2026 IEEE International Conference on Robotics and Automation (ICRA 2026)
June 1-5, 2026. Vienna, Austria

A Multi-String Traversing Violin-Playing Robot for Carnatic Music

Raghavasimhan Sankaranarayanan[1] and Gil Weinberg[1]

Abstract— **Over the past several decades, robotic musicianship researchers have mainly focused on Western music with only limited efforts addressing musical styles from other regions, such as South Indian Classical music (a.k.a. Carnatic music) - a music form popular in the southern part of India. In this work, we present Hathaani v2, a robotic system capable of performing Carnatic music on the violin. The robot is designed to translate pitch information into left-hand finger placement and amplitude information into bowing changes and dynamics, based on any monophonic audio recording. The left-hand mechanism is capable of reaching arbitrary finger positions along the strings, allowing the robot to play gamakas - continuous pitch ornamentations that are fundamental to Carnatic music. The differential bowing mechanism provides both pressure and angle modulation, while maintaining mechanical rigidity and allowing visual engagement for the audience. We assessed the system's ability to perform Carnatic music through expert listening studies involving ten professional musicians on intonation, timbre, quality of bowing, hand coordination, gamaka authenticity, and clarity. The proposed robot outperforms the baseline on all of the evaluated parameters, achieving average scores exceeding 4 on a 5-point Likert scale (0.5 increments). This work has the potential to transform education and production of Carnatic music by offering programmatic solutions that support complex gamakas. Compared to software-based emulations, this physical violin-playing robot offers an accurate and expressive medium for conveying the nuances of Carnatic music performance.**

I. INTRODUCTION

Research in Robotic Musicianship explores the development of machines that can generate sound, analyze musical input, and engage with humans in a musically expressive manner [1]. This interdisciplinary field lies at the intersection of robotics and computational music, applying the principles of robotics to technology-driven music making. It spans diverse areas such as instrument-playing robots like the LEMUR GuitarBot [2], prosthetic devices that help humans regain musical abilities lost due to amputation [3], and systems enabling interactive music performances [4]–[6].

Carnatic music is a traditional art form primarily associated with the southern part of India. A defining feature of this art form is its extensive use of microtonal ornamentations, where swaras (musical notes) are almost always performed with embellishments known as *gamakas*. A raga serves as a melodic framework in Indian classical music, similar to a scale or mode in Western music [7], but unlike modes or scales, which are only defined by the discrete notes and keys, most Carnatic ragas are intrinsically shaped by their characteristic gamakas.

A. Motivation

Current work in robotic musicianship research has largely focused on Western music traditions, with limited efforts aimed at exploring music from other cultural contexts, such as Carnatic music. The proposed work seeks to broaden the scope of music technology research by applying robotics to the distinctive performance practices and stylistic features of Carnatic music, thereby addressing the prevailing Western-centric bias in the field.

While Western music composers have numerous tools, such as keyboards and Virtual Studio Technology (VST) [8], to audition their compositions, Carnatic music lacks equivalent tools that natively support gamakas - the expressive pitch ornamentation that identifies the art form. Existing software-based emulations often approximate them using pitch bends or portamento, but they cannot capture the physical constraints or characteristic timbre of violin playing. Robotic violins, in contrast, can produce rich and authentic acoustic sound, addressing this gap.

Beyond composition, such systems could also support music education by providing fatigue-free, repeatable demonstrations of complex phrases at controllable speeds, enabling students to observe and practice subtle pitch manipulations. Additionally, human-robot collaborative performances could help increase global visibility and interest in Carnatic music.

In this work, we present a new violin-playing robot capable of performing Carnatic music (Fig. 1). The system plays on all four strings of an acoustic violin and can reach any point along the playable range, enabling the performance of gamakas. A differential bowing mechanism allows the use

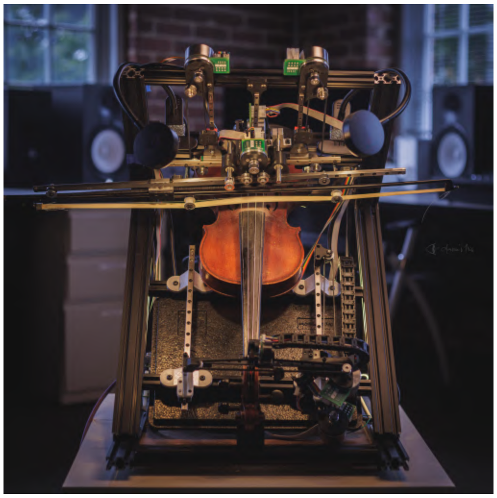

Fig. 1. Hathaani v2 - The Carnatic violin playing robot

---

[1] Georgia Tech Center for Music Technology, Atlanta, GA, United States. Correspondance: `violinsimma@gmail.com`

of a full-size violin bow while maintaining structural stability during bow pressure and angle modulation. Mirroring traditional Carnatic performance posture, where violinists sit cross-legged and hold the instrument between the shoulder and ankle (Fig. 2), the robot adopts a similar posture to enhance visual engagement. Its performance is evaluated through expert listening tests on parameters including intonation, timbre, bowing quality, right–left hand coordination, gamaka authenticity, and overall clarity, in tasks such as sarali varisai (raga scales) [9], gamaka identification, raga identification, and visual connect detailed in Section V.

II. RELATED WORK

Previous efforts in robotic musicianship for violin performance have predominantly centered on reproducing Western classical music, typically by playing pre-composed sequences of discrete notes. These systems often overlook expressive performance techniques such as glissandi or gamakas, which involve continuous pitch variation. Early examples include the Hupfeld Phonoliszt-Violina [10] and Violano Virtuoso [11], which featured distinctive mechanical sound production methods but relied entirely on fixed piano rolls, preventing them from performing glissandi.

A more recent and well-known attempt was Toyota's violin-playing robot [12], an andro-humanoid robot designed to hold and play the violin like a human. However, its primary purpose was to show the robot's social capabilities, and it lacks the subtle musical expressivity.

Ro-Bow by Seth Goldstein [13] introduced micro-tonal playing using a movable finger mechanism with a design that physically rotates the violin for string crossings. While this is a notable advancement, this system does not modify the bowing position relative to the left-hand movement, affecting the tonal consistency. It also relies on a large frame surrounding the violin, making it impractical for use in a Carnatic concert setting.

Kensei by Shibuya, K. [14] is an interesting idea which incorporates auditory feedback to improve its sound quality by adjusting the bowing parameters and modeling human-like performance. However, it is limited by the left-hand system that is unable to reach higher note positions or alternate scales, and it lacks coordination between the left-hand and bowing, limiting its suitability for live performance

Fig. 2. Traditional Carnatic violin playing posture showing an artist performing in a seated posture.

Mizuho et. al. [15] explored violin bow pressure using photo-reflective sensors, showing that the distance between the bow stick and hair changes with applied pressure, offering valuable insights into the bowing dynamics of violin playing.

In [16], the authors proposed a robotic violinist that can perform microtonal music, but the robot is constrained to a single string and uses a compact double roller design for bowing, limiting visual engagement that is important for Human Robot Interaction.

Ghost play [17] is a violin playing robot that can play ornamentations such as glissandi. However, the frame is large, and the posture does not reflect how Carnatic violinists perform. Additionally, the finger press units use solenoids, limiting the ability to modulate finger height along the strings.

A preliminary version of this system was presented as a short video at the ACM/IEEE International Conference on Human-Robot Interaction (HRI) 2025 [18]. It demonstrated Carnatic music performance on the robot in a limited form, focusing on the overview of the design. This paper extends that effort by providing a detailed description of the design and a formal human evaluation of the robot.

III. DESIGN

The robot's design includes two main sub-systems - the Fingerboard Traversal and the Bowing. The modeled view of the robot is shown in Fig. 3. The frame is constructed from aluminum extrusions and 3D-printed parts. To secure the violin, the left and right pads of a standard violin shoulder rest are mounted onto the frame, with an additional 3D-printed support at the scroll serving as a third point of contact. This allows the instrument to be held stable during performance while still enabling quick removal for tuning and maintenance.

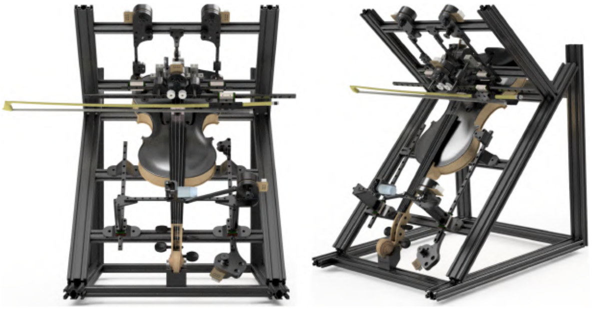

Fig. 3. The model of Hathaani v2 - The Carnatic violin playing robot.

The finger actuation of the system is driven by the Maxon EC32 Flat 100W BLDC, and all the actuators use the Maxon EC45 Flat 80W BLDC motor [19]. The specifications of the actuators are shown in Table I. All of the actuators are equipped with a shaft-mounted encoder with 4096 ticks per turn and a hall effect sensor for position feedback and closed-loop position control.

All the actuators are driven by the EPOS4 micro 24/5 positioning controllers [19] which communicate using the CAN bus protocol. These motors and controllers allow for precise trajectory control, faster response, and have a very low noise floor - suitable for applications in robotic musicianship.

TABLE I

ACTUATOR SPECIFICATIONS

Category	EC 45	EC 32
Power	80W	100W
Operating Voltage	24V	24V
No Load Current	270mA	179mA
Nominal Current	3.96A	4.24A
Stall Current	42A	51.6A
Nominal Torque	167mNm	103mNm
Stall Torque	1690mNm	438mNm
Torque Constant	40.4mNm/A	21.3mNm/A
Max. Efficiency	84.9%	89%
No. Pole pairs	8	6

A. *Fingerboard Traversal*

The design of the fingerboard traversal (also referred to as "left-hand") draws inspiration from human left-hand movements, incorporating vertical motion for pitch changes and horizontal motion for string changes. A simplified view of the left-hand system is shown in Fig. 4. Since the robot needs to play gamakas, its design must allow the end-effector to access any continuous point along the fingerboard rather than only discrete note positions. From a music perspective, the robot needs to be able to modulate the pitch in the continuous domain over time. Assuming an equal temperament scale for reference, the pitch position on the string is a function of the 12th root of 2. Given an open string tuning and a scale length L_s, the distance from the bridge L_p can be computed for any fret position n using eq. 1.

$$L_p = L_s\left(2^{\frac{-n}{12}}\right) \tag{1}$$

Mechanically, the traversal is achieved with a dual 300 mm linear slider for longitudinal motion, and the string crossing is implemented using a 100mm linear slider orthogonal to the strings' axes. Both degrees of freedom use belt and pulley mechanisms. The string change was initially driven using a slider crank design as shown in Fig. 4.a, but was later replaced with a belt and pulley as it produced consistent precision across length and more reliable string crossings.

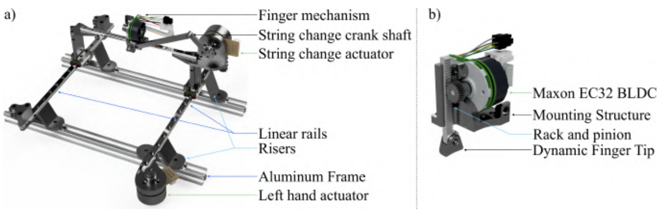

Fig. 4. a) Fingerboard traversal design showing the left-hand traversal. b) String stopping mechanism showing the dynamic finger tip.

1) String Stopping: The string-stopping system uses a Maxon EC32 BLDC motor to allow for trajectory control and motion planning while being compact. The design is depicted in Fig. 4.b. The fingertip is designed to conform to the curvature of the fingerboard, accommodating the varying surface normals across its width. We added a silicon coating to the tip so as to bring the damping factor closer to human skin, thus improving tonal quality [16].

B. *Bowing*

The bowing speed, bowing force, and sound point are the three factors relevant to bowing that determine the sound quality [20] with an additional factor - bow angle, to accommodate string crossings.

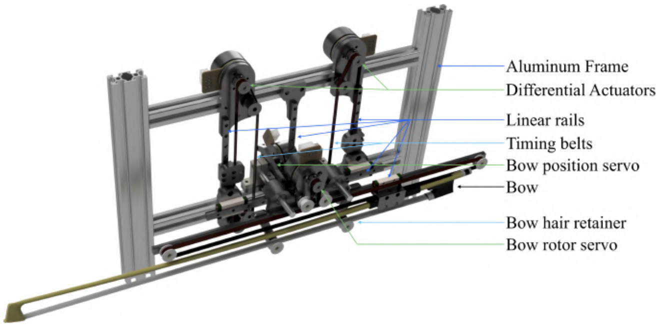

Fig. 5. Differential bowing design depicting the various components along with a 3D model of a bow

Fig. 5 shows the bowing mechanism, addressing the following parameters:

- Bow Rotor - moves the bow across the string
- Differential actuators - Controls the bow pressure and angle
- Bow Position - adjust the sound point along the string

To accommodate the physical properties of the conventional violin bow and to simplify programming the actuators, all the motors for the bowing system use the Maxon EC45. To play a note, the bow needs to move across the string, exciting it. This is done using a belt drive mechanism as shown in Fig. 5.

1) Bow pressure and angle: The hair pressure exerted on the string and the bow angle are modulated using a differential pair. Fig. 6 shows the kinematic diagram for the bow pressure and angle control. To change the pressure on the string, the bow needs to move d mm vertically. To change the angle of the bow, it needs to rotate by θ radians. To get the relation between motor shaft angle ϕ,

$$\phi_L = \phi_d + \phi_x; \quad \phi_R = \phi_d - \phi_x \tag{2}$$

where ϕ_L and ϕ_R denotes left and right motor angles respectively, ϕ_d is the angle required for vertical displacement and ϕ_x is the angle required to rotate the bow.

$$d = \frac{\phi_d}{2\pi} 2\pi r \implies \phi_d = \frac{d}{r} \tag{3}$$

$$x = \phi_x r, x = L\tan(\theta) \implies \phi_x = \frac{L\tan(\theta)}{r} \tag{4}$$

$$\implies \phi_L = \frac{d + L\tan(\theta)}{r}, \quad \phi_R = \frac{d - L\tan(\theta)}{r} \tag{5}$$

where L is the distance of the actuator from the centerline and r is the radius of the belt pulley.

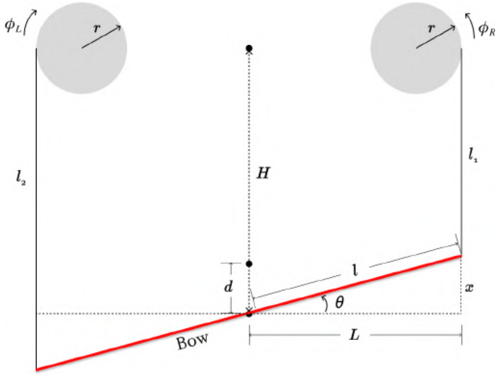

Fig. 6. Bowing kinematic diagram

2) Position: In [16], the authors demonstrated the effectiveness of modulating the sound point (bow position along the string) for improving tone quality. The proposed robot adopts a similar approach, where the bowing position is adjusted based on the left-hand finger position - tracked in real-time using the motor's built-in shaft encoder. As the finger moves higher along the string, the bow is shifted closer to the bridge to produce richer intonation and tone. The minimum and maximum positions depend on the violin used and are calibrated empirically to achieve the desired tonal quality. Unlike [16], which used an auxiliary encoder to track the left-hand position, the proposed system operates in real-time over the CAN bus and relies on the motor's built-in shaft encoder for position tracking.

C. Controller

The main controller for the robot is the STM32-based Robotis OpenCR1.0 microcontroller board [21] with an Ethernet shield. The communication and data flow architecture is depicted in Fig. 7. All communication lines are bi-directional. The termination resistors are omitted for brevity. All the actuators are on the same CAN bus, with the OpenCR controller being the master controller. All the initialization and setup happen via the Service Data Objects (SDO) while the trajectory data is sent via the Process Data Objects (PDO) [22]. The system is powered by a 24V 41A SMPS.

IV. SOFTWARE

The control architecture of the robot has two software components,

1) Input processor
   The robot uses monophonic audio as input. We used the singing voice and violin samples for this work. We first extract pitch and amplitude envelopes, normalize for the tonic note, adjust for deviations (section IV-D), detect parameters such as bow changes (section IV-A) and open string pitches (section IV-B), plan path (section IV-C), transform into motor trajectory data, and send to the controller. We use the RMVPE [23] for pitch tracking and a simple RMS-based algorithm for amplitudes. The communication uses a combination of TCP and UDP protocols for transmission. The preprocessed data is stored in a queue. When the controller requests new data through TCP, a set of trajectory values is sent to the controller via UDP from the queue. This stage happens on the master computer (user) to which the controller is connected via Ethernet. The feature set we obtain after processing is a $7 \times N$ array where N is the number of trajectory points in the phrase. Fig. 8 shows a generated trajectory for a short phrase in the raga Mohanam. Note that the time frames between the input and generated trajectories do not align. This is because we add a trapezoidal interpolation with a blend for a duration of 250ms to travel to the starting position of the trajectory from the current position of the robot, resulting in additional time frames.
2) Controller Firmware
   It is responsible for parsing the incoming trajectory data and sending it to the respective motor controllers via CAN bus. The interpolation time period used is 10ms, which corresponds to the pitch tracking of a signal of sample rate 16kHz with a hop size of 160 samples. Due to memory constraints, the controller only stores 1 second of trajectory at a time. As the data gets consumed, the controller requests the master for new data over TCP. Upon receiving a request, the master sends a set of trajectory values from its queue, and the cycle repeats. If no new data arrives, the controller sends current trajectory values to hold the torque and to prevent EMCY fault message triggers [22] until new data becomes available.

A. Bow change detection

Since the robot uses a conventional violin bow and cross between strings, it requires an efficient bow change detection algorithm to compute bow changes in the input audio, without which the robot will not be able to perform longer phrases. The bow change algorithm works as follows,

1) Using the amplitude envelope contour of the input, find dips / local minima.
2) Use a hyperparameter *"min bow time"* to denote the fastest possible bow change. This value is found to be 80 ms empirically and is dependent on the physical limitation of the actuators.
3) Rank and filter out the dips so that adjacent dips are at least *"min bow time"* apart.
4) The dips may not always be detected accurately due to computational errors. To correct this, nudge each

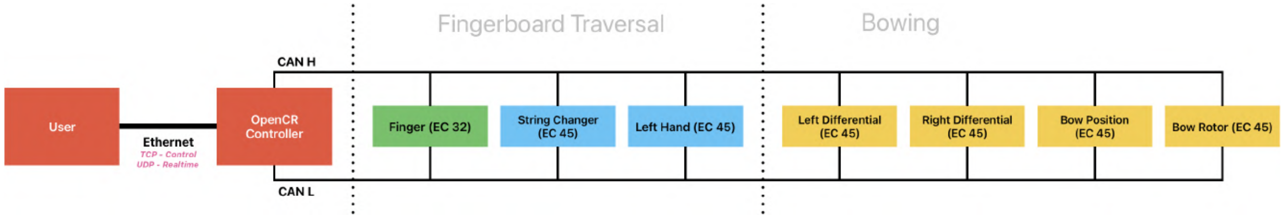

Fig. 7. Data flow diagram

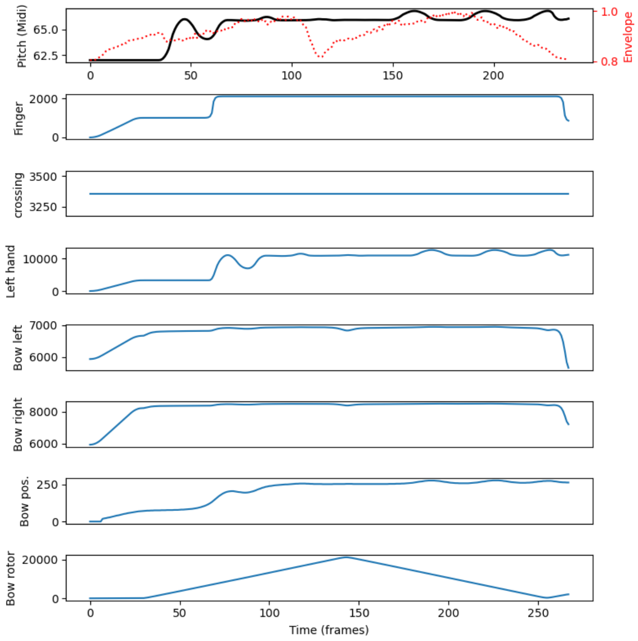

Fig. 8. Input pitch as midi note float values and normalized amplitude contour (1st plot) extracted from audio and the corresponding actuator trajectories as encoder ticks (plots 2 through 8)

dip to the closest local maxima/minima of the pitch contour of the input.

This algorithm is inspired by how human violinists recognize bow changes during a concert. The bow changes can be seen in the bow rotor subplot in Fig. 8, where the slope changes direction for each bow change in the phrase. The extracted amplitudes from the audio dictate both the steepness of the slope as well as the bow pressure.

B. Open string playing

The input given to the robot is audio, which does not contain information about open string pitches - pitch values that are played on the string without string-stopping (a.k.a. without pressing a finger on the fingerboard). It is essential to detect pitches played on the open string since this is the preferred way of playing a note when there is no gamaka involved, especially during string crossings. In this work, static pitches (non-oscillating pitches) that don't deviate from one of the 4 open string tunings by more than 25 cents are categorized as open string pitches. These are derived from Constant Pitch Notes (CPN) as described in [24]–[26]. Open string pitches are used to generate the finger trajectory shown in Fig. 8. We can notice that from samples 0 to ∼40, the robot needs to play the open string, and this is reflected in the finger trajectory as well.

C. Path planning

Since the robot plays on all 4 strings of the violin, path planning is required for efficient string crossings. An overview of the algorithm is provided below.

1) For a given phrase, find all the silent regions and split the phrase into multiple sub-phrases.
2) For each sub-phrase, find the pitch range by computing the minimum and maximum pitch. Compare this with the range of each string and assign it to the closest string whose range is equal to or larger than the sub-phrase pitch range. If multiple strings satisfy this condition, choose the string that requires the least minimum pitch - thereby performing in lower left-hand positions.
3) If none of the sub-phrase pitch ranges is greater than the range of all the strings, split the sub-phrase further using open string pitches and CPN in the phrase, and repeat 2) until all the pitch points are assigned a string. Open string pitches are used because switching strings is a time-demanding task. If the robot switches strings during open string playing, the switching time can be minimized since the left-hand movement takes place while the robot is playing an open string note.
4) While assigning a string, take into account the current string to minimize string jumps.

This algorithm was modeled after studying numerous performance videos of Carnatic violinists, as well as using the author's own musical background.

D. Deviation corrections

Human violinists develop muscle memory over years of practice to acquire the necessary intonation and timbre. Since the robot does not have any information about the instrument itself, we need to tune and correct various parameters to produce a convincing sound. For each parameter, we physically measured the corresponding values on the violin and used these to correct for the deviations. These deviations are,

1) Finger height
   The distance between the string and the fingerboard increases as we go away from the nut (towards the bridge). Thus, the finger height is modulated to compensate for this change.

2) String distance
The distance between the adjacent strings also increases as we go away from the nut (towards the bridge). Thus, the string change subsystem is modulated to compensate for this change.
3) Bow pressure
The bow pressure on the string changes when the finger is pressed (string stopped) compared to when playing an open string. It also depends on the action of the strings [27]. This deviation was tuned to match the amplitudes of open vs pressed states and is added to the bow pressure modulation subsystem.

Without these corrections, we start to hear problems, including artificial harmonics, incorrect intonation, and screeching noise. These parameters are unique to each violin. This is why human violinists practice on the same instrument they perform on so that they get used to these deviations.

V. EVALUATION AND DISCUSSION

[16] presented a quantitative evaluation of the first version of the robotic platform, demonstrating its mechanical feasibility and baseline performance. As the present work focuses on improvements in musical expressivity and stylistic fidelity, evaluation by domain experts is essential. We invited ten Carnatic music experts to evaluate the performance of the robot in playing Carnatic music and to compare it with a baseline and a professional human musician as a reference. The artists have experience ranging from 5 to 53 years in performing Carnatic music concerts and have in-depth knowledge of Carnatic music theory, especially in understanding and interpreting gamakas.

We followed the book - Sangita Sampradaya Pradarsini (SSP) [28], for gamaka nomenclatures. Our baseline for the evaluation is [16]. Thus, we used the same set of gamaka types as used in [16]. These are *Kampita*, *Sphurita*, *Tirupa / Nokku*, *Ahata*, *Vali*, *Ullasita*, and *Kurula*. In performing melodic phrases in Carnatic music, gamaka renditions have overlaps (i.e., a melodic phrase contains multiple gamakas). It is impractical to construct phrases with just one gamaka type. The recorded phrases contain a prominent gamaka type with other supporting gamakas. To control the comparison, for all the sections, we acquired the same set of source recordings as used in the baseline from the authors. This is used as the human reference for the tests. That is, the input features for both the baseline and the proposed robot are from the same set of audio recordings. The listening test consists of 4 sections described below.

A. Sarali Varisai

The first section tests the ability of the robot to play the basics of Carnatic music - the first Sarali Varisai [9] in four different ragas. A 5-point, 0.5 increment scale was used to rate each of the performances on the basis of pitching/intonation, timbre/tone, quality of bowing, right-left hand coordination (shortened as coordination for brevity), and overall clarity. The mean and standard deviation of the combined scores from participants for the baseline and the proposed robot are given in Table II.

TABLE II
SARALI VARISAI SCORES - MEAN (STD.)

	Baseline	**Proposed**
pitching / intonation	3.686 (1.210)	**4.016** (0.561)
timbre / tone	3.375 (1.000)	**4.047** (0.652)
quality of bowing	3.813 (1.016)	**3.969** (0.718)
coordination	3.891 (1.030)	**4.109** (1.083)
Overall clarity	4.016 (0.619)	**4.250** (0.648)

TABLE III
P-VALUES FROM T-TEST

Category	**p-value**
pitching / intonation	$8.444e^{-2}$
timbre / tone	$1.113e^{-3}$
quality of bowing	$2.549e^{-2}$
coordination	$1.327e^{-2}$
Overall clarity	$1.335e^{-2}$

The p-values from the one-tailed T-test between the baseline and the proposed robot are shown in Table III. It is interesting to see that there is a significant improvement in *timbre/tone, quality of bowing* and *Overall clarity* compared to the baseline, when using $\alpha = 0.05$.

B. Gamaka Identification

For this section, experts listened to 16 audio recordings of short phrases performed by the proposed robot. Each phrase was about three seconds long, containing one or more gamakas from the seven chosen types. The experts were asked to list all the gamakas present in each phrase and rate the performance.

For a subset of the performances, experts were also asked to rate the gamaka authenticity, which measures how accurately each gamaka was performed, comparing it with the same phrase performed by the baseline robot as well as the human violinist. The participants were able to spot the predominant gamakas most of the time. Table IV shows the experts' entries for each question. The first column lists the predominant gamaka(s) present in each phrase.

It can be seen that participants had no ambiguity when identifying the Spurita gamaka. It is notable that in some cases, the participants tagged Ullasita when tagging Ahata. This suggests that a second robotic finger may be necessary since the quick movement of the left hand to play Ahata could have been misinterpreted as Ullasita. The Vali gamaka was most often confused with other gamakas. This can be attributed to the fact that Vali involves playing shades of multiple swaras. Thus, it contains other gamakas associated with it. Though SSP is one of the standard references, its type nomenclatures are rather archaic. The gamaka classes used in the book are not truly orthogonal. This explains the reason for the misidentifying of gamakas in some cases when there are overlapping features between the types, as shown in Table IV. The mean and standard deviation of the combined scores from the participants are given in Table V.

TABLE IV

PROMINENT GAMAKA VS EXPERTS' GUESSES

No.	Prominent gamaka(s)	Kampita	Spurita	Nokku	Ahata	Vali	Ullasita	Kurula
1	Spurita	1	**10**	1	1	-	-	-
2	Kampita	**8**	-	1	1	1	2	-
3	Kampita, Ahata	**10**	2	3	**10**	2	1	1
4	Ullasita, Spurita	-	**8**	3	3	1	**10**	1
5	Spurita	-	**8**	2	-	-	1	-
6	Ullasita, Vali	1	1	3	2	**7**	**10**	3
7	Ahata	-	1	2	**8**	-	1	1
8	Spurita	-	**9**	1	1	-	-	1
9	Nokku	-	-	**8**	3	3	2	2
10	Kampita	**9**	-	2	1	-	-	2
11	Vali, Spurita	2	**9**	1	1	**9**	2	1
12	Kampita	**9**	1	2	3	1	1	1
13	Vali	3	-	1	2	**8**	4	4
14	Vali, Nokku	3	1	**7**	4	**9**	1	1
15	Kurula	-	1	-	-	1	2	**8**
16	Vali, Nokku	1	-	**8**	2	**9**	2	2

TABLE V

GAMAKA SCORES - MEAN (STD.)

	Baseline	**Proposed**	**human**
pitching / intonation	3.156 (0.995)	**4.344** (0.539)	4.469 (0.464)
timbre / tone	2.969 (0.903)	**4.281** (0.657)	4.531 (0.386)
quality of bowing	3.219 (0.856)	**4.219** (0.682)	4.531 (0.427)
coordination	3.719 (0.875)	**4.344** (0.790)	4.656 (0.352)
gamaka authenticity	3.438 (0.998)	**4.406** (0.584)	4.625 (0.428)
Overall clarity	3.469 (0.884)	**4.406** (0.523)	4.563 (0.512)

TABLE VI

P-VALUES FROM T-TEST

Category	**p-value** (Gamaka Id)	**p-value** (Raga Id)
pitching / intonation	$1.11e^{-4}$	$1.508e^{-3}$
timbre / tone	$2.717e^{-5}$	$1.508e^{-3}$
quality of bowing	$4.885e^{-4}$	$2.708e^{-3}$
coordination	$2.116e^{-2}$	$2.244e^{-3}$
gamaka authenticity	$1.091e^{-3}$	$4.386e^{-3}$
Overall clarity	$4.962e^{-4}$	$2.746e^{-4}$

The p-values from the one-tailed T-test between baseline and the proposed robot are shown in Table VI (Gamaka Id). It can be seen that the improvement is significant in all categories ($\alpha = 0.05$). This indicates that the proposed robot can perform better gamakas - a core aspect of Carnatic music.

C. Raga Identification

This section addressed raga identification, where experts listened to audio recordings of short phrases performed by the robot. As mentioned in section I, gamakas in Carnatic music are not just ornaments but a vital part of the rendition of a raga. We used the same characteristic phrases of 11 different ragas as the baseline - Neelambari, Bhairavi, Arabhi, Kaanada, Dhanyasi, Mohanam, Thodi, Sahana, Saveri, Anandhabhairavi, and Sindhubhairavi. None of the phrases contained the complete arohanam (ascending notes of the scale) and avarohanam (descending notes of the scale) - all the notes of the ragas were not revealed. Thus, the participants needed to rely on the gamaka to identify the raga. For instance, the phrase used for the raga Sindhubhairavi is | p D P d n s r G r S R S | (refer [28] for notation convention). These swaras (musical notes) are also valid in raga Thodi, but they differ only by the gamakas used to perform the phrase. The participants were able to guess all 11 ragas correctly. The mean and standard deviation of the combined scores from the participants for this section are given in Table VII.

TABLE VII

RAGA SCORES - MEAN (STD.)

	Baseline	**Proposed**	**human**
pitching / intonation	3.281 (0.966)	**4.188** (0.574)	4.719 (0.446)
timbre / tone	3.063 (0.929)	**4.094** (0.664)	4.594 (0.375)
quality of bowing	3.156 (1.012)	**4.094** (0.735)	4.625 (0.342)
coordination	3.406 (0.97)	**4.375** (0.806)	4.75 (0.365)
Gamaka authenticity	3.438 (0.981)	**4.313** (0.772)	4.844 (0.301)
Overall clarity	3.531 (0.67)	**4.344** (0.507)	4.781 (0.315)

The p-values from the one-tailed T-test between the baseline and the proposed robot are shown in Table VI (Raga Id). Here again, it can be seen that the improvement is statistically significant in all categories ($\alpha = 0.05$).

D. Visual Connect

The robot's posture is informed by how human violinists perform Carnatic music. For this section of the study, the experts were presented with a video that contained side-by-side performances of the two robots (baseline and proposed), labeled Robot 1 and Robot 2, respectively. The video is muted, and the video of the proposed robot performance was shot to match the baseline's lighting and quality. The experts were then asked to specify which of the two robot performances they would like to see in a concert. They were asked to make their choice in terms of visual connection, concert tradition, and posture. All of them preferred the robot 2 (proposed robot). When asked the rationale behind their choice, one participant said - *"Could connect more visually to the robot 2 because of the posture."* while another participant mentioned *"Robot 2 looks interesting and more closer to the usual human posture."*. Other interesting responses include *"Robot 2 looks more appealing to the eye and its diagonal posture looks better."*, *"Robot 2 posture is authentic. It felt like real human playing."*.

VI. CONCLUSION AND FUTURE WORK

This work presented a new design of Hathaani, the violin-playing robot capable of performing Carnatic music. The left-hand design allows continuous positioning along the string, supporting gamakas as well as string crossings during the performance. The differential bowing mechanism enables both pressure and angle modulation with structural stability. Unlike the prior design, the robot employs a conventional violin bow, enhancing visual engagement.

Expert listening studies with ten professional musicians showed that participants accurately identified all ragas and key gamakas, indicating the robot's ability to reproduce these core elements of Carnatic music. While this work demonstrated Carnatic music, the system could be extended to other microtonal music traditions as well.

Two primary application domains are envisioned. First, the robot could perform in concerts alongside human musicians. Carnatic performances rely heavily on interaction and improvisation, where accompanists respond to the lead musician in real time without prior rehearsal. A robotic violinist capable of participating in such interactions could provide a novel human-robot musical collaboration. As future work, machine learning models could be used to generate musical phrases conditioned on the lead musician, enabling real-time accompaniment and improvisational interaction on stage [26], [29], [30]. Additionally, the current single-finger actuation mechanism could be extended to a multi-finger design to support more complex fingering patterns and richer musical articulation.

Second, the robot could serve as an educational tool for Carnatic music training. Unlike human instructors, the robot can demonstrate complex gamakas repeatedly without fatigue and at controllable speeds, allowing students to study and practice intricate phrases at their own pace. Operating in the same physical space as the student also provides clearer visual and spatial cues than remote video-based learning platforms such as YouTube.

Finally, human-robot collaborative performances could spark interest in Carnatic music globally and help raise its visibility among international audiences.

ACKNOWLEDGEMENT

We thank the musicians for participating in this study.

REFERENCES

[1] G. Weinberg, M. Bretan, G. Hoffman, and S. Driscoll, *Robotic musicianship: embodied artificial creativity and mechatronic musical expression*. Springer Nature, 2020, vol. 8.

[2] E. Singer, K. Larke, and D. Bianciardi, "Lemur guitarbot: Midi robotic string instrument." in *Nime*, vol. 3, 2003, pp. 188–191.

[3] N. Yang, R. Sha, R. Sankaranarayanan, Q. Sun, and G. Weinberg, "Drumming arm: an upper-limb prosthetic system to restore grip control for a transradial amputee drummer," in *2021 IEEE International Conference on Robotics and Automation (ICRA)*, 2021, pp. 10 317–10 323.

[4] R. Savery, L. Zahray, and G. Weinberg, "Shimon the rapper: A real-time system for human-robot interactive rap battles," *arXiv preprint arXiv:2009.09234*, 2020.

[5] X. Gao, A. Rogel, R. Sankaranarayanan, B. Dowling, and G. Weinberg, "Music, body, and machine: gesture-based synchronization in human-robot musical interaction," *Frontiers in Robotics and AI*, vol. 11, p. 1461615, 2024.

[6] N. Yang, R. Savery, R. Sankaranarayanan, L. Zahray, and G. Weinberg, "Mechatronics-driven musical expressivity for robotic percussionists," *arXiv preprint arXiv:2007.14850*, 2020.

[7] J. G. Lochtefeld, *The illustrated encyclopedia of Hinduism*. The Rosen Publishing Group, Inc., 2002.

[8] G. Tanev and A. Bozhinovski, "Virtual studio technology and its application in digital music production," 2013.

[9] "Sarali varisai," http://www.shivkumar.org/music/basics/sarali-varisai.htm, accessed: 2021-01-19.

[10] "Hupfeld phonoliszt-violina," www.youtube.com/watch?v=qewdC3hX4iQ, accessed: 2023-11-27.

[11] "Violano virtuoso," https://www.youtube.com/watch?v=Y50ws6zgUNc, accessed: 2023-11-27.

[12] Y. Kusuda, "Toyota's violin-playing robot," *Industrial Robot: An International Journal*, vol. 35, no. 6, pp. 504–506, 2008.

[13] "Ro-bow - a kinetic sculpture that plays a violin by seth goldstein," https://www.youtube.com/watch?v=EPTUM2_bxnQ, accessed: 2023-11-27.

[14] K. Shibuya, "Violin playing robot and kansei," in *Musical robots and interactive multimodal systems*. Springer, 2011, pp. 179–193.

[15] Y. Mizuho, R. Kitamura, and Y. Sugiura, "Estimation of violin bow pressure using photo-reflective sensors," in *Proceedings of the 25th International Conference on Multimodal Interaction*, 2023, pp. 216–223.

[16] R. Sankaranarayanan and G. Weinberg, "Design of hathaani-a robotic violinist for carnatic music." PubPub, 2021.

[17] T. Kamatani, Y. Sato, and M. Fujino, "Ghost play - a violin-playing robot using electromagnetic linear actuators," in *Proceedings of the International Conference on New Interfaces for Musical Expression*, The University of Auckland, New Zealand, jun 2022. [Online]. Available: https://doi.org/10.21428%2F92fbeb44.754a50b5

[18] R. Sankaranarayanan and G. Weinberg, "A novel violin playing robot for south indian classical music," in *2025 20th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. IEEE, 2025, pp. 1823–1825.

[19] Maxon Group. (2025) Maxon motor ag. [Online]. Available: https://www.maxongroup.com/en-us

[20] W. Jo, B. Lee, and D. Kim, "Development of auditory feedback system for violin playing robot," *International Journal of Precision Engineering and Manufacturing*, vol. 17, no. 6, pp. 717–724, 2016.

[21] ROBOTIS e-Manual. (2025) Opencr 1.0 e-manual. Accessed: 14 September 2025. [Online]. Available: https://emanual.robotis.com/docs/en/parts/controller/opencr10/

[22] M. Bozdal, M. Samie, and I. Jennions, "A survey on can bus protocol: Attacks, challenges, and potential solutions," in *2018 International Conference on Computing, Electronics & Communications Engineering (iCCECE)*. IEEE, 2018, pp. 201–205.

[23] H. Wei, X. Cao, T. Dan, and Y. Chen, "Rmvpe: A robust model for vocal pitch estimation in polyphonic music," *arXiv preprint arXiv:2306.15412*, 2023.

[24] V. S. Viraraghavan, R. Aravind, and H. A. Murthy, "A statistical analysis of gamakas in carnatic music." in *ISMIR*, 2017, pp. 243–249.

[25] ——, "Precision of sung notes in carnatic music." in *ISMIR*, 2018, pp. 499–505.

[26] R. Sankaranarayanan and G. Weinberg, "Agnostic automatic melodic accompaniment for alapana in carnatic music," in *2025 IEEE International Conference on Acoustics, Speech, and Signal Processing Workshops (ICASSPW)*. IEEE, 2025, pp. 1–5.

[27] R. Mottola, "Guitar fretboard camber and action in the context of string bending," *Savart Journal*, vol. 1, no. 4, 2014.

[28] S. Dikshitar, *Sangita Sampradaya Pradarsini*. The Music Academy, 1973, vol. 1. [Online]. Available: http://www.ibiblio.org/guruguha/ssp_cakram1-4.pdf

[29] R. Sankaranarayanan and G. Weinberg, "Gamaka synthesis for kalpitha swaras in carnatic music," in *International Society for Music Information Retrieval (ISMIR)*, 2022, IBD.

[30] R. Sankaranarayanan, L. Heck, and G. Weinberg, "Gamaka synthesis for kalpitha swaras in carnatic music," in *2025 IEEE International Conference on Acoustics, Speech, and Signal Processing Workshops (ICASSPW)*. IEEE, 2025, pp. 1–5.