Virtual Reality (2002) 6:96–104

Development of a Learning-Training Simulator with Virtual Functions for Lathe Operations

Z. Li[1], H. Qiu[2], Y. Yue[3]

[1]Department of Technology Education, Joetsu University of Education, Joetsu City, Japan; [2]Department of Mechanical Engineering, Faculty of Engineering, Kyushu Sangyo University, Fukuoka City, Japan; [3]Faculty of Creative Arts and Technologies, University of Luton, Luton, UK

Abstract: A learning-training simulator with virtual functions for lathe operations has been developed and tested. The hardware is constructed based on the feed driving system of an actual lathe. A sense of force produced by the built-in direct drive motors provides the operator with some real feeling as if he or she were operating an actual lathe. With multimedia techniques incorporated into the software, the simulator can display animated pictures to demonstrate the rotation of the work-piece and the translation of the cutter on the screen in real time. A computer-controlled speaker generates several types of working sound, mixing the sounds of the lathe spindle rotation and cutting corresponding to the operation status in the progress. Other useful functions, such as warning of a dangerous operation and a demonstration of basic principles of metal cutting, have also been developed within the simulator to increase learning and training efficiency. Most teachers working in industrial high schools and students at Joetsu University of Education who actually operated the simulator gave a good evaluation of the learning effects of the simulator.

Keywords: Lathe; Machining Operations; Simulator; Skill Training; Virtual Reality

Introduction

Virtual Reality (VR), especially simulation technology, is becoming increasingly popular for a wide range of applications [1]. The technology allows construction of physical environments that are representative, detailed and realistic. Although the entertainment industry has attracted the most interest, VR has found application in other sectors such as education and training [2] for areas including medicine [3], construction [4] and engineering [5–8].

One typical application in engineering education and training is to help a beginner acquire the operating skills of a complex machine safely and efficiently. Simulation technology is an economical and effective way for beginners to acquire some basic operating skills using a simulator in the first stages of training, especially when there is a danger or high cost in training with an actual machine. For example, it is possible for a trainee to obtain an aeroplane pilot's qualification if the trainee passes the training courses with specific flight simulators, although he or she may have little actual experience in plane operations [9].

For practical courses using conventional manual machine tools such as a lathe, it is the curriculum generally requires students to learn a basic knowledge of metal cutting or operating skills for machine tools, in industrial high schools, vocational training schools, technical colleges and engineering faculties of universities. There is much evidence that such a practical education is necessary and indispensable to technician training even now. In a turning job with a lathe, the operator handles the lathe based on sensory information, harmonising the sight, force, hearing and touch. A considerable amount of experience and time is required to master the operating skills of a lathe. Further, a mistake in operation may result in damage to the machine or an injury. Thus, it is important that correct and safe operations are followed, and the operator is immediately provided with a warning message and operational safety information when a dangerous action is performed during a beginner's training sessions. As described above, from both safety and cost points of view, it is considered an efficient method of learning and training for a beginner to acquire basic skills and safety procedures with a simulator before operating an actual machine.

So far, there have been several research reports on the provision of training for machine tool use with simulators [10–13]. However, the simulators used in these applications were developed to examine the efficiency and fatigue of work in terms of ergonomics. Therefore, they are not suitable for general learning or training courses for machine tool operation skills.

In this research, a training simulator of lathe operations was developed for technical education courses in industrial high schools, vocational schools, technical colleges and engineering faculties of universities. The simulator has virtual functions such as a sense of sight, force, hearing and touch. It can provide the operator, in real-time, with some real operational feeling, as if he or she were operating an actual lathe. In the next section, the hardware and software, together with the main functions of the simulator, are described. The important techniques used to implement the virtual functions for the senses of force, sight and hearing are further explained in Sections 3–5, respectively. Evaluation results for the learning effects of the simulator from teachers working in industrial high schools and students at Joetsu University of Education who have operated the simulator are shown in Section 6. Finally, the main functions and characteristics of the simulator are summarised in Section 7.

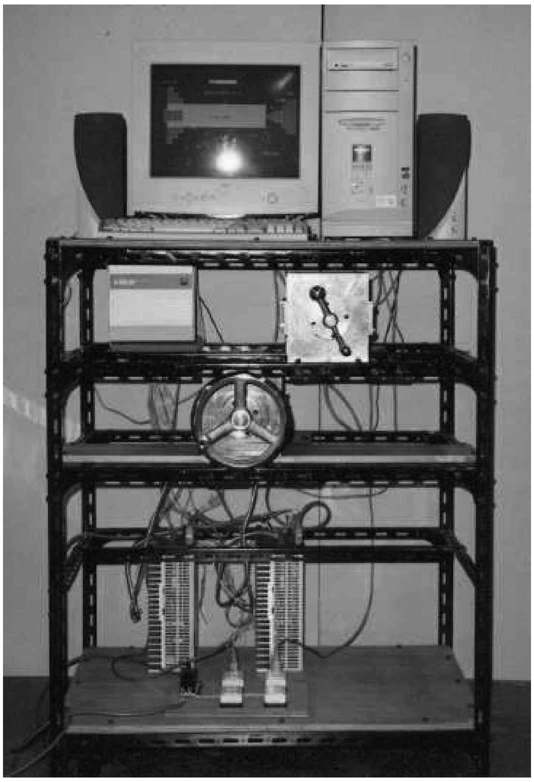

Fig. 1. Learning-training simulator for lathe operations.

Systematic Outline of the Simulator

Hardware Construction

Figure 1 shows the learning-training simulator for lathe operations. The hardware of the simulator is designed based on the feed driving system of a Takisawa TSL-550D high-speed lathe. The operation handles fixed on the frame are set at the same heights and positions as the feed handles of the actual lathe. The hardware, outlined in Fig. 2, consists of a display screen providing the visual information, two Direct Drive (DD) motors producing the sense of force that the operator can feel by operating the handles, and a Frequency Modulation (FM) sound source connected to a speaker generating audio information, such as cutting sounds. When the handle for the longitudinal or transverse feed is turned, the built-in rotary encoder of the motor which is directly connected to the handle shaft detects the rotation angle of the handle. The signal of the rotation angle is transferred to the control computer through a counter board. The rotation angle is used as a

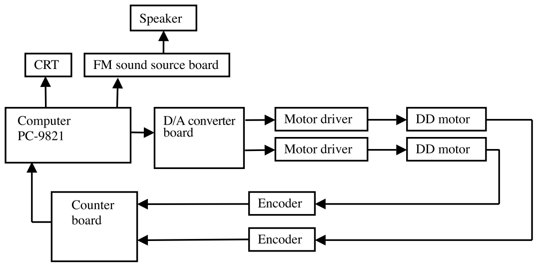

Fig. 2. Schematic diagram of the hardware.

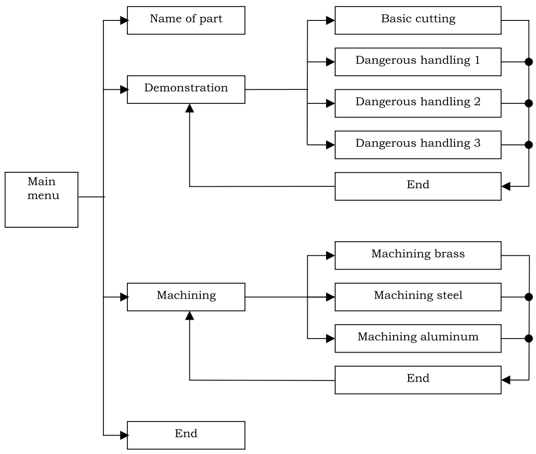

Fig. 3. Composition of the software.

reference to display animated pictures on the screen, and to perform a sound effect of working, with the FM sound source. The torque commands are generated by the control rule of the motor programmed in the software of the simulator, and sent into the motor's driver through a D/A converter so that the output torque of each motor can be controlled. Two Yokogawa Precision DR1030B DD motors are used in the simulator, which have a built-in rotary encoder with a resolution of 507,904 p/rev. The control computer used is an NEC PC-9821V200/M7 with a clock frequency of 200 MHz. An NEC PC-9801–86 board is installed in the computer as the FM sound source.

Software Composition

The composition of the software is illustrated in Fig. 3. The main menu comprises four submenus: 'Name of part', 'Demonstration', 'Machining' and 'End'. Further down, 'Demonstration' has four subprograms: 'Basic cutting', 'Dangerous handling 1', 'Dangerous handling 2' and 'Dangerous handling 3'. 'Machining' consists of three subprograms: 'Machining steel', 'Machining brass' and 'Machining aluminium '. When an item key on the main menu is clicked, the screen display changes to the scene of the submenu selected. Likewise, when a subprogram key on a submenu scene is clicked, the selected subprogram is executed. When the execution is finished, the display returns to the submenu scene. Therefore, a subprogram can be executed repetitively. The main functions of the software developed are described below.

The 'Name of part' submenu shows the names of lathe parts on the screen, for example, tailstock and chuck, with their shapes and positional relations.

The 'Demonstration' submenu displays cutting simulations on the screen while a working sound effect is played without handle operations, in order for a beginner to follow basic cutting operations and safety procedures. Within the 'Basic cutting' subprogram, the key points for operating the lathe handles are explained in letters, together with an animated picture for straight-line turning, where the byte on the tool rest moves and the chuck rotates corresponding to the cutting status in progress. This function can also be applied to learning a turning operation with automatic feeding. The subprograms for 'Dangerous handling 1' to 'Dangerous handling 3' give warning messages, along with visual and audio sensation information, for several dangerous actions which beginners often perform during lathe operation. These include setting the tip of byte approach to the tailstock as too close, setting the cutting depth too deep, and setting the byte approach to the chuck too near.

The 'Machining' submenu provides the operator with an artificial reality feeling of machining operations. The movement of the byte, and the change of work-piece in diameter and colour, are displayed on the screen in real-time, based on the handle rotation by the operator. A sound effect of machining is generated at the same time, which mixes the sounds for the rotation of the lathe spindle and the cutting of the work-piece. The different feelings of force for turning the feed handles, which depends upon the material of the work-piece selected by clicking a subprogram key (i.e. either steel, brass or aluminium), is also passed onto the operator's hands through the handles. In such a simulation of turning operations, once the operator takes a dangerous handling action, as mentioned above, the simulator stops immediately with a sound effect imitating an emergency shut-down of the lathe spindle, and a corresponding warning message is displayed on the screen. These functions can give the operator an effective guide to safe operations.

The software of the simulator is implemented using Microsoft C Compiler Version 7.0, which leads to a fast operational speed under the MS-DOS environment for

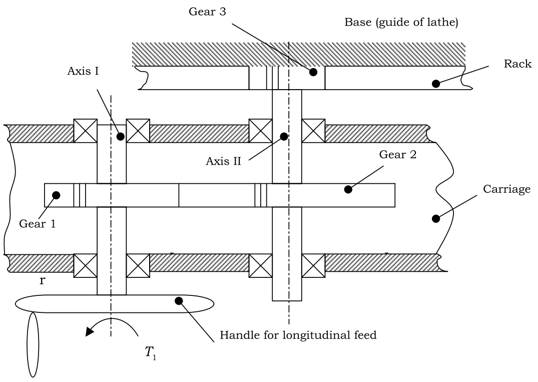

Fig. 4. Schematic diagram of the feed driving system of the TSL-550D high-speed lathe in the longitudinal direction.

program processing, so the software is available to simultaneously process the motor control, graphic display and sound effect performance. A detailed discussion on all the software programs implemented is impossible in this paper owing to space limitations. However, important issues for the implementation techniques for the virtual functions (e.g. the senses of the force, sight and hearing) are explained in the following sections.

Generation of the Sense of Force

Mechanical Model of the Feed Driving System

In a turning job with manual feed, the operator feeds the byte to cut into the work-piece, and then moves the byte along the feed direction to machine a part. In this case, the cutting force acting on the byte transmits respectively to the cross slide and the carriage through the tool rest, and further to the feed handles. The operator feels the cutting resistance to the material while turning the feed handles.

Figure 4 shows a schematic of the feed driving system of the TSL-550D high-speed lathe in the longitudinal direction. The rotating motion of the handle is transmitted to Axis II via Gears 1 and 2, and then translated into a linear motion of the carriage along the feed direction through the meshing of Gear 3 with the rack fixed on the guide base of the lathe. Let the operating torque that the operator applies to rotating the handle be T_1; the translated inertia moment of the carriage around the handle axis (i.e. Axis I) J_s; the torque

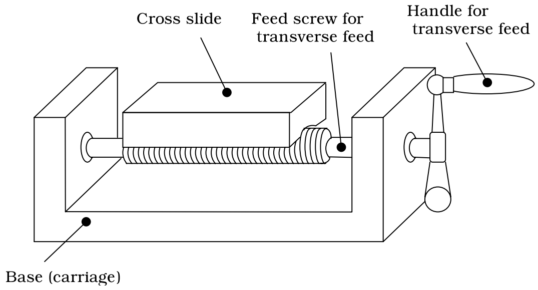

Fig. 5. Schematic diagram of the feed driving system of the TSL-550D high-speed lathe in the transverse direction.

of the cutting resistance acting on Axis I T_{fs}, that also contains the friction effect between each pair of parts with a relative motion in the driving system; and the angular acceleration of Axis I, $\ddot{\theta}_1$, the motion equation of Axis I can be expressed as:

$$J_s\ddot{\theta}_1+T_{fs}=T_1 \qquad (1)$$

where

$$J_s=J_1+i^2(J_2+m_1p_1z_3/2\pi) \qquad (2)$$

In Eq. (2), J_1 is the inertia moment of the handle with Axis I and Gear 1, J_2 is the inertia moment of Axis II with Gear 2 and Gear 3, m_1 is the mass of all movable parts in the carriage, p_1 is the pitch of the rack, and z_1, z_2, z_3 are respectively the tooth numbers of Gears 1–3. The transmission ratio, i, is defined as $i=z_2/z_1$.

Assuming that the cutting resistance acting on the byte is proportional to the area of the cutting section, the torque T_{fs} can be calculated from Eq. (3):

$$T_{fs}=k_1sv_s+C_f \qquad (3)$$

where k_1 is a constant related to the material of the work-piece, and C_f indicates a portion of T_{fs} caused by the friction (its value is considered a constant) as mentioned above. The values of k_1 and C_f are determined from experimental results, explained in Section 3.3. Moreover, s is the radial cutting depth, and v_s is the feed in the longitudinal direction; the value of v_s can be obtained from the rotating angle increment of the handle and the sampling time specified for data processing.

Figure 5 illustrates a schematic diagram of the feed driving system of the TSL-550D high-speed lathe in the transverse direction. Let the operating torque that the operator applies to rotating the handle be T_2, the translated inertia moment of the cross slide around the handle axis J_e, the torque of the cutting resistance acting on the handle axis T_{fe}, and the angular acceleration of the handle axis $\ddot{\theta}_2$, the motion equation of the handle axis can be expressed as:

Table 1. Values of the parameters for the feed driving system of the STL-550D high-speed lathe.

Parameters	Values
Inertial moment of axis I with gear 1, J_1	0.69×10^{-3} kgm^2
Inertial moment of axis II with gear 2 and gear 3, J_2	0.69×10^{-3} kgm^2
Inertial moment of feed axis with handle in transverse direction, J_3	4.93×10^{-4} kgm^2
Inertial moment of handle for longitudinal feed, J_{h1}	0.31×10^{-2} kgm^2
Inertial moment of handle for transverse feed, J_{h2}	5.13×10^{-4} kgm^2
Mass of carriage, m_1	92.0 kg
Mass of cross slide, m_2	29.0 kg
Pitch radial of gear 3, r	14.0 mm
Pitch of feed rack in longitudinal feed, p_1	6.28 mm
Pitch of feed screw in transverse feed, p_2	5.0 mm
Tooth number of gear 1, z_1	66
Tooth number of gear 2, z_2	15
Tooth number of gear 3, z_3	14

$$J_e\ddot{\theta}_2+T_{fe}=T_2 \tag{4}$$

where

$$J_e+J_3+m_2(p_2/2\pi)^2 \tag{5}$$

In Eq. (5), J_3 is the inertia moment of the axis with the handle, m_2 is the mass of the cross slide, and p_2 is the pitch of the feed screw. The torque of cutting resistance, T_{fe}, can be calculated from Eq. (6):

$$T_{fe}=k_2ev_e+C_e \tag{6}$$

where k_2 is a constant related to the material of the work-piece, and C_e indicates a portion of T_{fe} caused by the friction between the cross slide and the guide. The values of k_2 and C_e are decided from the experimental results. Further, e is the projection of the contact length between the cutting edge of the byte and the work-piece in the longitudinal feed direction, and v_e is the feed in the transverse direction. The value of v_e can be obtained from the rotation angle increment of the handle and the sampling time specified for data processing.

Table 1 shows the values of related parameters for the feed driving system of the TSL-550D high-speed lathe tested.

Torque Control of the DD Motor

The simulator is developed under the assumption that a TSL-550D high-speed lathe is used in turning jobs. The sense of the force for operating handles to feed the byte is produced by two DD motors connected directly to the axes of the operating handles in the simulator. Such force is generally caused by the cutting resistance of materials in an actual machining operation and the friction effect by the feed driving system. The operator can feel the action of the force while operating the handles. The equation of the DD motor motion with respect to the longitudinal feed can be written as

$$(J_{h1}+J_{m1})\ddot{\theta}_1=T_{m1}+T_1-T_{m10} \tag{7}$$

where the operating torque acting on the handle, T_1, is decided from Eqs (1) and (2), J_{h1} and J_{m1} are the inertial moment of the handle and the motor rotator, and T_{m1} and T_{m10} are the output torque and the rotator's friction torque of the motor, respectively. The output torque, T_{m1}, can be obtained by substituting Eq. (1) into Eq. (7):

$$T_{m1}=(J_{h1}+J_{m1}-J_s)\ddot{\theta}_1+T_{m10}-T_{fs} \tag{8}$$

Likewise, the motor output torque corresponding to the transverse feed, T_{m2}, can be derived as the follows:

$$T_{m2}=(J_{h2}+J_{m2}-J_e)\ddot{\theta}_2+T_{m20}-T_{fe} \tag{9}$$

where J_{h2} and J_{m2} are respectively the inertial moment of the handle and motor rotator, and T_{m20} is the friction torque of the motor rotator.

Two DD motors are used in the simulator, and the values of related parameters are $J_{m1}=J_{m2}=0.024$ kgm^2 and $T_{m10}=T_{m20}=3$ Nm. The handle parts used are the same as those of the actual lathe to ensure that the sense of touch is the same. The values of J_{h1} and J_{h2} are given in Table 1. In addition, the angular accelerations of the motors, $\ddot{\theta}_1$ and $\ddot{\theta}_2$, are obtained using a numerical differentiation with respect to the motor rotation angles, θ_1 and θ_2, which are detected by the built-in rotary encoder of the motor, corresponding to the longitudinal or the transverse feed, respectively.

As the output torque of motors is directly transmitted to the operator's hands via the handles, the limits to

Table 2. Comparison examples of the operating torque between actual cutting and verification test.

Material	Operating torque on simulation handle Nm	Operating torque on actual handle Nm
Steel	2.16	2.25
Brass	1.86	1.86
Aluminium	1.18	1.27

the output torque, angular speed and rotation angle of the motor are set for the simulator to prevent unexpected dangers such as a motor running out of control. Should such a situation happen, the power supply to the motor is automatically shut down immediately.

Identification of Cutting Resistance Torque and Verification of Operating Torque

Some cutting experiments with a lathe have been conducted to identify the values of the parameters k_1, k_2, C_f and C_e used in Eqs (3) and (6). In these experiments, a straight turning byte and three types of materials, SS400 steel, C3604 brass and A1050 aluminium, are used. The same experiment was repeated three times for each combination of cutting speed, cutting depth, feed and material. The operating torque with which the operator rotates the feed handle is measured through a torque sensor installed on the handle axis. The values of k_1, k_2, C_f and C_e are obtained by substituting the average values of the torque taken from three measurements into Eqs (3) and (6), and further into Eqs (1) and (4), and by applying the minimum square estimation to resolve the equations. As a result, the following values were identified: $k_1 = 4.21 \times 10^7$ N/m and $k_2 = 3.37 \times 10^7$ N/m for steel; $k_1 = 2.73 \times 10^7$ N/m and $k_2 = 1.91 \times 10^7$ N/m for brass; $k_1 = 1.08 \times 10^7$ N/m and $k_2 = 0.81 \times 10^7$ N/m for aluminium; and $C_f = 1.27$ Nm and $C_e = 1.02$ Nm.

On the other hand, verification tests with the simulator have been carried out after programming the obtained values of k_1, k_2, C_f and C_e, and the parameter values explained in Section 3.2 into the software. In these tests, the operating torque of the operator to rotate the handle is detected using a torque sensor installed on the handle axis with respect to the longitudinal feed direction. Table 2 shows a comparison of the operating torque between the actual cuttings and verification tests. In these examples, the rotation speed of the lathe spindle was 155 rpm, the cutting depth 0.2 mm and the feed in the longitudinal direction 0.1 mm/rev. It can be seen that the sense of the force for the handle operation provided by the simulator almost exactly agrees with that by the actual lathe to the operator.

Display of the Sense of Sight

MS-C Compiler Version 7.0, the programming environment employed in the simulator's software, is supported with a standard graphic library tool. By linking GRAPHICS.LIB and GRAP.H, a declaration file for graphic functions, in the tool with the software, displaying several types of animated pictures on the screen can be conveniently performed.

Display of the Byte and Work-piece

To quickly display the byte movement on the screen, a diagram of the byte is first drawn in a visible colour at a suitable position and then re-drawn in the background colour with some time delay, i.e. the diagram is crossed out. Therefore, by repeating this process of drawing and crossing at each appropriate position according to the progress of the 'machining operation', the state of the byte movement is perfectly displayed on the screen. The drawing positions are determined based on the rotating angles of handles detected by the built-in rotary encoders of the DD motors.

Figure 6 shows the method developed to illustrate the work-piece in animated pictures on screen. A virtual byte is drawn in the background colour at a symmetrical position to the cutting byte with respect to the centreline of the work-piece. The diagram of the virtual byte moves following the movement of the cutting byte, i.e. it always keeps symmetry with the cutting byte. Although the virtual byte cannot be seen on screen, the locus of its tip generates the machined surface on the work-piece. Further, the machined portion of the work-piece is changed in colour along its boundary (i.e. the line connecting the tips of both the virtual and the cutting bytes).

Display of the Spindle Rotation

Figure 7 depicts the method developed to display quickly the rotation of the spindle with the chuck.

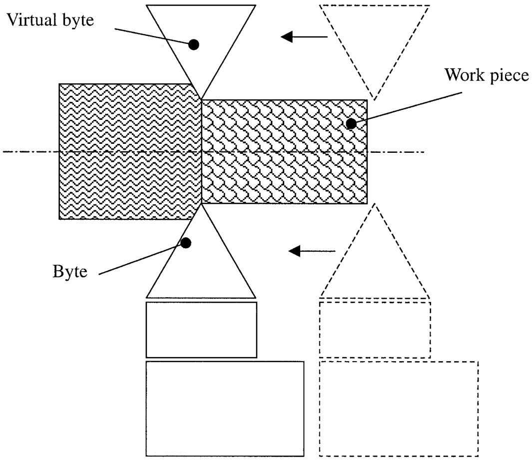

Fig. 6. Display of the byte movement and work-piece shape in machining.

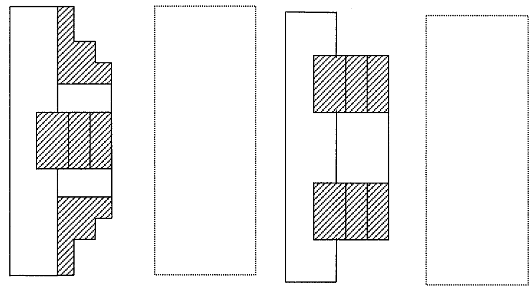

Fig. 7. Display of the spindle rotatin.

Diagrams of the spindle with the chuck jaws corresponding to the different rotating angles of the spindle (i.e. graphic 1, graphic 2) and an erasure scene are drawn up beforehand and stored in a graphic arrangement by using the GET command in GRAPHICS.LIB. During a display process, each diagram is continually displayed in the order of graphic 1 → the erasure scene → graphic 2 → the erasure scene → . . . graphic 1 → the erasure scene → graphic 2 → the erasure scene → . . . by using the PUT command to illustrate the spindle rotation animatedly.

Warning of Dangerous Operations

During operation of the simulator, once the operator performs a dangerous operation by an unreasonable handle action, the simulator makes an emergency stop immediately and plays a warning sound. A warning message 'Dangerous! The lathe stops!' is simultaneously displayed on the screen. The judgement of a dangerous operation is based on the position of the byte relative to the work-piece, the tailstock or the chuck. A threshold value of 5 or 10 mm is used for the approaching distance between the byte and the work-piece or other parts, or for the cutting depth, respectively, in the simulator.

Performance of the Sense of Hearing

A FM sound board and a driver for the FM sound source, FMP-SYSTEM [14], are used in the simulator to produce working sound effects. A module developed by Saito using the C programming language to control the driver [15] is installed in the control computer.

Eight sound source files, which correspond respectively to the sound of spindle rotation, the sound of a warning (e.g. emergency stop sound of lathe) and the sound of machining – mixed sounds of spindle rotation and cutting the material (either of the three types), have been implemented with the Music Micro Language (MML). A sound source file is automatically selected and executed by the software based on the type and operation status in progress so as to perform the sound effect. For example, only the sound effect of spindle rotation is played if the byte is not cutting the work-piece, whereas the sound effect of a machining that mixes both the spindle rotation and the cutting is played when the work-piece is being cut. The sound source files were created using the judgement of several technicians who are experienced lathe operators. The MML compiler FMC [16] is used for editing the source files.

Evaluation of the Learning Effects of the Simulator

The simulator developed has been adopted for use in a technical education subject for metal cutting at Joetsu University of Education for the last two years. The purpose of the subject is to enable the students to acquire basic knowledge of metal cutting through simple turning operations with an actual lathe. Twelve students, expecting to obtain a technical teacher's qualification in the future, took the subject in each year.

Table 3. The students' evaluation for the learning effects of the simulator.

Evaluation item	Answer				
	A	B	C	D	E
(1) To understand the structure and part names of the lathe	6	18	0	0	0
(2) To understand the feeding and cutting motions of the lathe	16	8	0	0	0
(3) To understand the basic and danger operating for the lathe	20	4	0	0	0
(4) To understand the contents of the subject under study	18	6	0	0	0
(5) To pay attention to safety in your operation of the lathe	10	14	0	0	0
(6) To feel the diffeerence in cutting resistance with respect to cut materials	20	4	0	0	0
(7) To perform the operation with positive consideration	7	13	4	0	0
(8) To provide a good presentation of graphs and characters on the screen	4	15	5	0	0
(9) To provide good colour arrangements on the screen	8	12	4	0	0
(10) To provide a good menu layout of operations on the screen	9	12	3	0	0
(11) To provide good effects of working sound	8	16	0	0	0

Answer, 'A' means: 'I strongly think so'; 'B' means: 'I think so'; 'C' means: 'It may be so'; 'D' means: 'I do not think so': 'E' means: 'I strongly do not think so'.

Table 4. The teachers' evaluation for the learning effects of the simulator.

Evaluation item	Answer				
	A	B	C	D	E
(1) To have a sufficient real feeling	3	3	3	1	0
(2) To give effective safety guidance related to operating mistakes	6	2	2	0	0
(3) To improve the study efficiency for basic operations	3	4	2	1	0
(4) To have a good understanding to the study contents	4	4	2	0	0
(5) To improve safety in lathe operation training	4	4	2	0	0
(6) To utilize the simulator in your teaching in the future	4	3	1	1	1

Answer, 'A' means: 'I strongly think so'; 'B' means: 'I think so'; 'C' means: 'It may be so'; 'D' means: 'I do not think so': 'E' means: 'I strongly do not think so'.

After being given simple guidance related to the basics of turning operations, the students operated the simulator for 90 min. At the end of the session, a questionnaire was administered. The answers of all 24 students (12 in each year) are summarised in Table 3. The results cannot be considered to be perfect or sufficient because most of the students had almost no experience in actual lathe operations. However, it may be concluded from the results in Table 3 that the students positively evaluated the learning effects of the simulator. On other hand, about 20% of the students did not give a satisfactory answer to the 8th, 9th and 10th items (related to graphical presentation on the screen). This suggests that some improvement of the visual functions is needed to the simulator in the future.

The simulator has also been demonstrated in a technical lecture course, taught in Niigata Prefecture of Japan, to teachers working in mechanical departments of industrial high schools. Ten teachers evaluated the learning effects in the form of a questionnaire after operating the simulator. Their answers, summarised in Table 4, show that most of them gave a good evaluation, and seven hoped to use the simulator in their teaching in future.

Conclusion

A learning-training simulator with virtual functions for lathe operations has been developed to safely and efficiently enhance metal cutting education courses in industrial high schools, vocational training schools, engineering faculties of universities, and so on. The main functions and characteristics of the simulator are:

1. A synthetic operating sense harmonising sight, hearing, force and touch is available to the operator in real-time. This makes the operator feel as if he or she were operating an actual lathe while operating the simulator.
2. High speed processing with a sampling time of 29 ms has been achieved with the software developed, therefore the simulator can provide

the operator with a sufficiently real feeling for operating the feed handles of a lathe.

3. The machining simulation that responds correctly and directly to the feed handle rotation related to the operator's action is displayed on screen in real-time.
4. Sound effects of working, including the sounds of spindle rotation, spindle rotation and cutting, and warnings, is played in real-time corresponding to the operational status in progress.
5. Useful functions with visual and audio information (e.g. explanation of basic operations and safety procedures, demonstration of machining and warnings for dangerous actions) are effectively applied to increase the training efficiency.
6. Most teachers working in industrial high schools and students at Joetsu University of Education who have operated the simulator gave a good evaluation for learning from the simulator.

References

1. Nakamura K (1999) Simulator has contributed to the technology of virtual reality. J Japan Soc Mech Eng 102: 639–641
2. Johnston R, Weiss P (1997) Analysis of virtual reality technology applied in education. Minimally Invasive Therapy & Allied Technol 6: 126–127
3. Issenberg SB, Gordon MS, Gordon DL, Safford RE, Hart LR (2001) Simulation and new learning technologies. Medical Teaching 23: 16–23
4. Turk Z (2001) Multimedia: providing students with real world experiences. Automation in Construction 10: 247–255
5. Crumpton LL, Harden EL (1997) Using virtual reality as a tool to enhance classroom instruction. Comput & Ind Eng 33: 217–220
6. Pantelidis VS (1997) Virtual reality and engineering education. Comput Applic in Eng Educ 5: 3–12
7. Fang XD, Luo S, Lee NJ, Jin F (1998) Virtual machining lab for knowledge learning and skills training. Comput Applic in Eng Educ 6: 89–97
8. Tam EK, Badra F, Marceau RJ, Marin MA, Malowany AS (1999) A web-based virtual environment for operator training. IEEE Trans Power Syst 14: 802–808
9. Aviation Bureau, Ministry of Transportation of Japan (1996) Aircraft inspection technical security volume [regarding to the identification essential of the simulated aircraft device etc.], TCL-506–1–9
10. Kato H, Sato T (1996) Effect of auditory feedback on operating efficiency and fatigue – in the case of manual cut-off turning with virtual lathe. Int J Japan Soc for Precision Eng 30: 325–330
11. Kato H, Kobayashi K, Liu S (1997) Skill learning in manual machine tool operation – development of new virtual lathe and study on minute grooving by using it. In J Japan Soc for Precision Eng 31: 221–226
12. Chen W, Kato H (1998) Skill training of manual machine operation by simulator – in the case of small-diameter deep-hole machining with drilling machine. Int J Japan Soc for Precision Eng 32: 31–36
13. Chen W, Kato H, Yang Y (1999) High efficiency skill training of small-diameter deep-hole drilling by simulator. Int J Japan Soc for Precision Eng 33: 313–318
14. Nagai O (1996) Agreement and explanation of FM sound source driver [FMP-SYSTEM] (FMP.DOC), FMP424A.LZH (free software downloaded from http://www.vector.co.jp/)
15. Saito H (1997) FMP–USED.DOC, FMP–C.LZH (free software downloaded from http://www.vector.co.jp/)
16. Nagai O (1996) Explanation of MML Compiler (FMC-.DOC), FMP424A.LZH (free software downloaded from http://www.vector.co.jp/) 1996

Correspondence and offprint requests to: *Dr H. Qiu, Department of Mechanical Engineering, Faculty of Engineering, Kyushu Sangyo University, 2–3–1 Matsukadai, Fukuoka City, 813-8503, Japan. Email: chiu@ip.kyusan-u.ac.jp*