

Haptic Simulations for Training Plumbing skills

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Abstract—The objective of this work is to augment actual hands-on conventional vocational training workshop with simulated training using virtual haptic simulations as part of computer-based vocational education and training. We have developed a system to simulate various common tool exercises and procedures in virtual environments for vocational training programs targeted towards illiterate and semi-literate populations. In our previous work, we designed a cost-effective multi-tool haptic simulator that can train the use of 19 hand-held and powered tools. This simulator is designed to replace traditional training tools and materials in the primary stage of vocational skill training. This paper discusses the design and computational modelling of the virtual training interface that allow this simulator to be used for training in multiple vocational trades — with a special focus on plumbing—that bring the experience of a vocational workshop training environment to the end user. This approach of a virtual, computer-based vocational training environment holds the potential to offer vocational training to a diverse audience with varying skill sets.

Keywords—*Virtual training Interface, Haptic simulation, Force feedback, Vocational training, Plumbing skill learning*

I. INTRODUCTION

Vocational education in the developing world faces many serious challenges. These include a dearth of sufficient vocational education and training (VET) schools and expert instructors to meet the demand, limited access to raw materials, lack of funds for necessary equipment, and in some areas, pervasive social stigma associated with vocational trades [1]. What is needed is an appropriate set of vocational education policies for developing countries like India [2]. Computerized VET programs hold potential solutions to many of vocational education's existing challenges. However, in order to have practical value, computerized education model has to be accompanied by hands-on training. In the interest of incorporating hands-on training into the model, we proposed the haptic virtual workshop simulator, as seen in our previous work [3]. We designed the APTAH simulator (Amrita Progressive Training Assistance using Haptic simulation), a cost-effective, multi-tool haptic simulator that can train the use of 19 hand-held and power tools used in several vocations that could replace traditional training tools and materials in the primary stages of vocational skill training. As an extension of this work, we have so far developed virtual simulations for six different tools, incorporating haptic force-feedback for the haptic simulator. This paper describes the design and

computational modeling of the virtual training interface used with APTAH for various vocational tools and the corresponding scenarios, with a special focus on plumbing. This model brings a simulated yet lifelike experience of an actual vocational workshop training setting to the end user.

II. PREVIOUS WORK

Until now, mainstream haptic technology and virtual reality research has focused on standard applications in medical, chemical, virtual design prototyping, immersive gaming and entertainment, *etc.* [4]. Virtual reality (VR) technology is increasingly used to support training and learning [5]. To attain more realism, most systems combine several forms of sensory stimulations including visual, auditory [6] and haptic feedback [7]. As shown in previous experiments, this approach can be efficiently used to train students in technical procedures [8], medicine [9], military strategy [10], occupational skills [11] or academic contents [12], *etc.* Morris *et al.* [13] have discussed the role of visio-haptic training applying to force skill learning, while Sewell *et al.* [14] investigated the transference of motor skills learned in a haptic-enabled virtual environment to performance.

Very little reported work has been devoted to the development of haptic simulations for VET. In 1976, Thompson *et al.* [15] and Sarwar *et al.* [16] proposed an algorithm to simulate the power hacksaw operation and investigated the effects of numerous machine parameters on the performance of the operation. Visio-haptic training methods for VET have been used to develop applications enriched with touch- and gesture-based technology to train operators of numerically controlled milling machines[17], welding[18], soldering[19] and fabric painting[20][21]. Bhavani *et al.* proposed a virtual media-enhanced vocational education curriculum incorporating a multimodal interactive learning approach to help people with limited education become sufficiently skilled to obtain gainful employment [22].

We describe a method for virtual haptic simulation for computer-based vocational education and training (CVET). The proposed model can track all relevant parameters for a given training exercise. The model provides audio, visual, haptic and performance feedback to the trainees, offering a realistic simulation of a workshop training session.

II. SYSTEM DESIGN

The virtual training setup is comprised of a computer with a visual display connected to the APTAH simulator fitted with the detachable hacksaw handle. The virtual reality screenshot shown in Fig. 2 is built on the open source Chai3D haptic API. The simulator provides tool position, stroke rate, time taken, and force applied in both forward and downward strokes. The user receives corrective feedback in the form of real-time audio, visual and haptic cues from the user interface. The simulator generates real-time feedback as well as evaluative metrics that are a function of the comparison between recorded data with the stored expert performance data in the system.

A. Visual Feedback

1. Visual interfaces

Two kinds of user interfaces are developed for the virtual training.

i. Tool selection interface (2d graphics)

The tool selection interface for selecting language, tools, and training modes (see Fig. 1) is handled by Adobe Flash. Once the trainee has selected the language, tool, exercise and training mode, the relevant training simulation interface appears. After the tool exercise is completed, a detailed result page is displayed.



Fig. 1 Tool selection interface for carpentry and plumbing tool simulations

ii. Training simulation interface(3D graphics)

The virtual workshop atmosphere integrates the visual, audio and haptic interactions between the 3D virtual models of tools and materials. The trainee can select the job material and tool type, and then control the virtual tool using the haptic simulator. The haptic simulator provides the trainee with accurate force feedback, vibrations and the feel of using the actual tool. Prior to this project, we developed haptic training simulation interfaces for tools including a hacksaw and hand file. The respective tool interfaces together offer a set of exercises used in training student plumbers to cut a pipe and then file it down as needed.

a. Hacksaw Training Simulation:

For the pipe-cutting exercise simulation for plumbing skill training, we created the virtual workshop for hacksaw training, as shown in Fig. 2. All the variables accounted for in a conventional pipe cutting training exercise as conducted in a real-world environment were replicated in the simulation interface. Inside a virtual workshop the hacksaw, blades, different pipe materials (PVC, copper, brass, GI) are on display, with navigation buttons to change blades and materials. The interaction between trainee and simulation is conducted with the use of the haptic simulator (for simulation)

and the mouse (for changing variables). The instructions to the trainee are given by both audio and messages displayed on the screen.



Fig.2 Hacksaw training simulation UI.

The trainee can select the pipe material from the tool bar and a pencil to draw the cutting position. After marking the cutting position, the trainee can select the pipe vise in order to secure the pipe in place. Then the trainee aligns the hacksaw blade with the marked line in the pipe and moves the hacksaw back and forth. In order to cut a groove in the pipe, downward pressure is applied with a backward motion using the haptic simulator. Once the groove is formed, the hacksaw is moved back and forth while applying downward force on the forward motion. After the pipe is cut completely, the pipe is shown to separate into two pieces, with the cut piece falling onto the workshop table. The evaluation screen is then displayed, showing the cutting speed, average downward pressure, deviation from the cutting mark, the number of blades broken and an aggregate final score for the exercise based on these variables. Depending on the pipe material selected and depth of the required cut, haptic feedback provided to the trainee varies in magnitude.

b. Hand File training simulation:

Filing is an integral part of the pipe cutting process wherein a hand file is used to file away burrs at the edge of the pipe that was cut using the hacksaw as shown in Fig. 3. The skills required for mastering the hand file are similar to that of the hacksaw.



Fig.3 Virtual pipe edge after cutting using the hacksaw.

With the pipe positioned vertically, proper usage of the tool entails keeping the file steady and parallel to the ground while applying downward pressure only on the forward strokes, with frequent visual inspection of progress.

This simulation immediately follows the hacksaw training application using the same pipe mesh that was cut as shown in Fig. 4. Trainees are taught the skills involved in filing including positioning the cut pipe in a bench vise, drawing a mark around the pipe surface that indicates the target depth to file down to, application of force only on

forward strokes, periodical visual inspections, and the maintenance procedure of cleaning the file using a metal brush during the filing process. Once the trainee files down to the marked line, performance feedback is provided on parameters including pressure, speed, and procedural skills.



Fig. 4 Hand File training simulation UI.

2. Visual guidance, assistance and cues

The system provides visual guidance, assistances and cues that provide helpful additional information to the trainee for skill development. The visual guidance includes step-by-step procedural instructions, error messages and safety information. Visual assistance indicating the desired depth of cut, length of cut, position of the tool and replacement of broken blades are all incorporated in the model.

Rhythm-of-cut cues: In hacksaw training simulation interfaces, visual cues include moving arrows to indicate the desired rhythm of cutting and markers to indicate the desired range of motion of the hacksaw. Colors are also used to indicate progress; the arrows are red until the hacksaw is used in the correct rhythm, at which point they turn green. By moving the hacksaw in alignment with the onscreen arrows, the trainee learns both the rhythm and the required length/range of motion to operate the hacksaw correctly.

Tool alignment cues: The same concept of color-based visual cues is implemented to impart the skills of tool alignment and the proper application of downward pressure. The cutting position, marked red initially, turns green when the tool is aligned correctly with it. The tilting or deviation of hacksaw tool from the cutting mark is indicated by the color change of the cutting mark.

Downward pressure cues: When the applied downward pressure is in the correct range, the tool handle in the interface turns from red to green. The trainees can adjust their downward pressure on the haptic simulator based on this visual cue. The trainee aims to keep all the above-mentioned visual cues in the green state. In this way, the trainee learns all skills required to perform this exercise successfully in a real-world environment.

Broken tool cue: To simulate the break of a tool or blade, the broken tool or blade is displayed visually and a red error message is displayed for five seconds.

Navigation buttons: A navigation panel implemented in the top right of the training interface helps the trainee to navigate through the virtual 3D workshop world.

3. Visual deformation rendering

For our visual deformation simulation we adapted the voxel/dexels-based algorithm [23]. An array of voxels/dexels is used to model the shape of the material. The surface deformation is simulated, at each update of the main

simulation loop, by modifying the arrays of voxels/dexels that are located inside the collision area, detected by collision detection algorithms. The modified portions of the arrays are set transparent or removed, which ensures low computation time. 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 limits the number of polygons to draw. With this simple rendering method, the frame rate of our application remains always superior to 50Hz.

B. Audio feedback

Sound is a fundamental cue that is often used during the vocational training task in the real-world environment. Our virtual training interface provides auditory feedback in order to increase the trainee's feeling of immersion. Two kinds of audio feedback are provided.

1. Audio instructions

Step-by-step audio instructions are integrated into each training task in the virtual training interface. Multiple languages are provided. The audio instructions are enabled for all procedures, error cases and safety features.

2. Audio effects

Audio effects are implemented for the main tool operations. However, for reasons of simplicity, we did not synthesize all the audio characteristics of real tools and machines. A limited number of sampled sounds were recorded and digitized from the real workshop environment. The sounds for the pipe cutting and filing and exercises are tailored to the blade, file, job material, feed rate and depth of cut. They are replicated with recordings matching actual case-specific conditions. After analysing the differences between the sounds with experts, a "free state" and "cutting state" were designated, and respective sampled sounds selected. These sampled sounds are modulated in pitch and volume to ensure a continuous variation of the final sound.

C. Haptic feedback

1. Haptic simulator

After an exhaustive analysis of all the tools used in the various vocational trades of the construction industry, we categorized and sorted the tools based on their properties and functions. Using this information, we designed APTAH, [3] a cost effective multi-tool haptic simulator that can train the use of 19 hand-held and power tools used in several vocations. The trainee can feel the force feedback and vibrations from the virtual training interface with the help of the haptic simulator APTAH, which consists of one active translational and three passive rotational degrees of freedom along the yaw, pitch and roll axes. APTAH has interchangeable handles and uses different VR interfaces to simulate different tools.

2. Haptic effects

Two kinds of haptic feedback effects are provided: linear force feedback and vibratory feedback. Linear feedback is achieved using a brushed DC maxon motor producing a maximum force of 40.22 N at the end effector. Vibratory feedback is produced by vibratory motors placed in the handles of the simulator.

3. Haptic rendering

The simulator moving position can be categorized in three states: at rest ($v = 0$), moving forward (+v,) and moving backward (-v). The force feedback algorithm receives tool position, collision detection, downward pressure, yaw, pitch and roll from the haptic simulator through the Ethernet communication driver. The effective force parameters and feedback are calculated and sent back to the simulator with a 1000Hz update haptic rendering loop, which generates forces using these parameters, providing the trainee with kinesthetic feedback of the haptic simulation.

D. Skill evaluation feedback

1. Procedural and Kinesthetic skills

In training mode, the simulation provides step-by-step procedural instructions as well as visual and audio guidance and graphical cues. When the trainee has completed the training mode, the simulation moves on to an evaluation mode, in which the simulation doesn't provide any audio-visual guidance or graphical cues. In this mode, the trainee is not guided by the virtual reality simulation, unlike the case of the guided virtual reality of the training mode. In both modes, the simulation tracks the trainee's procedural flow; kinesthetic skills including tool position, stroke rate, time taken; and downward applied force in forward and backward strokes. In training mode, these variables are all matched against the pre-recorded expert's data and corrected by real-time audio-visio-haptic feedback and graphical cues.

2. Safety skills

In the real-world environment of vocational training and vocational trades, a working understanding of safe practices is of paramount importance. Our model incorporates common error cases, and educates the trainee on safety features of the respective tools as well as safe practices. For example, in the hacksaw simulation, if too much pressure is applied on the downward side or if the hacksaw is tilted while cutting, the blade breaks. Using error cases and safety procedures, the simulation provides the requisite safety skill training for the vocational industry.

III. SYSTEM ARCHITECTURE AND PROCESS FLOW

After the study of individual tool characteristics, we identified the exercise steps that involve graphics and haptic interaction and the visual effects (for mesh deformation, particle effects), the requisite audio-visual-haptic cues and the essential UI elements. We developed a framework engine for developing the haptics simulations called Haptic Workshop Simulation applications using Chai 3D [24], OpenGL, QT and Microsoft Visual studio 2008 IDE. Using this framework engine, we can build any number of haptic simulations. The framework engine also helps to group, package and customize the tool simulations.

The system process flowchart for CVET haptic simulations as shown in Fig. 5 is a simplified framework that outlines the simulation process; each task box shown in the flow chart contains a detailed activity definition. The trainee can select the language, tool and exercise from the selection interface, which calls the corresponding exercise simulation interface.

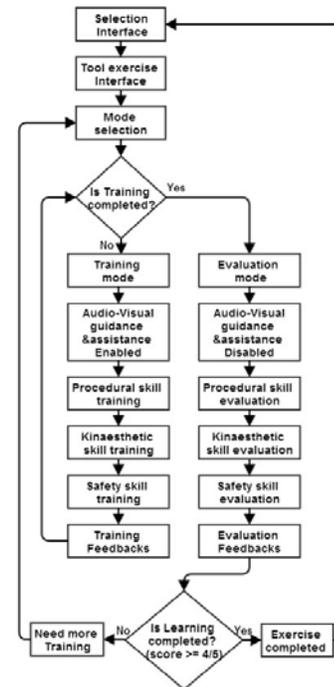


Fig. 5 Process Flow chart for CVET Haptic simulations.

As noted above, both training and evaluation modes have been implemented, wherein the training mode provides audio-visual guidance and assistance to the trainee, while the evaluation mode leaves the trainee alone with the tool and workshop simulations as a means to replicate the real-world testing environment. All skills needed for VET including procedural, kinesthetic and safety skills are imparted with audio-visual-haptic feedback, guidance and assistance. When the user trains on this system, position, stroke rate, time taken, and force applied in forward strokes and downward are recorded by the system and corrected by real-time audio cues and visio-haptic feedback. The corrections are based on the data recorded from experts using this system to perform the same simulated task. For example, in the case of hacksaw training, the skill parameters involved in cutting a pipe are measured, analysed in comparison with expert data and corrective feedback is provided.

Once the trainee has obtained a sufficient score in training mode, the simulation moves to evaluation mode, in which all learned skills are evaluated. Skill evaluation feedback effectively concludes the efficiency and quality of the task performed, similar to that described by Suzuki et al. [25]. Certification for skill proficiency can then be provided using the results obtained from the system after completion of the various trials.

IV. COMPUTATIONAL MODEL

The computational model for the haptic workshop simulation proposed here is approximate and provided sufficient accuracy to enable effective pipe cutting and filing exercise for plumbing vocational skill training with the custom haptic simulator.

A. Computational model for Hacksaw simulation

The hacksaw and pipe model in the virtual interface measures progress of a cut in terms of sawing forces and movements of the trainee and computes force feedback to be provided by the simulator. It addresses dependence of the force feedback on the applied downward force and on trueness of the cut. It also describes how yaw, pitch and roll motions affect the trueness of the cut. Here the x-axis is defined as forward-backward, the y-axis as right-left, and the z-axis as up-down. Roll (γ) is taken to be about the x-axis, pitch (β) about the y-axis and yaw (α) about the z-axis. A true cut is defined as a cut that follows a plane surface coincident with the intended direction of the cut, which would usually be the xz-plane.

Cutting rate depends on the downward force applied by the trainee F_D , the length of the cutting area l (the area of contact between bottom of the saw teeth and the material) and the total forward x-motion of the blade. Mathematically, the cutting rate is $\frac{\Delta d}{\Delta x_f} = \frac{k_D F_D}{l}$ where k_D is a constant that depends on the blade and the material (much smaller for steel than for plastic), Δd is change in depth of cut, and Δx_f forward only change in x-position for the saw.

Force feedback F_C resisting the sawing motion along the x-axis (forward-backward) has two components; the force feedback resisting cutting motion along the x-axis and an increase in friction (F_{rf}) due to a change in the roll or yaw angle of the cut, represented by

$$F_C = \mu_C F_D + \max\left(\frac{\Delta\gamma_w}{\gamma_{max}} k_{rf} w, \frac{\Delta\alpha_w}{\alpha_{max}} k_{rf} L\right)$$

μ_C is the frictional coefficient that depends on forward or backward motion, F_D is the downward force applied to the saw by the trainee, $\Delta\gamma_w$ is the total change in roll angle and γ_{max} is the maximum achievable curvature in roll over the last w distance along the depth of cut and depends of the stiffness of the normally flat blade, k_{rf} . Similarly $\Delta\alpha_w$ is the total change in yaw angle α , and α_{max} is the maximum achievable curvature in yaw over the last w distance along the depth of cut. Where k_{rf} must be determined in a manner similar to k_{rf} and L is the length of the cutting area.

Force feedback F_y along the y-axis (side-to-side) should be zero at zero cut depth, and then increase to $F_{y_{max}}$, the maximum the simulator can provide as the cut depends. It should reach $F_{y_{max}}$ by the time depth of the cut d reaches some critical value d_0 , which can be found experimentally. Initially we can try $d_0 = 2$ or 3 mm. Mathematically,

$$F_y = \min\left(\frac{d}{d_0} F_{y_{max}}, F_{y_{max}}\right)$$

The direction of the cut is always perpendicular to the cutting area, *i.e.* perpendicular to the area of contact between the material and the cutting edge of the saw blade. To avoid curvature in the cut, a trainee must carefully maintain a zero roll angle in spite of $\pm\gamma_0$ free play in the roll. If the cut becomes curved while in the free-play regime, the free play will be reduced by the amount of curvature,

$$\gamma_{free} = \min(\gamma_0 - \Delta\gamma_w, 0),$$

Where γ_0 is the free roll motion of the blade in the cut, given by $\tan \gamma_0 = (t_2 - t_1)/2w$ which depends on the width w and thickness t_1 and t_2 of the blade as shown in Fig. 6. Beyond γ_{free} in either direction, there should be torque feedback τ_γ resisting the applied roll torque, given by

$$\tau_\gamma = -\min(\tau_{\gamma_{max}}, \tau_{\gamma_{applied}} \min\left(\frac{d}{d_0}, 1\right))$$

Where $\tau_{\gamma_{applied}}$ is the roll torque applied by the trainee and $\tau_{\gamma_{max}}$ is maximum roll torque value, dependent on the simulator.



Fig. 6 The cross section of hacksaw blade.

Something similar happens when yaw torque is applied by the trainee. The yaw torque feedback τ_α is given by

$$\tau_\alpha = -\min\left(\tau_{\alpha_{max}}, \tau_{\alpha_{applied}} \min\left(\frac{d}{d_0}, 1\right)\right)$$

Where $\tau_{\alpha_{applied}}$ is yaw torque applied by the trainee and $\tau_{\alpha_{max}}$ is maximum yaw torque value, dependent on the simulator. The $-$ sign is because τ_γ is torque feedback, opposite to the applied torque.

If the cut becomes curved through application of roll and/or yaw torque by the trainee, there will be friction resisting a change in pitch. The pitch torque feedback needed to simulate this friction can be approximated by

$$\tau_\beta = L F_{rf} \max\left[\frac{\Delta\gamma_w}{\gamma_{max}}, \frac{\Delta\alpha_w}{\alpha_{max}}\right]$$

Where all quantities on the right are defined above in the sections on roll and yaw torques. The penalty for a trainee who manually overrides maximum torque feedback, either roll or yaw, is a broken saw blade.

B. Computational model for Hand file simulation

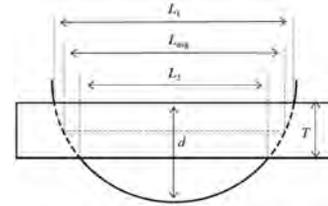


Fig. 7 The file contact with pipe.

This model covers progress of filing across the end of a vertically mounted pipe, in terms of forces and torques applied by a trainee, and force and torque feedback needed from the simulator for hand file simulation. It is assumed that ideal filing with a hand file is steady filing that files down to a marked line on the pipe surface. Filing rate depends on the downward force F_D applied by the trainee,

$$\frac{\Delta x}{\Delta t} = \frac{k_f}{L_{avg} T} F_D \min\left(1 - \frac{F_D}{F_{f_{max}}}, 0\right)$$

Where k_f is a constant to be determined by experiment, L_{avg} is the average length of the filing area, T is the width of file shown in Fig. 7 and F_{fmax} is the maximum possible force feedback in the filing direction. The frictional effect is increased for a longer and deeper filing. The force feedback in the direction of the filing is

$$F_f = \mu_f(F_D + w) + k_T T + \frac{\Delta\alpha_L}{\alpha_{max}} k_f L_{avg}$$

Where $\Delta\alpha_L$ is the total change in yaw, α_{max} is the maximum curvature of filing during the last L distance of travel along the file, and w is the weight of the file. The constants μ_f and k_T, k_f should be scaled to keep F_f below F_{fmax} .

V. CONCLUSION & FUTURE WORK

A preliminary evaluation of haptic VET simulations showed that vocational trainers could successfully use this simulator. It can be used to teach the basic principles of VET and in safer conditions, while also solving some of the fundamental problems facing the field today, including dearth of trainers and classroom environments, limited availability of materials for practice and training, and the remote location of many prospective trainees. Further most trainees are exposed to computers, broadening their horizons and instilling a sense of potential and self-confidence, which is of inherent value.

Future work deals with the design and development of more tools and vocational courses on this system. Further, the potential use of haptic VET simulations should be compared with the current use of real conventional training methods in vocational training courses.

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