

Virtual Technical Trainer: Learning How to Use Milling Machines with Multi-Sensory Feedback in Virtual Reality

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ABSTRACT

This paper describes the use and characteristics of a virtual reality system called the Virtual Technical Trainer (VTT). This system is dedicated to vocational training courses on using and programming numerically-controlled milling machines. It aims at replacing the conventional mechanical milling machines which are currently used in such vocational training courses.

VTT proposes an interactive manipulation of a cutter of a virtual milling machine, with visual, audio and haptic (force) feedback. VTT uses a haptic device which was specifically designed for the purpose of our pedagogical application. When the virtual cutter mills a piece of material, a plastic deformation algorithm is used and the material is progressively carved. Trainees can feel the cutting effort thanks to a force feedback which varies as a function of different simulation parameters (rotation speed of the tool, type of material to carve, etc). Realistic audio feedback (which was recorded in real situations) and additional visual assistances may be added, in order to increase the perception and understanding of the milling task.

A preliminary evaluation of VTT showed that this simulator could be used by vocational trainers successfully. It could help them to teach the basic principles of machining at the first stages of vocational training courses on numerically-controlled milling machines.

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1 INTRODUCTION

Each year, hundreds of people are trained in AFPA⁷ centers to use Numerically-Controlled Milling Systems (NCMS). In this course, AFPA trainees are taught how to use and program numerically-controlled milling machines. The duration of the training course is of one year.

The pedagogical approach is based on concrete “job-like” situations. Before learning how to program numerical milling machines, the training period begins with a set of physical manipulations with conventional milling machines (see Figure 1). This step is considered by AFPA trainers as fundamental to discover the milling process slowly and progressively. Thanks to the crank of the conventional machine, the trainee can “feel” how the machine reacts. He/she can “perceive” the cutting efforts that are necessary to carve the pieces of material and to achieve the task.

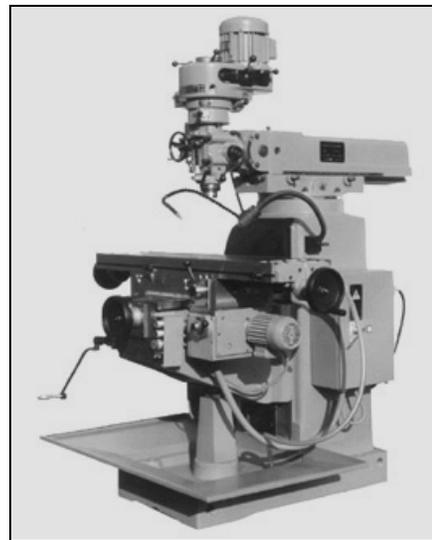


Figure 1. Conventional Milling Machine Used at AFPA.

However, learning with a conventional machine is a long and complex process. It is expensive since it requires a large amount of material and it implies maintenance costs. Furthermore, considering the current development of numerical machines, conventional machines will soon become extinct. Thus, an alternative solution must be quickly found, in order to replace them in NCMS courses in training organizations such as AFPA.

Therefore, we propose a new system called the Virtual Technical Trainer (VTT). This system is dedicated to vocational training in Virtual Reality (VR), when teaching the use of milling machines. VTT proposes an interactive manipulation of the virtual cutting tool of a milling machine with visual, audio and haptic feedback.

The following paper describes the use and characteristics of the VTT system. It begins with related work on training in virtual environments. It follows with a global description of VTT. Then it details the visual, audio and haptic stimulations which were implemented. It focuses on a haptic device which was specifically designed for VTT. Then it describes the results of a preliminary evaluation made with a group of AFPA trainees. It ends with a general conclusion.

2 RELATED WORK

Training is a major field of application for VR technology [5] [16] [18]. VR training can be used in various fields such as: technical procedures [15], medicine [2], military strategy [13] or education [5]. Several projects recently demonstrated the efficiency of VR for technical training in industry, e.g. [1] [7].

Pedagogical approaches are generally focused on the notion of “realism” of the situation [5]. For this aim, most systems provide users with interactive simulation based on visual feedback and sound [5]. Some systems use haptic feedback in order to recreate the realistic sensations of manipulating tools [2] [3]. The well-known PHANTOM device of SensAble Technologies [17] is currently used in several virtual environments dedicated to the training of aeronautical maintenance operations [12] [15]. In some other cases, an ad-hoc haptic device is specially designed for the purpose of the training task. This is often the case with surgical simulators which need to provide users with interfaces that look like the medical instruments used in the real procedures [9].

Burkhardt et al. [4] have recently proposed an alternative to the “realism-oriented” approach. It is based on the use of multi-sensory structures to afford the cognitive and learning activity of the trainees. This new approach is grounded on one side on empirical investigations of learning in VR which suggest that additional sensory information enhance the learning of abstract concepts [6]. On the other side, it is grounded on studies of perception and cognition which have emphasized the strong relationships between senses, such as between vision and touch [10][11].

3 GLOBAL PRESENTATION

VTT is a virtual reality system dedicated to vocational training in the use of milling machines.

A user-centered and iterative approach has been set up in order to design VTT. It was developed by a multidisciplinary team involving hardware and software engineers, specialists of ergonomics, training and learning, and AFPA trainers.

Several pedagogical hypotheses were made prior to the design of such a virtual training system:

- Interactive manipulation can improve the learning process.
- Multi-sensory stimulation can improve the learning process.
- Haptic feedback can be used to display the effect of the mechanical parameters involved in the milling process.

The design of VTT is thus based on interactive manipulation with visual, audio and haptic (force) feedback. In the simulation, the trainee manipulates a virtual cutting tool (a spindle) which corresponds to the “extremity” of the milling machine. Visual

assistances are proposed to guide and inform about the milling process. Realistic sounds of milling (which were recorded in real situations) are added. Force feedback is activated when the tool carves the virtual piece of material. Force feedback varies as a function of different simulation parameters: rotation speed of the tool, advance speed of the tool, type of tool used (number of teeth, material, diameter). The trainee can feel differences of “cutting effort” (or resistance) when these parameters are changed. We assume that the direct perception of the variations of the cutting effort can improve the understanding of both the milling process and the relations between the several mechanical parameters.

VTT uses a PC (Pentium III, mono-processor, 333MHz, 384RAM, GeoForce2). The software architecture of VTT is modular in order to integrate the several sensory feedbacks. With this configuration, the frame rate of the visual feedback is of 25-30Hz. The frequency of the main simulation loop of the milling process is of 100Hz. The fast computation and control of the force feedback is ensured at a 1kHz frequency (haptic loop). The frequency of the audio loop is of 22.05kHz.

VTT can be used by non-programmers thanks to the use of configuration files. These files are filled off-line, to define the different parameters of the visual, audio and haptic feedback and to enter global information about the training session.

The following parts detail the characteristics of the visual, audio and haptic feedback which were implemented in VTT.

4 VISUAL FEEDBACK

The visual feedback of VTT is displayed in monoscopic conditions, on a computer screen.

This part describes briefly the characteristics of the visual feedback: the two possible views of the virtual environment, the additional visual assistances and the simulation of the visual deformation of the material part.

4.1 Two Possible Views

VTT provides the trainee with two possible views of the virtual environment.



Figure 2. Environment-Oriented View.

First, an “Environment-Oriented view” displays the complete environment with realistic details (see Figure 2). It displays the entire milling machine as well as the rotating tool and the material

part. This view is used as an intuitive overview of the scene. It is mainly proposed at the beginning of the use of the simulator.

Then, a “Process-Oriented view” gives a simplified view of the virtual environment. It only displays the cutting tool and the piece of material (see Figure 3). This view is used to focus the attention of the trainee on the milling task.

In both views, the camera is positioned in front of the cutting tool (see Figures 2 and 3). The point of view is kept constant in order to improve the positioning of the cutting tool according to the workpiece, as well as to avoid problems of disorientation. The cutting tool always remains displayed at the center of the screen, as if the camera was glued on it. To do so, the motion of the user (while manipulating the input device) is inversely applied to the motion of the virtual scene, apart from the cutting tool. With this technique, the trainee may fully concentrate on the tool and on the milling process.

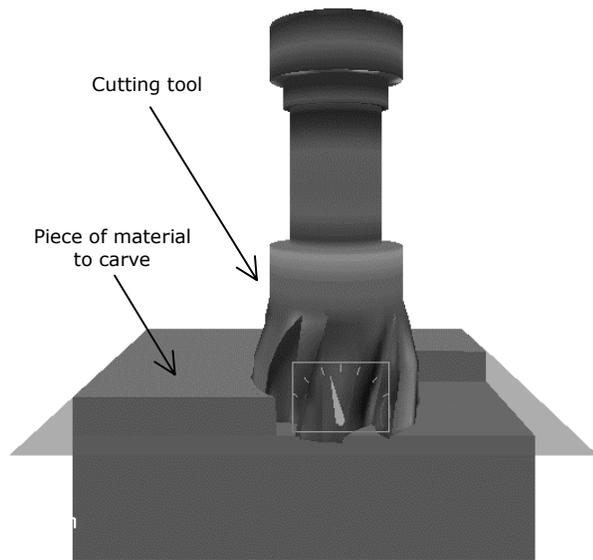


Figure 3. Process-Oriented View.

4.2 Visual Assistances

Using the possibilities offered by virtual reality, the system provides visual assistances which can be activated at will.

The visual assistances were defined with AFPA trainers in order to provide helpful additional information to the trainee. These assistances are:

- **Depth Cut Assistance:** The depth of cut can be displayed by using a semi-transparent green plane (see Figure 3). This plane indicates the limit under which the tool can not go. It is also helpful to visualize the remaining quantity of material to carve.
- **Positioning Assistance:** A 2D top-view of the scene is available (top-right of Figure 2). This assistance indicates more precisely the position of the tool (black disk) relative to the material part (white rectangle).
- **Feed-Rate Assistance 1:** This tool consists in a 2D abacus (top-left of Figure 2). When carving, the trainee must theoretically keep a white cross inside the black zone of the abacus. However, this indicator might distract the trainee’s attention from his/her principal task. A second feed-rate indicator is thus proposed:

- **Feed-Rate Assistance 2:** It consists in a rectangular dial and a needle, located in front of the cutter (see Figure 3). The offset angle of the needle informs about the current feed rate. It indicates if the advance speed of the tool is below or above the instruction speed. The trainees can then adjust their advance speed by applying higher or smaller forces.
- **Broken Tool Alarm:** To simulate the break of a tool, the tool is simply removed visually and a red error message is displayed for five seconds.

These assistances have a fundamental role to play concerning the pedagogical issues of VTT. However these issues will not be discussed in the present paper – which is voluntarily more oriented towards the interface issues.

4.3 Simulation of the Visual Deformation

In previous works on plastic⁸ deformation, the deformation algorithm is generally based on 3D voxels [19] or 2D dexels [20]. The surface deformation is simulated by eliminating the voxels (or dexels) that fall inside the volume of the carving tool.

In our milling scenario, the cutting tool carves the material part only from the top and the sides. As a consequence, our deformation algorithm is simplified and close to dexels-based algorithms [20]. The tool’s deforming surface is a disk with a constant diameter. A simple 2D elevation matrix is used to model the shape of the material. Each cell of the matrix contains the elevation (or height) of a square element of the material part. The resolution of the matrix is of 0.1mm. At each step of the main simulation loop, the elevation of the cells of the matrix which are located inside the disk is modified. The values of the cells are set to the current height of the tool. This very simple model of deformation ensures low computation times.

Polygonal models are used for the graphic rendering of the virtual environment. For each 0.1mm strip, one quad polygon is drawn for each elevation value. This graphical technique is used to limit the number of polygons to draw. With this simple rendering method, the frame rate of our application remains always superior to 20Hz.

5 AUDITORY FEEDBACK

Sound is a fundamental cue which is often used during the milling task. Therefore VTT provides an auditory feedback in order to increase the trainee’s feeling of immersion.

However, for reasons of simplicity, we did not want to synthesize all the audio characteristics of a real milling machine (using for example a spectral analysis of the different parts of the machine).

Therefore, a limited number of sampled sounds were digitalized. For this aim, we used a microphone which was placed on the milling table of a real milling machine. Different milling conditions were recorded by using different types of tool, material, feed rate and depth of cut.

After analyzing the differences between the sounds with AFPA trainers, three different states were chosen and 8 sampled sounds were selected:

⁸ Plasticity is defined as a “property which precludes an object from regaining its original and undeformed shape once the interaction ends” [3].

1. **Free motion state:** the tool (spindle) is rotating freely and no material is carved. In this case, three sounds are used with a tool's rotation speed of respectively: 140, 990 and 2200 RPM.
2. **Milling state:** the tool is carving some material. In this case, four sounds are possibly used. They correspond to carvings with a depth of cut of respectively: 1, 2, 3 and 4 mm.
3. **Transient state:** The tool is carving very few particles of metal. One specific and very special sound is used to simulate this particular case.

For the first and second states, the final sound played is a combination of the sampled sounds. The sampled sounds are modulated in pitch and volume to ensure a continuous variation of the final sound. The volume modulation of the sampled sounds is based on triangular modulation. The final pitch of each sampled sound is modified to become close to the current rotation frequency of the tool.

According to numerous AFPA trainers, the resulting auditory feedback seems "realistic". But further evaluations are necessary to measure this "realism" and its impact on the pedagogical objectives of VTT.

6 HAPTIC FEEDBACK

6.1 Specific Haptic Device

One haptic device (see Figure 4) has been specifically designed for VTT.

This haptic device is a Cartesian joystick with 2 active Degrees Of Freedom (DOF). The user grasps the extremity of the device with the dominant hand. The user can then feel resistive forces on the 2D horizontal plane. A third and passive DOF is also proposed on the vertical axis by using an elastic property of the device.

The 2-DOF Cartesian structure seemed particularly well suited for the vocational training of milling. Indeed, during the real milling task, most motions of the cutting tool are performed in one DOF, along the left-right or forward-backward directions.

The 2 axes of the device are constrained by using linear guides and ball bearings. Two DC brushless motors and a system of toothed pulleys are used for the transmission of the force feedback. The structure of the prototype is built in Medium Density Fiber wood. The workspace of the device is of 24x14cm. The maximum continuous forces are of 13N.

The grasping and manipulation of the device are based on the "prop"⁹ concept proposed by Hinckley et al. [8]. The user grasps a cylinder which looks very similar to the cutting tool displayed visually in the simulation. This should improve the intuitiveness of the system and the learning of VTT.

The vertical axis is driven by an elastic system. The vertical position of the tool is modified when the user applies a force on the grasped cylinder upwards or downwards. The system used is based on two linear springs and a distance measurement using the reflection and attenuation of an infrared beam light. The maximum amplitudes of the vertical motion of the cylinder are of +/-5mm.



Figure 4. Dedicated Haptic Device.

The electronic design of the device is based on a specific "all-in-one" electronic board. It includes the monitoring logic, the control, as well as the power stages of the motor control. It uses a Field Programmable Gate Arrays (FPGA) component associated with a 8-bit micro-controller. The specific development of the electronic board decreased the final cost of the system. The current system enables a 1kHz frequency for the control of the force feedback.

6.2 Haptic Rendering

This part describes the haptic rendering that was implemented in VTT. It first reports on previous work on haptic feedback with plastic deformation. Then it describes the contact model and the algorithm used.

6.2.1 Previous work on plastic deformation

Several haptic renderings with plastic deformation have been already proposed in previous works [3] [19] [20]. For instance, Burdea et al. [3] achieved the deformation of a virtual soda can, grasped with a force-feedback exoskeleton glove. In the carving algorithm proposed by Yamamoto et al. [19], each voxel of the virtual scene resists the motion of the user by a small force which depends on the object's stiffness. The total interaction force depends on the number of voxels inside the tool at time t . At the next time step, the voxels are carved and a new force is computed. The FreeForm software of SensAble Technologies [17] is an available commercial solution for the haptic sculpting of 3D models. FreeForm proposes an interactive carving of 3D parts

⁹ Hinckley et al. [8] have proposed the notion of "passive interface prop" for the design of 3D user-interfaces. This represents a "physical manipulation of familiar real-world objects in the user's real environment" [8].

with different shapes of tool (sphere, cone and cylinder). The carving algorithm of FreeForm also uses a scene based on voxels.

The haptic rendering implemented in VTT is inspired by these previous techniques. However, it makes a full use of the simplifications implied by our milling scenarios. It is a 2-DOF haptic rendering which is close to the dexels-based algorithms [20]. It computes a force-feedback in the 2D horizontal plane.

6.2.2 Contact model

At each step of the main loop (at 100Hz), the system computes the number of particles (i.e. of 0.1mm-side cells of the elevation matrix) in contact with the tool. It considers separately the four quadrants A, B, C and D (see Figure 5a). The four values obtained are used to generate the activation of four possible contact planes (PX1, PX2, PZ1, and PZ2 on Figure 5b). The activation of each plane depends on two values. For example, the plane PZ2 is activated if particles are in contact with the tool in quadrant A or quadrant B. The plane PX1 is activated if particles are in contact in A or D.

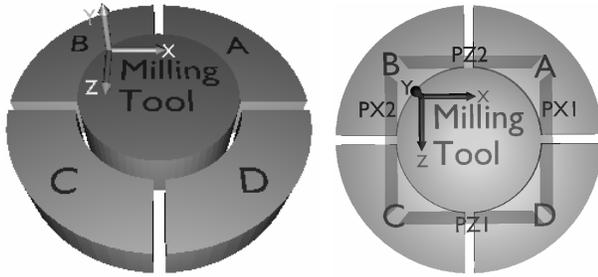


Figure 5. (a) Quadrants - (b) Contact Planes.

The force-feedback is computed in the haptic loop at 1kHz. The 4 contact planes limit the movements of the tool in the 2D horizontal plane. If the user pushes against one plane, he/she receives a resistive force along the direction of the normal of the plane. This force is proportional to the “penalty” – i.e. the distance of penetration inside the plane. The penalty method is a classical method used in numerous previous papers on haptic rendering (e.g. [12] [14] [21]). In our case, one penalty and one force are computed per contact plane. The resulting force is obtained by adding the 4 forces.

6.2.3 Haptic simulation of the plastic deformation

The sensation of deformation is obtained by moving the contact planes. Each contact plane is moved along its normal and in the direction of the tool’s motion. The advance speed (S_A) of each contact plane is computed in the haptic loop, using Equation 1.

The advance speed depends on several parameters which may be variable, set by the user, or set in the configuration files. These parameters are described in Table 1.

$$S_A = K_S \times \frac{F_U \times S_R \times D \times K_T}{(N_P \times K_M) + 1} \quad (1)$$

The properties of our haptic rendering were defined and adjusted with AFPA trainers. The result is not “realistic” from a physical point of view. But it enables the display an effect of many mechanical parameters on the resulting force feedback.

Further evaluations are now necessary to evaluate its impact on the pedagogical objectives of VTT.

7 INFORMAL EVALUATION

A formative and preliminary evaluation of VTT was carried out with three objectives. First, we wanted to evaluate the ability of the system to generate an accurate perception of the “cutting effort” of the milling process. Second, we were interested in investigating how the prototype can be used with a real pedagogical objective. Third, we were interested in using this preliminary study as a concrete starting point for end-users (i.e. trainees and trainers) to further explore and develop the potential pedagogical and vocational uses of VTT.

Table 1. Parameters used in the computation of the advance speed of the contact planes

Symbol	Unit	Meaning	Value
F_U	N	Force applied by the user	Variable
S_R	RPM	Rotation speed of the tool (spindle)	Set by the user
D	mm	Tool diameter	Set by the user
N_P	-	Number of particles in contact	Variable
K_S	-	Speed rate global coefficient	Constant (set in a configuration file)
K_T	-	Tool cutting coefficient (depends on number of teeth, type of material, etc)	Constant per each tool (set in a configuration file)
K_M	-	Material resistance coefficient (metal, wood, fibre, etc)	Constant per each material (set in a configuration file)

7.1 Participants

Six participants took part in this informal evaluation. They were all male adults, aged between 20 and 35. All participants were AFPA trainees enrolled in a one-year vocational training course on Numerically Controlled Milling Systems (NCMS). Three of them were “novices” in using milling machines. The three others had previous experience with NCMS, and thus will be considered as “experienced users” or “experts” in the rest of the paper.

7.2 Procedure and Results

The evaluation took place in the hall usually used for training courses on NCMS. Evaluation was separated into distinct tests.

The tests were made using all available sensory stimulations (visual, haptic and auditory feedback). The process-oriented view was selected and used through all the session. Participants had constantly at their disposal all the visual assistances.

At the end of the session, participants had to fill a questionnaire about the usability of VTT and their preference.

7.2.1 Test 1 – Perceptive test

This first test was a perceptive test. We wanted to evaluate the ability of the system to generate an accurate perception of the cutting effort of the milling task.

We conducted a discrimination task between two values of cutting effort. Participants were asked to discriminate between two situations and choose the one in which the cutting effort was perceived “higher”. Each participant performed two sequences of trials. In the first sequence, one parameter -the rotation speed- varied between 75 and 1200 RPM in a set of 7 trials. In this case, the advance speed and depth of cut were both kept constant. In the second sequence, three parameters (rotation speed, advance speed

and depth of cut) varied simultaneously within a second set of 7 trials. Answers for each trial and each participant were collected.

We found a global and average percentage of correct responses (correctness) of 80% (SD=11,6%). This result is promising since it suggests that variations of effort that are generated by VTT are actually well perceived by the trainees.

Further analysis showed that novices tended to have a better performance than experts. Indeed, average correctness for novices was of 87% while correctness for experts was of 73%. This suggests that experience in NCMS could have an influence on performance with VTT. Such difference might be due to the fact that experts expect a “realistic” simulation while novices’ expectations merely stem from the trainers’ instructions. This hypothesis is supported by the fact that experienced trainees asked in the final questionnaire for a “more realistic virtual environment”; while all novices reported that they fully “appreciated the haptic, visual and auditory stimulations of VTT”.

7.2.2 Test 2 – Pedagogical test

This second test was a pedagogical test. We wanted to verify that trainees could build generic rules about milling and machining effort using their perceptive experience within VTT.

Each participant was given the task of “exploring” VTT when changing the value of one parameter at a time: the rotation speed or the advance speed. They were asked to formulate orally one “rule” or “law” per varying parameter. The first rule that trainees were supposed to recover was: “when the rotation speed increases, the cutting effort decreases”. The second rule was: “when the advance speed increases, the cutting effort increases”. Collected data were trainees’ verbalizations and final responses.

We observed that 4 participants out of 6 were able to recover the two correct rules. Five trainees succeeded in finding the correct rule for the rotation speed, and 4 trainees succeeded for the advance speed.

Once again, there seemed to be an influence of the trainee’s experience on the ability to find the rules. Surprisingly, all novices were able to recover the rules successfully. However, only one experienced trainee was able to recover the rules of both the advance speed and the rotation speed.

7.2.3 Exploration of potential pedagogical use

At the end of the two previous tests, we wanted to explore how VTT could be used to support and illustrate a theoretical course on milling.

Participants were first taught by an AFPA trainer the classical formulas for the computation of milling parameters (e.g. rotation speed or advance speed). Participants were then asked to sort different combinations of milling parameters (numerical values of rotation speed, advance speed and depth of cut) as a function of the resulting cutting effort. Participants were given the opportunity to use VTT to verify their assumptions and their choices. Using VTT, they could enter the numerical values and check if the cutting effort corresponded to their predictions.

We noticed that the use of VTT enabled the participants to experience a real “sensorial checking” of the theoretical exercise. They actually felt haptic sensations consistent (or not) with their theoretical computation. Five trainees out of 6 actually modified their answers (their sorting) after this check. At the end of the check, all trainees completely succeeded in sorting the different combinations of parameters correctly.

7.3 Perspectives

This evaluation – though incomplete and achieved with a low number of participants – is useful for future developments. The results suggest that VTT seems to fit better with novice users. The over-simplification of the milling simulation might indeed disturb more advanced learners who expect a very realistic display. An open question concerns the characteristics of VTT that could explain why expertise seems to affect performance. Several hypotheses should be investigated in further studies.

The preliminary evaluation of VTT confirmed the feasibility, usability and pedagogical utility of such a training resource. VTT provides haptic, visual and auditory feedback correlated with the cutting effort of the milling task. VTT fulfills the expected requirements at this stage of the design process. Furthermore, VTT enables further educational developments since it can now support effective training sessions.

8 GENERAL CONCLUSION

This paper described a virtual reality system called the Virtual Technical Trainer (VTT). VTT is dedicated to vocational training, when teaching the use of milling machines. It aims at replacing the conventional milling machines which are currently used in such vocational training courses.

VTT proposes an interactive manipulation of a virtual cutting tool with visual, audio and haptic feedback. The visual scene displays the entire workbench, the milling machine, the cutting tool and the piece of material to carve. When the tool mills the material part, a plastic deformation algorithm is applied and the part is progressively carved. The trainee can feel the cutting effort of the milling process thanks to the force-feedback of a haptic device which was specifically designed for our vocational application. Audio feedback and additional visual assistances can also be added in order to increase the perception and understanding of the milling task.

A preliminary evaluation of VTT showed that this simulator could be successfully used by vocational trainers. It could be helpful to teach the basic principles of milling faster and in safer conditions, in the first stages of vocational training courses on numerically-controlled milling machines.

Future Work. Future work deals with the design and development of a complete pedagogical approach based on the possibilities offered by VTT. This approach should for example take into consideration new pedagogical objectives such as the limits of the milling task (break of tools), or economical costs associated with the wearing out of tools. Furthermore, the potential use of VTT should be compared with the current use of real conventional milling machines in vocational training courses.

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