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Infrared Powered Vibro-Haptic Piano Training System for the Visually Impaired

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Abstract

The proposed system uses an infrared enabled haptic glove which is programmed for a fast paced learning of the piano for the visually impaired. The system provides haptic cues to the player facilitating the spatial knowledge of the key to be pressed along with the finger to be used.A string of Infrared (IR) devices are positioned over the keys of the piano. Each IR device corresponds to the individual white and black keys, which are configured to be activated by electrical signals synchronized with the musical notations. The tactile-actuators on the glove are excited as soon as the correct key and user's fingers are aligned. It facilitates spatial Passive Haptic Learning (PHL) of the user. A group of 7 visually impaired participants were selected, at a local music studio for one month, 3 of them used the proposed system, whilst 4 of them learnt the traditional way with the instructors.The findings demonstrate that multisensory PHL provides a rich and vivid learning experience and a shorter learning curve with increased efficiency.

Keywords: *Soft Computing, Training, PHL, piano, tactile, vibro-haptic, visually impaired.*

1. Introduction

Haptic feedback can rather prove to be a very effective tool for learning and rehabilitation. It has been observed that certain skills need rigorous practice in order to be able to perform considerably. One of those skills is playing the piano. Although the process of piano playing finally boils down to the reflexive hand movements of the player, yet, during the initial learning phase, the vision is very important to see which key needs to be played.

The proposed system, tries to bridge the gap between a visually impaired user and the ability to see/ascertain the position of the piano keys, by virtue of providing real-time vibro-tactile feedback to the player. The system consists of two major parts: First part is a glove device embedded with a microcontroller, 5 flex sensors (one for each finger), IR receiver and 5 micro vibration motors.Second part is an array of IR emitters mounted on a strip, which is placed on top of any regular piano and connected to a host computer/smartphone.The host computer plays a sound and activates the IR emitter placed on top of the corresponding key. As soon as the player floats his/ her gloved hand over the correct key on the keyboard, he/ she receives a vibratory stimulus and thus instantly knows the right key to play.

This augmented cognition, enables the user to learn the keyboard faster and remember the distances between keys more efficiently. It’s just like adding two supporting wheels on a bicycle while a child is learning to ride a bicycle, and removing them once the child is confident. This provides a seamless learning curve and facilitates the natural learning process [1]. The proposed system prompts a vibro tactile feedback and facilitates the user to hit the right key with the correct finger, while trying to learn a song on the piano.

2. Passive Haptic Learning and Related Work

2.1 Passive Learning

According to H. E. Krugman and E. L. Hartley [2], passive learning is typically effortless, responsive to animated stimuli, amenable to artificial aid to relaxation, and characterized by an absence of resistance to what is learned, thus opening up possibilities that, depending on one's point of view, one may welcome or deplore. A complete book [3] on piano playing with discussion of practice methods, use of the pedal, playing pieces, and other rules has been written. Passive haptic learning inspires the user to develop what is called a “muscle memory” [4]. This muscle memory is highly useful to do repetitive tasks with high levels of dexterity, from typing to playing a piano or playing a guitar or even driving to an extent. All of these tasks are enhanced and made more efficient by an effective “muscle memory”.

Passive Learning is the type of learning that occurs while not actively trying to grasp the skill. For example, piano playing in which the grasping of the new knowledge for long term retention requires dedicated practice else the player starts to quickly forget as soon as the person stops active learning [1].

2.2 Haptic Interfaces

In the field of haptic devices, many such interfaces have come into the modern parlance. A multimedia system has been described [5] for learning handwriting and pronunciation of alphabet letters or characters in different languages. The system provides haptic, audio and visual information according to the desired letter or character chosen by a user. A device [6] is proposed to study the effects of physical guidance on percussion learning. The first system, called the FielDrum, uses a combination of permanent and electromagnets to guide a player's drumstick tip through the motions involved in the performance of arbitrary rhythmic patterns. The second system, called the Haptic Guidance System, uses a servo motor and optical encoder pairing to provide precise measurement and playback of motions approximating those involved in snare drum performance. Experiments [7] were conducted to improve visuo-manual tracking of Arabic and Japanese-inspired letters and untrained ellipses based on the two types of haptic guidance - control in position (HGP) or in force (HGF) – based on psychophysics laws of movement production. Human-human haptic collaboration [8] to understand how haptic information is exchanged is investigated. They introduced WYFIWIF (What You Feel Is What I Feel), a haptic communication paradigm. This paradigm is based on a hand guidance metaphor. The paradigm helps operators to construct an efficient common frame of reference by allowing a direct haptic communication. Passive Haptic Rehabilitation (PHR) [9] is possible using vibrotactile stimulation of the hands in persons classified as tetraplegic due to incomplete spinal cord injury. A training aid [10] is introduced to facilitate the learning of touch typing. The system also uses electro-neural finger stimulation to enhance learning of the correct finger key associations.

2.3 Philosophy behind the Research

The sense of touch is indeed a very rich sensory input which can facilitate the multisensory learning paradigm, [11]. R. C. Atkinson and R. M. Shiffrin in 1968 in their paper proposed that there were three aspects to the human memory: “The Sensory register”, “The Short term store” and “The long term store”, [12].

The Sensory register is taken to be rich, vivid and large yet very short lived. Sensory inputs here tend to only last from .25 to 2 seconds before getting erased from the memory. Here some amount of human attention is required for the memory to be graduated to be saved onto the short term memory which lasted about 5 – 20 seconds. However for the memory to be graduated to storing in the long term store, rigorous rehearsal and practice is needed [12].

Multisensory input based learning is more vivid, rich and longer retained [13]. In a research in 2002, Molholm showcased that how multisensory inputs and learnings were processed and treated by the human brain with respect to unisensory inputs. They demonstrated how multisensory inputs and learnings worked on different topographies of the brain and the reaction time for the multisensory inputs were faster than unisensory inputs, [14]. Schoonderwaldt explored successes of teaching the violin playing by Passive haptic learning, [15,11].

3. The Proposed System

The proposed system tries to leverage the benefits of passive learning to the visually impaired by providing a Haptic interface. The proposed system augments the concept given by Zukin & Snyder [4], which helps the visually impaired user who wants to learn the piano. This system facilitates muscle memory development to quickly remember the piano keys with respect to their relative positions on the keyboard. Thus, this paper analyzes and verifies:

1. The effectivity of PHL paradigm helping visually impaired subjects to learn a new motor skill (in this case playing a piano).
2. The impact of the PHL paradigm in short term and long term skill retention.
3. The effectively of haptic feedback/guidance with respect to other non-haptic cues.

The skill of piano playing on a physical level consists of two major inputs for the learners. (Casio Song Book [1])

1. Which key to play (w.r.t. the notes).
2. Which finger to use in order to play the key (to maintain the fluidity of the music).

The system uses four a step architecture. Refer Fig. 1.

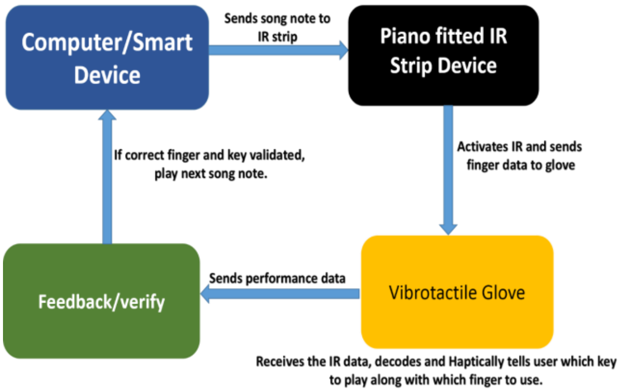

Fig. 1: Four step process involved in the proposed system.

Step 1: This step involves a host, which can be any digital computer or even a smartphone. The computer is fed with a sheet music along with a corresponding MIDI file. The computer reads the MIDI file and plays the first few notes on the computer as a sample for the user to listen and thus try and replicate on the piano. Once the notes are played (audibly on the host), the same notation of keys and the respective finger data is sent to the IR strip controller placed on the keyboard.

Step 2: In this step, an array of Infra-Red transmitters, attached on a strip/belt referred to as the “IR strip” is activated, which holds an IR transmitter for each key of the piano. This IR strip is powered by a microcontroller and is connected to the computer via serial communication. This microcontroller receives the key and finger signals from the host computer. As soon as the key data is received, the IR transmitters start to activate corresponding to the key data. The IR codes that the transmitter transmits are based on the finger data sent by the host computer. See Fig. 2.

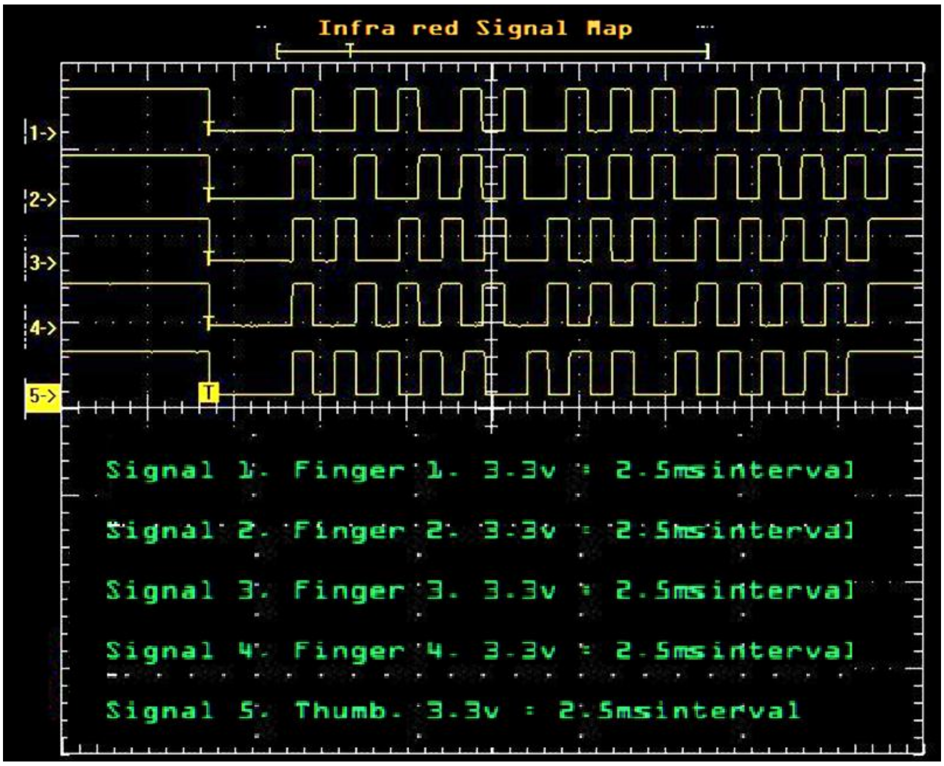

Fig. 2. An oscilloscope/visual representation of the 5 IR codes corresponding to the 5 fingers, transmitted by the IR strip and thus received by the haptic glove to identify which finger to vibrate.

Step 3: In this step a haptic glove (evolution of the glove design and other considerations discussed in Section IV) is worn by the user (refer Fig. 3), and user starts to glide his hands over the piano keys, until he/ she comes across the correct key, which has an IR transmitter firing. As soon as both glove and correct key come in line, the IR receiver mounted atop the haptic glove (refer Fig. 4) receives the IR signal and thus decodes the signal and actuates the vibrator on the particular finger depending on the finger code. This instantly notifies the user of two things,

1. The key to play (the key right in front of the hand)
2. The finger to use in order to play the key (as that finger is already vibrating due to the finger code)

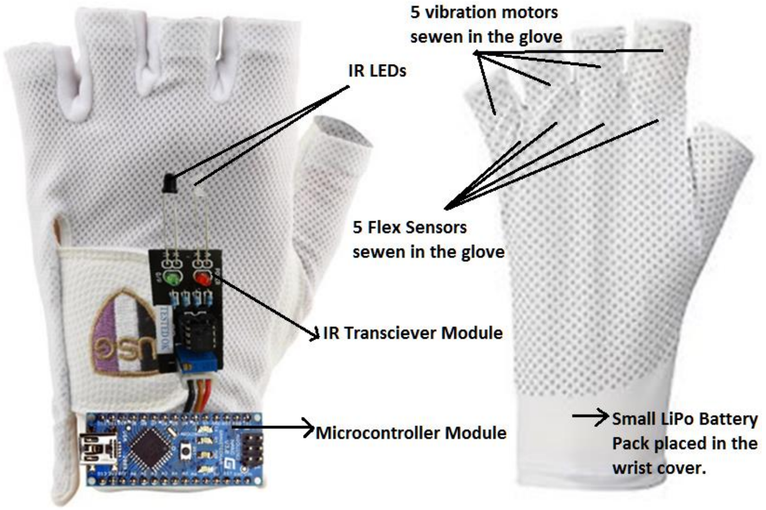

Fig. 3: The haptic glove device.

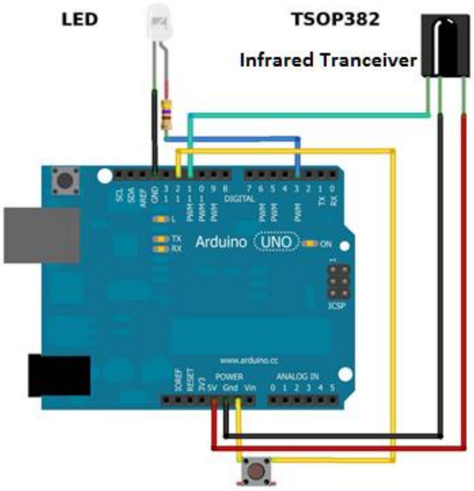

Fig. 4: Block diagram of an IR transmitter receiver circuit.

Step 4:

Here, the user action is validated and either the system chooses to wait until the user hits the correct key with the correct finger, or moves on to the next key if it senses a correct key press. This system works by utilizing the flex sensors on the glove. Refer Fig. 5-6. This is done by evaluating the values from the flex sensors and the IR-GLOVE alignment. This process provides rich haptic feedback and inspires learning a quicker, more effective permanent muscle memory development.

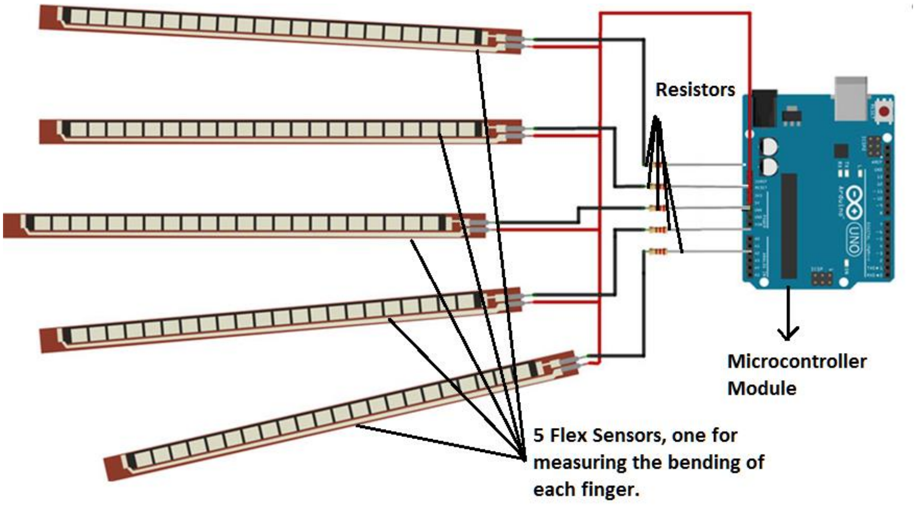

Fig. 5: Block Diagram Circuit implementation of the flex sensors in the proposed glove system.

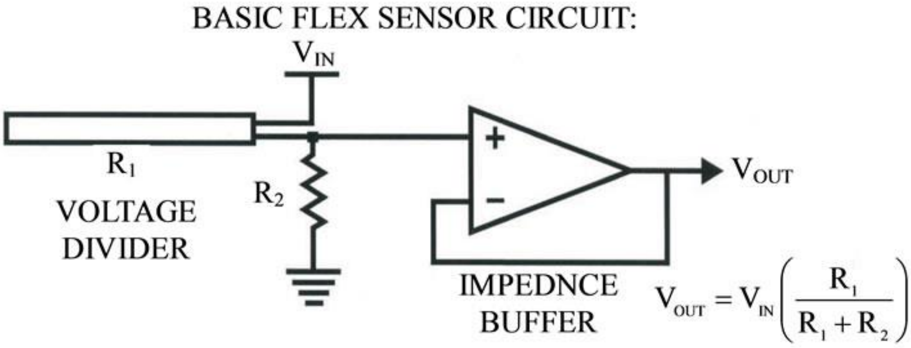

Fig. 6: Basic flex sensor circuit diagram.

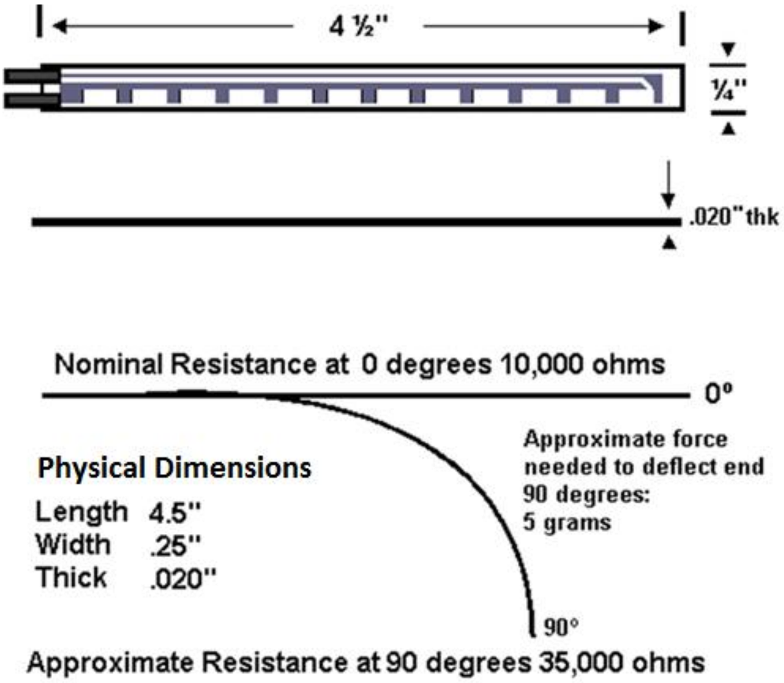

Fig. 7: Working of the flex sensors in the proposed system.

4. Construction and System Components

There are three basic constituents required to build the system:

A. Infra-Red module strip

This strip is the core backbone of the key identification system. It consists of multiple IR modules mounted on a strip, which is thus affixed on any piano. This strip can be used with any existing piano/ electronic keyboard. The construction of the IR LED strip consists of a power source, microcontroller such as Arduino MEGA 2650 and the individual IR LED modules. The IR LED strip is attached above the piano keys at right angles so that whenever the gloved hand comes in line with the IR, it is able to transmit the code to the glove. Refer Fig. 7-9.

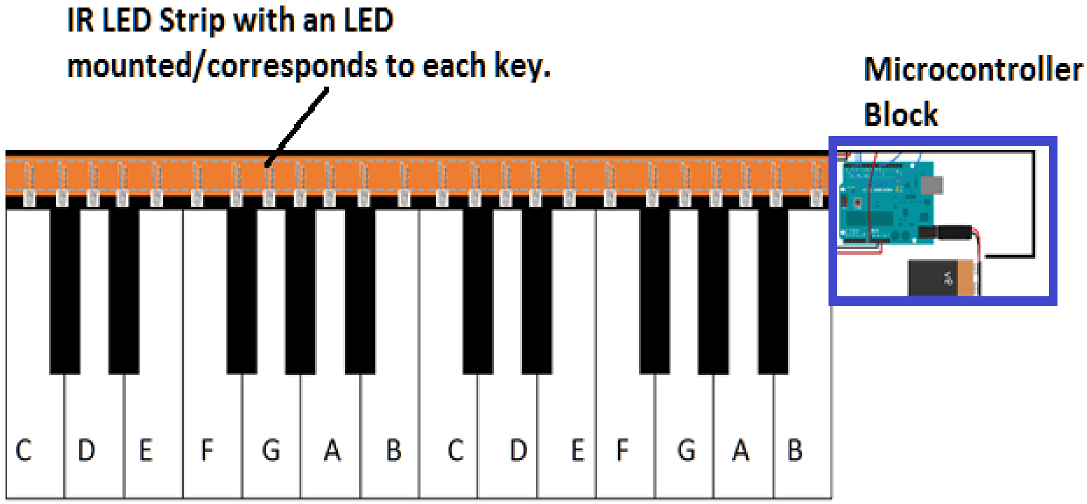

Fig. 8: Block Diagram showcasing the basic idea of arrangement of the IR LED Strip with IR LEDs pointing from each key.

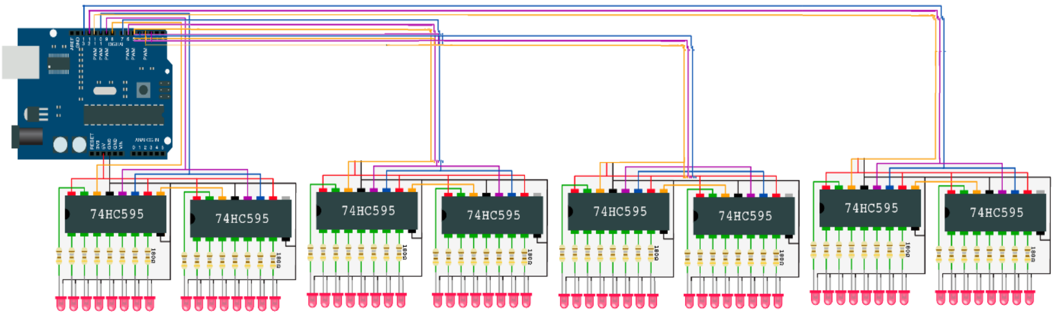

Fig. 9: Block Diagram/Visual representation of IR LED Strip with IR LEDs pointing from over the top of each piano key, connected with a microcontroller using shift registers.

B. The Haptic Glove:

The glove was subject to a major design considerations as it had to be worn for long hours and a fully covered glove could prove to be invasive in nature. Thus the final glove is the result of optimizing the initial glove based on feedbacks from participants based on questions about, comfort of the gloves, long term wear ability, amount of invasiveness in terms of the natural touch with the piano, fatigue, how much /or less the vibration needed to be in order to be just enough to perform without intruding much in the natural flow of the player and some free text generic feedbacks.

The vibro haptic glove consists of: (Refer Fig. 3)

a. Microcontroller: the brain of the system.

b. Bluetooth module: to connect to the computer for verification of correct and incorrect key press.

c. Flex Sensors: to detect the bending of each finger and assimilate which finger has been pressed. Flex sensors vary resistance on the basis of the amount they are bent. At a normal unbent position, the resistance is around 10000 ohms, however while it is bent, the resistance starts to change reaching almost close to 35000 ohms. Each flex sensor is approximately 4.5 inches long and .25 inches wide. This data is analyzed and sent to the computer for further action. Refer Fig. 4-7.

d. 5 micro vibration motors: one for each finger to "haptically" notify the user of which finger to use to press the corresponding piano key.

e. A battery module: to power the glove.

f. IR Receiver: An Infra-Red receiver module to receive infra-red signals transmitted by the IR LED strip and ascertains the piano key to be pressed.

C. A digital computer or a smartphone

This is required to connect to the piano mounted Infra-Red (IR) strip, communicate with the vibro-haptic glove, and receive signals from the glove mounted flex sensors to assimilate if the correct key and finger combination was pressed so that the next note can be played. Refer Fig. 10.

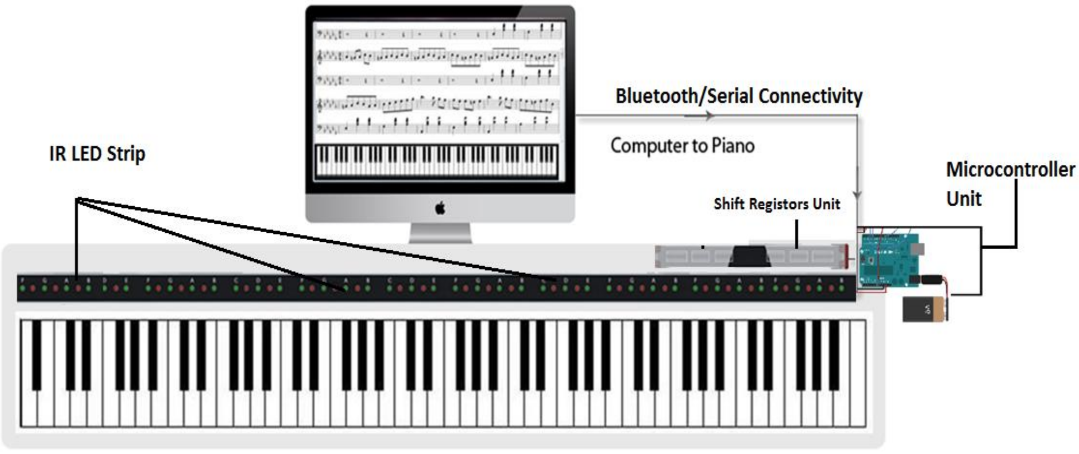

Fig. 10: Visual Representation showcasing the basic idea of the Computer to IR strip connectivity.

4.1 The Roadmap of the Study

The proposed roadmap of the study to test the effectiveness of the PHL paradigm and its impact on the Mid Term and Long Term retention of the skill is mentioned as following:

- Build a prototype for evaluation of the system and its effectivity.
- Find suitable candidates. (Similar aged, visually impaired, gender balanced, no prior knowledge of piano playing)
- Divide the candidates into two groups. (One group would learn by PHL, while the other learns in the conventional way of instructor led training for a comparative analysis.)
- Train both groups of candidates for a period of 4 weeks.
- 1st Level of evaluation to be conducted every week for both groups. (Showcasing the efficiency of the learning curve, and ease/difficulty of learning.)
- 2nd Level of evaluation testing to be done post 1 month of completion of training, assimilating the Mid Term retention data results.
- 3rd Level of evaluation testing to be done 6 months post the completion of trainings, ascertaining the Long Term retention data results.
- Compare the findings and deduce any visible/computable patterns.

5. The Experiment and the Test of Applicability

The experiment was conducted with 7 visually impaired participants who were visually students and had recently joined a Piano class in a local blind school (Avg. Age: 14.42, Standard Deviation of Ages: .975). All these students were starters, and had no prior knowledge of piano playing.

These students were divided in to two groups for a comparative analysis, thus 3 students were randomly identified to be trained with the proposed PHL system, while, the remaining 4 students were to continue learning by the conventional way of an instructor led tutoring. Both the batches had the same curriculum for the month, which were the basic three songs from the Casio Song Book [1].

There were three levels of testing and evaluation:

1. Level 1: Test of performance during the training: This testing was conducted weekly for 4 weeks to provide insightful data on the adaptability of the system and early training results, along with the comparative data.
2. Level 2: Test of performance was conducted post 1 months of conclusion of training to evaluate the mid-term retention of the system

3. Level 3: Test of performance was conducted post 6 months of conclusion of training to evaluate the long-term retention of the system

The Dynamic Time Warping Algorithm (DTW) was used to assess the performance in comparison to the pre fed sequences of sheet music. The DTW helps in comparing the sequence with no impact of time variance. The DTW was used twice on each sequence of keys/notes, the first pass to assimilate the errors of key presses, and the second pass to assimilate the time variances to evaluate errors based on missed rhythm. This mechanism helped to evaluate errors of insertion, substitution, and deletion.

The DTW works on the costs associated with the encountered errors and tries to minimize the costs involved tracing the most optimal mapping between the two given sequences. See Fig. 11.

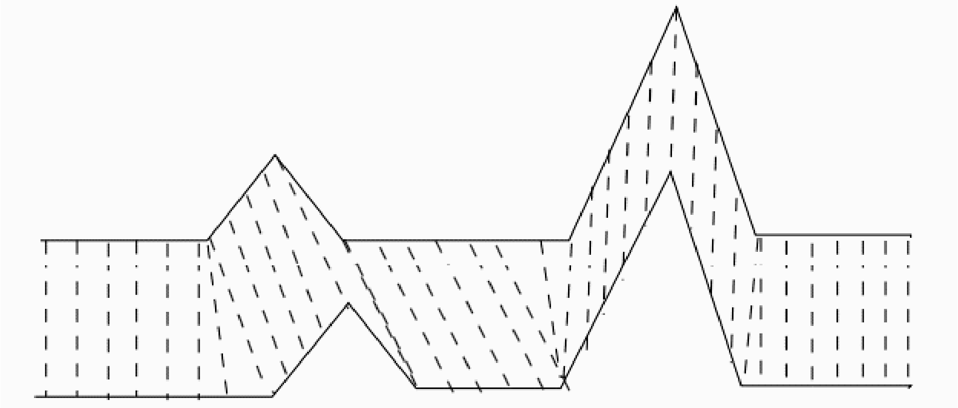

Fig. 11: Visual representation of the DTW sequence mapping

The proposed experiment implements the following costs:

1. **Cost of space in the 1st Phrase: (C_{S1})**
2. **Cost of space in the 2nd Phrase: (C_{S2})**
3. **Cost of the note difference: (C_N)**

All types of possible errors of playing the piano (insertion, omission, substitution of the keys) were considered equal and denoted with 1 as the numeric value. This valuation uses a similar predication to the ISO speech recognition accuracy standard.

A typical scenario:(Happy Birthday Notations)

Original Correct Sequence:
G G A G C B. G G A G D C. G G G^ E C B A. F F E C D C.

Actual Performed Sequence:
G G A G B B. G G A - D C. G G G^ E C B A. F F E - D C.

In the above mentioned scenario, the 1st sequence is the way the song should be played correctly and the 2nd sequence is an attempt by a learner, It can be observed that in this case the participant's error score would be 3, as the user substituted B in place of C in the first segment, omitted the G in the second segment, omitted the C in the fourth segment. All errors account for 1, thus 3 errors would give a score of 3.

6. Test Cases and Observations

The Casio song book [1] has been taken as reference. The Casio song book defines multiple songs to be played on the piano, including the fingers to be played and their corresponding notations. All the songs in the book are ranked and graded from difficulty perspective from A to E, where A refers to a complete novice level song whereas E represents an expert level song.

For test purposes, B level (advanced beginner) songs were selected and all 7 subjects were asked to play the song. These tests were conducted weekly for 4 weeks, and one post one month to validate the Mid-Term retention of the skills and another test 6 months post the training to evaluate Long Term Retention of the skills. While 3 participants practiced for 60 minutes every day for 30 days on the proposed system while the other 4 participants attended the conventional classes of 60 minutes daily.

Initially during the first week, both sets of participants appeared to be on a similar skill level, the errors also appeared to be on an equivalent scale The initial slowness by the PHL group could also be credited to the effort of adapting to a new methodology of learning and calibrating to Haptic feedback and the intrusiveness of the glove itself.

However, with each passing week, there were improvements in both the sets but the PHL group started showing faster decline of average DTW errors till the fourth week this difference was about **33%**. Wherein the Conventional group's DTW errors fell by **34.31 % from day 1** and PHL group reduced the errors by **66.46%** with an enhancement over the prior by **193%**. Test results of the same are given in Table 1. (See also, Fig. 12-13).

Table 1: Song 2; My Darling Clementine; Level B

Type	Name	Week	AVG DTW error
PHL	Participant 1	1	4.5
PHL	Participant 2	1	3.96
PHL	Participant 3	1	3.7
PHL	Participant 1	2	4
PHL	Participant 2	2	3.4
PHL	Participant 3	2	3.33
PHL	Participant 1	3	3.1
PHL	Participant 2	3	2.79
PHL	Participant 3	3	2.8
PHL	Participant 1	4	2.7
PHL	Participant 2	4	2.5
PHL	Participant 3	4	2.1
Conventional	Participant 1	1	4.4
Conventional	Participant 2	1	4.2
Conventional	Participant 3	1	3.9
Conventional	Participant 4	1	3.88
Conventional	Participant 1	2	4.1
Conventional	Participant 2	2	3.8
Conventional	Participant 3	2	3.66
Conventional	Participant 4	2	3.76
Conventional	Participant 1	3	3.5
Conventional	Participant 2	3	3.43
Conventional	Participant 3	3	3.12
Conventional	Participant 4	3	3.3
Conventional	Participant 1	4	3.12
Conventional	Participant 2	4	3
Conventional	Participant 3	4	2.96
Conventional	Participant 4	4	3.1

The table enlists the participant’s performances over the weeks with respect to the corresponding average DTW errors.

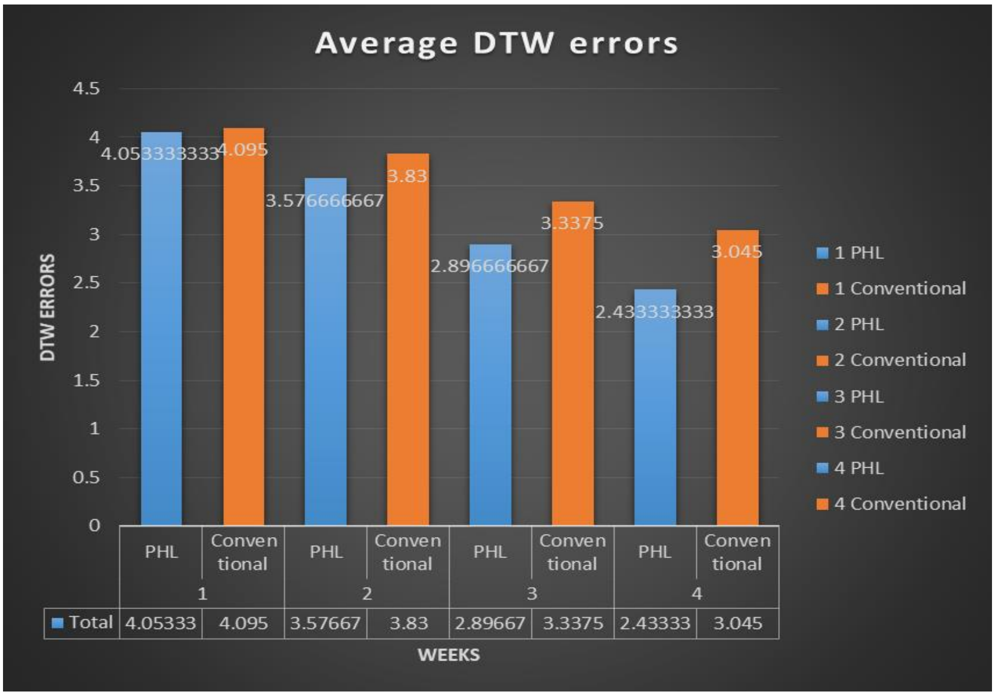

Fig. 12: A Comparative Number of mistakes by participants on a weekly basis, showcasing a steeper decline of errors by the users learning through the proposed system as compared to the students learning conventionally.

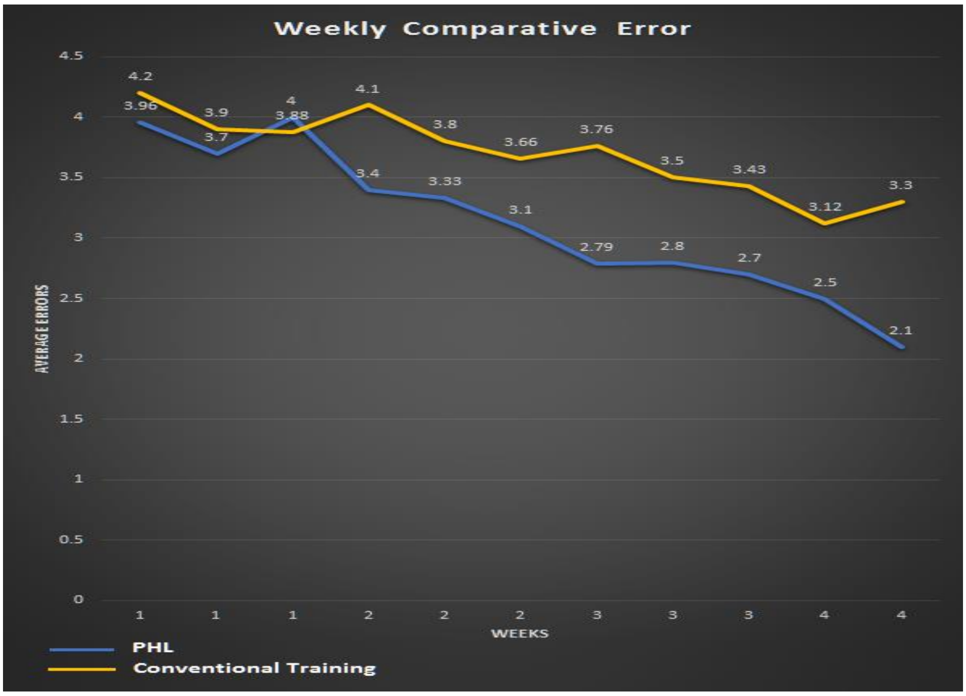

Fig. 13: A Comparative DTW error graph over the period of 4 weeks.

6.1 Mid Term Skill Retention

A similar test was taken with the same set of students post 1 month of their training completion. See Table 2.
It was observed that the PHL students showcased greater retention and far less DTW errors. On a comparative scale, PHL students showcased **52.8% less errors.** See Fig. 14.

Table 2. Showcases the Average DTW errors post one month of training

Type	Name	Months Post Training	AVG DTW error
PHL	Participant 1	1	2.8
PHL	Participant 2	1	2.9
PHL	Participant 3	1	2.4
Conventional	Participant 1	1	4.12
Conventional	Participant 2	1	3.9
Conventional	Participant 3	1	3.4
Conventional	Participant 4	1	3.9

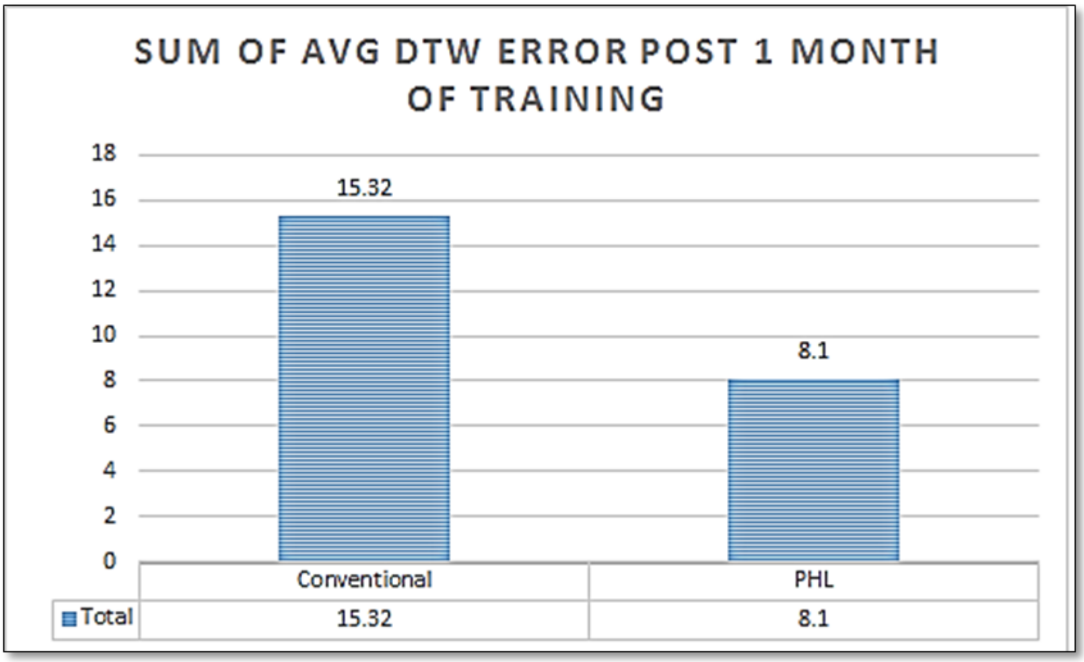

Fig. 14: The graph showcases the Sum of AVG DTW error post 1 month of training.

6.2 Long Term Skill Retention:

A similar test was conducted post 6 months of the original training in order to ascertain the Long Term retention of the motor skill.
The test showcased inspiring results. Even though both the groups showed some signs of increased errors, however it was observed that the **PHL group committed 55% lesser DTW errors.**

See Fig. 15 and Table 3.

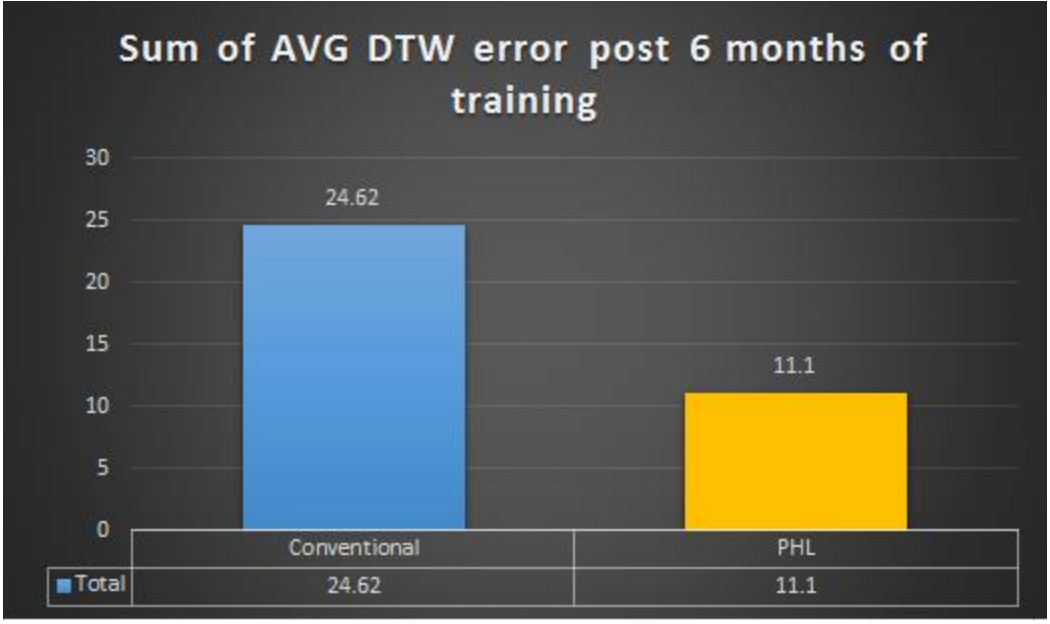

Fig 15: The graph showcases the Sum of AVG DTW error post 6 month of training.

Table 3. Showcases the Average DTW errors post six months of training.

Type	Name	Months Post Training	AVG DTW error
PHL	Participant 1	1	3.5
PHL	Participant 2	1	3.7
PHL	Participant 3	1	3.9
Conventional	Participant 1	1	4.12
Conventional	Participant 2	1	5.2
Conventional	Participant 3	1	7
Conventional	Participant 4	1	8.3

It was seen that the conventionally learned piano skill was relatively more prone to forgetfulness as compared to the PHL paradigm.

Therefore, it can be deduced that the long term retention of the PHL is greater and far more effective by virtue of the rich multisensory memory creation and retention as compared to the conventional learning, thus it was observed that PHL was a much better way of learning to play the piano for the visually impaired.

6.4 Feedbacks from the users:

Over the multiple feedback surveys conducted over the course of the PHL training, the users, initially were found to be skeptical of the technology, however over the weeks of familiarization with the tool, and the device itself undergoing iterations and enhancements the final prototype was adapted well, and the users felt less restrained by the final device as compared to the first iteration. The users were willing to try the prototype to learn newer skills if possible, thus provided the scope for the PHL glove based learning for other motor skills, such as blinds learning to type on a keyboard etc.

6.5 Feedbacks from the music instructors:

On multiple occasions the 2 music teachers (of the music studio where the experiment was conducted) were requested to gauge the learning of the PHL students and how they coped as compared to their conventionally learning counterparts.

The teachers found the device unique and also suggested certain enhancements, such as to remove some area of the palm, to alleviate the piano-hand touch. Overall, they also exclaimed that the device was very a powerful tool, and the learning capability of the system could be greatly increased if a proper system of training was crafted that involved a seasoned professional teacher and this tool, working together.

However even while working in standalone mode, the device showed great promise over conventional means of training, which is in fact another proof of the efficiency and potential of multisensory learnings using Haptics, especially for the visually impaired users.

7. Concluding Remarks

The substitution of visual cues by other auxiliary modes was found to be a rich source of input cues to the test subjects, even though initially the results of both the traditional and haptic training resulted in similar learning and retention results. However during the longer course of time, the haptic training appeared more deeply engrained in the minds of the subjects. After close monitoring of each student’s progress it was observed that during the six months of this experiment, a multisensory route of learning indeed proved to be a richer experience for the visually impaired learners giving them a quick jumpstart over the spatial domain by virtue of the haptic cues. Even though conventional training was effective, however the multisensory haptic training approach was found to be more vivid and faster to adapt, thus implying a more reliable, effective and richer training system for motor learning skills especially for learning to play the piano.

8. Future Work

Future work could involve laser diodes instead of IR to increase the accuracy of the hand – key coordination. Another implementation of the system could in fact eliminate the use of a host computer by getting all the host functions carried out from the IR strip controller, housing a memory card slot and loading the song data directly to the strip, this would make the system portable and more adaptable to players. Also, newer codes of vibration patterns could be used to provide more data to the player, such as a metronome in order to keep the timing intact. The above mentioned improvements could greatly contribute the proposed device's ecosystem.

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