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Violin Gesture Recognition Using FMCW Radars

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***Abstract* — Bowing gestures are a key component of violin playing and can be analyzed to provide feedback on a violinist's performance. Radar systems have increasingly been used to recognize human movements but not yet in a musical context. In this study, a portable frequency-modulated continuous-wave (FMCW) radar is used to detect various violin bowing gestures. Range profiles and time-Doppler spectrograms are extracted from the raw signal data, and their unique characteristics allow for the differentiation of different bowing techniques and the recognition of incorrect bowing motions. The results of this study demonstrate the potential of radars in aiding musical instrument training.**

Keywords — frequency-modulated continuous-wave (FMCW) radar, time-Doppler, range profile, violin, bowing gestures

I. Introduction

Learning a musical instrument is linked to a host of cognitive benefits such as improved memory, advanced reasoning, and greater mental flexibility. It is also shown to strengthen one's self-esteem, confidence, and ability to self-motivate [1]. However, as private instrumental lessons are often expensive and not always accessible, there is a need for affordable and quality music instruction. In the past decade, there have been increased efforts to develop smart devices to provide automatic feedback on musical performance based on data collected from the user's motions or sounds.

Several studies have attempted to create a digitized approach to analyzing musical performance, often using wearable devices to track the musician's movements and determine the gesture being performed. For string instruments specifically, a popular method involves attaching multiple sensors to the human body and/or parts of the instrument to provide data on the position and motion of the area of attachment [2]-[3]. However, the size and weight of wearable technology and sensor attachments can impede certain movements or alter the way gestures are performed. Other research uses computer vision to capture images of the user, yet this data is best suited for recognizing large gestures, not the more subtle motions in instrumental performance [4]. Furthermore, cameras are sensitive to lighting and weather conditions and may be limited in performance by clothes that camouflage or conceal precise limb movements. There is also a privacy concern associated with using vision systems.

Instead, radar systems can be used as a non-contact, non-invasive method of sensing the position and velocity of a moving target. This study uses a portable frequency-modulated continuous-wave (FMCW) radar which generates a signal whose frequency is gradually increased during each period of measurement. The signal reflects off the target and is received by one of the radar's antennas. By comparing the transmitted and received signals, the range and velocity of the target can be identified.

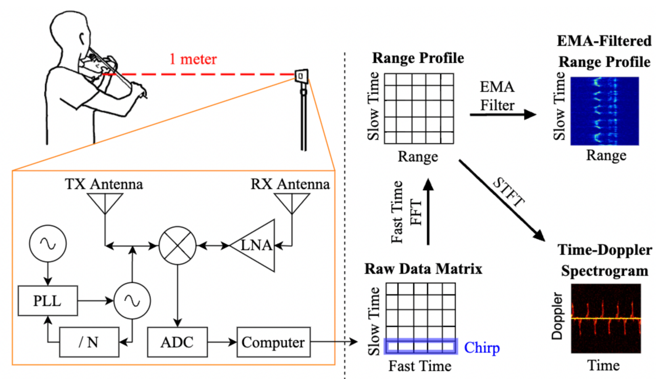

Fig. 1. Experimental setup showing relative positioning of person, violin, and radar. Block diagram of the 60 GHz FMCW radar along with the data processing flow for extracting the range profile and time-Doppler spectrogram.

FMCW radars have been used in a variety of applications, including vital signs monitoring, fall detection, and surveillance [5]-[7]. However, their potential in pedagogical applications to music remains unexplored. In this study, an FMCW radar is used to observe different violin bowing techniques (i.e. détaché, staccato, spiccato, and tremolo) and to distinguish between right and wrong bow motions. The distinct range profiles and Doppler spectrograms produced by different bowing techniques demonstrate the potential of FMCW radars in recognizing and evaluating violin bowing gestures and in providing automated feedback on music performance.

II. Theory of Violin Gesture Recognition Using Millimeter-Wave Radar

This study uses an Infineon 60 GHz FMCW radar that transmits a signal with a center frequency of 60.5 GHz and a bandwidth of 5 GHz. Such a bandwidth allows for a range resolution of 3 cm, enabling the detection and evaluation of small hand and wrist movements unique to certain bowing techniques such as spiccato. The chirp was produced using a sampling rate of 2 MHz.

Fig. 1 shows a block diagram of the radar as well as the steps for extracting the range profile and time-Doppler spectrogram from the raw signal data. First, a matrix of the raw data is generated from the beat signal provided by the radar's mixer, with each row in the matrix representing a single chirp. The range profile is generated by performing a fast Fourier transform

TABLE I

DESCRIPTIONS OF BOWING TECHNIQUES

Bowing Technique	Description
Détaché	Separate bow strokes played smoothly and without accent
Spiccato	Light, bouncing bow strokes
Staccato	Short, detached bow strokes played on the strings
Tremolo	Tiny and rapid up and down bow movement, typically performed at the bow tip

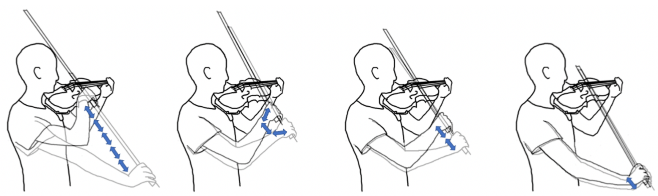

Fig. 2. Hand and arm motions for four violin bowing techniques.

(FFT) along the fast time of the data matrix while the time-Doppler spectrogram is generated by isolating the range-of-interest in the range profile and performing a short-time Fourier transform (STFT). The range profile is filtered using an exponential moving average (EMA) filter.

This study collects FMCW radar readings for four violin bowing techniques: détaché, spiccato, staccato, and tremolo. Each of the four techniques are described in Table I, and an illustration for each can be found in Fig. 2. The détaché, spiccato, and staccato techniques are each performed for ten consecutive bow strokes (five up-bows and five down-bows). Each technique is performed alongside a 60 beats-per-minute metronome click, with a single bow stroke falling on every other click. The only exception is the tremolo technique which is performed so rapidly that a single click consists of multiple up and down bow motions.

III. EXPERIMENTAL SETUP

The bowing techniques are performed by two subjects to account for possible variations in instrument hold, body posture, body dimensions, and bowing technique among different individuals. Each subject is seated so that the violin is located 1 meter from the radar. The subject is positioned in a way such that a plane perpendicular to the ground and passing through the long axis of the violin (along the fingerboard) is parallel to the radar board.

The radar height is adjusted so that it is aligned with the bottom-most portion of the violin, where the shoulder-rest contacts the instrument body. This method enables the most distinguishable time-Doppler spectrograms of all four bowing gestures to be extracted from the same range bin, as determined by experimenting with various radar height alignments. Another method of determining the ideal range for spectrogram extraction is by finding the range of maximum power. For violin bowing gestures, however, the range bin with the greatest power often does not produce time-Doppler spectrograms that are easily distinguishable for the different techniques.

IV. RESULTS

A. Bowing Technique Recognition

Each bowing technique is performed ten times on the A string by both subjects. For each technique, the range profile for all ten bow strokes is shown in Fig. 3 (a), and the time-Doppler spectrogram of a single up or down bow stroke (isolated from a 2-second window of the complete spectrogram) is shown in Fig. 3 (b) and (c).

Simply observing the unique range profiles for every gesture is sufficient for distinguishing bowing techniques. For all the bowing techniques, the range decreases during the down-bow as the forearm and hand approach the radar; the range increases on the up-bow as the forearm and hand approach the violin. The détaché and tremolo techniques have especially distinct range profiles, while the staccato and spiccato range profiles are similar as both techniques involve short, quick bow strokes at the center of the bow.

To add another layer of certainty to the classification of gestures, one can observe the time-Doppler spectrogram in conjunction with the range profile. Since the up-bow spectrogram for each of the gestures is simply a mirror image of the down-bow spectrogram, only the down-bow motions for each gesture will be analyzed here.

For the détaché, spiccato, and staccato down-bow strokes, the Doppler signature is negative for the entire motion. The magnitude of the Doppler signature increases in the first half of the bow stroke as the forearm and hand accelerate towards the radar. It then decreases in magnitude as the bow approaches the tip and the forearm and hand decelerate until the Doppler signature is zero and the motion ceases. The tremolo Doppler signature fluctuates between positive and negative values due to quick oscillations between up and down motions in this gesture.

In the détaché spectrogram there is a distinct wave crest that curls towards the left so that at certain times there are two largely different Doppler frequencies are present in the graph. This unique feature can be attributed to the different movement speeds of the hand and forearm during détaché. Throughout the stroke, the hand and wrist extend outwards, traveling faster towards the radar than the forearm. The curled crest is not apparent in the other bow strokes because, unlike the broad détaché stroke, the other techniques involve much shorter distances; thus, most of the motion is created by hand-wrist movement and there is substantially less forearm motion. The spectrograms for Subject 1 and Subject 2 are generally consistent with one another across different bow strokes. Compared to Subject 1, Subject 2's spectrogram exhibits more environmental noise, although the gesture signature is still clearly visible. The shape and maximum frequencies of both subjects' spectrograms are generally the same, with slight variations in the power levels at different points of movement.

B. Bowing Technique Evaluation

The time-Doppler spectrograms of certain incorrect bow motions can be distinguished from those of standard bowing

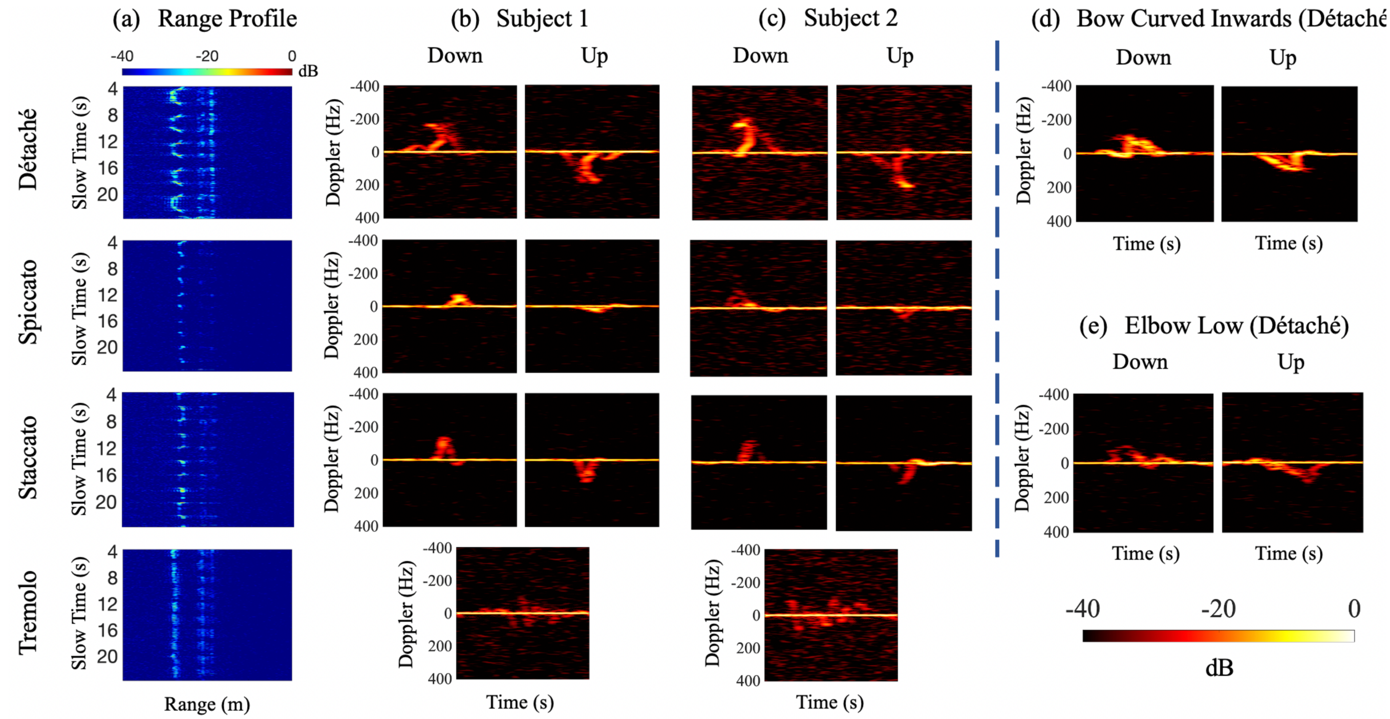

Fig. 3. (a) Range profiles for ten consecutive (up and down) bow strokes of each bowing technique. (b), (c) Two-second windows isolated from time-doppler spectrograms of both subjects, showing one gesture performed as an up- or down-bow. (d) Single détaché up- and down- bow stroke performed with the subject's elbow path creating a concave curve. (e) Single détaché up- and down- bow stroke performed with the right elbow low and tight against the subject's side.

techniques using radar. Figure 3 (d) shows the time-Doppler spectrogram for an up-bow and down-bow détaché stroke performed with the elbow path creating a concave curve (from the perspective of the musician). This incorrect bow motion produces a signature that resembles a flattened version of the standard détaché bow signature and has a smaller maximum velocity. Figure 3 (e) shows the time-Doppler spectrogram for an up-bow and down-bow détaché stroke performed with the right elbow held tightly against the subject's side, limiting freedom of bow movement. This restrained bowing method results in a signature that has a very low maximum velocity and lacks the distinct curled crest of the correct détaché stroke.

V. Conclusion

This study uses an Infineon 60 GHz radar to detect four different bowing techniques on the violin: détaché, spiccato, staccato, and tremolo. The range profiles and time-Doppler spectrograms for the violin motions of two subjects are analyzed, and the unique features of the signatures allow for the different techniques to be easily distinguished. The time-Doppler spectrogram for each stroke type is fairly consistent between subjects, despite their different body dimensions and bowing preferences. The results of this study demonstrate the potential of FMCW radars in recognizing various violin bowing gestures as well as differentiating between right and wrong bowing techniques. Future work could develop machine learning models for automatic classification of bowing techniques and provide real-time feedback to the user. The radar-based motion data could also be combined with audio or visual motion data to further enhance the effectiveness of digital music training.

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