Gestural Control of Augmented Instrumental Performance: A Case Study of the Concert Harp

John Sullivan
IDMIL, CIRMMT
McGill University
Montreal, Canada
john.sullivan@mail.mcgill.ca

Alexandra Tibbitts
CIRMMT
University of Montreal
Montreal, Canada
alexandra.tibbitts@umontreal.ca

Brice Gatinet
CIRMMT
McGill University
Montreal, Canada
brice.gatinet@mail.mcgill.ca

Marcelo M. Wanderley
IDMIL, CIRMMT
McGill University
Montreal, Canada
marcelo.wanderley@mcgill.ca

ABSTRACT

We present a gestural control system to augment harp performance with real-time control of computer-based audio affects and processing. While the lightweight system was designed for use alongside any instrument, our choice of the concert harp represented a unique case study in gestural control of music. The instrument's large size and physically demanding playing technique leaves the performer with little spare bandwidth to devote to other tasks. A motion capture study analyzed instrumental and ancillary gestures of natural harp performances that could be mapped effectively to control of additional signal processing parameters. The initial findings of the study helped to guide the design of custom gesture control devices and user software, and a new work for solo harpist and electronics was created. We discuss our findings, successes and challenges in the study and design of gesture control for augmented instrumental performance, with particular focus on the concert harp.

CCS CONCEPTS

• **Human-centered computing → Gestural input**; *User centered design*; • **Applied computing → Sound and music computing**;

KEYWORDS

harp, gesture, controller, motion capture, movement

ACM Reference Format:

John Sullivan, Alexandra Tibbitts, Brice Gatinet, and Marcelo M. Wanderley. 2018. Gestural Control of Augmented Instrumental Performance: A Case Study of the Concert Harp. In *MOCO: 5th International Conference on Movement and Computing, June 28–30, 2018, Genoa, Italy*. ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3212721.3212814

MOCO, June 28–30, 2018, Genoa, Italy

ACM ISBN 978-1-4503-6504-8/18/06…$15.00
https://doi.org/10.1145/3212721.3212814

Figure 1: Performance with harp and motion-controlled electronics

1 INTRODUCTION

While gestural control of music has been extensively explored, a standardized model for performers has yet to emerge. This is not surprising, as the notion of gesture in music is a broad topic [23], and there are many different objectives, approaches and technologies that have been applied. The widespread availability of inexpensive sensing technologies and programmable microcontrollers [14], not to mention a variety of commercially available motion tracking systems devices like Leap Motion, Xsens, and until recently, the Kinect[1] provide accessible means of interfacing motion data with live performance. This has made implementation of gesture a viable option for many performers.

For this project, we were interested in designing a lightweight gestural control system that could augment live instrumental performance. Our proposed system would be flexible enough to be used with any instrument, and integrate easily into common live

[1] Microsoft has discontinued production as of October 2017.

performance workflows. Most importantly, it would be simple for a performer to set up and configure without requiring extensive technical knowledge to operate. Given these parameters, we devised a small wireless device that could attach unobtrusively to either the performer or instrument, accompanied by an OSC-based software interface for connection to other audio applications.

Our choice of the concert harp represented a unique case study in gestural control of music. The instrument's large size and playing technique leave little physical freedom for the performer to dedicate to other activities. Thus, any system of gestural control would need to be integrated into the natural playing movements of the harpist. These factors were explored through a motion capture study of harp performance. From it we devised basic strategies to inform the design of our gesture control system.

Utilizing an exploratory, user-centered approach, the project tested these strategies through the development of hardware and software that culminated in the creation of a new live work for solo concert harpist and gesture controller.

Here we present an overview of each phase of the project, and discuss our approaches, outcomes and lessons learned in the areas of gesture acquisition and analysis, interface design, mapping, composition and performance. With the harp as our primary focus, we offer additional insight and reflection on the study of augmented harp performance.

2 BACKGROUND

Research in the field of digital musical instrument (DMI) design has paved the way for new methods of performer-instrument interaction. New instruments and interfaces provide unique approaches to performance and offer new sonic palates to explore. The use of gesture is well-established in certain areas, particularly electroacoustic, experimental and mixed music, yet still represents a novel and emerging form of musical practice that is ripe for exploration.

In [15], four categories of gestural controllers, or interfaces, for music interaction are defined. *Alternate controllers* have no explicit affinity with existing instruments. *Instrument-like controllers* and *instrument-inspired controllers* emulate certain characteristics of existing instruments. These types of controllers benefit from leveraging a performer's preexisting knowledge of technique on a given instrument, which can aid in learning and mastery of a new instrument.

The gestural control system described here is most closely related to the fourth category, *extended instruments*. These augment the capabilities of existing instruments, usually through the addition of extra sensors that can measure various properties of movement in performance. Augmented instruments can be used to extend the sonic possibilities, performance practices, and metaphors of their original counterparts. There are many examples in literature, including the trumpet [11, 17, 19], piano [2, 13], flute [18], and djembe [12], to name just a few.

2.1 Spare bandwidth

In the choice of the harp as the instrument of our investigation, we are inspired by Perry Cook's corollary on interface design that "Some players have spare bandwidth, some do not" [9]. A trumpet, for example, is operable with the mouth and a single hand, leaving the other hand, arm, and both legs, available for other tasks. But the concert harp is played with both hands and both feet, requiring a full-body physical engagement to command the large instrument. In Cook's terminology, the player has very little spare bandwidth. Yet the skilled harpist moves with a graceful choreography that, while facilitating the functional operation of the instrument, creates its own language of movement and rhythm. Creatively, we see an opportunity to map both instrumental (sound-producing) and ancillary (non-sound-producing, or *accompanist*) gestures [4] to additional musical parameters in a real-time computer-based performance workflow.

2.2 Gestural Control of Harp

There is relatively little documentation on the harp as a basis for an augmented instrument. This may be due to its scarcity of spare bandwidth, making it potentially less suited for augmentation than other instruments. It could also be related to the instrument's long history and formal traditions, though this has hardly slowed the augmentation of other traditional instruments like those mentioned previously.

Perhaps the most recognizable connection of harp to new interface design and extended performance is the laser harp[2], an instrument-inspired controller that projects an array of laser light beams that bear some resemblance to the strings on a harp. The interface is "played" by interrupting the light beams with the hand, while sensors measure the distance at which the light is broken for additional gestural input.

2.2.1 Gestural Control Strategies. In the area of extending harp performance, we can look at the work of Úna Monaghan [16]. Her work has explored techniques and implications of electronic and experimental music practices in contemporary Irish traditional music. Monaghan has documented a variety of different methods and technologies for augmenting harp with gestural control, each which offered its own advantages and disadvantages.

An early approach employed a microphone attached inside the sound cavity of the harp to use the direct audio as an input signal. With computational analysis of the signal in both the time and frequency domain, this approach can yield low-level parameters of the signal such as fundamental frequency, spectral envelope, the frequency, amplitude and phase of the partials making up the spectrum. Additional analysis can also produce higher-level parameters relating to the perceived timbre of the sound [21]. This method of indirect acquisition can be highly effective at parameterizing performance data while remaining unobtrusive for the performer. However, this approach presents certain challenges for harp performance. Because the instrument is both polyphonic and highly resonant, it is difficult to isolate single notes for successful analysis.

A simple technology that Monaghan tested entailed fixing a small MIDI controller (Korg nanoKontrol) to the soundboard of the harp near where the left hand would naturally rest. The system functioned well, and gave the performer access to a discrete set of controls for manipulating electronics while playing. However, the author was unsatisfied with the outcome. They found that the

[2]Several laser harp versions have been manufactured based on similar principles: http://www.laser-harp.com/, http://www.harpelaser.com, http://www.kromalaser.com, to name a few.

Figure 2: Motion capture studio setup.

input gestures took too long to work effectively. More importantly, they found that the setup was not "organic" enough and lacked the feel necessary for the required gestures.

A motivation to leverage natural playing gestures led both Monaghan and our harpist to the prototype MIDI harp built by Camac Harps. During the early stages of our project we arranged a short residency at the Camac studio in Paris to explore the instrument and experiment with different techniques for its use in performance. While the process was informative, we found that the MIDI harp was not well-suited for generating expressive continuous control signals that we were interested in exploring, nor was it available for longer term use.

Ultimately, both Monaghan and our team arrived at similar systems for gestural controllers to augment harp performance: small wireless motion acquisition devices worn on the back of the hands instead of attached to the instrument. We describe the design and implementation of our system in Sections 4 and 5.

3 HARP GESTURE STUDY

To better understand the movements of harp performance and how they could be integrated into a gestural control system, we began the project with a motion capture study. Our particular focus centered on the concept of spare bandwidth, and the differentiation of instrumental and ancillary gestures. We hypothesized two general methods of mapping gestures to musical parameters. On one hand, the organic movements of harp playing could be used, allowing the performer to play naturally without altering their technique. Gestures, both instrumental and ancillary, could be mapped to events and processes as specified in the composition and realized with computer-based audio processing and effects. On the other hand, isolating ancillary gestures might present an opportunity for a performer to explicitly control other parameters without interfering with their harp performance.

3.1 Experimental Procedure

The protocol for our motion capture study was adapted from the work of [7], who had previously studied musician/instrument interaction in the case of the concert harp. Their study yielded high-level kinematic descriptors of harp performance posture and dynamics [8], as well as a detailed analysis of hand and finger mechanics of harp plucking [6].

3.1.1 Excerpt Selection. Four short excerpts of well known orchestral works were chosen for the study: two from Tchaikovsky's *Nutcracker Suite: Waltz of the Flowers*, Berlioz's *Symphonie Fantastique Mov. II*, and Debussy's *Danse Sacré*. The excerpts were taken from the first few bars of each piece, with the Tchaikovsky passage divided into two. The duration of the excerpts ranged from under 15 seconds to one minute.

The pieces are well known and part of the standard harp repertoire. They were chosen in hopes that the participating harpists would already be familiar with them, allowing them to play freely and comfortably with the most natural motions. Additionally, the collection of excerpts contain a wide variety of dynamics and technical passages. As we regarded the analysis with an eye to map performance gestures to control of other parameters, it was important to see a broad range of techniques.

3.1.2 Participants. Eight highly skilled harpists participated in the study. Six were graduate students pursuing degrees in harp performance.[3] One was an undergraduate, also pursuing a degree in harp performance, and the last was a faculty member and harp instructor. All participants reported several years of private studies, with an average of 13 years across the group. All participants had orchestral experience, with an average of 14.5 years. Each participant reported that they practice every day. Of the excerpts, everyone had experience performing the Tchaikovsky and Berlioz. Five of the eight had performed the Debussy, though the other three were familiar with and had no trouble playing it.

3.1.3 Experimental setup. The study took place in a motion capture studio, shown in Figure 2. A Qualisys motion tracking system was utilized, comprised of twelve infrared cameras placed around the perimeter of the room and suspended from a grid on the ceiling. Reflective markers were fixed on the participants and harp which were recorded by the cameras and translated into 3-dimensional motion data. For marker placement, the *Plug-in Gait model*[4] was utilized with the right shoulder marker removed where the harp rests during performance. Markers were also placed on the harp to track its movements.

A force plate was placed underneath the harpists' stool, which captured the amount and angle of downward force applied by the

[3]One participant the principle harpist for our project, and is the second author here.
[4]https://docs.vicon.com/display/Nexus26/Full+body+modeling+with+Plug-in+Gait

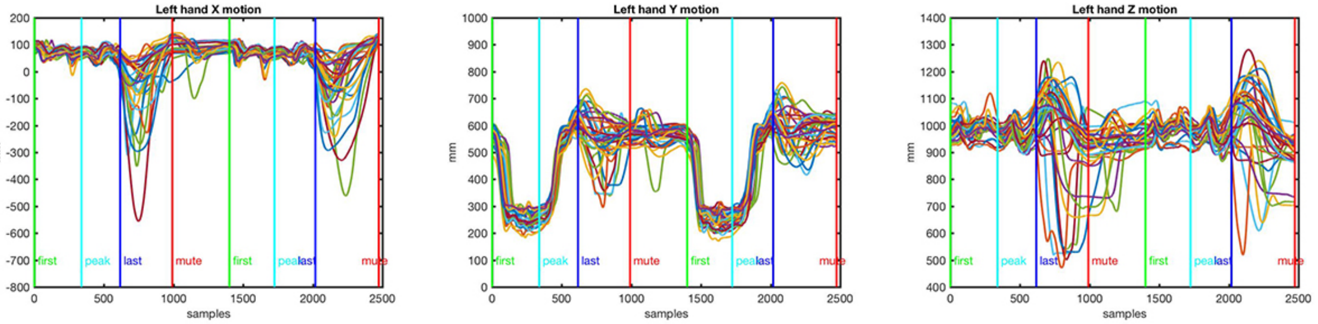

Figure 3: Left hand movement of all participants, all styles, playing the the opening arpeggios of Tchaikovsky's *Nutcracker Suite: Waltz of the Flowers* (first excerpt).

seated harpist, however, this data was not used in the analysis presented here. Additionally, video and audio was recorded with an HD digital video camera. All data was synchronized to the same SMPTE timecode to aid the later analysis.

Participants were instructed to play each excerpt one time in four different styles: *normal*, *deadpan*, *expressive*, and *immobile*. This follows similar protocols used in previous musical gesture studies of clarinet [24], piano [20], and concert harp [7]. The first three styles relate only to musical expression, and explicitly do not infer any instruction or restriction on movement. Conversely, the last, *immobile*, is a movement constraint and does not pertain to musical expression. Our intent was to observe both uniform and unique gestural features between participants and between the different playing styles. The participants were given no further instructions and left to interpret the different styles as they saw fit.

3.2 Analysis and Discussion

Because the gesture study was just one component in the overall project, our analysis was limited to a summary overview using a mix of quantitative and qualitative methods. The motion capture data was recorded and processed with the Qualisys Track Manager software. Processing included identification and labeling of markers according to the Plug-in Gait model, cleaning and gap-filling data where needed, and constructing a 3-D model of each performance. The data was then exported as video files of the 3-D animations and raw data formatted for import into MATLAB.

3.2.1 Analysis. In MATLAB, the data was further processed using the Motion Capture Toolbox [3], which provides a set of functions for processing and analyzing motion data. A marker reduction process was performed to reduce the markers down to the most salient components. The coordinate system was translated so that the axes matched those of our proposed gesture space: X axis extended horizontally to the right and left, Y axis extended horizontally forward and backward, and Z axis extended vertically.

Dynamic time warping (DTW) was employed to allow us to compare excerpts across participants and styles [22]. To demonstrate, Figure 4 shows the score of of the first excerpt, the two opening arpeggios of Tchaikovsky's *Waltz of the Flowers*. First, the following dynamic events were chosen to warp to: the plucking of the first note (green vertical line), highest note (cyan line) and last note (blue line), and the muting of the strings at the end of the last note (red line). This yielded eight "warp" points, four for each arpeggio. Using digital audio editing software, the warp points were identified in each performance (for each participant, in each style) and exported as SMPTE timecodes. In MATLAB, the timecodes were used to align the motion data to a fixed reference, which was the first participant's *normal* excerpt. This allowed for the comparison of movement trajectories across participants and styles making it easy to identify both common and unique gestures.

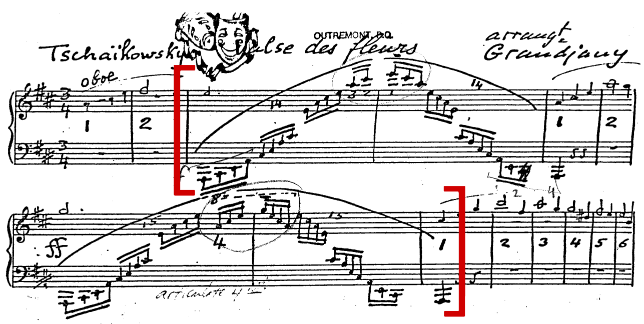

Figure 4: First excerpt: Tchaikovsky - *Nutcracker Suite: Waltz of the Flowers*, opening arpeggios.

Figure 3 shows one such analysis, of the left hand movement on the X, Y, and Z planes for all participants playing all styles. The vertical lines indicate the warp points, and the phrasing of the passage is especially evident in the Y axis as the hand moves towards the body in the ascending half of the arpeggio and back out on the descending notes. Then between the blue and red lines, the last note is played and left to ring out until the hand returns to mute.

This example shows the type of high-level information we were able to extract from the data and apply to the design of our gestural control system. On one hand we see clear movements that directly relate to the music being played: the hand deliberately moves along a single axis when playing ascending and descending lines in a controlled and predictable manner. We can see this as an opportunity for a reliable mapping if the composer has a desired parameter they wish to control during this type of passage. On the other hand, looking at the segment where the notes are sustained (between the blue and red vertical lines), we observe different behaviors between the axes. In the X and Y axes, while there is variation in amplitude, the direction and shape of the motions are relatively consistent. But in the Z axis, the directions and shapes are varied as well. This ancillary gesture is freely interpreted by the performer and can be exploited as an opportunity for the performer to take control of another process without interfering with the instrumental harp performance.

3.2.2 Visual Analysis. Additional qualitative analysis was done simply by observing the videos of participants to note general characteristics of performance, noting potential implications for mapping strategies. Figure 5 shows the split screen analysis videos, with the 3-D animation synchronized to the video-recorded performance. One observable trait pertained to movement of the harp. We had hypothesized that movement of the harp could be a compelling motion to map, however visual analysis showed that the overall movements of the instrument are quite small linked to the physical mechanics of playing. Thus in practice the actual movement is not well suited as a control signal.

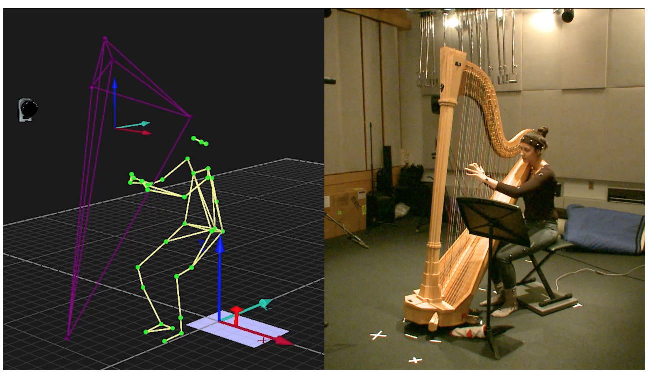

Figure 5: Image taken from analysis video, showing 3-D animation synchronized with video recording.

4 CONTROLLER DESIGN

From the motion capture study and initial research, we arrived at a plan for the use of small self-contained wireless devices that could be worn on the performer or fixed on the instrument. A software interface connected the controller data to commonly used digital performance software that would allow for flexible mapping of the signals to musical parameters.

4.1 Hardware

The motion controllers we used were research prototypes developed by our collaborator Ólafur Bogason and his team at Genki Instruments[5].

4.1.1 Physical Design. Shown in Figure 6, the devices are comprised of a custom printed circuit board (PCB) to which is connected an ESP8266 microprocessor, MPU-9250 motion acquisition sensor device for motion tracking, two LED lights, haptic motor and driver, internal battery connector and charging circuit, and on/off switch. The unit is powered by a 350mAh 3.7V LiPo rechargeable battery. The unit is housed in a matchbox-sized 3D printed enclosure with tabs to attach an elastic strap to. The top of the enclosure is minimally translucent so light from the LEDs is visible from the outside.

Figure 6: Inside and outside of the prototype gesture control devices.

4.1.2 Wireless Communication. The core of the unit is an ESP8266 MPU chip, with firmware written in the Arduino programming language. This chip was chosen because of its capabilities for 2.4 GHz (802.11 b/g/n) WiFi transmission, i^{2}C support, and general purpose input/output pins. The devices communicate bidirectionally with the host computer over UDP, sending streaming motion data out, while receiving messages to control the onboard haptic motor and one LED. All data is formatted and sent via Open Sound Control (OSC) messages.

4.1.3 Gesture Acquisition. The MPU-9250 integrated motion tracking device is a Magnetic, Angular Rate, and Gravity (MARG) sensor module equipped with 3-axis accelerometer, gyroscope, and magnetometer [1]. An on-board processor performs sensor fusion to produce a stable measure of device acceleration, angular rate of motion, and orientation which is output as OSC-formatted motion data in quaternions, roll/pitch/yaw (euler angles), and individual 3-axis outputs for the accelerometer, gyroscope and magnetometer.

4.1.4 Added Functionality. Along with their primary motion tracking capability, the devices are equipped to provide basic visual and haptic feedback to the user. One LED provides device status information, while a second is user programmable. The haptic unit consists of a single coin style eccentric rotating mass (ERM) motor, paired with a motor driver chip containing a library of haptic effects that can be triggered. Control of the programmable LED and motor are available from the user interface.

4.2 User Interface Software

The main objective of the user interface (UI) was to provide a simple set of controls to integrate motion data into a live performance workflow and communicate with the device. The interface was built in Max, and is designed to function in three primary ways: (1) integrated as part of a larger Max performance patch, (2) as a Max

[5] https://www.genkiinstruments.com/

Figure 7: *Top:* User interface for Max and stand-alone use. *Bottom:* Max for Live device.

for Live device in Ableton Live, or (3) as a standalone application that can communicate with other devices via OSC.

The main control panel is shown at the top of Figure 7 and is comprised of four main sections: motion data acquisition from device; device settings, including device addressing and preset storage and recall; device LED and haptic controls; and data output and visualization.

The software interface exists as a Max abstraction equipped with outlets to apply the motion data to parameters elsewhere when used inside of a main Max patch. With the abstraction open, all of the interface controls are accessible on screen. Additionally, OSC routings are included along with appropriate inlets and outlets, so the interface can be controlled remotely via OSC messages even while the UI is not displayed. An alternate standalone version was implemented as well, with UDP send/receive functionality for use with other networked OSC-compatible applications.

4.2.1 Max for Live. The interface was also ported to a Max for Live device for use with Ableton Live. The motivation for this was to further simplify use of the system and to make it compatible with one of the most popular and widely used music performance software applications. The Max for Live device contains the exact the same functionality as the Max interface. The front panel contains a subset of the controls for basic operation, while the full control panel can be opened with an onscreen button. Additionally, the device leverages built-in features that help to streamline the workflow. Output from the motion data can be directly scaled and mapped to any parameter in Live, and device's LED and haptics can be synced to Live's global tempo and transport controls.

4.2.2 Motion Data Calibration and Scaling. Several parameters are available to give the user control over the incoming data, including controls for coordinate rotation and translation. In practice, we found the two most important controls to be the calibration and range controls. To calibrate, the device is held still in a predefined "home" position and the calibrate button is pressed. This resets the *X/Y/Z* axes to zero. If the controller measurements begin to drift (which was often an issue in rehearsals), the user can recalibrate on the fly to restore confidence in the measurements. To create a usable range of motions, as second type of calibration was implemented which allows the user to define minimum and maximum limits of their motion on each axis.

4.2.3 Where is the Machine Learning? Implementing machine learning into gestural control systems has become a popular topic in musical interface design [5]. It is appealing for many reasons, and was proposed to overcome constraints of our current system like limitations of single-axis direct mappings and gimbal lock that can occur with simple 3-axis motion data.

Preliminary experiments were carried out using MUBU, a library of Max objects for the multimodal analysis of sound and motion data, including a suite of machine learning tools [10]. However, promising developments were offset by the addition of significant complexity for the perfomer and ran counter to our stated goal of achieving simple and lightweight system. As a result, we carried on with our *X/Y/Z* control system, favoring simplicity and ease of use over advanced functionality. We do, however, plan for an updated version with this functionality included.

5 IMPLEMENTATION

The final objective for the project was to bring everything together in a new creative work and performance. This was done in collaboration with composer Brice Gatinet, who prepared a work for solo harp and gesture-controlled electronics to be performed by Alexandra Tibbitts.

The three phases of the project — gesture study, controller design, and implementation into a new work — often overlapped despite being mostly sequential in their execution. This was advantageous on all accounts as each phase informed the others. In this way, work on motion data analysis provided instant insight into how best to utilize the controllers in performance, while rehearsals for the piece provided direct input on software development and updates.

5.1 Composition

Gatinet's composition *...prends-moi, chaos, dans tes bras...* is a reflection on mounting refugee crisis and asylum seekers in recent years affecting the Middle East and Europe. The title comes from the translated collection of Arabic poems written by famous Syrian poet, Adonis, and is based on three different materials: the choreographed motions of a harpist's musical gestures; narration of a Sumerian creation poem; and a transcription of *Hurrian Hymn no.6*, a Mesopotamian song, known as the first written piece of music (ca. 1400 B.C.E.), discovered in the 1950's in the Ugarit, Syria.

The work requires amplified harp, gesture controller, voice microphone, foot-switch, and four speakers. Audio from the harp and voice is processed through several effects modules by GRM Tools. Parameters are mapped to the *X/Y/Z* axes of the controller, allowing expressive gestures to manipulate the sound in real-time. The piece is implemented in a Max patch with interchanging audio effects and a foot switch used to toggle between various preset banks of effects and parameters. To perform the piece, effects are applied to their desired axis (e.g. *pitch* controlling granulation and *roll* controlling delay) in order to blend between multiple effects.

5.2 Development

The work was developed over three stages. First, the functionality and range of the controllers were freely explored through improvisation sessions, enabling the performer and composer to investigate relationships between musical gestures and sound. In the second stage, a basic gesture vocabulary was defined to fine-tune the tracking of the controller for skilled control over effects parameters. In the last stage, the the score and Max patch was finalized for concert setup and performance.

In the exploration phase, different effects and mappings were auditioned to match various performance motions that had been identified in the motion study. The biggest challenge for the harpist was to understand the responsiveness of the controller and refine their movements. Naturally, the harpist's arm and hand movements are not fixed on a singular axis; therefore the performer must take care to understand how each respective movement affects the processing.

While gaining familiarity with the system, it was natural for the harpist to react to sounds generated by the controller. However, this was not the controller's intended purpose. With dedicated practice and increased understanding between movement and control, a personalized gesture vocabulary was more freely developed and integrated into the natural movements of intrumental harp performance.

Through the rehearsals, the composition took form with a bottom-up approach where Gatinet's writing explored the relationship between the instrument and controller. While various complex mapping strategies were rehearsed, ultimately the choice was was to use direct one gesture-to-one axis mappings, which provided the best results and were more controllable by the performer during instrumental passages.

5.3 Performance

Two performances of the piece were given, approximately one month apart. The first was at a recital given by Tibbitts (shown in Figure 1).[6] The second performance was included in a mixed concert of new music. While the first performance went off without issue, issues with WiFi connectivity led to dropouts of the controller in the second performance. Tibbitts was able to continue through the piece with minimal disruption, though the actual manipulation of electronics processing was missing in those sections.

5.4 Challenges and Future Work

In assessing the project after the performances, we were able to reflect on some of the challenges we experienced and identify areas for continued development.

5.4.1 Technical Design. Technical challenges during rehearsals (and in the second performance) included controller failure, networking and communications issues and software bugs. One issue in particular was difficulty in achieving accurate and reproducible calibrations, which were critical to ensure that the performer could control the effects parameters effectively. The devices were early prototypes, and many of the issues have been resolved over time through updates and upgraded hardware. Since our experiments, Genki Instruments has released Wave, a new gesture controller based on these early prototypes that was launched with a successful crowdfunding campaign.[7].

5.4.2 Gesture Vocabulary. While the motion capture study provided a blueprint for the design of gestures for our system, in practice the selected gestures emerged through experimentation during rehearsals and were focused on achieving specific compositional and musical objectives. Therefore it is hard to directly correlate the motion analysis results with the selected gestures. However, the general principle of applying both instrumental and ancillary gestures taken from natural harp performance movements guided the overall process. In future work we would like to continue to analyze and refine movements in rehearsals and performances, especially with new controllers providing more dependable measurements.

Another intended direction will be to implement more advanced gesture recognition through machine learning. While it may represent a steeper learning curve for the performer, it will allow for capture of complex, multidimensional gestures that more closely resemble those analyzed in our motion study. It will also alleviate some of the problematic issues of working with our simplified 3-axis system, as the gestures are higher level representations of movements, and not restricted to movement along single calibrated axes.

5.4.3 Learning and Performing. A final reflection on both the challenges of working with this system and directions for future work come from a learning perspective. Performers develop a specific relationship to learning their primary instrument. Controlling a new device that modifies the sonic result of the instrument profoundly disrupts that relationship. The first exploratory rehearsals allowed Tibbitts to investigate her own response to the potential of her gestures on the sound. The freedom of movement, when she was in full control of the effects, allowed her to develop virtuosity and precision. But as parts of the composition became fixed it became difficult for her to embed the gesture, score, and her interpretation into one sound result. The composition required the performer to trust what they were hearing and be able to make nuanced adjustments to correct. To help with this, we briefly experimented with providing visual feedback by adding an iPad in front of the performer that displayed the gesture-controlled parameters. However, that became just one more element for the performer to keep track of and was ultimately removed.

The large quantity of information to be managed and additional movement constraints when the controllers are in use require a significant retraining and recalibration of the relationship between instrument and player. Future work will consult complementary

[6]Video of the first performance can be seen at https://vimeo.com/269375405.

[7]https://www.indiegogo.com/projects/wave-control-sounds-with-motion/

research in the areas of performer-instrument interaction, embodied cognition, and musical pedagogy to develop strategies for the performer to learn and adapt to the new augmented performance paradigm.

6 CONCLUSION

We have presented a project that researched, designed and implemented a new gestural control system to augment instrumental performance. Using the concert harp as a case study, we built our system according to the constraints and affordances that the instrument provides. We have discussed previous instances and techniques of harp augmentation, to which we add our own experiences and results.

Out of a motion capture analysis we developed a high-level understanding of movements characteristic of harp performance, and illustrated examples of both instrumental and ancillary gestures that could be mapped to gestural control of other musical parameters. These served as the basis of a gesture language for augmented harp performance.

Hardware and software gesture acquisition device prototypes were developed, while working closely with the composer and performer to put on a new musical work for solo harp and gesture-controlled electronics. While successful overall, we documented challenges with acquiring consistently accurate motion data and reliable device calibration results, that led to difficulty in maintaining precise control of gesture parameters.

From our experiences, we have identified areas of further work, some of which has already taken place. New hardware and software has been developed by our engineering partners, which alleviates the technical issues that we encountered during rehearsals and performance. We envision future improvements to the gesture vocabulary through the continued analysis of rehearsals and performance, and the implementation of better gesture recognition algorithms. Finally we reflect on the demands of, and learning approaches to, augmented instrument performance.

ACKNOWLEDGMENTS

The authors would like to thank the Center for Interdisciplinary Research in Music Media and Technology for their support of this project. Additionally we would like to extend our gratitude to Ólafur Bogason and Genki Instruments who provided hardware prototypes and firmware revisions, and to Jakez François at Camac Harps for making the MIDI harp available for this project.

REFERENCES

[1] Eric Bachmann, Xiaoping Yun, Doug McKinney, Robert McGhee, and Michael Zyda. 2003. Design and implementation of MARG sensors for 3-DOF orientation measurement of rigid bodies. Taipei, Taiwan.
[2] William Brent. 2012. The Gesturally Extended Piano. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Ann Arbor, Michigan.
[3] Birgitta Burger and Petri Toiviainen. 2013. Mocap Toolbox - A Matlab Toolbox for Computational Analysis of Movement Data. In *Proceedings of the 10th Sound and Music Computing Conference*. Stockholm, Sweden.
[4] Claude Cadoz and Marcelo Wanderley. 2000. Gesture-music. In *Trends in Gestural Control of Music*, Marcelo Wanderley and Marc Battier (Eds.). IRCAM, Paris, France, 71–94.
[5] Baptiste Caramiaux and Atau Tanaka. 2013. Machine Learning of Musical Gestures. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Daejeon.
[6] Delphine Chadefaux, Jean-Loíc Le Carrou, and Benoît Fabre. 2013. A model of harp plucking. *The Journal of the Acoustical Society of America* 133, April (2013), 2444–55.
[7] Delphine Chadefaux, Jean-Loíc Le Carrou, Benoît Fabre, and Laurent Daudet. 2014. Investigation of the Harpist/Harp Interaction. In *Sound, Music, and Motion: 10th International Symposium, CMMR 2013 Marseille, France, October 15-18, 2013 Revised Selected Papers*, M Armaki, O Derrien, R Kronland-Martinet, and Solvi Ystad (Eds.), Vol. 8905. Springer, 5–6.
[8] Delphine Chadefaux, Marcelo Wanderley, Jean-Loíc Le Carrou, Benoît Fabre, and Laurent Daudet. 2012. Experimental study of the musician/instrument interaction in the case of the concert harp. In *Proceedings of Acoustics 2012*.
[9] Perry R Cook. 2001. Principles for Designing Computer Music Controllers. In *Proceedings of the CHI 2001 Workshop New Interfaces for Musical Expression*. Seattle, WA, United States, 3–6.
[10] Jules Françoise, Norbert Schnell, Riccardo Borghesi, and Frédéric Bevilacqua. 2014. Probabilistic Models for Designing Motion and Sound Relationships. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. London, United Kingdom, 287–292.
[11] Jonathan Impett. 1994. A Meta-Trumpet(er). In *Proceedings of the International Computer Music Conference*. San Francisco, CA, United States, 147–150.
[12] Teemu Maki-Patola, Perttu Hämäläinen, and Aki Kanerva. 2006. The Augmented Djembe Drum - Sculpting Rhythms. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Paris, France, 364–369.
[13] Andrew McPherson and Youngmoo Kim. 2010. Augmenting the Acoustic Piano with Electromagnetic String Actuation and Continuous Key Position Sensing. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Sydney, Australia, 217–222.
[14] Carolina Brum Medeiros and Marcelo Wanderley. 2014. A comprehensive review of sensors and instrumentation methods in devices for musical expression. *Sensors (Basel, Switzerland)* 14, 8 (2014), 13556–13591.
[15] Eduardo R. Miranda and Marcelo Wanderley. 2006. *New Digital Musical Instruments: Control and Interaction Beyond The Keyboard*. A-R Editions.
[16] Úna Monaghan. 2014. *New Technologies and Experimental Practices in Contemporary Irish Traditional Music : A Performer-Composer's Perspective*. PhD. Queen's University Belfast.
[17] Dexter Morrill and Perry Cook. 1989. Hardware, Software, and Composition Tools for a Real-Time Improvised Solo Trumpet Work. (1989).
[18] Cléo Palacio-Quintin. 2003. The Hyper-Flute. In *Proceedings of the 2003 Conference on New Interfaces for Musical Expression*. Montreal, QC, Canada, 206–207.
[19] Joseph Thibodeau. 2015. Trumpet Augmentation and Technological Symbiosis. *Computer Music journal* 39, 2 (2015), 28–46.
[20] Marc R. Thompson and Geoff Luck. 2012. Exploring relationships between pianists' body movements, their expressive intentions, and structural elements of the music. *Musicae Scientiae* 16, 1 (2012), 19–40.
[21] Caroline Traube, Philippe Depalle, and Marcelo Wanderley. 2003. Indirect Acquisition of Instrumental Gesture Based on Signal , Physical and Perceptual Information. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Montreal, QC, Canada, 42–47.
[22] C Verron. 2005. *Traitment et visualisation de données gesturalles captés par Optotrak*. Technical Report. McGill University, Input Devices and Music Interaction Laboratory, Montreal, QC, Canada.
[23] Marcelo Wanderley and Philippe Depalle. 2004. Gestural control of sound synthesis. *Proc. IEEE* 92, 4 (2004), 632–644.
[24] Marcelo Wanderley, Bradley W Vines, Neil Middleton, Cory McKay, and Wesley Hatch. 2005. The Musical Significance of Clarinetists' Ancillary Gestures: An Exploration of the Field. *Journal of New Music Research* 34, 1 (2005), 97–113.