Malletwand: the Pendulum as a Handheld Interface to Musical Timing

Shiqing Lyu
Academy of Arts & Design, Tsinghua University
Beijing, China
claire@ayu.land

Hanxuan Li
Academy of Arts & Design, Tsinghua University
Beijing, China
lihanxua22@mails.tsinghua.edu.cn

Ruhan Wang
Academy of Arts & Design, Tsinghua University
Beijing, China
wangrh22@mails.tsinghua.edu.cn

Haipeng Mi
Academy of Arts & Design, Tsinghua University
Beijing, China
mhp@tsinghua.edu.cn

ABSTRACT

We devise and implement an interface in the form of a handheld pendulum device for manipulating the timing of musical playback. The physical properties of the pendulum make this interaction scheme steady and intuitive, and particularly suitable as an introductory means of musical engagement for untrained participants. We build a self-playing glockenspiel around this interface to demonstrate how our design encourages musical exploration and social play. We conclude by discussing potential extrapolations and integrations of the design in mobile and hybrid scenarios.

Author Keywords

Musical interface, pendulums, self-playing instruments, pose estimation, tactility, HCI

CCS Concepts

•Applied computing → Sound and music computing; •Human-centered computing → *Interaction devices;* **•Hardware →** *Sensor applications and deployments;*

1. INTRODUCTION

Throughout our experience, we have always been able to capture the instinctive desire to actively and earnestly engage in music from those that have not had the advantage to experience music full-scale. In our lasting endeavour to expand the reach of musically-meaningful interactive experiences, we set out on a search of an interaction scheme that is easy to understand and operate without musical expertise, while navigating the participant in sensible directions to manipulate the sounds to their own imagination, deepening their connection with the musical elements they have been presented with.

We settled on the periodic motion of the pendulum. The stability and self-recovering property of pendular motion make for a reliable framework of periodic musical time, i.e., tempo, or beats.

We devise and implement a controller interface, which we title the Malletwand, in the form of a handheld pendulum device (the "wand"). By swinging the pendulum, the participant is able to feel and manipulate the speed of musical time, while the kinematic properties gently guide them through the tendency to keep a stable period, preventing excessive deviance from a steady tempo.

We imagine that this interface be paired with various types of musical actuators. For this report, we build a self-playing glockenspiel (the "mallet") operated by up to two such controllers in order to demonstrate how our design encourages musical exploration and social play.

The rest of the article is outlined as follows. We provide an overview of related work in various relevant fields before presenting the details of our design and implementation of the controller interface and the self-playing instrument. We go on to discuss potential extrapolations and integrations of the design in mobile and hybrid scenarios, some of which we plan as our future work. Algorithmic details are laid out in the appendix.

2. RELATED WORK

As we direct our design towards approachability for all levels of expertise, we look for intuitive universalities among human music, ideally natural kinesthetic and auditory stimuli that are processed and understood subconsciously. We directed our attention to the formation and perception of isochronal patterns based on the abundant argument that humans naturally tend to perceive time, and especially in the musical context, in cycles and patterns [1, 7, 8]. To paraphrase our forerunners, repeating cycles of time set the boundaries of our activities as well as form grounds on which we anticipate our sensory stimuli. Discussions went further to establish the metaphorical and cognitive interplay of our sense of time with embodied motion [4, 3].

Indeed, there have been a number of devices that manifest the link between periodic bodily movement and stable temporal patterns. Scrubbing is a standard technique for turntablists to manipulate the speed of sounds by rotating vinyl records. Hand-cranked musical boxes provide a more approachable way to drive the flow of music by one's own hands; although the Swedish band Wintergatan went as far as to build an entire machine, the Marble Machine, that turns the revolution of the manual crank into the progression of a musical piece [10].

However, these devices share the common limitation that they require practice, or at least familarity with steady

NIME'24, 4–6 September, Utrecht, The Netherlands.

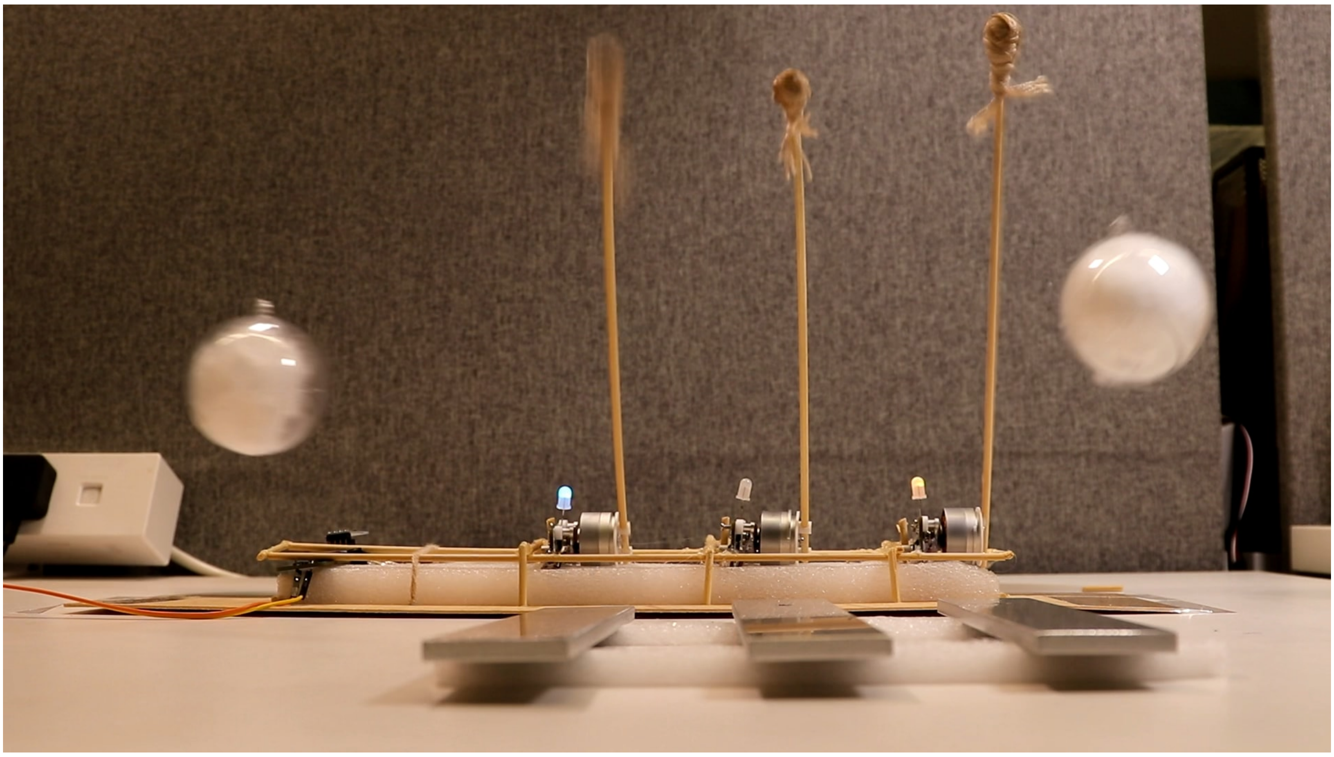

Figure 1: The Malletwand controllers with the prototype self-playing glockenspiel.

bodily movement, to prevent sounds from being distorted in the temporal domain. Laypeople tend to invoke unsteady musical time on such devices, rendering the music less understandable and aesthetically pleasing, while it remains unclear to them how they should refine their actions in the reasonable directions. Thus, they will not be able to get the most out of the tactile musical experience.

From another perspective, we are delighted to see novel musical devices that employ pendular motion or handheld physical controllers. Kugelschwung [2] is a digital musical instrument that relies on a set of pendulums mounted on a tabletop frame supplying control signals for soundscapes. Le Bâton [12] maps the chaotic behaviour of the triple pendulum into unpredictably varying electronic sounds. Gyrotyre [11], on the other hand (no pun intended), is a handheld controller that maps oscillating signals from a gyroscope installed on a precessing wheel to various musical applications.

Still, these interfaces and instruments take larger physical forms and mainly aim at stage performances and/or dedicated experimental production setups. Our design adds to this ensemble a missing piece: a lightweight handheld controller interface that can be enjoyable and meaningful regardless of the participant's prior musical experience.

3. THE "WAND"

3.1 Design Overview

We first present the details of the handheld controller interface. It takes the form of a handle with a hanging bob (ball) that can freely swing and spin around, forming a pendulum. The participant swings the pendulum at their desired frequency while the bob's quasi-periodic motion is mapped to continuous musical time such that each fastest-moving point in a period corresponds to the start of a beat. (This point is usually perceived to be the "central" or the "lowest" point in simple pendulums, but since ours has an extra degree of freedom, i.e., is a spherical pendulum, this appointment needs to be extrapolated.) Such generated timing signals are wirelessly transmitted to an actuator, such as a self-playing instrument, that plays a piece of music according to the manipulated flow of musical time.

We add a few simple features to enrich the feedback and the interaction. Haptic feedback at beat onsets is provided by a vibration motor. A tri-colour LED is placed inside the bob that is flexible in its responses to interaction, e.g., it may indicate the changing beats by alternating tints or identify the voice by colour coding in the case of multiplayer interaction. Furthermore, the controller is intended to be normally at rest, so it is equipped with a tilt sensor that wakes up the entire circuit from sleep when the device is picked up by a participant. A single-pole, single-throw (SPST) switch allows the overall power to be turned off during times without participants.

3.2 Construction

We design customised electronics for all of our devices. In addition to the aforementioned components, the handle contains a lithium polymer (Li-Po) battery, a microcontroller, and a radio transceiver; the bob contains a separate low-power microcontroller and MEMS chips that form a 9-axis IMU (an accelerometer, a gyroscope, and a geomagnetometer). The complete structure is illustrated in Figure 2.

The board is fabricated as one, in order to ease soldering and debugging as we build the prototype. After testing is complete, we cut the board at the thin connection (in Figure 2a) and connect the two parts with soldered thin wires (3 strands of 32 AWG, establishing an asynchronous USART connection). The handle part is glued inside a 3D-printed casing with the wires hanging down onto the bob part (Figure 2b), which is inserted onto a holder made of polymeric foam glued in a translucent plastic sphere filled

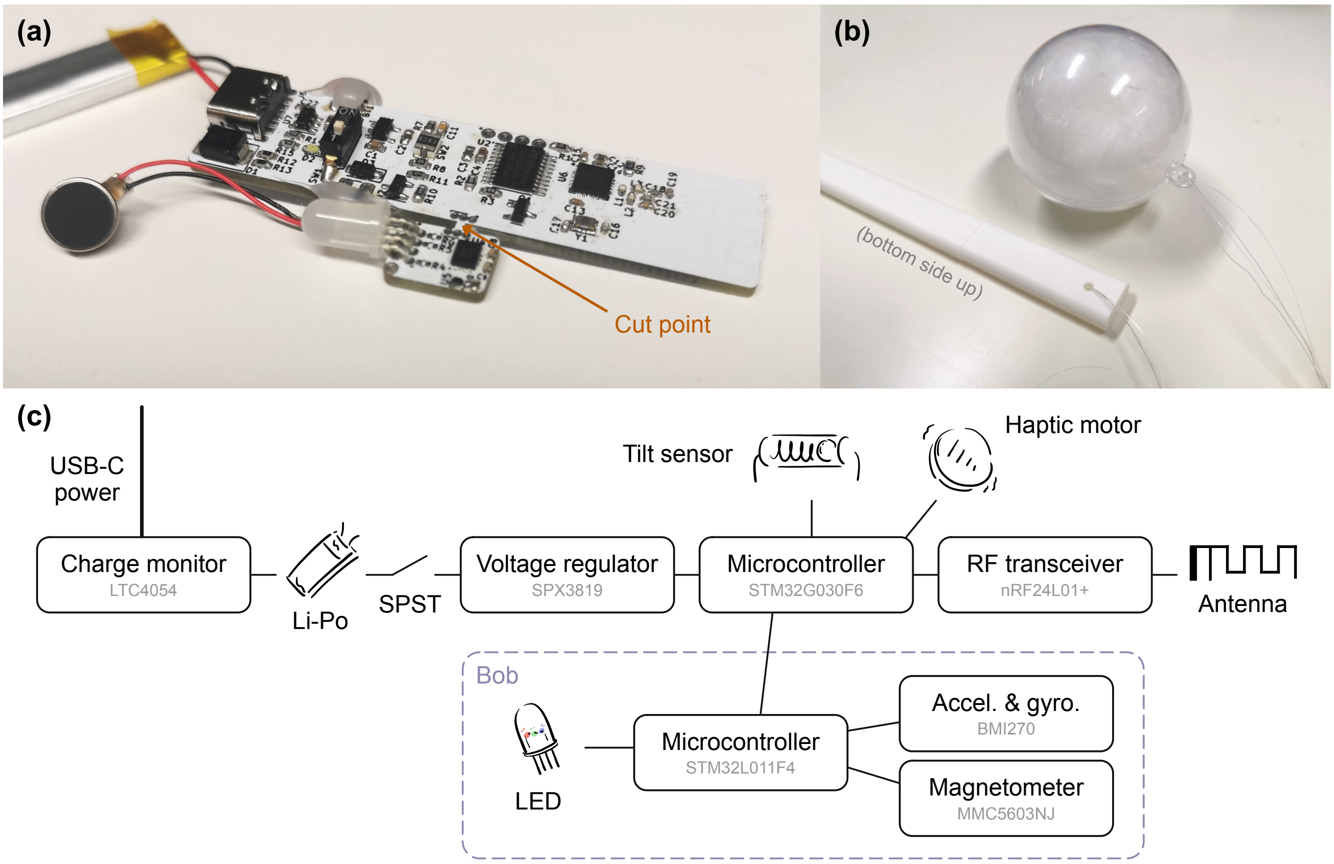

Figure 2: (a) Photo of the assembled circuit board before being cut. (b) Photo of the assembled wand with the casing and the bob. (c) Block diagram of the electronic components involved.

with down cotton. We add fishing wires to strengthen the connection and prevent the electric wires from excessive tension and fatigue.

3.3 Estimation Algorithm

All processing is done on the microcontroller device. The microcontroller we used, STM32G0, is an Arm Cortex-M0+ processor without a dedicated FPU, but our complete algorithm runs well within its 64 MHz system clock with software floating-point arithmetic.

The algorithm requires an initial reference frame calibration, run once after assembly. An ensemble of filters is then employed to process the sensor signals. We introduce these steps respectively. To keep our description concise, we defer all of the mathematical details to Appendix A.

3.3.1 *Reference frame calibration*

After assembly, the tilted orientation of the circuit board inside the bob should be compensated for.

The calibration is initiated by a manually-issued wireless radio signal. The operator is then expected to hold the handle and let the bob stay stationary for a short while. Signals from the accelerometer are continuously monitored until they reach a sufficiently low deviation throughout a fixed time window of 3 seconds. This yields an axis vector that acts as the reference for future motion estimation from sensor readings which is saved in the persistent flash storage of the microcontroller. For details, please refer to Appendix A.1.1.

3.3.2 *Magnetometer calibration*

As our algorithm relies on the geomagnetometer to improve the accuracy of pose estimation, the distortion of the ambient magnetic field should also be compensated. Since indoor environments contain prominent and variable magnetic interference, this calibration is done in real time during operation. This works by continuously collecting the readings of the magnetometer and finding an ellipsoid fit that tries to distort the collected data in the form of 3D vectors onto a unit sphere. We employ the adjusted least squares estimator introduced by [5] with complementary steps by [9].

3.3.3 *Motion signal processing*

Our IMU produces readings at a sampling rate of 100 Hz, and the filtering algorithms run at the same rate. At each time step, we first estimate the facing of the bob through a complementary filter, inspired by [6], combining signals from the gyroscope and the magnetometer. The result is turned into a rotational transform that cancels out the bob's rotation around its own axis. Sensor readings adjusted by this transform are then fed into an extended Kalman filter (EKF) that estimates the trajectory of the bob in 3D space, and more importantly, its current phase within the period of motion. This is the value that gets interpreted as the driving signal of musical time, and is transmitted to the actuator.

A confidence indicator is derived from the Frobenius norm of the estimation covariance matrix in the EKF. This value is used to avoid muddled time progression when the motion is not stably periodic, e.g., during the first few seconds since the beginning of interaction.

4. THE "MALLETS"

4.1 Design Overview

Our self-playing instrument is a robotic glockenspiel. We use a 3-key prototype for demonstrative purposes, but an extension of register requires no change in implementation.

The instrument is accompanied by two Malletwand controllers and can operate in both solo and co-operative mode. Signals received from the controllers drive the musical time in a preprogrammed piece, similar to a musical box. Co-operative mode is entered by two controllers being operated simultaneously, where each controller corresponds to one voice (part) indicated by colours of the lights. The music only progresses when the motion of the two are roughly in synchronisation.

4.2 Construction

4.2.1 *Keys*

The keys are laser-cut from aluminum of 5 mm thickness. We chose aluminum instead of an alloy since we would like a mellower timbre. Prior to production, we ordered a small number of samples from the fabricator to determine the acoustic characteristics of the material. The resonant frequency of a vibrating metal bar is inversely proportional to the square root of its length; we thus calculate the desired lengths according to equal-temperament tuning, create the blueprints programmatically in OpenSCAD and send them for fabrication.

4.2.2 *Electronics*

The electronics of the instrument comprise a main unit and multiple sub-units, one for each key. The main unit is responsible for the communication with the controller(s) as well as the delivery of power and control signals to the sub-units. Each sub-unit has a small brushless DC (BLDC) motor that holds a yarn mallet, fixed onto a circuit board bearing a magnetic encoder, a tri-colour LED, and a microcontroller carrying out vector control. The entire device is powered by a single DC supply between 9 V and 25 V into the main unit. The complete structure is illustrated in Figure 3.

We choose I^2C as the communication protocol, requiring only two electrical signals for multiple parallel devices. We use an I^2C accelerator chip on the main unit to mitigate the rise time issue due to increased bus capacitance of long transmission wires.

4.2.3 *Mechanical and miscellaneous*

We fix all units (both the main one and sub-units) onto polymeric foam which is glued onto a thin wooden board that serves as the base. Slots created on the foam hold the units as well as the electrical lines. We glue an extra frame made of wooden sticks around the foam to improve stability.

The mechanical parts for the fixation of motors and mallets are 3D-printed in PLA and installed with screws. Yarn on the mallets is manually wrapped around a wooden core and slightly melted with a lighter in order to tighten it.

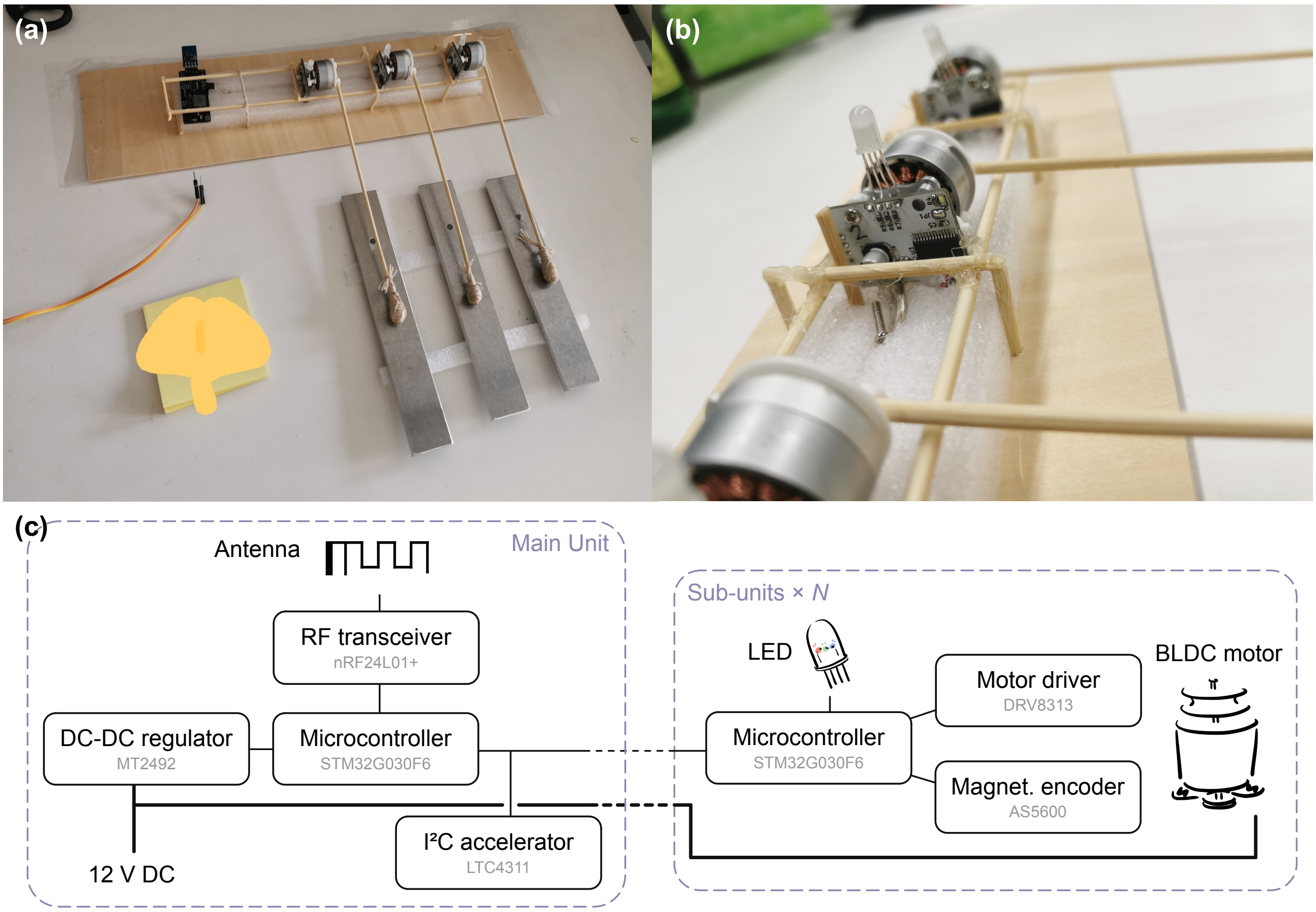

Figure 3: (a) Overall photo of the instrument. (b) Close-up of a single sub-unit. (c) Block diagram of the electronic components involved.

4.3 Performance

During operation, the glockenspiel plays a tune as the pendulums swing back and forth. The tempo of the music adjusts to the period of pendular motion. Haptic feedback and lights on both the bob and the keys add tactility and visualisation to the embodied musical experience. Figure 1 is a photo of the instrument in action.

Please refer to the demonstration video for a performance recording.

5. DISCUSSION

5.1 The Experience of Malletwand

Our design accomplished our initial goals. The algorithms yield a reliable estimation of motion, successfully running the glockenspiel through a tune steadily with little external intervention on the pendulum, while being able to respond reasonably fast to changes in motion (within 1˜2 swings). We enjoyed our own work.

Our pilot study with outside participants was preliminary, but sufficient to bring forth a few insights. We confirmed that the pendulum-based interface is appreciated for its accuracy and ease of use. First-time users might not instantly figure out how to reliably manipulate the speed (period) of the pendulum, but were able to do so with their own exploration or with a hint. Since participants were able to quickly grasp the mapping logic and its control, musical exploration was instantly opened up to them. Participants tended to experiment with extremes before resorting to a steady tempo, trying gentler articulations. They considered the interaction intuitive and manageable, and reported being generally successful in their pursuit of musical engagement and expression.

Social play is encouraged through the attempts to synchronise between the duo. This resembles the experience of musicians in ensembles, orchestras, or bands, and is appreciated by such practitioners. However, we notice that this is a rare and precious chance for participants with less musical experiences, and we hope to bring such meaningful and joyful activities to their reach through our design. We are still yet to conduct more extensive studies with such participants.

One major shortcoming of the co-operative mode is the difficulty to synchronise the phases between the duo, due to inertia preventing quick changes in speed, even more so regarding phase and position. This has the benefit of extending conversations and explorations between participants, but the less experienced of them might not figure out effective ways quickly and intuitively. In this regard, we are considering improving on the co-operative play mode, either by revamping the interaction rules or by extra hints in the form of synchronised haptic feedback or textual hints.

5.2 Extrapolations and Future Work

As we have written in the Introduction section, we imagine that this interface not be limited to our glockenspiel instrument. Any device that plays music can employ a pendulum interface to invite participants into musical time. Hybrid formats, including projections and mappings, or musical devices remotely incited beyond kilometers, open doors to tactility in a hybrid world.

Other musical features or temporal formats, or even spatial expositions, may be involved as well. What about an installation that gives procedurally generated sounds? What about a film? A dance? A video game where cats chase the wand? A revolving kaleidoscope or a planetarium?

The estimation algorithms in the pendulum enable it to act as a standalone sensor, adding to the toolkit of digital artistic expression. What about an electronic mimicry of a windbell? A big hanging simulated telescope? A sparkling earring?

Another possible extrapolation lies in the mobile scenario. The sensors we used are standard in today's smartphones, and relevant APIs are readily available on modern web browsers. Thus, with the processing algorithms ported to JavaScript, websites will be able to create novel interactive experiences without special equipment, simply by asking the visitor to put their phone in a holder, attach a string, and swing it to their liking. What about such a musical box? We leave all these for the reader as exercises while we try our hands on a few.

6. CONCLUSION

Malletwand is our first step in spreading the enjoyability of music through a tactile medium. It is to our delight to have implemented the system and seeing it bear the unique approachability and adaptability to varied levels of musical expertise, adding to the state-of-the-art repertoire of physical-system controller interfaces. We realise that this interface has the potential to adapt to more instruments and scenarios, and put forward what we have envisaged. We share our work in the hope that our methods and insights can be useful to those who share the aspirations with us.

7. ETHICAL STATEMENT

This research does not involve processes or experiments that might raise ethical concerns. In addition, the authors have made conscious efforts to abide by the NIME ethical guidelines.

8. ACKNOWLEDGMENTS

We would like to thank the anonymous reviewers for their valuable feedback. We would like to extend our gratitude towards Yao Zhihao for the enthusiastic help in handicraft work; and to Dr Mier, for offering aid in mathematical concepts. A special acknowledgement goes to Tsinghua University Symphonic Band, without which this motif would not have developed.

9. REFERENCES

[1] C. Brower. A cognitive theory of musical meaning. *Journal of Music Theory*, 44(2):323–379, 2000.

[2] J. Henson, B. Collins, A. Giles, K. Webb, M. Livingston, and T. Mortensson. Kugelschwung - a pendulum-based musical instrument. In *Proceedings of the International Conference on New Interfaces for Musical Expression*, Ann Arbor, Michigan, 2012. University of Michigan.

[3] M. Johnson. *The meaning of the body: Aesthetics of human understanding*. University of Chicago Press, Chicago, IL, 2008.

[4] M. L. Johnson and S. Larson. "something in the way she moves"-metaphors of musical motion. *Metaphor and Symbol*, 18(2):63–84, 2003.

[5] I. Markovsky, A. Kukush, and S. Huffel. Consistent least squares fitting of ellipsoids. *Numerische Mathematik*, 98, 07 2004.

[6] H. G. Min and E. T. Jeung. Complementary filter design for angle estimation using mems accelerometer

and gyroscope. https://www.academia.edu/6261055 (accessed 2024-02-07).

[7] U. Neisser. *Cognition and Reality: Principles and Implications of Cognitive Psychology.* W.H. Freeman, New York, NY, 1976.

[8] A. Ravignani, T. Delgado, and S. Kirby. Musical evolution in the lab exhibits rhythmic universals. *Nature Human Behaviour*, 1(1):0007, Dec 2016.

[9] V. Renaudin, M. H. Afzal, and G. Lachapelle. Complete triaxis magnetometer calibration in the magnetic domain. *Journal of Sensors*, 2010:967245, Dec 2010.

[10] M. Rundle and V. Woollaston-Webber. 16 months to build, two hours to demolish: watch the marble machine being taken apart, Mar 2017. https://www.wired.co.uk/article/marble-machine-video (accessed 2024-02-07).

[11] E. Sinyor and M. M. Wanderley. Gyrotyre: A dynamic hand-held computer-music controller based on a spinning wheel. In *Proceedings of the International Conference on New Interfaces for Musical Expression*, pages 42–45, Vancouver, BC, Canada, 2005.

[12] M. Skarha, V. Cusson, C. Frisson, and M. M. Wanderley. Le Bâton: A digital musical instrument based on the chaotic triple pendulum. In *Proceedings of the International Conference on New Interfaces for Musical Expression*, Shanghai, China, June 2021.

APPENDIX

A. DETAILS OF THE SIGNAL PROCESSING ALGORITHMS

We try to outline the mathematical derivations of the algorithms. For details, please refer to the source code.

A.1 Calibration

A.1.1 Reference frame

An accelerometer reading is a 3-dimensional vector. When a sufficiently low variation of readings is achieved during calibration, their average vector is normalized and taken as the reference axis $\mathbf{u}$. We find a quaternion $\mathbf{q}$ that rotates this vector to the $+z$ unit vector, $\mathbf{z}^+ = \begin{bmatrix}0 & 0 & 1\end{bmatrix}^\intercal$. This is achieved by setting $\mathbf{q}_1 = \begin{bmatrix}\mathbf{u}\times\mathbf{z}^+ & (1+\mathbf{u}\cdot\mathbf{z}^+)\end{bmatrix}$ and $\mathbf{q} = \mathbf{q}_1 \;/\; |\mathbf{q}_1|$.

This quaternion $\mathbf{q}$ transforms the reference frame of the accelerometer such that the xy plane corresponds to the local ground, whose normal vector is the z axis. The rotation specified by $\mathbf{q}$ is applied to future raw accelerometer readings $\tilde{\mathbf{a}}$ and gyroscope readings $\tilde{\mathbf{g}}$, assuming that their reference frames are aligned, to yield a carlibrated 6-axis reading: $\mathbf{a} = \mathbf{q}\tilde{\mathbf{a}}\mathbf{q}^{-1}$, $\mathbf{g} = \mathbf{q}\tilde{\mathbf{g}}\mathbf{q}^{-1}$.

A.1.2 Magnetometer

This task can be formulated as follows: given a set of 3-dimensional vectors $\{\tilde{\mathbf{m}}_i\}$, find an affine transform $(\mathbf{Q}, \mathbf{o})$ such that the set of $\{\mathbf{Q}\tilde{\mathbf{m}}_i + \mathbf{o}\}$ best fits onto a unit sphere.

We follow the method of [9], employing the ALS estimator in [5] to find a fit $(\mathbf{A}, \mathbf{c})$ to the set of equations $(\tilde{\mathbf{m}}_i - \mathbf{c})^\intercal \mathbf{A}(\tilde{\mathbf{m}}_i - \mathbf{c}) = 1$ and then calculating an inverse transform that converts this ellipsoid back to the unit sphere.

Since the ALS estimator only requires an accumulated matrix $\mathbf{\Psi}$ and not the individual values of $\tilde{\mathbf{m}}_i$, we are able to carry out the calculation continuously with constant rather than linear memory consumption.

A.2 Estimation

A.2.1 Facing

We treat the 2-dimensional orientation angle on the xy plane as the value being estimated. The calibrated magnetometer provides a proportional signal φ, while the calibrated gyroscope provides a derivative signal $\dot{\varphi}$. The input signals are given by $\varphi = -\arctan\frac{\mathbf{m}_y}{\mathbf{m}_x}$ and $\dot{\varphi} = \mathrm{d}\mathbf{g}_y \;/\; \mathrm{d}t$. Here $\mathbf{m}$ is the calibrated and aligned magnetometer reading,

$$\mathbf{m} = \mathbf{q}\;(\mathbf{Q}\tilde{\mathbf{m}} + \mathbf{o})\;\mathbf{q}^{-1},$$

and $\mathbf{g}$ is the calibrated gyroscope reading as is mentioned in section A.1.1.

Following the design in [6], we construct a complementary filter by the transfer equation

$$\hat{\varphi} = \frac{1}{s^2 + k_\mathrm{p}s + k_\mathrm{i}}\left(s\dot{\varphi} + (k_\mathrm{p}s + k_\mathrm{i})\varphi\right),$$
$$k_\mathrm{p} = \frac{\omega_0}{Q_\mathrm{P}}, \qquad k_\mathrm{i} = \omega_0^2.$$

This filter yields an estimation $\hat{\varphi}$ balancing between the two signals. We fix the pole quality factor as $Q_\mathrm{P} = 1 \;/\; \sqrt{2}$ and empirically tune the corner frequency at $\omega_0 = 24$ rad/s $\approx$ 3.8 Hz.

A.2.2 Motion

In the extended Kalman filter we formulate the state vector as $\mathbf{x} = \begin{bmatrix}\omega & A & \theta & B & \phi\end{bmatrix}^\intercal$, charactising an elliptical orbit around the origin — the ideal observation $\mathbf{z} = \begin{bmatrix}A\cos\theta & B\cos(\theta+\phi)\end{bmatrix}^\intercal$ is compared against the gyroscope readings adjusted by the facing estimation,

$$\hat{\mathbf{g}}' = \mathbf{r}_{z,\theta}\hat{\mathbf{g}}\mathbf{r}_{z,\theta}^{-1}$$
$$\text{where}\quad \mathbf{r}_{z,\theta} = \begin{bmatrix}0 & 0 & \sin\frac{\theta}{2} & \cos\frac{\theta}{2}\end{bmatrix},$$

projected onto the xy plane. Varying θ over $[0, 2\pi)$ traces out an elliptic trajectory of this point and θ is the current phase within the period. ω is the rate of change of phase, $\mathrm{d}\theta \;/\; \mathrm{d}t$, thus the prediction function is

$$f(\mathbf{x}) = \begin{bmatrix}\omega & A & \theta + \omega\Delta t & B & \phi\end{bmatrix}^\intercal.$$

The process noise covariance matrix is set to be a diagonal matrix with the first entry prominently larger than the others, since ω is actively changed by the participant.

After the estimations of A, θ, B, ϕ are obtained, we find the corresponding parameter θ at the major axis (which is also the fastest-moving point) by

$$\theta_0 = \frac{1}{2}\arctan\frac{A^2 + B^2\cos 2\phi}{B^2 \sin 2\phi} + \frac{1}{4}\pi,$$

and report the difference $\theta - \theta_0$ as the final output, so that an output phase of zero aligns with this fastest-moving point.

B. SOURCE REPOSITORY

All of our design files (printed circuit board assemblies, mechanical models) and source code, as well as extended documentation and demonstrations, are published at https://github.com/ayuusweetfish/Malletwand.