.

- CNC_Stop : The stop command of the CNC machine is applied.

- CNC_Hold : The hold command of the CNC machine is applied.

- Self test : The communication between the server side and the client side is simulated with the aid of random data values when the interface between the server contents and the CNC is not possible.

- Close : The server contents module is closed.

The server contents module has the structure of an OPC-type program. If the server contents uses the CNC shared memory, a real-time kernel (RTX) Application Programming Interface (API) library is used, and the step related to the OPC is replaced with the RTX API part of the server contents module.

3.2 Client contents

Figure 3 shows the structure of the client contents.

The structure of the client contents module enables the module to connect to the server contents, receive monitoring data from the server contents, and send control commands to the server contents. The structure is as follows :

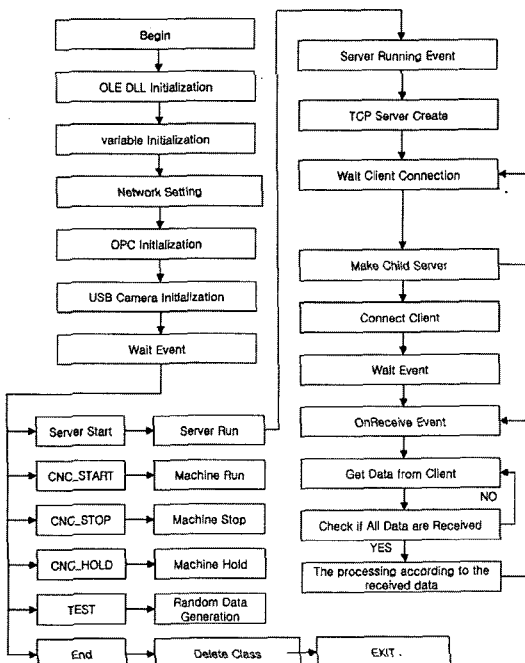- Variable initialization : The variables required in the early stage are initialized.

Fig. 2 The structure of the server contents by using the OPC method

- Network Internet Protocol (IP) check : The IP address and port number of the registered server are read. A new IP address and port number can be registered and all registered IP addresses are displayed in a list box of a mobile terminal, such as a PDA phone. If one of the IP addresses on the list is selected, the terminal is connected to the server contents.

- Network connection : The connection to the server contents is attempted. If the initial connection is successful, the basic monitoring data from the server is automatically transferred. The server then waits for the client user's control command event.

- Disconnection : The connection is separated.

- Start/stop/hold reservation : To execute a reserved command, the commands are executed in reserved time if the control data with a set reserved time is transferred.

- Machine status check : The machine status data is checked just once.

- Automatic machine status check : The machine status data is continuously checked.

- Camera image receipt : If the USB camera is set up, the image data (Quarter Common Inter-mediate Format (QCIF) 176×144 size) is transferred and displayed on the mobile terminal.

- Screen (monitor) image receipt : The screen shot of the CNC is transferred and displayed in the mobile terminal.

- Screen image position setting : The resolution of the CNC screen is high (generally over 640×480), and the data size of the screen image is much bigger than the control command and monitoring data. Therefore, the Region Of Interest (ROI) of the screen is generally monitored by selecting the ROI.

- Screen image size definition : The received image size is defined by the client user. The size of the CNC screen can be determined through the early communication in the initialization process of the client contents.

- Image receive auto : The image of the USB camera, or of the CNC screen, is continuously received from the server side.

- Close : The client contents module is closed.

4. The Interface Between CNC Machine and Developed Application Module

Applied machine tools have an open CNC architecture. The structure of the CNC architecture is shown in Fig. 4. The open architecture of the CNC map includes the interconnected signals X, Y, G, F and R, where X is the input signal, Y is the output signal of the Programming Logical Controller (PLC), G is the input signal from the PLC to the CNC, F is the input signal from the CNC to the PLC, and R is the relay signal. By accessing the shared CNC memory and alarm log data, the interface between the server contents and the CNC domain is performed on the same platform and the server contents can be executed as an internal function of the CNC domain. The server contents can extract the key data required for monitoring from the CNC and PLC. Moreover, for remote control, the server contents can apply control commands that have been transferred from the client contents to the CNC and PLC domains.
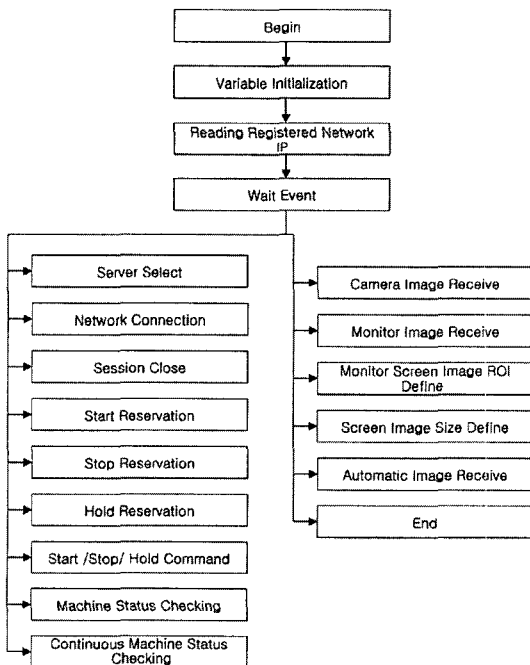

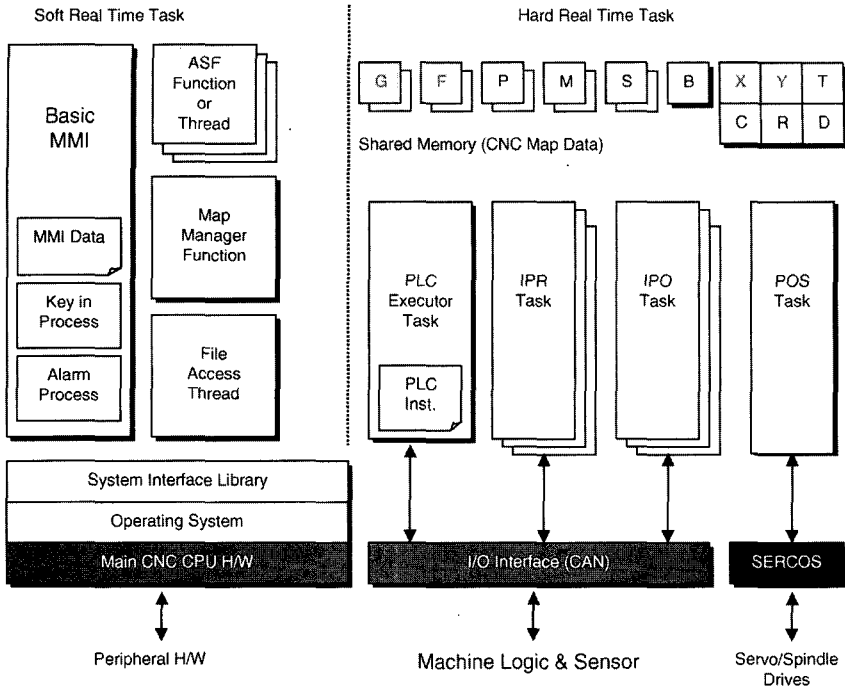**Fig. 3** The structure of the client contents

Fig. 4 The structure of the CNC machine with an open architecture controller
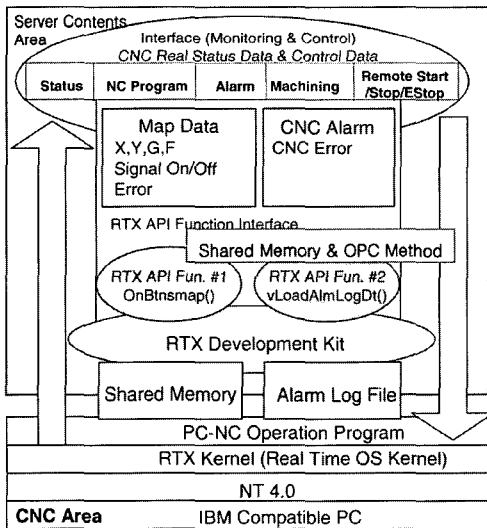

Fig. 5 The interface structure between the server contents and the CNC domain

Figure 5 explains the interface process between the server contents and the CNC domain. The purpose of the interface process is to acquire information on the status of the real machine, such as the machine running state, the used NC pro-

gram name, the current alarm information and the position of the stage axes. The purpose of the interface process is also to control the CNC machine by using the control command transferred from the client side.

The CNC generally has an RTX for multitasking in an infra platform. Hence, the API functions supported by the RTX are used to access the memory map and alarm data of the CNC domain. The parametric values of the API functions are mutually referred and transmitted by the OPC.

5. System Function and Test

The key functions of our system are as follows :

- Random status generation and real machine status acquisition
- Screen capture by selection of the ROI and the captured image transmission
- USB camera capture and the captured image transmission
- Transmission of the real machine status and machining information
- Transmission and execution of the remote

control command.

The key functions are explained as follows :

- The function of generating the random status is designed as a communication test between the server contents and the CNC when data cannot be acquired from the real machine. The OPC method in the server contents acquires the real data from the machine.

- The function of the screen capture is to capture the CNC screen when the capture command is transferred from the client to the server contents. When the control command for the capture is received, the parameters for capturing the size and position are concurrently received. The server contents captures the CNC screen according to the given size and position. After the capture, the captured image is compressed to a Joint Photography Experts Group (JPEG) image and transmitted to the client monitor. The default size of the JPEG image is fixed at 176 QCIF for quick transmission. If necessary, the client can change the size.

- The function of the USB camera capture is to aid the monitoring of the work pieces, peripheral equipment and workplace circumstances.

- The real machine status and machining in-

formation are transmitted at the client's request. The transmitted data include the current machine status, the alarm status, information on the machining NC program, information on the stage axes, and the feed status.

- The remote control commands are performed in the server contents by the control commands received from the client contents.

A detailed explanation of the key functions is given in the next two sections, with respect to both the sever and the client.

5.1　The function of the server contents

As shown in Fig. 6, the main frame of the server contents comprises the following :

- "1. Server Start" is the button that starts the server. If the server starts successfully, the icon "3. Operating Status" is on.

- "2. Set Network Conditions" is the menu button for setting the network environment. This menu normally selected before the server is started. The maximum packet size, the packet delay time and port number are set in a pop-up window of the menu. The packet size refers to the size of the data (bytes) in a single transmission. The packet delay time refers to the delay between
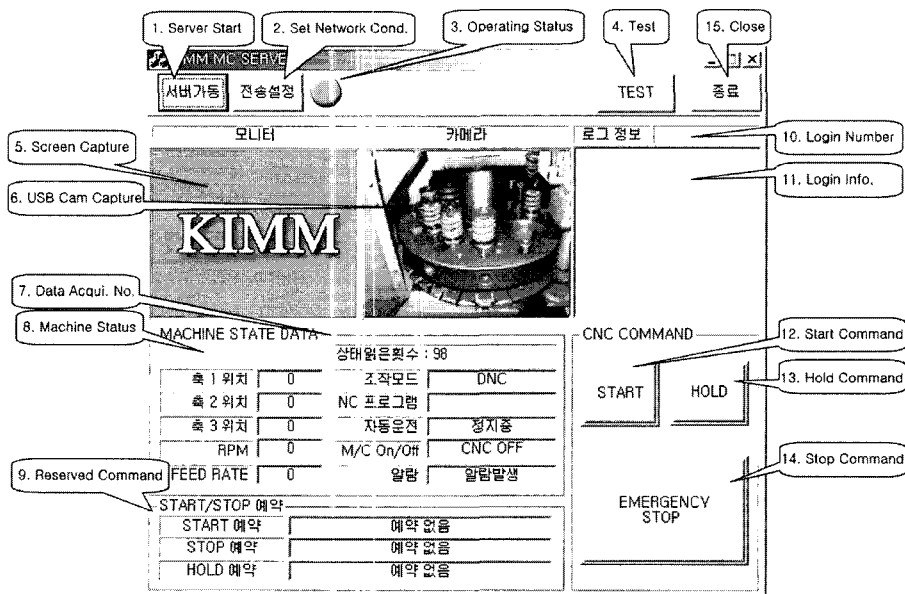
Fig. 6　The main frame of server contents

transmission. These network conditions were set to guarantee a secure data transmission. The port number is the port through which data is transmitted between the server and the client.

- "3. Operating Status" indicates the successful start of the server contents.

- "4. Test" refers to the use of random data to test the data communication between the server contents and the client in a failed interface with the CNC domain.

- "5. Screen Capture" displays the machine CNC screen to be transmitted to the client contents.

- "6. USB Camera Capture" displays the USB camera image which is to be transmitted to the client contents.

- "7. Data Acquisition Number" displays the frequency at which data is acquired from the real machine.

- "8. Machine Status" displays the acquired information on the machine status. The displayed machine status includes the position of each axis, the RPM, the feed rate, the operation the name of the NC program, the machining status, the machine on/off information and the alarm information.

- "9. Reserved Command" displays the control command reserved by the client. The reserved

commands are the commands for starting, stopping and holding the machine.

- "10. Login Number" displays the client number connected to the server contents.

- "11. Login Information" displays which client is connected and when the session is disconnected.

- "12. Start" starts the machine.

- "13. Hold" pauses the machine.

- "14. Stop" stops the machine.

- "15. Close" finishes the server contents.

5.2   The function of the client contents

The client contents was implemented into a PDA, and used embedded visual c++ for the programming. The functions of the client contents are as follows : connecting to the server contents, monitoring the data acquisition from the server side, sending the control commands to the server side, acquiring image data from the server side, and various other related functions.

As shown in Fig. 7, the main frame of the client contents comprises the following :

- "1. Connect" connects the user to the server contents. Before attempting the connection, the server must be selected in "2. List Box".
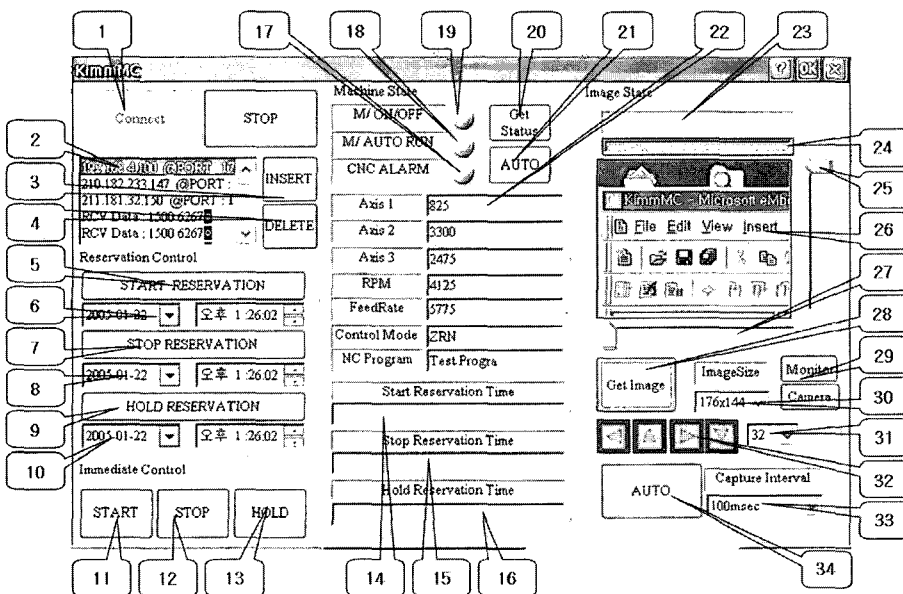

Fig. 7   The main frame of the client contents

- In the "2. List Box" window, the IP addresses of the registered server are displayed. The address format is "xxx.xxx.xxx.xxx @PORT : yyyy," where "xxx" is the IP address and "yyyy" is the port number.

- "3. Insert" opens a pop-up window for registering the IP address and server number.

- "4. *Delete*" *deletes the IP address and port* number in the "2. List Box" window.

- "5. Start Reservation" sends a command to the server side the control that remotely starts the machine in reserved time via the "6. Start Time Reservation" combo box.

- "6. Start Time Reservation" selects the time for the reserved start.

- "7. Stop Reservation" sends the control command to the server side to remotely stop the machine in reserved time via the "8. Stop Time Reservation" combo box.

- "8. Stop Time Reservation" selects the time for the reserved stop.

- "9. Hold Reservation" sends the control command to the server side to remotely pause the machine in reserved time via the "10. Hold Time Reservation" combo box.

- "10. Hold Time Reservation" selects the time for the reserved hold.

- "11. Start" sends the control command to the server side to remotely and immediately start the machine.

- "12. Stop" sends the control command to the server side to remotely and immediately stop the machine.

- "13. Hold" sends the control command to the server side to remotely and immediately pause the machine.

- "14. Start Reservation Time" displays the reserved starting time.

- "15. Stop Reservation Time" displays the reserved stopping time.

- "16. Hold Reservation Time" displays the reserved pausing time.

- "17. Machine On/Off" displays information acquired from the server side on the machine's on/off status.

- "18. Machine Auto Running" displays data acquired from the server side on the machine

running status.

- "19. CNC Alarm" displays data acquired from the server side on the machine alarm status.

- "20. Get State" requests data from the server side on the machine status.

- "21. Auto" continuously requests data from the server side on the machine status.

- "22" displays the data acquired from the server side, such as the RPM, the feed rate, the control mode, and the NC program information.

- "23" displays data acquired from the server on the start position of the screen.

- "24" displays the receiving status of the CNC screen image in transmission.

- "25 and 27" set the start position of the received image. The setting values are displayed in the area of "23".

- "26" displays the received image.

- "28" requests the image from the server side.

- "29" selects whether the image to be received comes from the CNC screen or the USB camera.

- "30" selects the size of the received image.

- "31" selects the step used in "32".

- "32" refers to the control buttons for moving (in four directions) the position of the ROI by the step in "31". The control buttons are useful for searching the ROI in a CNC of a remote site.

- "33" selects the interval for receiving an image transferred from the server side.

5.3 Efficiency test

As shown in Fig. 8, a three-axis milling machine with an open CNC architecture was used for an efficiency test on the target machine. The stage of the open CNC machine had a spindle and the three axes X, Y, and Z.

The scenario for the efficiency test is as follows :

- Machine monitoring : Initial monitoring of the current status of the machine, such as the running and stopping status and the alarm status.

- Machine operating : Automatic operating by the NC program in the model plant.

- Changed status monitoring : Remote monitoring, via a PDA phone, of the running status, the selected name of the NC program, the current
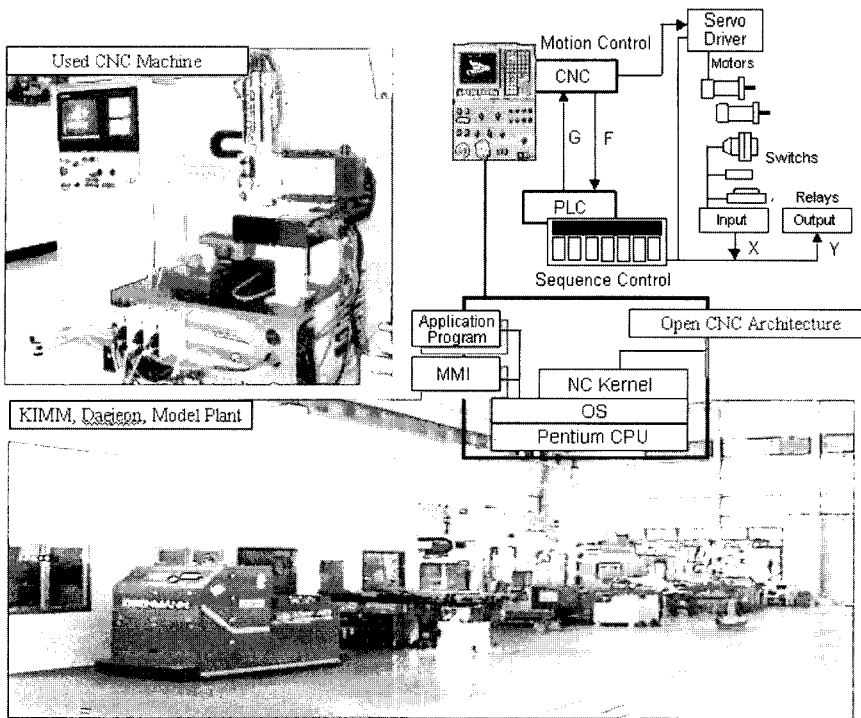
Fig. 8 The CNC machine and its architecture for the efficiency test

alarm status, and the position of each axis of the stage.

- Remote holding command : Remote control via an IMT2000 network or wireless LAN for holding and pausing the current running machine.

- Remote restart command : Remote control via an IMT2000 network or wireless LAN for restarting the current running machine.

- Remote stop command : Remote control via an IMT2000 network or wireless LAN for stopping the current running machine.

- Current status monitoring : Remote monitoring, via a PDA phone, of the current status of the machine status re the stop or emergency stop mode.

- Remote reserved start : Remote control for starting the machine at the reserved time after the reserved time has been set via a PDA phone.

- Status monitoring : Remote monitoring, via a PDA phone, of the machine status re the success of the reserved start.

- Remote reserved stop : Remote control for stopping the machine at the reserved time after the reserved time has been set via a PDA phone.

- Status monitoring : Remote monitoring, via a PDA phone, of the machine status re the success of the reserved stop.

- Bidirectional communication test : Confirmation, in an emergency, of automatic notification to registered mobile terminals, such as general cell phones.

During the test, the machine status and key data of the CNC machines in the wired and wireless environments of an IMT2000 network and a wireless LAN were monitored, and the results showed that a CNC machine could be controlled from anywhere and at anytime. From the test results of the model plant at the Korea Institute of Machinery and Materials, the operating efficiency were improved by more than 50 percent with the added advantage of flexible controls and quick management in emergencies.

6. Conclusions

Our study on the ubiquitous-based mobile controlling and monitoring of CNC machines for

u-machines was successful. A PDA phone was used for the terminal because of its mobility and screen extensibility. The software for the WinCE. Net operating system was designed with an embedded programming language, thereby solving the license restriction of the phone service company such as Qualcomm Co., Ltd., for up-loading developed software contents to a general cell phone.

The communication between the developed contents, such as the server contents and client contents, was performed via a wireless LAN as well as a wireless telephone network. Hence, CNC machines can be controlled and monitored in real time, from anywhere and at anytime. Moreover, the prompt notification from CNC machines to mobile terminals, such as a cellular phone or PDA phone, can be automatically realized in an emergency.

The results of this study are summarized as follows :

- By using the OPC method and sharing the CNC memory, real-time data acquisition of the machine status was enabled in the position of each axis of the stage, the NC program, the alarm information and the machining status.

- To ensure that the monitoring data could be accessed on a PDA phone, the acquired monitoring data was enabled to be transmitted in real time to the client side through an IMT2000 network or a wireless LAN.

- By selecting the ROI, the CNC screen of the machine was enabled to be captured and tra nsmitted.

- The capture and transmission of USB camera images was enabled.

- Real-time remote control and reserved remote control of a CNC machine was enabled via a PDA phone.

- For emergencies, registered mobile terminals, such as a PDA phone or cell phones, were enabled to be notified remotely and automatically without a client request.

- In a model plant test, the operating efficiency was improved by more than 50 percent, with the added advantage of flexible controls and quick

management in an emergency.

In short, by implementing the mobile controlling and monitoring technology in manufacturing system with an efficient approach and system architecture without a special licence restriction, the foundation for the development of u-machines has been laid.

Acknowledgments

References

Erol, N. A., Altintas, Y. and Ito, M. R., 2000, "Open System Architecture Modular Tool Kit for Motion and Machining Process Control," *IEEE/ ASME Transactions on Mechatronics*, Vol. 5, No. 3, pp. 281~291.

Jung, M. S., Park, H. S. and Kim, B. S., 2001, "Architecture of Web-based Real-Time Monitoring System," *Journal of ICASE*, Vol. 7, No. 7, pp. 632~639.

Kim, D. H., Kim, S. H. and Koh, K. S., 2005, "A Scheme for an Internet-based Checking Method of Machine-Tools with Variant CNC Architecture," *Journal of Mechanical Science and Technology*, Vol. 19, No. 1, pp. 97~105.

Kim, D. H., Kim, S. H. and Koh, K. S., 2005, "CNC-implemented Fault Diagnosis and Web-based Remote Services," *Journal of Mechanical Science and Technology*, Vol. 19, No. 5, pp. 1095~ 1106.

Kim, S. H., 2004, "Ubiquitous — Machine," *Proceedings of the KSPE Spring Annual Meeting*, pp. 742~745.

Kim, S. H., Kim, D. H. and Park, K. T., 1999, "Open Manufacturing System Using MMS Service and Object Oriented Manufacturing Devices (1st Report)," *Journal of KSPE*, Vol. 16, No. 5, pp. 91~97.

Kim, S. H., Kim, D. H. and Park, K. T., 2000, "Open Manufacturing System Using MMS Service and Object oriented Manufacturing Devices (2nd Report)," *Journal of KSPE*, Vol. 17, No.

10, pp. 41~48.

Lee, D. J., Kim, S. H. and Ahn, J. H., 2004, "Breakage Detection of Small-Diameter Tap Using Vision System in High-Speed Tapping Machine with Open Architecture Controller," *KSME International Journal*, Vol. 18, No. 7, pp. 1055~1061.

Lee, S. Y., Kim, J. W. and Lee, J. M., 2003, "Chatter Analysis of a Parallel Mechanism-based Universal Machining Center," *KSME International Journal*, Vol. 17, No. 5, pp. 691~697.

Oldknow, K. D. and Yellowley, I., 2001, "Design, Implementation and Validation of a System for the Dynamic Reconfiguration of Open Architecture Machine Tool Controls," *International Journal of Machine Tools & Manufacture*, Vol. 41, pp. 795~808.

Ong, S. K., An, N. and Nee, A. Y. C., 2001, "Web-based Fault Diagnostic and Learning System," *International Journal of Advanced Manufacturing Technology*, Vol. 18, pp. 502~511.

Rober, S. I. and Shin, Y. C., 2001, "Modeling and Control of CNC Machines Using a PC-based Open Architecture Controller," *Mechatronics*, Vol. 5, No. 4, pp. 401~420.

Tahk, K. M. and Shin, K. H., 2002, "A Study on the Fault Diagnosis of Roller-Shape Using Frequency Analysis of Tension Signals and Artificial Neural Networks Based Approach in a Web Transport System," *KSME International Journal*, Vol. 16, No. 12, pp. 1604~1612.

TurboTek, 2002, Turbo HX-M Reference Manual.

TurboTek, 2001, Operating manual for Turbo HX-M.

Wright, P. K., 1995, "Principles of Open-Architecture Manufacturing," *Journal of Manufacturing Systems*, Vol. 14, No. 3, pp. 187~202.

Yellowley, I. and Pottier, P. R., 1994, "The Integration of Process and Geometry Within an Open Architecture Machine Tool Controller," *International Journal of Machine Tools & Manufacture*, Vol. 34, No. 2, pp. 277~293.