In-Tool Motion Sensing for Evaluation of Violin Performance

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A system that is able to measure motions is necessary for preserving the skills of experts. A previously reported study proposed a system that precisely measures and reproduces motions. However, this type of system must physically interact with the subject whose motions are measured. Such interaction can be troublesome when the measured motions require precise control of force or position or even a high degree of freedom. Therefore, this study proposes a novel method for sensing motions without interference and applies the approach to measure the skill of playing a violin. Using the data measured by the proposed system, the skills of an experienced violin player and a novice violin player are compared. This study attempts to visualize the differences between the two types of players by applying wavelet transform on the measured data and analyzing them in the frequency domain.

Keywords: Sensing, Motion Control, Skill Acquisition, Motion-Copying System, Violin

1. Introduction

There are various ways to preserve information. For example, when preserving a performance by a violinist, a microphone is used to record the audio. However, microphones cannot preserve the motion of the violinist. The skill of violinists cannot be preserved. Furthermore, the quality of recording equipment such as microphones would affect the quality of the recording. There are inevitable losses in the recording system. The only way to faithfully preserve the violinist’s performance would be to save the motion of the violinist completely.

There have been studies attempting to save and reproduce the motion of humans. One example is the motion-copying system (9) which enables saving and reproducing of calligraphy motion by preserving both position and force data of the brush. There has also been a study that attempts to visualize personal characteristics by analyzing the saved data in frequency domain (2). These systems utilize bilateral control in which a set of manipulators is synchronized so that the position and the contact force are synchronized between the manipulators bilaterally. Using the information acquired from the encoders coupled with motors, the force is estimated by a DOB (Disturbance observer). The advantage of using the DOB is confirmed in many other studies (3–14) as well. The estimated position and force data can be reproduced faithfully using the same set of the manipulator in the same environment. However, the writer must use the brush constrained to the manipulator. This prevents the writer from using the full degree of freedom and also interferes with the motion. Therefore, the skill of manipulating the robot is measured rather than the actual skill of writing. In order to solve this problem, it is necessary to develop a system that works without interfering with the motion.

For the particular task of playing the violin, there have been various studies proposing methods for measuring the motion (15–18). For example, Hyperbow (16) is a modified bow that features a motion capture system for measuring the position, strain gauges for measuring the force, and an accelerometer for measuring the acceleration of the bow. The authors claim to have measured not only the vertical force but also the lateral force using only the strain gauges on the bow. However, in the experiment results, a clear correlation between the vertical force and the lateral force can be observed. This suggests that either force is not properly decoupled from another. The use of strain gauges can be practical for sensing the force applied to certain parts of a system (19–20). Hyperbow transmits this information wirelessly. Hence, this system does not interfere with the motion of the violinist. The use of strain gauges for measuring the force applied to the bow is attempted in many other studies. In another study (21), the strain gauge is attached to a leaf spring which is fixed to the frog of the bow. The leaf spring directly measures the tension of the hair, unlike Hyperbow which measured the strain of the stick. These types of measuring systems measure the vertical force which is in the direction of pressing the bow against the string.

There have been studies attempting to make robots play the violin (22–25). Maruyama et al. developed a violin-playing robot (26) that features both a bowing mechanism and fingering mechanism. Another example by Shibuya et al. (23–25) used a commercial 7-DOF (degree of freedom) manipulator to play the violin. These robots seem useful for reproducing the violin playing by experts, however, these studies did not go far as to imitate the motion of humans. In order to make the robots imitate humans, we must develop a sensing system for measuring human motion, then generate commands based on the measured data.

There has also been a study that goes so far as to capture the motion of the player and give real-time feedback via vibrotactile sensors to teach the appropriate position to the player (27). This method combines an electromagnetic motion capture system and vibrotactile sensors to realize a real-time
Playing the violin is one of the cases where constraints by measuring instruments can be problematic. The timbre of a violin is controlled by the position and force of the bow.\textsuperscript{(24)-(25)} Delicate control of position and force can easily interfere with any kind of external measuring instrument. Therefore, this study aims to develop an in-tool motion-sensing framework that does not interfere with the motion of the player and apply it to the case of playing the violin. The proposed system consists of a motion capture system that enables the measurement of position and strain gauges that enable the measurement of force.

In the second section, the conventional method, motion-copying system is explained. In the third section, the proposed method, in-tool sensing system is explained. Various experiments are conducted and explained in the fourth section. In the last section, the conclusion of this study is stated.

2. Motion-copying System (Conventional Method)

One method for saving and reproducing the performance of the violin is to use the aforementioned motion-copying system. The Motion-copying system utilizes a master-replica system which consists of two same manipulators. The system used in this study is shown in Fig. 1. The schematic view of the manipulator is shown in Fig. 2. Both the force and the position of each side are synchronized interactively between these two manipulators. The motors are equipped with encoders, and angles of these two motors can be obtained at the sampling rate of 10000 Hz. Using this information, the position of the end effector of the arm can be easily estimated by the following equations.

\begin{align}
  x &= -l \sin \theta_2 - l \cos \theta_1 \quad (1) \\
  y &= -l \sin \theta_2 - l \cos \theta_1 \quad (2)
\end{align}

Here, \(x, y, \theta_1, \theta_2, l\) denote \(x\) coordinate of the end effector, \(y\) coordinate of the end effector, angle of the first motor, angle of the second motor, and the length of the arm respectively. The \(z\) coordinate can directly be obtained from the linear encoder.

The torques applied to the motors can be estimated using a DOB. A DOB estimates the external force applied to the motor from acceleration reference \(\dot{\mathbf{x}}^{\text{ref}}\) and position response \(\mathbf{x}^{\text{res}}\). In the following experiment, two motors were used for controlling the manipulator in the XY plane, and a linear motor was used for controlling the tip in the \(z\)-axis. By using two sets of these motors and applying bilateral control with reaction force observer, we were able to obtain external torques applied to the two motors \(\tau_1, \tau_2\), and external force applied to the linear motor \(F_z\). For the \(z\) axis, the force value is directly obtained from the linear motor. However, for the \(x\)-\(y\) plane, \(y\) axis (lateral) force \(F_y\), and \(x\) axis (vertical) force \(F_x\) must be derived from the torques by the following equation,

\[
F = (J_{aco}^T)^{-1}\tau \quad (3)
\]

where

\[
F = \begin{bmatrix} F_x \\ F_y \end{bmatrix} \quad \tau = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \quad J_{aco} = \begin{bmatrix} -l \sin \theta_2 & -l \sin \left( \theta_1 - \frac{\pi}{2} \right) \\ l \cos \theta_2 & l \cos \left( \theta_1 - \frac{\pi}{2} \right) \end{bmatrix}.
\]

Using the motion-copying system enables robots to not only save the motion but also reproduce the motion faithfully within the same environment. However, there are drawbacks to this system. One drawback is that one must hold the manipulator while performing the motion. The motion-copying system saves the skill of manipulating the robot rather than the actual skill of the performer. The motion of the performer is affected by the inertia or friction of the manipulator throughout the performance. This is why in-tool sensing is necessary for saving motion.

3. In-Tool Sensing (Proposed Method)

Another method for measuring the motion is to use external sensors. To measure the force applied to the tool, force sensors should be placed in between the hand and the tool. However, placing the sensors between the hand and the tool would bring different sensations to the subject. Therefore, we propose an in-tool sensing system that does not interfere with the subject. The idea of in-tool sensing is to integrate various sensors into the tool in order to prevent the change of sensation.

We apply this in-tool sensing system to the motion of playing the violin and measure the motion of the bow by using an optical motion capture system and strain gauges. This would
In order to measure the force applied to the bow and the violin, strain gauges were attached to the bridge and the bow as shown in Fig. 4. This allows decoupling the lateral force measurement and vertical force measurement, unlike the Hyperbow. On the bridge, we mounted strain gauges on four different positions as shown in Fig. 5: two on the front side of the bridge and two on the backside of the bridge. For each side, we mounted one gauge horizontally and another gauge vertically to see whether y-axis force and z-axis force can be measured. On the bow, we mounted two strain gauges; one on the surface of the middle of the stick and another on the backside as shown in Fig. 6. The strain gauges attached to the violin and the bow had the resistance of 120 Ω, and the gauge factor of 2.1. The strain gauges were connected to the bridge box which consists of three resistors of 120 Ω. The strain gauge and the bridge box together form a Wheatstone bridge which converts the variation of resistance into the variation of voltage. The change of voltage was then amplified by a commercial strain amp DPM-911B (Kyowa Electronic Instruments). This amplifier covers DC to 2.5 kHz AC. The gain of the amplifier was set to 20000. The range of output voltage was from −10 V to +10 V. The output was recorded on a PC through a 16-bit D/A board PCI-3135 (Interface Corporation).

In order to measure the position of the bow, an optical motion capture system (OptiTrack™) was used. Markers were attached to the bow, and the motion of the bow was captured at 120 frames per second. This motion capture system is able to capture the x, y, z coordinate of each marker. We did not mount any markers on the violin as the violin was fixed to a stand throughout the experiment.

4. Experiments

4.1 Setup

The diagram of the system used in Experiment 1 and 2 is shown in Fig. 7. The procedure of the experiment is as follows. Using the motion-copying system, the performer held the master side of the two manipulators and controlled the bow on the replica side. The motion of the bow was measured by two different methods; the motion-copying system, and the in-tool sensing system. The violin has four strings to be played with a bow; G string, D string, A string, and E string, ordered from the thickest (lowest) to the thinnest (highest). In the following experiments, the bow was played on either single string.

4.2 Experiment 1

The purpose of this experiment is to show that the position measurement of the proposed system is valid. In this experiment, the performer executed détache bow strokes on the G string of the violin repeatedly while obtaining position data using two different systems; the motion-copying system and in-tool sensing system. By following the steps of estimating the position as shown in the second section, the position of the frog of the bow was estimated. The results are shown in Fig. 8. Here, the x coordinate and y coordinate are matched. The slight error was caused by the resolution limit of the motion capture system. The error of the z coordinate was probably caused by the deflection of the manipulator. Since the linear motor is attached to the tip of the two-DOF manipulator, the manipulator deflects when the end effector is lifted from the initial position. The root mean square error between the motion-copying system and in-tool system is shown in Table 1. The largest error was that of the y coordinate which was as small as 2.32 mm.

4.3 Experiment 2

The purpose of this experiment is to show that the force measurement of the proposed system is valid. In order to determine the placement of strain gauges, we first compared the data obtained by the four strain gauges placed on the bridge with the force data obtained by the motion-copying system. Excerpts of the results are shown...
Comparing the data obtained by the strain gauge placed vertically on the front side of the bridge with the $z$-axis force $F_z$, it can be expected that there is a strong correlation between the value of the strain and the $z$-axis force. Similar results were obtained on the backside of the bridge as well. However, the strain gauges on the front side of the bridge appeared to be more sensitive to the pressure of the bow. Therefore, we decided to use only the data obtained by the strain gauge placed on the front side for further considerations.

By assuming that the strain is a linear function of force, the relationship between the force and the strain can be expressed by the following equation.

$$ F = EA\varepsilon $$

(4)

Here, $F, E, A, \varepsilon$ denote force, Young’s modulus, cross-sectional area, and strain respectively. The relationship between the measured voltage and the strain can be expressed by the following equation.

$$ V = K\varepsilon $$

(5)

Here, $V, K$ denote the measured voltage and the output gain of the amplifier respectively. Hence, the relationship between the actual force and the measured voltage can be expressed by the following equation.

$$ \frac{F}{V} = \frac{EA}{K} = \text{Const.} $$

(6)

By applying the least square method, the constant can be estimated. After estimating the constant, the force value can be estimated from the strain value. The estimated force is shown in Fig. 10. As shown in the figure, the force data estimated by the proposed method well matches with the force estimated by the motion-copying system.
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4.4 Experiment 3  As the third experiment, we compared an experienced violin player and a novice player by analyzing the force data in the frequency domain. There are two major advantages of the proposed force measuring system compared to previous systems. One advantage is that the proposed system is capable of frequency up to 2.5 kHz. Another advantage is that the proposed system is able to measure the force in high resolution. The A/D converter used in the system covers the voltage range of ±5 V or ±10 V in 16-bit resolution. When the input range is set to ±5 V, the resolution is as small as 1.53 × 10⁻⁴ V. This would enable the measurement of the precise motion of an expert violinist. Using these advantages to the full extent, the measured force data were analyzed in the frequency domain.

The violin playing skills of two subjects were compared in this experiment. One subject had 4 to 5 years of experience in playing the violin. The other subject had no experience of playing the violin. The inexperienced subject received about 30 minutes of basic instruction on how to play the violin before the experiment. The subjects were instructed to perform bow strokes on the A string while listening to the sound of the metronome. The metronome was set to 60 BPM (beats per minute) and the subjects were instructed to bow the string in four different conditions; four beats for each stroke with a small force, four beats for each stroke with a large force, two beats for each stroke with a small force, and two beats for each stroke with a large force. The subjects were instructed to start with a down bow, and bow the string back and forth four times. Throughout the experiment, vertical force applied to the instrument was measured by the proposed system. The voltage range of the A/D converter was set to ±5 V in order to increase the resolution of measured force, and the sampling rate was set to 10 kHz. The audio data were recorded simultaneously by the microphone (AKG C411PP) attached to the bridge of the violin at 44.1 kHz.

The force data and audio data of when subjects were instructed to bow two beats for each stroke with large force are shown in Figs. 11 and 12 respectively. We extracted these results as the difference was most evident among the four conditions.

The results show clear differences in the force applied to the bow. The experienced player showed the almost same variation of force in every stroke. Meanwhile, the novice player showed different variations of force in every stroke. Furthermore, the vibration of force was more evident in the force data of the novice player.

In order to analyze the vibration, we applied wavelet transform to the measured data using Morse wavelets. This returns the magnitude of each frequency in the time series. The wavelet transform of the strain data is shown in Fig. 13.

![Fig. 9. Comparison between force data and strain data.](image1)

![Fig. 10. Comparison of force data measured by two systems.](image2)
One difference between the two is evident around 10 Hz in Fig. 13. The novice player showed a large magnitude in this range. The experienced player maintained a small magnitude except for the stroke around 9 s.

The wavelet transform of audio data is shown in Fig. 14. One difference that can be confirmed is that the gaps between each stroke are less noticeable in the figure of the experienced player. The difference between the two is also evident around 1000 Hz to 10000 Hz. Here, the experienced player maintained a relatively constant magnitude in each frequency range. Meanwhile, the novice player was unable to maintain the magnitude in each frequency range. Also, the fundamental frequency (440 Hz) is clearer in the result of the experienced player. These results suggest that the unnecessary vibration of the bow at 10 Hz causes inconsistent timbre.

4.5 Experiment 4 In addition, we have measured the position of the violin and the bow during Experiment 3 using...
the motion capture system. Using the data of four different markers, the vector of string and the bow can be derived as follows.

\[
\vec{v}_{\text{string}} = \vec{v}_{\text{nut}} - \vec{v}_{\text{bridge}}, \quad \vec{v}_{\text{bow}} = \vec{v}_{\text{tip}} - \vec{v}_{\text{frog}}
\]  

(7)

Here, \(v_{\text{nut}}, v_{\text{bridge}}, v_{\text{tip}}, v_{\text{frog}}\) denote the position of nut, bridge, tip, and frog. The angle between the bow and the string, \(\theta\) can be derived as follows.

\[
\cos \theta = \frac{\vec{v}_{\text{string}} \cdot \vec{v}_{\text{bow}}}{|\vec{v}_{\text{string}}||\vec{v}_{\text{bow}}|}
\]

(8)

The angle between the bow and the string is shown in Fig. 15. In order to produce a pleasant sound, it is important to keep the angle of the bow and the string close to \(\pi/2\). Here, the results suggest that the experienced player was better at maintaining the angle close to \(\pi/2\). Such a difference can only be observed from the motion capture data.

The distance between the bow and the string acquired by the motion capture system is shown in Fig. 16. These results show how much the bow is pressed against the string. The difference between the experienced player and the novice player can be observed from these data as well. However, in order to analyze the motion of the bow in the direction of pressing against the string, it is more practical to focus on the force data rather than the position data. One reason is that the estimated error of the motion capture system is 0.284 mm which is not negligible considering the very small displacement. Another reason is that the bow flexes when force is applied making it difficult to precisely measure the distance between the bow and the string.

5. Conclusion

In this paper, we proposed the in-tool sensing method for evaluating violin performance. The system used an instrument integrated with strain gauges and motion capture markers to realize measurement without interfering with the motion of the player. We compared the measured data between the conventional motion-copying system and the proposed in-tool system. We confirmed that both position and force data measured by the proposed system matched with the conventional method. Furthermore, we used the system to compare the motion of two subjects; experienced violin player, and novice violin player. We first focused on the force data and analyzed the difference between the two. By applying wavelet transform to the force data measured by the proposed system, we succeeded to visualize the force data. We also applied wavelet transform to the audio data to see how the force is related to the sound of the instrument. The results suggested that the unnecessary vibration of the bow at 10 Hz causes inconsistent sound. We also observed the angle of the bow against the string and the distance between the bow and the string. We confirmed that the experienced player was better at maintaining the angle close to \(\pi/2\). The results suggested that force data is suitable for analyzing the motion in the direction of pressing the bow against the string, and position data is suitable for analyzing the motion in other directions.

As future work, we would like to realize a system that efficiently teaches violin skills to novice and intermediate learners.

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