A Review and Design Methodology of Preserving Piano Playing Techniques through Contactless Sensor Fusion System

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ABSTRACT

The art of planning the movement of hands in order to produce the desired sound of the piano is one of the important part of piano technique. Different types of sensors have been used in order to capture motion data of piano playing. However, one area in this research had been under-represented, which is finger position and pressure measurement applied by the musician while playing the musical instrument. Research that embark on this area faced a common problem, the sensors used in these research are directly in contact with the pianist, which causes a change of piano playing experience. Because piano playing consists of very delicate interaction between the pianist and the piano, such change of experience may affect the pianist’s performance. These sensors are considered to be intrusive to the piano playing experience. Concluding the challenges faced by current technologies, the proposed solution for this problems should meet few a criteria. The proposed sensor system should be a non-intrusive sensor that remotely monitors the finger and arm position of a pianist. The proposed sensor system should also able to investigate the strategy of finger positioning and arm motion of virtuoso pianists. Since each pianist plays the piano differently, this system could be used for storing and preserving a pianist piano technique. The data of the professional pianist could be shared easily through the internet, users will have access to the information about the technique of a famous pianist, which will provide good references for their piano learning. Furthermore, a piano technique demonstration from teachers could be stored for the use of their students. The stored data could be reproduced by robots performing on an acoustic piano, potentially recreating the same atmosphere of a live piano performance.

Keywords: Piano Pedagogy; Piano Technique Preserve; Capacitive Sensing; Robotic Arm.

INTRODUCTION

Musician had been striving to perfect the technique of musical instrument playing for centuries. Along with advancements of technologies, a number of methods were developed to capture the movements of the musical instrument players in order to analyze their techniques. The mentioned technologies often fuses sensors with the musical instrument, creating augmented musical instruments. By definition, augmented musical instruments are created by the addition of sensors to existing acoustic or electric instruments [1]. These sensors collect various types of input from the musical instrument players, not only tracking the movement of the players, but also allowing them to control additional digital audio effects or sound synthesis processes through their gestures. These methods offer numerous possibilities for musical performance [2]. For these augmented instruments, one area had been underrepresented, which is finger position and pressure measurement, applied by the musician while playing the musical instrument [3]. The area of interest of this research is piano playing movement analysis, more specifically the movements of the arms, fingers position and pressure applied by the pianist. These information are crucial for technique analysis because there was a distinct difference in hand posture and movement strategy of the arm between the professional and amateur pianists [4]. There are three main applications for pianist movement analysis:

a) Piano pedagogy:

Piano pedagogy refers to the interactions of piano instructors teaching students how to properly play the piano. These interactions consist of verbal communications, auditory perception, visual demonstrations, physical interaction and an instructor’s feedback based on audio and visual.
inspection and verification of the student’s performance. In the last few years, the field of piano pedagogy has gradually been opening up to innovative advancements in technology in order to enhance the learning experience [5]. Sensor-based feedback provides a new way to study piano technique, which could enable new pedagogical applications that lead to new path to learn technique. Technique is only one of several areas of study addressed in piano pedagogy or, more generally, in instrument pedagogy [6]. Advanced pianist normally spend a lot of attention on piano technique. This is shown by [7] who analyzed the music department’s lesson content of an English university. Based on the survey, piano technique is the predominant area of study, which occupies more than half of the corresponding survey data [7]. Sensor-based feedback can provide an immediate, objective feedback on the student’s movements. This may improve the student’s ability to perform conscious introspection on their movements. Thus sensor-based feedback supports the analytical side of piano pedagogy. During normal practice, the student could apply this ability to examine and work on technical problems he/she faces in a particular music piece.

b) Technique Preservation:
Performing music on a piano requires refined and rapid movement of the arms, hands and fingers that changes direction frequently, this demands the coordination of many different muscles and parts of the body [8]. Pianist movement analysis can be used to record the technique of a pianist, the acquired data can be served as a reference for other pianist, and the piano playing could be reproduced without the physical attendance of the particular pianist. The acquired data also provide information on how a pianist interpret a piece of music, and the movement strategy to execute difficult passages. This research especially focus on the different finger position of the pianist on the same key, as well as the speed of the movement of the lower arm of the pianist moving across the key, which up to date, very few research on this area had been carried out [3].

c) Music Reproduction: One of the main research that serve as the complement of this paper is music reproduction. Despite digital piano possess the ability to reproduce piano playing, and electro-acoustic engineers had strived to synthesize the sound of grand piano through research in digital signal process [9] [10], digital piano is yet to match acoustic piano in terms of timbre control [11]. Consequently, numerous work had been done to develop piano playing robots that could perform on acoustic pianos. Piano playing robots utilize the data acquired by pianist in attempt to reproduce the exact music on a piano. One of the earliest two hands playing robot for piano playing was proposed in [12]. The developed robot has two hands and each hand has 5 fingers, as shown in Figure 1.

Another example of piano playing robot was developed by [13]. The span of palm and fingers of a pianist is emulated through robotic hands as shown in Figure 2.

![Fig. 1: Piano Playing Robot developed by [12].](image1)

![Fig. 2: The span of palms and fingers emulated in [13].](image2)

Eric et al. developed Anatomically Correct Testbed (ACT) hand (as shown in Figure 3), that could play a single key trill on the piano. The ACT Hand (shown in Figure 1) mimics the interactions among muscle excursions and joint movements produced by the bone geometries and tendon connectivity of the human hand. This mimicry results in a high-dimensional system with the redundancies and nonlinearities of the biological hand [14] [15]. This implies that good reference data from pianist provides better and more complex control for robot arm.
The main areas that this paper covered are, firstly, the related technologies used in consumer product that developed by major piano manufacturers. Next is the main pianist finger data collecting method used in current research, which consist of capacitive sensing, user mounted sensors and optical motion capture. Additionally, a methodology is proposed in attempt to improve and solve the common challenges faced in this research.

**Fig. 3:** Anatomically Correct Testbed (ACT) hand by [16].

**Major Piano Manufacturers:**

According to current technologies, major piano manufacturing companies in the world had pursue the research in reproducing the human piano performance. Two systems are most commonly used in this research are, the Bösendorfer SE ([17] [18] [19] [20] [21]) and the Yamaha Disklavier ([22] [23] [24] [25] [26] [27] [28] [29] [30] [31] [32]) as shown in Figure 4.

**Fig. 4:** A Yamaha disklavier (http://au.yamaha.com/en/news_events/artists/disklavier/images/yamaha_disklavier.jpg)

These pianos measure movements of key and hammer in order to replicate human piano performance. Unfortunately, these pianos are not designed for scientific research purpose and their exact functionality is unknown or held back by the respective companies [33]. Exploratory studies on carried out to examine their accuracy of recording and playback. Only a few studies provide systematic information for the exact functions of these devices. Coenen et al. tested five different reproduction devices (among them a Bösendorfer and a Yamaha system) on various parameters, but their goal was to evaluate the reliability of these systems for compositional use, their main focus was therefore on the production unit. S. Bolzinger et al. performed tests on a Yamaha upright Disklavier (MX-100 A), but his goal was to measure the interdependencies between the pianist’s kinematics, performance, and the room acoustics. A complex methodology was proposed by [26] to run tests on a Disklavier (DS6 Pro), but no systematic results are reported so far. The system of a Yamaha Disklavier consists of two main parts: first is the measuring unit, and secondly the reproduction unit. The first stores information derived from two shutters per key: one below the key, and another at the hammer shank. The hammer shank shutter provides two trip points, whereas the one at the key only one. In this design, it is very similar to the Bösendorfer SE system [21]. The reproduction unit possesses solenoids below the back of each key in order to push them as the pianist did [37]. The finger position tracking ability is not featured in any of these pianos.

**Capacitive Sensing:**

The basic operating concept behind capacitive sensors is converting capacitance changes to electrically measurable signals such as frequency, duty cycle, current, or voltage [38] [39]. This sensor are widely used to measure pressure, acceleration,
linear and angular position, and displacement [40] [41], where it is a common industrial applications to measure liquid levels, humidity, and material composition. As technology progresses, capacitive sensors is used in many human-to-machine interfaces, a good example is the finger position detection on a mobile phone. In addition to that, new interfaces will soon be required to satisfy the ever-increasing needs and complexities of such markets [42]. Currently, capacitive sensing method is also introduced in finger position tracking in piano playing. Tobias et al. proposed capacitive sensing method to detect finger position as shown in Figure 5. A flexible printed circuit board (PCB) is wrapped on the piano key as the electrode for capacitive sensing. The result of the data is shown graphically, providing the data of the position of fingers and the force applied to the key.

Despite the ability to track main movement of piano playing, changing the surface of the piano key alters the normal experience of piano playing. Because piano playing is consist of very delicate interaction between pianist and the piano, such change of experience may affect a pianist performance. This type of sensor is considered intrusive to the piano playing where they introduce uncontrolled deviations in the measurement of the actual body movement [8]. “TouchKeys” (as shown in Figure 6) developed by [43] uses a similar approach to track finger position. This is also an example of intrusive sensor.

**User-Mounted Sensors:**

Human-mounted or wearable sensor system had led to many useful applications. The main application of this sensor system includes data collection from athletes and clinic patients where the sensors monitor and diagnose the users [44]. Their current capabilities of this sensor system include physiological and biochemical sensing, and also motion sensing [45] [46]. Figure 7 shows a wearable finger position tracking method for piano playing developed by [47]. The sensors are mounted on the hand of pianist instead of on the piano. This similar method is also used in [48] where accelerometers and gyroscopes are placed at the hand of the pianist to track the position of the arm and force applied to the piano (as shown in Figure 8).
Another common example of user mounted sensor system is obtaining pianist muscle information through electromyogram (EMG). Genta et al. classified different motions in piano tapping as shown Figure 9. The EMG sensors are attached to users arm to obtain electrical signals that accompanied by muscle contractions.

Fig. 4: Sensors developed by [48].

Even though user mounted sensors shows promising result on obtaining finger position of the pianist, these methods require sensors to be attached to the pianist. Thus they are considered intrusive to the experience of piano playing, which might affect the natural or usual performance of a pianist.

Optical Motion Capture:

Optical motion capture is the procedure that collects data from a human or a moving object to evaluate its movement. Studies using motion capture technologies had been carried out with pianists which focus on quantifying the small, quick movements of the wrist, hand, and fingers [50] [51] [52] [53] [54] [55]. Numerous marker based systems have been proposed where sensors (e.g. magnetic [56]) or visual markers [57]) are attached on the moving subject, and provide specific points to track. These approaches have the reputation of being cumbersome and relatively complex to operate. Therefore, marker-less optical motion capture approaches eliminate the constraints associated with the use of markers on specific attachment points and open the door to free motion performance and minimal setup requirements [58]. Researches have already begun to explore many promising applications on this non-intrusive motion capture systems in the fields of music pedagogy and performance [59] [60] [61] [62]. The possibility of non-intrusive or unobtrusive motion capture and analysis of characteristics and timing of gestures during musical performances has important implications for researchers interested in quantifying the movement of performers. Mostafizur et al. employs image processing method to track a pianist’s hand motion as shown in Figure 10.

Fig. 5: Motion capture using camera developed by Mostafizur et al. [63].
Dmitry et al. developed finger detection algorithm by examining for the presence of what they called crevices (Figure 11), which are defined as the locations in the image where two convex shapes meet. They also outlined that the present finger detection algorithms mainly focus on deal with hands with well visible fingers, which in most cases very well protrude from the center of the palm, and which serves as the main cue in detecting the fingers. The mentioned techniques includes cylinder-based 3D model fitting [64], correlation with predefined templates [65] [66], image-division based decision tree recognition [67], skin colour detection with edge merging techniques [68] [69], and recent work [70] based on the hysteresis-type colour segmentation of skin colour. However, the challenges for pianists’ finger detection is, the pianist fingers are never protruded. In addition to that, they are mostly bend towards the keyboard, which is away from camera, often touching and occluding each other [71].

Fig. 11: Finger Detection Method developed by [71].

Another marker-less finger recognition for piano application is presented by [72]. In this research, Kinect sensor manufactured by Microsoft Corp. is used to acquire depth images by a spatial median filter to reduce random noise. This sensor is installed above the piano’s keyboard area and the distance between the sensor and the keyboard is ensured to remain constant, this enables background subtraction technique to be utilized to extract hand regions from images (as shown in Figure 12).

Fig. 12: Finger Detection Method developed by [72].

Motion capture method provides non-intrusive method for obtaining finger position data of pianists. However, camera operates in line of sight, at the event of pianist’s finger blocked by other body part, such as arm or fingers blocking the sight of fingers, the accuracy of the data could drop drastically. Furthermore, this method is prone to light interference, causing data lost, and their use is often impractical due to the high costs and the time consuming process of data preparation and analysis [71].

**Design Methodology:**

A methodology is proposed in attempt to improve and solve the common challenges faced in this research. The proposed sensor system consist of two main parts as shown in Figure 13. For the sensors and signal processing part, capacitive sensors are proposed to detect the position of the fingers whereas infrared (IR) range sensors to detect the height and location of the arm. The data from the sensors are processed by a digital signal processing (DSP) unit. The processed data is sent for display,
providing useful information to users. The displayed data includes the position of the fingers in graphical and numerical form, force applied on the piano keys, and finally data comparison for multiple users. The stored information of a particular pianist is then reproduced using robot arm, playing on an acoustic piano.

The system’s function flow is shown in Figure 14. Firstly, IR range sensors detects the position of the arm, this includes the speed of the arms travel across the keyboard, the height of the arm when they travel and also the rate of change of height of the arm when they approach and presses the keys. The capacitive sensors detects the position of the fingers in three axis. This data provides information of the position of the fingers pressing the key, the depth as well as the rate of change of depth of the pressing finger, and also the gliding motion of the finger on the keys. The data of the rate of change of height from IR range sensors is coupled with the rate of change of depth from capacitive sensors using Kalman filter. Coupling of these two data provide higher accuracy information of the force and speed of the fingers applied on the piano keys. The processed data is then stored and displayed. The displayed data provides information of the pianist, especially how he/she execute their technique on the keyboard through the collected data. Multiple pianist data could be compared for piano technique analyzing and piano teaching purpose. The stored data is then reproduced using robot arm playing on an acoustic piano, replicating the music from a pianist in real sound. More details of aspect of the system is discussed in the next section.

![Fig. 13: Two Main Parts.](image)

![Fig. 14: System Functional Flow Diagram.](image)

A basic capacitive sensor encompasses a receiver and a transmitter, where each of them consists of conductive electrodes as shown in Figure 15. Between the electrodes of receiver and transmitter, an electric field (E field) is formed. The capacitance changes when a user interferes the E field, which induce the change of capacitance that provides information of the position of the finger.
Fig. 15: Capacitive Sensing Principle [73].

As shown in Figure 16, the capacitive proximity sensing principle detects distances of up to 10 cm easily, while up to 30 cm and more can be obtained depending on the electrode design.

Fig. 16: Range of detection [74].

In this research, capacitive sensor is proposed to detect finger position of the pianist. The electrodes are placed under the keyboard as shown in Figure 17. Without altering the surface of the keys, the three dimension position of the fingers could be detected.

Fig. 17: Electrode mounted right below the keyboard.

IR range sensors are proposed to detect the height and the speed of arm moving across the keyboard. An example of IR range sensors is shown in Figure 18, this sensor provides an analog output that varies from 3.1V to 0.4V, for objects placed at distance of 10cm to 80cm.

An array of IR range sensors is installed on the keyslip area of the piano as shown in Figure 19. The lower arm which extends from the body of pianist move across this area so that the fingers and wrist could access the higher and lower register of the keys. The array of IR range sensors captures the movement of the upper arm during piano playing.

Figure 20 shows the standard placement of electrodes of the capacitive sensor. Depending on the position of the hand, the electrodes receives different electric field and generates different signals. Because there are multiple ways user could interfere the
electric field at a given position, the system is required to learn and recognize the pattern of the signals and eventually produce an accurate position of the finger. In order to achieve this, Artificial Neural Network (ANN) is proposed to interpret the signal from capacitive sensor.

**Fig. 18**: Infrared proximity sensor made by Sharp. Part # GP2Y0A21YK [75].

**Fig. 19**: Placement of IR range sensors.

**Fig. 20**: Standard Electrode Design [76].

The processed data from the sensors are to be displayed graphically and in numeric value. As shown in Figure 21, the position of fingers is displayed and the force applied at a given instance. In addition to that, rhythmic data is also stored. Comparison algorithm is developed to compare the piano playing of different pianist for learning and teaching purposes. Field testing in piano school is carried out to collect data for piano technique classification.

**Fig. 21**: Finger Position Display [43].
Conclusion:

The current researches show that it is important to track the movement and finger position of the pianist. These data are important for piano pedagogy where teachers could provide accurate finger positioning data for students. Furthermore, information of virtuoso pianist could be accurately stored so that the details of their piano technique can be preserved. However, challenges arise if these data were to be obtained without intrusive methods, which alter the experience of piano playing. In addition to that, research on tracking of the finger position and force applied to the key is underrepresented. Hence, overcoming these challenges and developing an accurate and non-intrusive piano playing movement tracking system should be the main focus of current research. The proposed solution is firstly, a non-intrusive sensor that remotely monitors the finger and arm position of a pianist. The proposed sensor system will be able to investigate the strategy of finger positioning and arm motion of virtuoso pianists. Since each pianist plays the piano differently, this system could be used for storing and preserving a pianist piano technique. The data of the professional pianist could be shared easily through the internet, users will have access to the information about the technique of a famous pianist, which will provide good references for their piano learning. Furthermore, a piano technique demonstration from teachers could be stored for the use of their students. The stored data could be reproduced by robots performing on an acoustic piano, potentially recreating the same atmosphere of a live piano performance.

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