Design and Evaluation of a Haptic Simulator for Vocational Skill Training and Assessment

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***Abstract*—While mainstream haptics has been focusing on training elite skills, the haptic simulator described in this paper addresses a problem with a phenomenal social impact that addresses teaching of vocational skills to the growing unskilled and impoverished populations in India. This is an unconventional attempt at designing a multi-tool haptic trainer that could potentially replace traditional training tools and materials in the primary stages of vocational skill training. 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 Amrita Progressive Training Assistance using Haptic simulation (APTAH), a cost effective haptic simulator that can train the use of over nineteen hand-held and powered tools used in several vocations. The simulator provides audio, visual and haptic cues that can help the novice master the use of the tools in the absence of a human trainer. This paper also discusses the preliminary trials conducted to study training effectiveness of the haptic simulator proposed.**

Keywords—Haptic interfaces, Force feedback, Vocational training, Educational technology, Knowledge acquisition, Interactive systems, Human factors, Human computer interaction

I. Introduction

Vocational education and training (VET) is quintessential to addressing the socioeconomic development of impoverished communities [1]. In India, VET is paralyzed by social stigma and a lack of trainers, materials, equipment, current technology, and quality training. Over 12 million people enter the workforce every year, while the accumulative capacity of training institutions can only handle training 3 million [2]. Additionally, while the Indian rural population is in the majority (nearly 80% of India), existing training institutions are concentrated within urban areas, out of the physical reach of rural and tribal communities [3]. Consequently, computerised VET remains the only scalable, portable and affordable solution to provide training to the unskilled population, especially located in remote areas [4].

While computerized VET modules involving video tutorials and multimedia enhanced interactive labs can address a significant aspect of the training [5], the actual knowledge of tool manipulation might be more effectively learned with the inclusion of haptic simulation training. Training on tools often involves perfecting manipulation of forces along a trajectory. The significant difference in vocational training is that the

Fig. 1. A novice learning to cut a pipe on the Aptah haptic simulator

tools used in vocational trades usually involve higher force feedback, large workspaces and lower fidelity. Morris et al. have discussed the role of visio-haptic training applying to force skill learning and its advantages over visual and pure haptic feedback [6]. The human adaptation to interaction forces [7], positive influence of haptics on human motor skill training [8] and effectiveness of haptic guidance [9] has been extensively studied. Based on their research, one may conclude that haptic feedback, as a value-addition to training although a plausible solution, must be carefully evaluated as the complexity of the tasks increases.

Training in areas like surgery [10] and aeronautical maintenance [11] using visio-haptics to improve skill has been received well and it may be extended to teach the tools used in vocational trades. Visio-haptic training methods for VET have been explored in numerically controlled milling machines [12]. While skill evaluation with the use of haptics has gained popularity especially in the medical field [13], certification of proficiency in tool handling in VET is currently limited to the skill of the trainer and its evaluation is subjective. One of the greatest benefits to introducing haptics in VET will be to provide the standard performance and evaluation benchmark. This opens possibilities to provide standardization in workmanship.

We have categorized 139 vocational tools and their characteristics in terms of movements, learning and forces. The justification for employing an approach using simulators in teaching was weighted by the following considerations: safety, tool and material cost, tool portability, time and trials required for skill acquisition, and the availability of trainers. Most tool movements do not necessarily require the six natural degrees of freedom and it is interesting to note that most tools are limited to less that four natural translational and rotational degrees of freedom. The force feedback for tasks performed using vocational tools is typically in the range of 10 to 80 N.

This paper discusses the design of a haptic simulator shown in figure 1, that would allow for simulation of a wide range of tools, compensate for the lack of trainers, and eliminate the necessity for expensive materials. This simulator has been used in combination with sensor based technologies [14] and computerized coursware for vocational skill training in India.

II. Device Design

Of the tools used in the building and construction sector including plumbing, carpentry, sheet metal fabrication, masonry and fitting, our preliminary studies shortlist about 19 different tools that require motor control for manipulation along a linear trajectory and force feedback of less than 38 N. Aptah consists of one active translational and three passive rotational degrees of freedom. The rotational degrees of freedom are along the yaw, pitch and roll axes. Aptah has interchangeable handles and uses different VR interfaces to simulate different tools. Aptah is designed specifically to simulate the tools that share similar motor movements. To facilitate this, the degrees of freedom have been restricted to those essential to the learning of the tools.

The velocity and force information of the novice's movements are recorded and then compared with existing stored profiles of experts to effectively conclude the efficiency and quality of the task performed, similar to that described by Suzuki et al. [15]. Certification for skill proficiency can then be provided using the results obtained from the system after completion of the various trials.

A. *Mechanical*

All the mechanical parts of Aptah were machined from LM4 aluminium casting alloy, which exhibits good corrosion resistance and can withstand high tensile stress of up to 280 N/mm^2. The device workspace is designed to accommodate a full stroke length (~ 600mm) commonly known as 'arms length'. The rotational angles corresponding to yaw, pitch and roll are 126, 80 and 180 degrees respectively and can be locked manually using pins based on tool being trained shown in figure 2.

In order to provide high stiffness in the design, we sought to avoid kinematic linkages between the actuator mechanism and the end effector. This will also facilitate the use of low-cost sensors. The linear guide system (Igus DryLin-N low profile linear guide, 27mm) carriage runs without lubrication in anodized aluminum profiles. It has a very low static frictional coefficient of 0.1, offers low inertia and can operate at 15m/s. The linear guide system is chosen for the translational axis as it requires less maintenance and it operates at speeds sufficiently surpassing the known dynamic range of the human arm.

B. *Actuation*

A brushed DC maxon motor with a nominal torque of

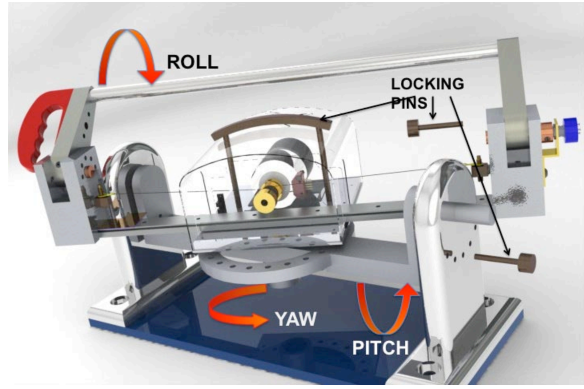

Fig. 2. Schematic showing the 3 degrees of rotation and corresponding axis locking pins of the Aptah device

362 mNm is fitted with a capstan of 18mm winding diameter, effectively producing a maximum force of 40.22 N at the end effector, has been selected as the actuator. The motor is coupled with the end effector using a cable drive system which provides back drivability and converts the rotation at the motor pulley into translational motion at the end effector. A tensioning mechanism at both ends of the cable prevents any slip and ensures no backlash.

The motor is powered by a current controlled amplifier controlled by a uni-polar PWM that is modulated by the desired torque input. The amplifier consists two BTN7960 half H-bridge motor drive ICs that are powered by a 12V power supply. The input PWM frequency is 10 KHz and has a resolution of 10 bits.

C. *Sensing*

The active axis translational motion is sensed by a US digital EM1-1-1800 transmissive optical encoder module with a resolution of 0.2 degrees/encoder tick, mounted on the motor shaft. The Euler's angles' motions are measured using three infinite turn precision potentiometers (Bourns 6639) that have an electrical angle of 340^o and a maximum backlash of 0.1^o. The advantages of using potentiometers are that they are low-cost, offer a suitable resolution of 0.79 degrees at the passive axes, and have a reasonable lifetime of 10,000,000 shaft revolutions. A homing mechanism comprising of a slotted opto-coupler and a slide switch that is fixed on the linear guide rail at the end effector end is used for locating the index position of the translatory axis. A 40 kg load cell with a precision of 0.02 is mounted on the base plate of the haptic device, and provides the reading for the downward force applied by the user.

D. *Control*

The control system implemented on the Aptah is a closed loop impedance control system [16] that includes a current sense feedback for torque control. The closed loop impedance control shown in figure 3 is implemented by sensing the current flowing through the motor and feeding it back to the controller. From the motor current, value the output torque delivered by the motor can be indirectly obtained.

$\dot{X}$ and X denote the velocity and displacement of end effector; F_e and F_d denote the virtual force computed by virtual environment and the force at the end of haptic device;

and $Z_d(s)$ is the desired environment impedance that receives the position information X and generates desired output force command F_e.

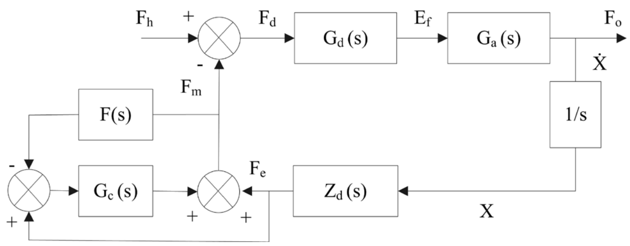

Fig. 3. Illustrates the closed loop impedance control system of Aptah

A first order filter $F(s)$ is used to suppress the high-frequency force component. The error between the virtual force F_e and the filtered force signal is given as input to the PID controller $G_c(s)$ and its output is added to the virtual force F_e to generate the control signal F_m. The force signal F_d that is a difference of the control signal F_m and operator force F_h is transferred via the driver $G_d(s)$ into a force-proportional energy form E_f. This energy is then altered into the output force F_o by the actuator $G_a(s)$.

For motor control and data acquisition from the sensors, a 32-bit MIPS microcontroller (Microchip PIC32) running on 3.2V at a clock frequency of 80 MHz is used. It has 5 PWM channels to control the motor and a 10-bit built-in ADC to read angular displacement measurements from the potentiometers. The encoder is connected to the change notification interrupt that decodes the optical encoder readings.

E. Communication Protocol

A USB interface acts as the communication channel between the device and the host PC. In order to simplify the implementation of USB on the microcontroller, a FTDI module is used that provides serial to USB conversion. The FTDI's virtual com port and direct drivers in figure. 4, eliminate the requirement for complex USB driver development.

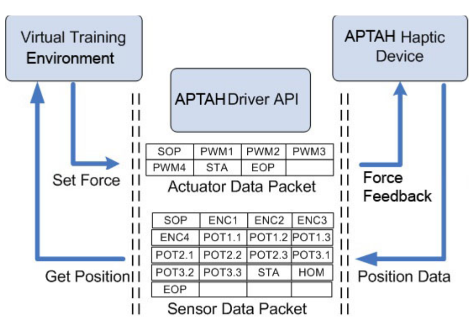

Fig. 4. Flow Diagram showing Aptah data packet transfer

F. Virtual Training Environment

The virtual training setup comprised of a 3.3 GHz computer running Windows 7 with a 17'' display connected to Aptah fitted with the detachable hacksaw handle. The virtual reality screenshot shown in figure 5 is built on the open source Chai3D haptic API.

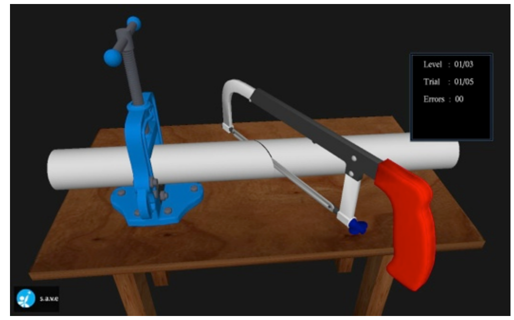

Fig. 5. Virtual Interface: pipe cutting using a hacksaw

When the user trains on the Aptah, position, stroke rate, time taken, and force applied in forward strokes and downward is recorded by the device and corrected by real time audio cues and visio-haptic feedback. The corrections are based on the data recorded from experts using Aptah to perform the same simulated task. For example, in case of hack saw training, the skill parameters involved in cutting a pipe is measured, analysed in comparison with expert data and feedback is provided.

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 device. It addresses dependence of the force feedback on the applied downward force and on trueness of the cut. It also describes how pitch and yaw 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.

Cutting rate depends on the downward force applied by the trainee, the length of the cutting area (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 F_D is the downward force applied to the saw by the trainee, l is the length of material actually in contact with the saw teeth, k_D is a constant that depends on the blade and the material, Δd is change in depth of cut, and Δx_f forward only change in x-position for the saw.

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

$$F_c = \mu_c F_D + \frac{\Delta\gamma_w}{\gamma_{max}} k_{rf} w$$

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 angle of roll without regard to the direction of the change over the last w distance in depth of cut. γ_{max} is the maximum achievable curvature per distance w along the depth of the cut and depends of the stiffness of the normally flat blade, k_{rf}. The penalty for a trainee who manually overrides maximum torque feedback, either roll or yaw is a broken saw blade.

III. USER STUDIES

A preliminary user study was conducted to study how effectively the device could train a person in using a particular tool. The tool we chose to simulate was a hacksaw. The critical learning parameters in the use of a hacksaw are the downward force, the stroke length, the rhythm, force in the forward direction and the lack of it in the backward direction. The parameters that contribute to learning the use of a hacksaw were taught using Aptah to the study participants before evaluating their performance on a real world task.

A. *Participants*

The study involved 16 participants, (4 female and 12 male) who had no prior experience in using a hacksaw. They were between the ages of 18-27 with a mean age of 22.25 years.

B. *Apparatus*

The height at which the device was placed was the same as that of a standard fitter's table so that the virtual workspace was identical to the real-life scenario. Participants with their height between 4ft 10 inches and 5ft 9 inches were selected, so that the device was comfortable to operate on and to limit a significant variation in the participants arm length. A 17'' LCD monitor and PC presented the participant with visual information and auditory feedback. A separate apparatus consisting of a single point load cell (max. load: 60kgs) and a National Instruments data acquisition system was used to measure hacksaw cutting forces on a polyvinyl chloride (PVC) pipe.

C. *Training*

Two certified experts were asked to cut the virtual pipe using Aptah and their motion data was recorded. The participants (here on referred to as novices) were divided into 2 groups: the control group who recieved conventional training to use the hacksaw, and the experimental group that was trained on the Aptah simulator. Each group consisted of 8 novices each. All the novices were first given to watch an introductory video tutorial explaining the use of a hacksaw.

The control group was given a piece of pipe that was held in place by a bench vise and they were asked to cut a length of the PVC pipe. The time taken and the score equivalent to the quality of each cut (performance quality score provided by certified expert) across six attempts were noted. These two parameters are what is typically noted to evaluate one's skill with a hacksaw.

The experimental group was trained first on the device with the virtual interface and their hand movement data recorded. (See graph) After every trial their data was compared to that of the experts. When the plots of their data were comparable, they were moved to the real scenario, given the same task that was given to the control group and their performance was similarly evaluated.

IV. RESULTS

Data acquisition from our prototype model is limited to position vs. time data and direction of the sawing motion. The expert data exhibits a regular sinusoidal sawing motion, see figure 7, utilizing the full length of the saw, while the motion recorded by a novice was found to be irregular and utilizing only a portion of the available saw length, as evidenced by smaller displacement amplitude variations and a less sharply peaked power spectrum.

Figure 6 shows the sawing motion of a novice's first, second and third trial. One can immediately see that the motion in trial 3 is more uniform than that in trial 1 and trial 2.

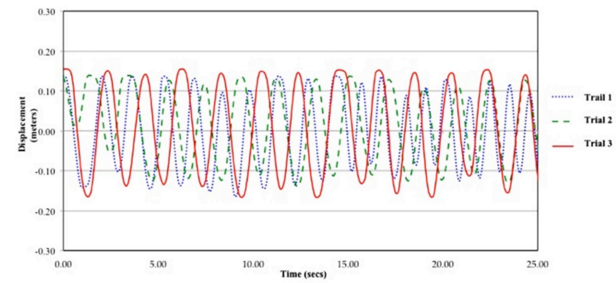

Fig. 6. Graph showing novice's stroke displacement plotted over time

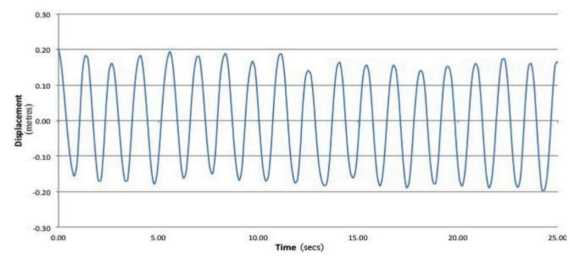

Fig.7. Graph of the expert's stroke displacement plotted over time

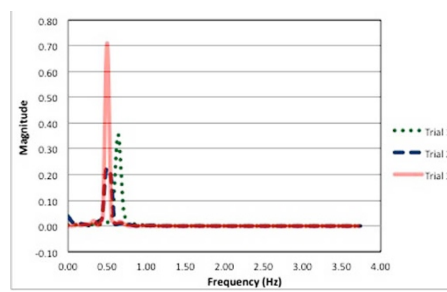

Fig.8. Power spectrum of a novice over 3 trials

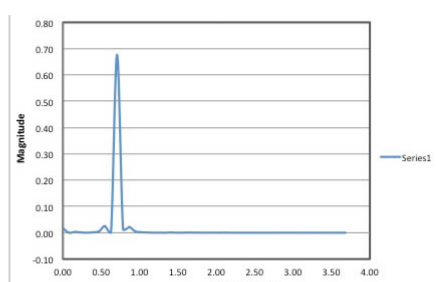

Fig. 9. Power spectrum of an expert cutting data

The power spectra confirm this, in that the single peak in trail 3, in figure 8, has an amplitude almost twice that in trial 1. This is due to the frequency of the sawing motion in trial 3 being relatively constant when compared with the motion in the first two trials.

In figure 9, we note that by the same criteria that the expert starts out with a more sharp narrow peak as compared to the novice. We believe that these preliminary results justify the use of our proposed criteria in a wider study with more subjects.

For those who were in the control group, at the end of their last attempt their cutting force was measured using the load cell apparatus and plotted. Similar measurements were made on the experimental group. The results of both were compared against the cutting force values of the experts to estimate correctness in technique.

A. Hacksaw Pipe-cutting Evaluation

Objective: To conduct statistical tests that may aid in answering the following questions:

- Do the prior practice runs on Aptah enable a reduction in the average time to cut pipes using an actual hacksaw?
- Is the average time to cut a pipe significantly different for people trained on the device versus those trained on actual hacksaws?
- Is the average performance (quality of pipe-cut and technique of using hacksaw) significantly different for people trained on the device versus those trained on actual hacksaws?

B. Analysis Result

The paired t-test is used to compare the average pipe-cutting time across 3 trials for each person when using Aptah versus the average time across 3 trials when using an actual hacksaw, shown in Table 2.

TABLE I. PAIRED T- TEST FOR HAPTIC VS ACTUAL HACKSAW TRAINING

	N	Mean	StDev	SE Mean
Aptah	7	8.00476	0.85579	0.32346
Actual_Hacksaw	7	8.01905	0.62059	0.23456
Difference	7	-0.014286	0.561366	0.212177

95% CI for mean difference: (-0.533463, 0.504892)
T-Test of mean difference = 0 (vs not = 0): T-Value = -0.07;
P-Value = 0.949

V. CONCLUSION

Since the p-value is large (>> default level of significance 0.05), we cannot conclude with confidence that there is no significant difference in the average pipe-cutting time for each person trained on Aptah versus an actual hacksaw.

The study involves the statistical method of ANOVA for "Nested Designs". The response is pipe-cutting time taken or the score obtained, the "novice" variable is a random variable, and this variable is nested with the treatment "Group" which has the two levels of "Experimental" and "Control".

In the analysis of time taken, the p-value for "Group" is 0.26 which is much greater than the default level of significance (0.05), and hence (as per normal procedures of statistical hypothesis testing) we cannot conclude that the average pipe-cutting time for novices trained on the device is not statistically different from the average pipe-cutting time for novices trained on actual hacksaws. In other words, the training on Aptah is not same as the conventional training (with respect to average pipe-cutting time).

A visual comparison of the data is shown below to support the numerical analysis is shown in figures 10 and 11.

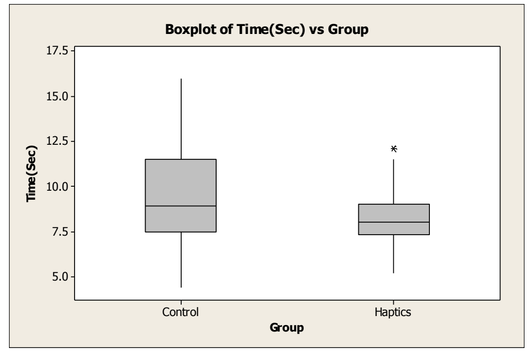

Fig. 10. Box plot of time taken for performance of Control vs Experimental group

In the case of Score obtained, the p-value for "Group" is 0.542 which is much greater the default level of significance (0.05), and hence (as per normal procedures of statistical hypothesis testing) we cannot conclude with confidence that the average pipe-cutting Score for novices trained on the Haptics device is not statistically different from the average pipe-cutting time for novices trained on actual hacksaws. In other words, the training on Aptah may or may not be as effective as the conventional training (with respect to average pipe-cutting score).

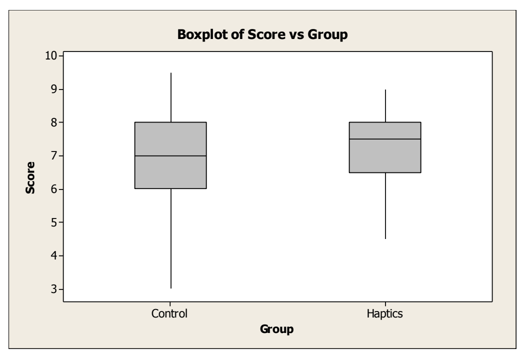

Fig. 11. Box plot of Data for performance of Control vs Experimental group

An additional feature to be observed from the plot is that the novices trained on the device achieve a more consistent quality of pipe - cutting.

VI. LIMITATIONS

The device holds the potential to provide more consistent training experience to the user. Being limited in its force feedback to just one axis is an advantage as well as a limitation. While the design allows for reduced cost in manufacturing which would be a critical factor in a large-scale deployment and it does away with any 'unwanted' degrees of freedom that may distract a novice, it excludes some of the tools that could potentially be added to this system. Translational motion in just one more axis if incorporated, would allow many more tools to be simulated using the same device. Rotational tools cannot be effectively simulated because of the lack of force feedback in the rotational axes. The potentiometers used are low-cost sensors but have a limited lifespan of only one million turns. The the metal used for handle fabrication dampens tactile sensations.

VII. Future work

Aptah can be improved upon by addition of more translational degrees of freedom with effective force feedback. It can be modified to accommodate a rotational tool simulator in the same device. Also contactless rotational sensors can be explored as a viable option. Future modifications include an adjustable table height and motors on the Euler's axes.

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