Study on Human-Oriented Interface for CNC Machine Tools*

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This paper deals with fundamental research on the development of human-oriented interface for CNC machine tools which allow workers to feel pride and pleasure in making full use of their ability in manufacturing. As a first step toward human-oriented CNC machine tools, three information feedback channels designed to provide workers with much useful information on machining phenomena have been proposed. They are the machining phenomenon visualizing system (MPVS), the machining vibration display dial (MVDD) and the machining conditions display system (MCDS). These systems have been evaluated by inexperienced and skilled operators of CNC machine tools using the information integration method. The results show that the combination system of MPVS, MVDD and MCDS greatly improves workers' satisfaction in CNC lathe work.

Key Words : Interface, CNC Machine Tool, Turning, Human-Oriented Manufacturing System, Information Integration Method, Machining Phenomenon Visualizing System (MPVS), Satisfaction of Workers, Machining Vibration Display Dial (MVDD), Machining Conditions Display System (MCDS), Feedback Channels

1. Introduction

Ideally, machining conditions should be determined by taking into consideration various factors: an understanding of the machined object's intended application; the relationship between the machining process at hand and the surrounding processes, including product management and the finishing condition of the previous processing stage; and the significance and impact that the process has within the overall process. These matters should be deliberated in view of the actual machining phenomenon, and the decision made in a flexible and careful manner according to the tool, workpiece, machine tool, and working environment. At times it is also necessary to consider such items as the management situation of the plant or corporation, or current manufacturing trends as

parameters within a multivariate system. Yet, in the automatic programming functions or expert systems built into today's CNC machine tools, the machining conditions are determined in a uniform manner based on a static database inputted in the past. These systems do not incorporate the environmental factors stated above, nor optimize machining conditions based on the actual machining phenomenon; besides such software-oriented considerations, they also fail to include hardware-oriented measures concerning the machining environment, such as the self-preparation of specialized tools or chucks.

In the future, the demand for a variety of high-precision products produced in small lots are likely to increase, and these conventional methods for determining machining conditions will become inadequate in terms of product quality or in the ability to make flexible manufacturing responses.

In this paper, we propose a human-oriented CNC machine tool which is based on the concept of human-oriented manufacturing system⁽¹⁾⁻⁽⁵⁾ and in which the CNC programming or CNC machining is not heavily computer- or machine-oriented as in conventional systems; instead, our research focuses on various

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human-oriented interfaces that allow humans to freely intervene with the machine system, so that a "synergistic effect results from the abilities of humans and computers/machines complementing each other."

The CNC machine tool with such a human-oriented interface should have a simple design based on the premise of a complementary coexistence with human capabilities (e.g., creativity, heuristics, intuition, artistry). Hence, in comparison to the fully automatic, unmanned production systems which are currently being developed under full steam, in the human-oriented systems, depreciation and maintenance costs can be kept low, while the occurrence of breakdowns or malfunctions can also be expected to be minimal. Moreover, because these systems take full advantage of human capabilities, their performance can be improved and functions kept evolving without the costly outlay needed for facility expansion. With skillful application, we can expect such CNC machine tools to have a high degree of flexibility, fully capable of meeting demands for the small lot production of diverse, high precision products. The products manufactured using these systems will naturally be of high added value, and we could perhaps expect to see a major transition take place from today's "economy of scale," achieved by selling large volumes of products with marginal unit profit, to an "economy of quality" based on appropriate cost and high added value. This shift to an "economy of quality" may well represent the most effective and realistic future direction in the economic framework towards resolving the various economic, labor, and environmental issues facing today's industrial society.

We introduced in a previous report^{(4),(5)} the machining phenomenon visualizing system (MPVS); in this paper we describe a system of "information feedback channels that convey to the human operator in a easily comprehensible manner the state of the work-piece being machined and the machining conditions," with the MPVS constituting one of those channels. Also reported are the results of an evaluation on the level of satisfaction felt by operators using the "machining conditions display system (MCDS)" and "machining vibration display dial (MVDI)", both of which were developed this year as part of the information channels.

2. Three Information Feedback Channels Proposed

In this study, as part of an effort to develop a human-oriented interface, we propose three new information feedback channels from the machine system to human operator for the case of an CNC lathe. Their functional requirements are as follows: [Functional requirement of the three information

feedback channels]

The various information on the tool (NC machine tool) controlled by an operator and its object (work-piece) shall be presented in a form that can be perceived, recognized and memorized by the human operator at a highly intuitive level.

There are human capabilities that can never be replaced by computers, and these are naturally based on information available to humans. Thus, for the human operator to be able to express those capabilities to the fullest, it is important that the various information concerning the tool being manipulated and its object be perceived and recognized by the operator at a highly intuitive level, and that it be memorized in a state that is most conducive to human performance. Yet, an interface design that considers the assisting or promoting of human intuition — the tacit, cognitive process carried out at the subjective and sensory level — has been conspicuously absent from conventional machine-oriented CNC machine tools. Within the context of developing a human-oriented interface that centers on human capabilities, this study thus proposes, based on the above functional requirement, three new information feedback channels from [object → human], [machine → human], and [information processing unit → human], so as to promote perception, recognition, and memorization on a subjective and sensory level, always keeping as a point of reference the cognitive structure of humans.

These feedback channels are depicted in Fig. 1 as ①, ② and ③, and given below together with the device or system that was specifically developed for the purpose:

① [object → human] : "machining phenomenon visualizing system"

② [machine → human] : "machining vibration display dial"

③ [information processing unit → human] : "machining conditions display system"

Note that channel ④ in the figure represents the conventional flow of information from [information processing unit → human] which usually consists of a

Fig. 1 Proposal of three information feed back channels

digital display. In considering the flow of information from machine system to human as above, the authors realize that there are various other possible feedback channels or devices besides those given here in the selection of channels ①, ② and ③. The selection of these channels in this study and the development of corresponding devices, however, reflect the authors' views that they are the most significant ones. This point will be elaborated upon below when we describe the respective functional requirements for the three feedback channels.

3. Functional requirements of the three information feedback channels and description of devices

3.1 Channel ① [object → human]

This feedback channel has the following two function requirements: [Functional requirement (1) for [object → human]]

In the [object → human] information feedback channel, the information shall be presented in a manner that minimizes the translation work done by humans, and fully utilizes superior human capabilities such as pattern recognition in optimizing the machining conditions.

When confronted by multiple and seemingly incongruous stimuli, humans are thought to project an "active subject" behind those stimuli⁽⁶⁾. The process of making such an "active subject" involves the taking in and ordering of disparate stimuli information onto a common map, that is, a cognitive map. Visual images are the most convenient means of ordering spatial relationships among randomly presented information and so are said to be frequently employed as the basis of such a cognitive map⁽⁷⁾. In other words, the diverse but related pieces of information (visual, auditory, tactile, olfactory, and taste) concerning some object are eventually mapped one by one onto the mind's cognitive map to form a matrix of visual images. Humans form (and manipulate) a mental model of the object based on this cognitive map, and through tacit cognitive processes that follow, eventually form a "true" image of the object.

In this study, we aim to provide from the above standpoint "a matrix into which various pieces of information can be fitted, and which is necessary for constructing a cognitive map as the starting point for all cognitive processes," and to this end define as the first functional requirement for the [object → human] feedback channel the presentation of visual information concerning the object to the operator. In an interface based on visual information, the operator does not have to translate the object's information in digital form into visual images as is the case for

conventional CNC machines, and so a cognitive map of the object is formed intuitively. Moreover, because realistic visual information on any effect that the operator's action had on "reality" can be immediately fed back to the operator, not only is it possible to confirm the results of an operation, enabling the early detection of errors, but the sense of self-esteem that derives from feeling that one is operating on the real world is enhanced⁽⁸⁾. In addition, because the operator is able to observe in real time how changes in the phenomenon take place as the operator manipulates the related parameters, the operator can be expected to learn the underlying principles or laws through inductive reasoning.

Thus, beginning with the in-process optimization of machining conditions through human intervention, such systems provide an environment where superior human capabilities such as pattern recognition are utilized to the fullest.

[Functional requirement (2) for [object → human]]

The presentation of information in functional requirement (1) shall be done within a speed range that is recognizable by humans; that is, a point of contact shall be maintained between the machining speed and human cognitive processing speed.

As we mentioned in functional requirement (1), the system should be designed so that the manner in which information is presented reduces the translation work on the part of humans. There is another important consideration, however, for the [object → human] information channel, and that is the difference in processing speed between humans and machines. Humans are able to accurately recognize an object's condition by tuning and adjusting the sensory organs based on expectations and predictions, and by synchronizing the mental model held in mind with external phenomena⁽⁹⁾. What this means is that, for the object's condition to be recognized accurately, the object's machining speed must fall within the human cognitive processing speed. However, in current CNC machine tools, the machining speed obtained by computer-controlled, automatically operated mechanisms far exceeds the cognitive processing speed attained by humans. In fact, this is a desirable feature of CNC machine tools, in which machining is controlled at speeds that exceed the human processing speed by design. The question then is: is it possible to create an interface which transmits machining information to humans while satisfying functional requirement (1) in a form that neither taxes the cognitive processing speed of humans nor sacrifices the machining speed achieved by today's CNC machine tools?

As one possible solution that satisfies these two functional requirements, we developed for this study

the "machining phenomenon visualizing system", which enables the operator to observe on a TV monitor a semi-static image of the rapidly spinning workpiece undergoing cutting. This device transmits the object as an intuitive visual image that requires no translation, while maintaining a point of contact between the speed of the machining phenomenon and the cognitive processing speed of humans. It enables the operator to clearly grasp various machining phenomena, including the surface conditions of the workpiece or the shape of chips, which had previously been difficult to capture with the naked eye. In the evaluation of the level of satisfaction attained, inexperienced and skilled operators both agreed that the system was highly effective^{(4),(5)}.

3.2 Channel ② [machine → human]

This feedback channel has the following functional requirement.

[Functional requirement for [machine → human]]

In the [machine → human] information feedback channel, information from the machine part that is directly and physically affecting the object shall be presented in a manner such that the "tool is felt as an extension of the human body."

By making the tool a part of the body, humans are able to psychologically "immerse" themselves into the object via the tool⁽⁶⁾. Whereas psychological immersion into the object was achieved for the [object → human] feedback channel employing the sensory organs and at an observational level, for the [machine → human] channel this involves the use of tactile organs at the tactile level. By taking in as an intuitive physical sense (memory) the machining process, which accompanies physical phenomena that can neither be communicated by language or by quantification, the operator is able to construct in his/her mind a more detailed picture of the machining phenomenon. If in CNC lathe work, where it is not possible to touch the object being machined, the information obtained by the tool part directly in contact with the object is fed back to the operator in the form of physical sensory information (tactile sense, sense of contact pressure, sense of vibration, etc.), it becomes possible to narrow the psychological distance between object and operator. We thus make the "tool an extension of the body" and help lead into the subsequent stages of "psychological immersion into the object via the tool" and the "interiorization of the object"⁽⁶⁾. The functional requirement of the [machine → human] information feedback channel is thus to present information on the tool, i.e., the machine part that is effecting direct physical change to the object, in a form that will assist the operator in making the "tool into a body extension."

In turning operation, operators view the two senses of "contact pressure" and "vibration" as important indicators of the machining conditions. While an ideal device should transmit both senses, we developed, as a first step this year, the "machining vibration display dial," which recreates only the tool's cutting vibrations on the operator's control dial.

Figure 2 shows the system schematic of the machining vibration display dial. After the vibration sensor picks up the cutting vibration, this is amplified at the signal processing unit, then converted back into mechanical vibrations on the vibration display dial, which has been installed above the tool jog dial on the CNC lathe's control panel. The construction of the machining vibration display dial is shown in Fig. 3. First the signal from the signal processing unit is fed to a two-pole slip ring of copper, then transmitted via the contact plate and electric wire to the electromagnet. The repulsive and attractive forces created by the electromagnet's pole alternations cause a magnet mounted to the plastic-cup vibration display dial to vibrate, recreating the vibration sense at the operator's fingers. Since the prototype device here

Fig. 2 System schematic of machining vibration display

Fig. 3 Construction of machining vibration display dial

was constructed for the purpose of demonstrating the validity of the "vibration information" transmission channel, as such it has no filter mechanisms for noise signals, such as those caused from movement of the turret or tool post.

We had inexperienced and skilled operators use this system installed in an CNC lathe, and the majority of responses were that the subjects got "the actual feeling and satisfaction that they were cutting with their own hands, and felt they were one with the machine tool." Thus we were able to achieve good results regarding the functional requirement, "tool as body extension," of this feedback channel.

3.3 Channel ③ [information processing unit → human]

This feedback channel has the following functional requirement.

[Functional requirement for [information processing unit → human]]

In the [information processing unit → human] feedback channel, the subjective and sensory information obtained from the channels of [object → human] and [machine → human] shall be refined by the use of objective information.

The purpose of the two information channels described above, [object → human] and [machine → human], was to help recognize and memorize in more detail the object and tool at the subjective, sensory level. The objective of the [information processing unit → human] channel, on the other hand, is to make it possible to refer, confirm, and memorize such subjective sensory information against objective quantitative data of a more universal nature (④ in Fig. 1). If machining precision is not an issue in the worked object, and artistry is the only factor concerned, the operator can perhaps satisfactorily execute a work using only the two information channels ① and ② of Fig. 1. For industrial products, however, where high precision is called for in a variety of ways, by storing (i.e. memorizing) the human subjective senses that are inexpressible in language only after they are collated and matched with objective numerical data of a more universal nature, is it possible to realize an operator intervention operation that is relevant from the viewpoint of production technology. Refining something is to take painstaking care to finish it; it entails the gathering of detailed information on the object.

Humans, however, do not and cannot refine all objects. We refine certain items in a selective manner⁽⁶⁾. Yet, in today's CNC machine tools, the machining condition, i.e. the objective information, is presented in the form of numerous figures on the display, all in identical five- or six-digit format that

keep changing rapidly before our eyes. Under such circumstances, it is next to impossible to collate and compare the sensory information obtained from feedback channels ① and ② with objective numerical data obtained from channel ④ for the purpose of refinement and storage (i.e. memorization). This is why the functional requirement of this feedback channel is to facilitate the refining of sensory information using objective data.

In specific terms, one method would be to take the objective data ④, typically in digital display, and convert them into a form ③ against which it will be easier to refer and memorize the two types of sensory information described above (① and ②), and have them displayed along with the original digital display. By using analog display to give the operator a "bird's-eye view," for instance, and thus bridge the gap between sensory information and objective data (digital numbers), the operator will be able to swiftly respond to matters in need of refining without losing sight of the overall process. Our system displays on the screen bar charts (or "gauges") of the "tool's feed speed" and "main spindle speed," which were selected considering their relevance to the visual image from the machining phenomenon visualizing system.

Figure 4 shows the actual screen configuration. For the screen layout, consideration was given to the operator's natural eye movement, so that the "gauges" indicating the tool's feed speed in the *X*- and *Z*-axis directions are aligned with visual tool movements in the image at screen center. Meanwhile, the spindle speed is displayed to the left of the visual image near the chuck, a natural place to mentally connect the spindle's rotation being transmitted to the workpiece. As auxiliary functions, at the screen's upper left is shown the setting magnification of the tool jog dial used for manual operation, while the upper right corner shows the resultant vector of the tool's feed speed in the *X*- and *Z*-axis directions.

When this system was installed in an CNC lathe and

Fig. 4 Screen configuration

Fig. 5 Evaluation of the interface by inexperienced operators

Fig. 6 Evaluation of the interface by skilled CNC operators

tested by inexperienced and skilled operators of CNC lathes, the typical response was that the subject could "see at a quick glance the overall relationship among multiple machining parameters in reference to the visual image, also making it easier to retain in memory." Thus we received high evaluation marks in regard to "refining the sensory information with the use of objective data."

4. Evaluation of overall satisfaction with the system

4.1 Subject selection and test method

In view of the possible difference in evaluation results among users of different experience levels, testing was done by dividing the subjects into two groups: "inexperienced" (three 4th-year university students who had few prior experience in handling general lathes or CNC lathes) and "skilled" CNC machine tool operators (three skilled operators who have worked with NC machine tools on a daily basis for over 15 years). We had each subject carry out the same machining operation under three cases: 1) conventional CNC lathe; 2) combination of machining phenomenon visualizing system (MPVS) and machining conditions display system (MCDS); and 3) combination of MPVS, MCDS and machining vibration display dial (MVDD). Details of the conditions under which the subjects were tested as well as the method and items of the questionnaire have been reported previously^{(4),(5)}. To check the reliability of the questions in the questionnaire sheet, we employed the internal consistency method (formula 20 by Guder-Richardson); the item with the lowest internal consistency coefficient had a value of 0.85, while we obtained an overall average of 0.91, showing that the results have a sufficiently high reliability.

4.2 Measurement results and observations

Based on the questionnaire results, we computed informations of seven satisfaction factors for the two

groups, inexperienced and skilled CNC operators, using the information integration method^{(2),(3),(10),(11)}. The results are shown in Figs. 5 and 6. Here, a smaller information value indicates that the operator feels a higher degree of satisfaction, which in turn indicates a superior system.

We shall focus here mainly on the general trends. Notice that in Figs. 5 and 6, the information value is drastically reduced across the board when the machining phenomenon visualizing system (MPVS) and machining conditions display system (MCDS) are added to the conventional CNC lathe. When the machining vibration display dial (MVDD) is further added, most of the satisfaction factors exhibit a further decrease in information value. These results show that the addition of MPVS, MCDS, and MVDD to the CNC lathe greatly enhances the operator's sense of pleasure in creating.

5. Conclusion

As part of the development of a human-oriented interface, we proposed securing three new information feedback channels in the conventional CNC lathe from the machine system to human operator. For these feedback channels, we developed the following systems:

- 1) [object → human]: machining phenomenon visualizing system
- 2) [machine → human]: machining vibration display dial
- 3) [information processing unit → human]: machining conditions display system

When we tested these systems and measured the operator's degree of satisfaction using the information integration method, we were able to confirm their effectiveness.

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