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The framework of a cloud-based CNC system

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Abstract

Machine tool vendors and customers have expectations of the control system of a machine tool being highly scalable, highly adaptable, fault-tolerant, easy to maintain and good protection of process know-how. The current CNC systems are however anything but. This is due to the limitation of conventional CNC's hardware and software. As a possible solution, Control System as a Service (CSaaS) defines a scenario whereby the control system is decoupled from the machine tool and exists in the cloud, so that control of a machine tool becomes a cloud-based service. This gives a machine tool high flexibility and scalability. In this paper, the framework of such a cloud-based CNC system is proposed.

Based on the analysis of the typical tasks of a CNC system, there needs to be a division between the tasks executed in the cloud and those in the local. CSaaS is also responsible for transmitting the motion control data over the Internet, which imposes a new challenge, i.e. the inability of the Internet infrastructure in transmitting data in a timely manner and at the same time error-free. The mechanism of dealing with this issue and the modes of the implementation are also discussed.

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Keywords: CNC system; Cloud manufacturing; CSaaS

1. Introduction

Computer Numerical Control (CNC) machine tools play a vital role in manufacturing industry. As illustrated in Fig.1, after tool-paths are generated by a Computer Aided Manufacturing (CAM) system or a toolpath generator, the interpolator interpolates the toolpaths into setpoints according to the geometry of the workpiece, the machining parameters and kinemics of the machine tool. The motor controller commands the motors or drives according to those setpoints [1]. The algorithm that the interpolator uses is essential to the quality and efficiency of the machining. In the early days, the interpolator is realized by hardware or firmware which is plugged into the socket of the computer and connects to the motor controller by point to point electrical connection. Therefore, the physical distance between the CNC system and the machine tool has to be very short (Fig. 1(a)). In recent years, fieldbus is widely used in automation control including CNC. It is able to transmit large quantity of small packages of data, i.e. setpoints for every control cycle can be transmitted cycle by cycle [2]. So the interpolator could be realized by software, which brings more flexibility and update ability (Fig. 1(b)). Nevertheless, the distance between the control system and the machine tool is still limited by the medium which the fieldbus uses.

Due to the limitation of the hardware and software of CNC system, the control system falls behind the expectation of both machine tool users and the machine tool vendors. On one hand, the machine tool user's expectation is to decrease the investment and increase the operation rate of their machine tools. However, modern control system is not only expensive but also increasingly complicated, which in turns causes high cost on maintenance, commissioning and repair. Nevertheless, the control system's updating ability and expandability are quite limited due to its hardware architecture. It is often that to

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use some particular functionalities users have to update the whole system and always have to pay for the functionalities they do not often use. On the other hand, the high cost restrains the demand of machine tool user for installing new systems or updating old systems. The machine tool vendor expects more possibility to provide affordable services in servicing and maintenance of their products and updating the legacy systems.

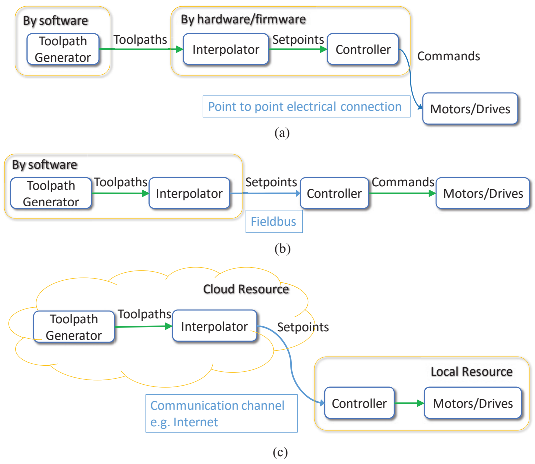

Fig. 1. Evolvement of the CNC system.

Cloud manufacturing is a promising way of organizing manufacturing. In this scenario, the manufacturing resources around the globe are virtualized, distributed and packaged as services [3, 4]. Illustrated in Fig. 1(c), the Control System as a Service (CSaaS) moves the control system from the machine tool itself to the cloud, and the control of a machine then becomes a service [5]. Powerful computational recourses of the cloud can be utilized to realize highly sophisticated algorisms. The control service can be flexible and be updated easily. The operational information of the machine tool can be gathered and analysed by the cloud to properly configure the machine tool. In addition, current CNC system uses G/M code [6] as the part programme, which explicitly expresses the process know-hows i.e. toolpaths and the corresponding cutting parameters. In the cloud manufacturing environment, that means the process know-hows will be exposed to other parties. Anyone who has the G/M code can easily extract the process know-hows or even duplicate the workpiece. By contrast, CSaaS transmits the setpoint rather than part programme to the machine tool, so the process know-hows are well protected.

2. Cloud-based CNC system in the user's point of view

The machine tool and its control system have become more and more sophisticated, and functionalities and algorithms are increasingly advanced. The user i.e. the operator uses the Human Machine Interface (HMI), switches and buttons to operate the machine. Each control system of the machine tool runs independently and is an "information isolated island". In the cloud manufacturing environment, the control of the machine is offered in the form of CSaaS. The user of the CSaaS is not limited to the operator of the machine but also includes the supervisory of the machine, the machine tool vendor and even the end-user of the final product.

2.1. The machine tool operator

The HMI has been evolving to provide a more comprehensive, straightforward and visualized information to the operator of the machine tool. However, the expense of the hardware and the software of the HMI escalates inevitably. Apart from that, the implementation and the information displayed of HMI are closely related to the hardware of the machine tool, making it hard or even impossible to update or upgrade.

The Augmented Reality (AR) or Virtual Reality (VR) is a promising technology for the future HMI, which will provide a revolutionary way of interacting between the human and the machine. It is not convenient for the operator to use individualized virtual environment for each machine tool. The current way of having an individual graphic display close to the machine cannot fit the future development.

The CSaaS is able to provide a universal way of accessing the HMI to variety of machines. The machine operator uses a HMI client, which is either a programme in a thin client, an Internet browser in a tablet or even an AR gaggle, to interact with the machine. The specific machine will be identified by the RFID tag, the barcode or the geographic position, and the interface for the particular machine can be displayed accordingly.

2.2. The shop floor supervisory

Current machine tools have very limited connectivity with the MES system and other shop floor management systems. Mostly logging the information to the system relies on the manual input which is neither efficient nor timely and costs additional labour.

In the CSaaS environment, all the machine tools of a shop floor are connected to the cloud. Information is gathered and uploaded to the cloud. The supervisory of the shop floor can have a centralized and comprehensive access to the information on the status of each machining job and each machine tool. By having a video stream of the machine tool's work space, the supervisory can have an intuitive view of the progress of the machining job.

2.3. The machine tool vendor

The CSaaS turns the control system, in the sense of a part of the product (the machine tool), into a service. The user can use the control system under a pay-per-use pattern which will decrease the initial investment of the control system. Highly power-consuming algorithms can be applied, and the updating and upgrading is merely a change of the version of the software in the cloud. The machine tool vendor will be able to collect various information about the machine tool such as the precision, error, vibration, deformation and etc. by using a variety of sensors during the operation. This statistical information can afterwards be used to assist the proactive maintenance and the remote diagnosis.

Furthermore, by connected to the CSaaS system, every machine tool becomes the source of big data, which provides new possibilities for the value-added services. Those process-related big data can be further analysed to form the knowledge, which can be used in three possible scenarios, (1) optimizing the design and the adaptive control of the machine, (2) optimizing the design and process planning of the workpiece and (3) matching the workpiece with specific GD&T to the appropriate machine tool.

2.4. The end-user of the product

In the mass production, there is no need for the end-user of the product to be involved in the production phase. Also there is no way for the current control system to provide the progress of the machining to the end-user. However, for the customized product, the end-user of the product profoundly participates the design or even is the designer of the product. The end-user of the product would like a deeper involvement in the production process. Maintaining all machining information, the CSaaS is capable of providing the video stream of the machining progress to the end-user.

3. Typical tasks of a CNC system

The task mentioned here pertains to the work of realizing various functionality of a CNC system. The tasks that a CNC system performs can generally be divided into two categories, realtime tasks and non-realtime tasks. The former requires that the system finishes each step of the work strictly within a pre-defined time interval, i.e. the control cycle.

3.1. Realtime tasks

One type of realtime tasks are related to providing the pulses to the motor drives and the command of other pieces of equipment and receiving and reacting to the feedback of the motor driver and the signal from sensors in every control cycle.

1. Interpolation.

The setpoints generated by the interpolator must be transmitted timely to the motor controller.

2. Soft PLC.

PLC takes charge of managing and controlling the input / output (IO). Devices, equipment and sensors working in the on-off pattern are connected to the IO such as the turret, the tool magazine, the chuck, the lubricant pump, the lighting system, the indicator, the safety interlock and other pneumatic and hydraulic devices. Those IOs usually work with the motors, and the status of the IOs are refreshed in every control cycle.

3. Monitoring.

The feedback from the encoder which is either absolute or incremental is read and transmitted to the CNC system and compared with the theoretical value. The comparison is performed every cycle and the error is compensated in the next cycles. Other equipment and sensors will provide the status information and some specific information e.g. tool condition. Some events such as the change of the status and the condition need immediate reaction.

4. On-machine inspection.

Touch probe may be used to perform on-machine inspection. The touch probe mounted onto the spindle triggers a signal when touching an object. The interpolator is involved by interpolating the inspection toolpath to reach the probe to the certain surface of the workpiece. On the moment of the touch signal, the reading of the encoder is obtained to indicate the current position of the probe.

5. Fieldbus communication.

The fieldbus is the information backbone which connects the CNC system with the motor drive and the devices. The task related with the fieldbus communication needs higher priority than other tasks.

3.2. Non-realtime tasks

Non-realtime tasks incorporate Human Machine Interface (HMI), part programme interpreting, cutting tool management and toolpath generation. Also included are the communications with other systems such as the ERP and the knowledge base.

One type of information being displayed by HMI is machine tool related information consisting of axis readings, status, warning of the components and devices and etc. Other information is related to machining tasks such as the text of the G/M code, the treeview of STEP-NC file, 3D display of the workpiece and possibly the simulation of the machining. The HMI does not have to be a realtime task simply because people's eyes are limited in refresh time. The delay in a small extend is acceptable because the operator only cares about the final axes reading when the machine tool stops.

Other tasks are performed either before the machining, for instance accepting the machining tasks, interpreting the part programme and toolpath generation if the part programme is in the STEP-NC format, or after machining, e.g. updating the information of the tool life, updating the status of the machining task and logging the workpiece related information such as the inspection result. These tasks do not require a realtime performance.

4. The framework of the cloud-based CNC system

CSaaS system introduces new challenges to the design of the system because of the inability of the IT infrastructure. Communication over the Internet will encounter delay and errors such as package loss, sequence error, package repetition and transmission interruption. Based on the analysis in Section 3, not all tasks can be executed in the cloud without affecting the functionality and the performance of the control system. The difficulty of relocating a certain task varies depending on whether it is a realtime task or a non-realtime task. Non-realtime tasks are easier to be servicelized and will be executed in the cloud, however realtime tasks are harder to do so and will mostly remain at the local. The framework of the cloud-based CNC system is illustrated in Fig. 2.

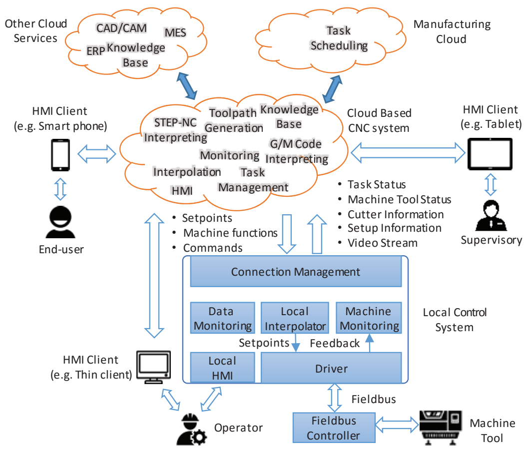

Fig. 2. The framework of the proposed CSaaS system.

Machine tools connected to the cloud are treated as the local resource. The machining jobs are scheduled and distributed among the connected machine tools considering their capability and availability. If it is a STEP-NC part programme, the cloud will generate the toolpath from the STEP-NC part programme. During the toolpath generation process the offline optimization such as the cutter selection, resequencing the workingsteps, and the cutting parameter can be performed with the help of the knowledge base of this CSaaS system or other optimization service, such as the cloud-based adaptive process planning service [7]. The HMI is also provided by the cloud which is able to take the advantages of new technologies e.g. augmented reality or mixed reality and provide new services [8].

If no adaptive control is involved, the interpolator generates the setpoints independent of the feedback control of the machine tool. It is the local control system's responsibility to make sure that the axes follow the setpoints precisely. If the setpoints can be received by the local control system without error, the machining can be finished correctly.

In the local control system, the connection management takes charge of managing the Internet connection between the cloud and local. Data monitoring is responsible for observing the data received and dealing with any transmission error. The setpoints will be fed to drives and be transformed into the pulse command which is finally transmitted through fieldbus and executed by the motors. The feedback from the encoder will be used by machine monitoring module. Combining the information from other sensors, the machine monitoring module will provide the status of the machining process and the machine tool. Although the HMI is provided by the cloud, in the local control system there is still a simple HMI displaying basic information for the operator to control the machine tool in case that the cloud service is not available. The local interpolator is responsible firstly for the interpolation of the simple path for setting up the workpiece and the machine and secondly for dealing with transmission error which will be discussed in Section 5.2.

The information transmitted from the local control system to the cloud includes current axis positions, the setup information and cutter information, which will be used when the toolpaths are generated. The progress of the machining tasks and the status of the machine tool e.g. operation status and warning information and etc. will be reported to the cloud. Apart from that, a video stream of the work space is delivered to the cloud for the supervisory and the end-user of the product to observe the machining process.

The security issue is among the concerns of the user of the cloud service, which is an important topic in the area of cloud computing research [9]. In particular, for the proposed cloud-based control system, the authentication of the server and the client, sensitive data protection and secure communication between the server and the client are the examples of the security concerns. There exist many technologies as the possible solutions for those issues such as certificate-based authentication, asymmetric and symmetric cryptography, IPSec and SSL.

5. Additional requirements on the data transmission

CSaaS introduces additional requirements on the data transmission over the Internet between the cloud-based control system and the local control system.

5.1. Network protocols for the CSaaS

Every computer network follows the ISO-Open System Interconnection (ISO-OSI) model [10]. The realtime Ethernet is capable of transmitting the data in the time-deterministic manner. To achieve the realtime performance, the mechanism in Layers 2-3 are modified [11]. However, in the cloud manufacturing environment, the data packet needs to travel through the Internet across countries by different Internet service providers' networks using different technologies, e.g. fibre, xDSL and coaxial cable. Those infrastructures are in different architectures in Layer 1 and Layer 2 of OSI model. The data packet of realtime Ethernet cannot travel across the boundary between WANs, LANs and sub-networks where variety kinds of network infrastructures e.g. hubs, repeaters, switches, routers, firewalls and etc. are implemented. To make data transmission over the Internet possible, no modification to Layers 1-3 of OSI model is allowed [12]. In addition, to ensure that the data packet can be transferred freely through firewalls, only standardized protocols in Layer 4 of OSI model should be used.

Table 1. The ISO-OSI model.

Layer	Data Unit	Example	Device
7. Application	Data	HTTP, FTP	
6. Presentation	Data		
5. Session	Data		
4. Transport	Segments	TCP, UDP	
3. Network	Packet/Datagram	IPv4, IPv6	Router
2. Data link	Bit/Frame	PPP, IEEE802.2	Switch
1. Physical	Bit	DSL, USB	Hub

TCP and UDP protocols are the dominant Layer 4 protocols [13]. The TCP protocol maintains a connection between the sender and the receiver and is able to deliver reliable packet transmission. It has built-in error detection, flow and congestion control to guarantee the quality of service (QoS). When the bandwidth is low or the network is in congestion, those mechanisms will induce long delay. The UDP protocol is connection-less and does not employ reliability mechanism, and generally speaking the delay is much smaller than that of the TCP protocol. Applications employing UDP protocol will either be tolerant for transmission errors or employ mechanism to dealing with the errors. Based on the experiment conducted by Schlechtendahl et.al, the delay of using TCP protocol to transmit machine control data between Germany and New Zealand is unstable and can be up to several hundreds or even thousands of seconds. However, transmitting data using UDP protocol suffered data loss [14]. Extension on UDP protocol has been developed by researchers to realize a reliable UDP by applying some of the QoS mechanism, however, the consequence is that the delay will become longer.

5.2. The type of information

There are three types of information being transmitted between the cloud control system and the local control system.

1. Setpoints

Transmitting the setpoints places additional challenges to the system considering that the interpolation is traditionally a realtime task and that the Internet is incapable of transmitting realtime data through the Internet.

As the motion control data are generated according to the geometry, the machining parameters and especially the dynamics of the machine tool, the machine tool has to follow every setpoint one by one, or the machine tool may travel beyond the tolerance or exceed the dynamics limitation.

Cloud-based control system has its own characteristics of transmitting machine tool control data.

- The packet is in small size but in large number [14].
- Integrity of the machine control data is essential. Any transmission error will deteriorate the machining quality and may even cause damage to the machine and the cutter.
- The machine tool cannot move beyond its dynamic property. The time needed for stopping the machine tool depends on the feedrate, the maximum acceleration and the toolpath it is following.
- If no adaptive control is involved, the interpolator generates the setpoints independent with the feedback control of the machine tool. The cloud only requires the machine tool to follow the setpoint precisely but not necessarily in a prompt fashion.

Based on the analysis, the TCP and the TCP-based protocols are capable of transmitting the setpoints because they can transmit large quantity of data through the Internet and guarantees no transmission error. However, the system needs to deal with the long delay and the transmission interruption.

The mechanism of dealing with the long delay is demonstrated in Fig. 3. A First-In-First-Out (FIFO) buffer is established, and the critical buffer is a fraction of the FIFO buffer. In a normal routine, when the FIFO buffer is full, the machining task will start. At the same time, the original toolpaths are estimated by curve fitting. If the critical buffer is not full due to the long delay, the system switches to the data starvation routine. In this routine, the local interpolator generates new setpoints to stop the feed following the estimated toolpaths. After the FIFO buffer is filled again, the interpolator restarts the feed and reaches the original feedrate at one of the original setpoints exactly. Then the system switches back to the normal routine.

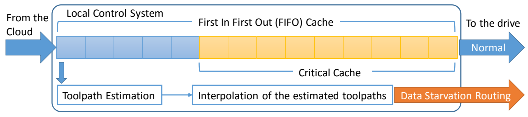

Fig. 3. Dealing with long delay for transmitting the setpoints.

The size of the buffer influences the lead time and has to be reasonable. It is unacceptable that the local control system starts the machining after receives all the setpoints from the cloud. As one buffer stores the data package for one control cycle, the size of the critical buffer is equivalent to the time taken to stop the machine. So, the size of the FIFO and the critical buffer depends on the maximum feedrate of the toolpaths and the maximum acceleration of the machine tool, which can be calculated before the start of the machining.

To validate this mechanism, a prototype system was developed, and the experiment was carried out. The prototype system contains a server application which runs on a virtual PC of Amazon EC2 in the data centre in Oregon, USA and a client application running in a physical PC in Auckland, New Zealand. The server interpolates the toolpath with a 4-millisecond interpolation period, and the generated setpoints were packed into data packages. The package includes an 8-byte serial number and three 8-byte positions of X, Y and Z axes. The minimum required bandwidth was therefore 64 kbps. The data transmission from the server to the client was realized by the TCP socket. As the bandwidth between the server and the client was normally much higher than 64 kbps, to test the mechanism to a greater extend, the Network Emulator of Windows

Toolkit by Microsoft was used to emulate a very harsh network condition in the local PC as follows

- Loss: 10% randomly
- Error: 10% randomly
- Delay: 1-100 ms uniformly distributed
- Bandwidth limit: 28 kbps

The client received the packages and draw a dot for each package on the screen. When the network condition was good i.e. the packages arrived in a timely manner, the blue dot was drawn. If there was a starvation of the package, the client generated new setpoints to safely stop the machine. Those setpoints were in red colour. When new packages were received and the FIFO buffer was filled, the client generates the setpoints to restart and accelerate the machine, which were shown by the dots in green. When the machine finally reached a suitable speed, the original setpoints were used afterwards, which were again illustrated by the blue dots. The maximum acceleration of each axes in each control cycle during the test were calculated and displayed in the user interface.

The screen shot of the client is demonstrated in Fig. 4. As the network condition was deliberately restricted, many stoppings and resumings were discovered. During the whole process, the maximum accelerations were not beyond the limit, which proved that the client can safely stop the machine when the network condition was getting worse i.e. long delay happened and resume the machine when there were sufficient packages in the buffer.

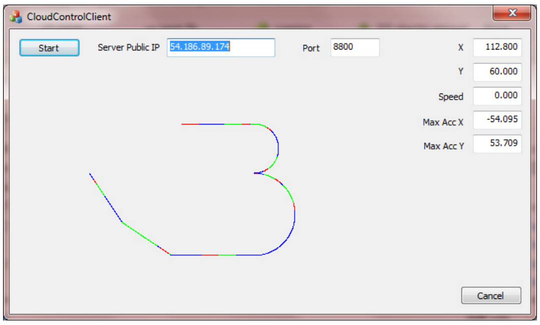

Fig. 4. The client of the prototype system

In other tests when network conditions were not influenced by the Network Emulator, the network condition between the server and the client was good enough that long delays seldom happened. With the development of the ICT technology and the investment of the ICT sector, the network condition is guaranteed to be more capable of transmitting the setpoints over the Internet. The machining controlled by the cloud-based control system will be as smooth as by the current control system at the local. In case that the long delay happens, which will be rare, this communication mechanism as a fault-safe measurement will guarantee the safety of the operator, the machine and the workpiece.

2. Commands

A command can be either from the cloud to the local or from the local to the cloud. Some commands are only the trigger of an operation e.g. starting, pausing and resetting the machining job. Others such as the resetting coordinates may combine a data with the command. When the machine is not in the machining state, the auxiliary equipment is controlled by the cloud CNC system and the IO signal is treated as the command. However, during machining, the IO control should be performed by the local control system, and the IO control logic is received with the setpoint. The transmission of the command should be reliable, because the command will trigger the machining task or the corresponding control logic. Reliable Internet protocols are essential for transmitting the command.

3. Status information

Status information is only used for displaying, monitoring and statistical analysis, and will not be directly used for controlling. Transmission errors within a certain extent are acceptable as the status information is refreshed every cycle. For displaying and monitoring, only the latest information matters, and for the statistical analysis, the algorithm is able to eliminate the abnormal data. The UDP or UDP based protocols are capable of transmitting the status information with a shorter delay and smaller network cost than using TCP or TCP-based protocols.

6. Modes of implementation

Divided by the way the cloud-based CNC system providing the control system service, there are two modes of implementation, the virtual CNC system and the server-client model.

6.1. Virtual CNC system

In the virtual CNC mode, the cloud-based CNC control system operates under a virtual machine in the cloud. The user of the CNC system can access the system by a remote access system such as Remote Desktop and Virtual Network Computing (VNC). The CNC system will be the same as in the local however the buttons of the control panel will be virtualized. By duplicating and configuring the virtual CNC system, more local machine tool can be connected and controlled.

In this mode, the client is of thin-client. The requirement for the computing power can keep as minimum, as all the computational power consuming tasks are executed in the cloud, e.g. 3D rendering in 3D display and simulation. However, the issue of this mode is that the remote access system needs to maintain a constant stream between the virtual CNC machine and the thin-client, which takes a great extent of the bandwidth. Considering that the manipulation of the machine tool mostly happens in the preparation of the machining which only takes a small part of the entire machining process, this part of data transmission is a waste of the bandwidth in the entire machining process. Apart from that, the HMI has to include all the functionality for every role of the user, although the user will have different privileges to access functionalities.

6.2. Server-client model

In the server-client mode, the HMI is the client and runs at the local for the user, while the server operates in the cloud. The server provides functionalities to the client by a set of Application Programming Interface (API). The client programme can operate either in the local device, e.g. terminal or tablet, which is called the native application or in the browser of the device, which is called the Web application. The client and the server for the Web application are called the front-end and back-end, respectively.

There will be different programme / front-end providing different sets of information for different roles of the user. Compared with the virtual CNC system mode, the information transmitted between the server and the client is all related with the manipulation of the CNC system, which save lots of bandwidth.

7. Conclusions

CSaaS turns the control of a machine tool to a service function which brings benefits to the operator of the machine tool, machine tool vendor, shop-floor supervisory and end-user of the product. Non-realtime tasks of the CNC system are executed in the cloud while most of the realtime tasks which require the realtime data transition with the machine tool remains at the local control system due to the inability of the Internet's transmitting data package in the realtime manner. Information exchange between the cloud and the local control system is identified and assigned with proper Internet protocols. A mechanism of transmitting the setpoints using TCP protocol makes it possible that the interpolation is also executed in the cloud. The feed movement of the machine will be stopped safely when long delay occurs and will restart the feed when the subsequent package arrives; this guarantees the safety of the operator, workpiece and machine tool. The cloud-based CNC system has two modes of implementation, the virtual CNC system and the server-client model. The virtual CNC system is easier to deploy; however the server-client model will provide more flexibility and save the network bandwidth.

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