SOUND STRAND DESIGN

Designing Mechanical Joints to Facilitate User Interaction within a Physical Representation of Digital Music

By

Yan Shen

Submitted to the Department of Mechanical Engineering
In Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

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Abstract

This project involved the mechanical design of a modular musical instrument, named the "Sound Strand." Intended to be attached end-to-end one onto another in order to produce a string of music, each module was constructed to be easily maneuverable by hand and compactly contained within a 4"x2"x2" space. The result was a module that contains three mechanical joints, which allow three separate degrees of motion within the module. A final design was achieved with a three-piece mechanism that allows Elongation, Rotation, and Bending movements. Analog potentiometers serve as the electronic tools that read the physical changes in each joint by sensing movements and outputting a voltage signal; a microcontroller with an analog-to-digital converter then transforms the electrical outputs into a digital signal, which leads to circuit boards intended to also fit within the modular space. After several iterations, the design was streamlined to optimize mechanical freedom while minimizing size, loose joints, and material used.

Thesis Supervisor: Tod Machover
Muriel R. Cooper Professor of Music & Media

1. Introduction

The roots of music lie in the physical world: as sound waves. Dating back to the beginning of human culture, composers have played with sounds, manipulated waves, and created melodies with physical instruments. An instrument, defined as a device or apparatus designed to produce sounds, has traditionally been contained in the physical world, but recent decades have brought music into the digital realm. Digital synthesizers, audio recorders, and other electronics have allowed us to record sound using simply a receiver (microphone) and beyond that, digitally stored information. However, interest in the intersection of digital and physical realms serves as the inspiration to this project. While purely physical instruments (e.g. piano, violin, drums) as well as purely digital composers (computer programs e.g. Finale) both exist, the goal here is to join the two worlds by creating a physical device that translates tangible movements into digital, audio outputs.

Sound Strand's ultimate goal was to provide, as a physical structure, an analogous visual representation of music. When pieced together, the individual modules should stand together as a unified structure, straying upward and downward, stretching forward and backward, visually painting out the ebbs and flows of music. To be able to build a fragment of sound, a piece of synthesized music, and then put it on one's bookshelf, was the end goal.

This thesis project focused on specifically the *mechanical* design of a modular music composer. The vision was to create a physical product that would enable users to think about and "play" music in an entirely new way. Initial thoughts pointed toward a design of modular components, which would be connected to one another but whose joints could be varied in configuration. Each module would represent a certain musical motif, effect, or manipulation of the sound wave and other input signals it receives; the modules in turn create a string of musical motifs, and output an altered sound signal as the joints move.

However, moving forward with basic mock-ups, the fundamental choice of dynamic joints proved to be a less intuitive design than that of *dynamic modules* with *static joints*. Thus the concept of Sound Strand was reviewed and re-defined as a connectable strand of individual modules whose own physical properties changed, while the junctions between modules remained static. All of the information would be stored within each module, rather than at the boundaries between modules.

This project focused specifically on research and development of mechanical joint configurations and mechanisms, which are used to connect and contain the instrumental modules. The scope did not cross into the electrical and computer design of the signals, but rather contained all mechanical design of how the modules connect, are made, look, feel, and built.

For easy reference, joints in this paper will be referred to in short as E-joint, B-joint, and R-joint to indicate the elongation, bending, and rotational joints, respectively. Similarly, parts of the overall design, such as an arm, a pin, or gear may be preceded by an E, B, or R to indicate which joint or section the part belongs to (e.g. E-frame for the frame of the elongation joint).

The two halves of the thumbwheel potentiometer will be referred to as side A and side B, with side A indicating the side designed with a slot for turning and side B to the non-circular white half from which the leads extend (refer to Figure 1).

2. BACKGROUND

2.1. Design Research

As background for brainstorming and design, research was conducted on existing precedents in the field. An understanding of similar physical manipulation systems was developed, both for inspiration toward the user interface and hardware design. There exist various paradigms of physical manipulation systems, as well as examples of mechanical joints built for structural soundness.

Several projects within MIT's Media Laboratory have touched on this particular field, namely the intersection between digital content and tangible products. It is with inspiration and guidance from these existing creations that Sound Strand is designed. As primary collaborator and head-of-project, Eyal Shahar of the Media Lab provided much guidance on user interface design and end goals. The ultimate look and feel of Sound Strand was determined with Eyal, setting direction for the project.

Much like the SoundBlocks and SoundScratch created by John Harrison[1], the Sound Strand aims to charter into territory between the creation of and education in sound. In the user's hands, the product should be perceived as simultaneously a tangible programming language, a musical instrument, and a toy (Harrison 2005). This method of sound manipulation enables learning, creation, and more accessibility to digital sound manipulation. Both of Harrison's environments were designed to facilitate children in their quest to create their own sounds; the physical product with which the user directly interacts is simple, intuitively labeled with colors, lights, buttons, and sliders, putting focus on the expressivity of sound rather than the intricate programming occurring behind the scenes.

Sound Strand's ultimate intention aligns with a similar concept – that ideally, users do not perceive it as a product, but rather a *process* of creation. Interacting with the blocks and the strands of music gives the user freedom of expression with the numerous ways in which each block can be connected and manipulated. The environment of this "play" should be flexible, open, and facilitate creativity, striving toward a more seamless interaction between users and digital information.

In designing the physical expression of Sound Strand, Matthew Gorbet's Triangles project[2] highlighted an insightful concept: that any physical design must communicate its functionality with its form (Gorbet 1998). His urging that physical "affordances" be considered instigated Sound Strand to regard its mechanical and aesthetic design as a metaphorical expression of its potential uses. Thus, user interface decisions (discussed in Section 3) focused on expression of Sound Strand's digital capabilities through its physical capacities. The concept of expressing the *affordances* of a digital system in its physical form directed Sound Strand toward its connectible, modular physical setup.

Another project consulted during the brainstorming phase was the Tangible Media Group's Topobo[3] toy for its modular assembly methods (Raffle, Parkes, Ishii 2004). Topobo is defined as a constructive assembly system, whose parts are static or active and connect via dynamic joints; these connections change in discrete steps, enabled by custom-designed, snap-fit parts that give each motion (such as twisting or bending) an integer number of steps. In testing, Topobo's creators found that users responded more successfully to "iterative design," referring to the continual

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[1] http://cratel.wichita.edu/research/SoundBlocks/assets/JH%20thesis.pdf
[2] http://www.gorbet.com/matt/Thesis.pdf
[3] http://tangible.media.mit.edu/project.php?recid=34

configuring of parts done as each new part is added to the assembly. In contrast to the alternative of regarding the structural building and motion programming as two separate processes, the iterative design process resulted in better final products. It is this concept that directed part of Sound Strand's decision to have actively programmable pieces. Building a small part of the creation, programming until it had reached a desirable outcome, and then adding on new components, would rise to more successful creations than constructing the entire toy all at once and programming each module only at the end. Thus, the user interface of Sound Strand involves individual modules that can be configured via its three movements, and then attached one onto another.

Specifically for the design of Sound Strand's mechanical joints, references were drawn from daily household objects, which consistently and reliably enable physical manipulation. Particular attention was paid to joints whose function was to enable rotational movement such as swiveling, turning, bending, twisting (e.g. rotating television mounts, gear trains in clocks, ratchet tools, ball-and-socket joints on furniture) and longitudinal motion such as elongating, collapsing, sliding (e.g. sliding desk drawers, grocery basket handles, digital keyboard pedals, camera tripods, collapsible tables, telescopic pointers). Of these everyday objects, some also gave insight into how its mechanical movement could be read. A guitar pedal, for example, uses a potentiometer to read longitudinal motion (up and down displacement of the pedal's top plate). Others presented guidance on how translating motion back and forth between linear and rotational (an automobile's steering wheel turns a rack and pinion assembly, which in turn adjusts the tires' orientation).

2.2. Phase I – Digital Synthesizer Block Scheme

The original intent of the Sound Strand was to design a physical version of a digital synthesizer. A synthesizer is defined as a sound generator based on analog and digital techniques, with instructions mapped into a network through which to channel the sound signal.

Each module was to represent a separate instruction within a digital synthesizer e.g. filter, amplifier, etc. which would manipulate the sound in a different way. The starting signal would originate before the first module, and as it traveled through the various units, would be altered in the characteristic that each particular module controlled. For example, a filter could sift through the waves and change the timbre of the sound, while an amplifier would adjust the volume of sound.

Design for the joints required that they:

- connect and disconnect easily
- do not allow unintended detachment
- carry connectivity of five wires for five signals

We therefore started off with a block structure: a signal-bearing unit with six faces (six physical mates and six associated electrical connections). The intent was to use a male-female joint to allow connections on all faces. Because there are six faces to a cube, the maximum number of connections was the same – but the challenge was in designing a method for the cubes to make multiple attachments to other cubes, while adhering to spatial constraints posed by the structure's geometry.

Questions regarding the structure included:

- How is the block derived from its function?
- How is the block derived from its connectivity?
- What is the general look and feel of the mechanism?

2.3. Phase II – Modules Defined as Music Motifs

Stimulated by discussion with more users, a sample of user preferences about intuition in each of the potential designs, and revisiting the conceptual expression of the desired product, the paradigm was changed from the block system to a user-friendlier interface. Insights from surveying suggested that a physical assembly directly expressing digital commands did not do much to enhance the user's experience with digital information. Instead of pursuing a physical contraption to model a digital synthesizer step-for-step, Sound Strand changed its direction to imitate a more instrument-like modular system.

With focus on the overall intuition of this musical apparatus, Sound Strand was defined to be a string of modular components that each represents a musical motif. Instead of the modules representing a component that *manipulates* the sound signal, each would represent a motif itself. These independent snippets of sound would be altered and controlled by physical changes in the module, rather than by the digital instructions contained within each module.

Moving away from the digital synthesizer paradigm did not mean giving up on developing Sound Strand as a *process* of creation rather than *product* of creation. Much like Harrison's SoundBlocks, in which "the user designs the instrument by creating the network configuration, then performs on it by interacting with the sensors" (2005), Sound Strand took on a direction of assembling musical motifs, which could individually be manipulated, but strung together to create a continuous segment of sound. Its modules would, however, be designed not to represent foreign computer commands, but rather music itself, allowing Sound Strand to become less about manipulating computer science and more of a personal, artistic experience.

This fundamental change in the end product called for investigation into a completely different paradigm, in terms of physically designing joints. Instead of designing mechanical joints for module-to-module connectivity, the task was to design mechanical joints that could change the form, shape, or overall look and feel of the module itself, thereby altering properties of the music itself, such as tempo, volume, key, timbre, etc.

2.4. Definition of Project Goals

By virtue of this project's fundamentally mechanical-engineering-based nature, the three main challenges within this task included:

1. To design mechanical joints within a small module (~ 2x2x4 in^3 space) that would provide three distinct types of motion
2. To ensure that each type of motion is able to be "read" digitally
3. To allow the joints' parts to attach to each other and maintain overall structural rigidity (as a self-sustaining structure)

The scope was later redefined to focus on the three mechanical joints, finding solutions for:

1. How the three types of motion would be possible within one small space
2. How this mechanical motion could be translated into digital information

2.5. Digital Reader Selection

Producing music using the Sound Strand apparatus is by each module's transmission of a digital audio signal. The use of digital signals to produce sound required that the Sound Strand could translate physical motion into digital outputs.

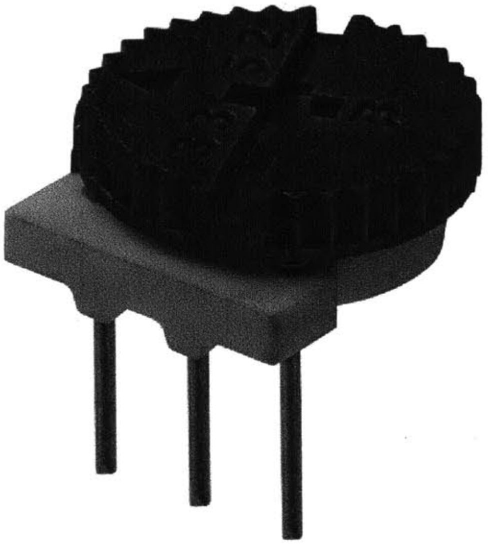

Figure 1. Thumbwheel Potentiometer

Evaluation of several different digital readers concluded that a thumbwheel potentiometer would best fit the Sound Strand's design. The 3351 T20 series thumbwheel potentiometer matched the SS's needs in size, compactness, and sensitivity; it adds little bulk to the module, and is intended for sensing and reading very slight changes. As an off-the-shelf product, this potentiometer is guaranteed to be available in small or large quantities, deliver consistent performance, and eliminates the need to design a custom motion-reading mechanism.

Colloquially called a "screwdriver potentiometer," this analog reader is made to measure small rotational changes. Its functionality depends on the relative rotation of the two halves (the black – side A, and the white – side B). A three-terminal resistor, the potentiometer has a sliding contact that forms an adjustable voltage divider within the instrument, outputting varying voltages as the contact slides between terminals. This implies that one side must remain stationary while the other is rotated. The outputted electrical signal is then translated to a digital signal by the receiving microcontroller.

It is around this principle that each of the Sound Strand module's joints is designed. Both halves of the potentiometer display distinct features by which that side is to be controlled. Side A exhibits a thin slot in its face; side B's circular perimeter converges to a flat side whose width is the diameter of the potentiometer. In addition to facilitation the distinct motion (bending, elongation, rotation), each of the joints bears design details that facilitate turning side A by while holding side B in place.

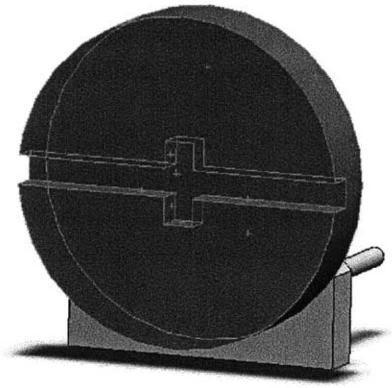

Figure 2. Potentiometer - Side A

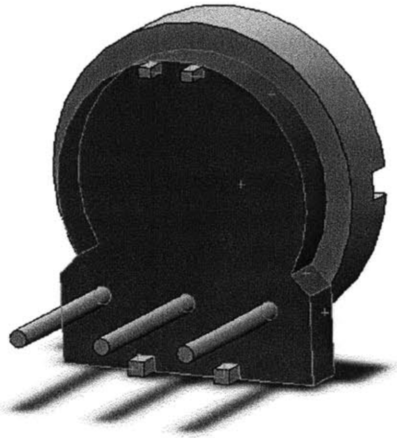

Figure 3. Potentiometer - Side B

3. USER INTERFACE DESIGN

As a user manipulates the Sound Strand module in hand, he is able to literally play with music.

3.1. Motions of Sound Strand

Guided by Gorbet's emphasis on expressivity of the physical form, several ideas were generated to match the physical allowances of Sound Strand modules to conceptual changes in the music it contains. Ideally, there would be multiple axes of movement within each module, distinct enough such that its implications would be distinguishable in the user's mind. The decision came to three axes of motion allowing the user to control three corresponding characteristics about the sound produced. Physical changes within the module translate into digital changes in the sound produced by that module, whether it be volume, tempo, timbre, pitch, or another variant in music.

Intuitive motions for a user were determined to be pulling, bending, and twisting; this was the rationale behind designing elongation, bending, and rotational joints. Pulling on the ends of the module with both hands, a user should be able to feel a significant change if the module extends in length by at least half an inch, and twisting the ends even a quarter turn should be felt in the wrist. Thus, the technical specifications of the module were designed with these criteria in mind, resulting in an elongation of ~0.83" and a three-quarters rotation of 270°.

As for the conceptual implications of pulling, bending, and twisting, Sound Strand modules were to associate these movements with changes in the musical motif. Elongating, bending, and rotating were chosen as the types of motion, with initial ideas for their implications including:

- Elongation = slowing down/speeding up tempo, changing rhythm of motif
- Rotating = changing pitch/key of motif, adjusting timbre of sound, creating harmonies
- Bending = altering the progression of notes in the motif, new directionality of melody

3.2. Justification of Module Size

From the user-interface aspect, this design strove toward a friendly, easily navigable, but sturdy design. Each module should be able to sustain decent, though not exorbitant, amounts of force; in the hands of children or under the weight of other household objects, the structure should not collapse. In terms of size, each module should fit easily into a user's hand without becoming overwhelmingly large once multiple modules are connected together. Because the intended purpose of each individual module is to join with other modules in a linear fashion to create "strands" of sound, the size of the overall structure can grow rapidly as modules accumulate.

An adult's palm size was used as reference; on average, an adult hand spans approximately 4" from its base to the start of the fingers. To comfortably grip an object within, the object was sized to span only half the palm, at 2" in diameter. Ultimately, the module was targeted to resemble an overall cylindrical shape, taking up a length of 4" with two end disks of diameter 2".

At roughly this physical size, the resulting Sound Strand does not take up an overwhelmingly large space when the modules, each representing one bar of music, are compiled to represent a verse. In music theory, common forms in song structure include the 32-bar-form; a standard verse of blues music is defined as 12 bars; a country song verse as 16 bars. That means, the Sound Strand could reach up to (32 bars) x 4" = 128" in length, given the unlikely scenario that every single module is extended to its maximum length, and none of the modules are bent. However, taking an average length of a music verse as 16 bars, each physically manifested in a 2x2x4 = 16 in^3 space, the volume taken up by a complete Sound Strand would total (16 bars) x 16 in^3 = 256 in^3. Assuming that the modules are all bent in such a way that total volume taken up is roughly square, then this standard verse of music would take up only $\sqrt[3]{256\ in^3}$ ~ cubic space with sides of 6.3" in length.

From the user's perspective, a finished Sound Strand sits atop the bookshelf as a structure coiled into a cube-like volume, roughly 6"x6"x6". With each side slightly shorter than an average adult's hand span, this size is deemed appropriate.

4. Technical Design

In this section is the discussion of technical design aspects. It will cover the rationale behind mechanical design decisions, including size specifications, mechanisms, and mechanical features of the parts. It is broken into three parts to specifically address the three joints, which were the focus of this project.

4.1. Elongation Joint

Size of E-Joint
Volumetric Space of E-Joint = 2.50" x 1.17" x 0.65"
Length of E-Frame = 1.50" | Thickness of E-Frame = 0.10"
Length of E-Rack = 2.50" | Thickness of E-Rack = 0.15"

The elongation joint is the central piece upon which the Sound Strand's modular structure is based. Its fundamental mechanism is a rack and pinion assembly, which translates the physical motion of the apparatus into a digital signal; it does so by translating *linear* motion of the rack into *rotational* motion, which is then read by the potentiometer and produces an electrical signal. A rack with gear teeth serves as the part that elongates, sliding along a structural frame that exists to keep the rack in place by wrapping around all four faces of its rectangular cross-section (Figure 4). This feature of the frame ensures that motion for the rack is not possible along any but the intended axis.

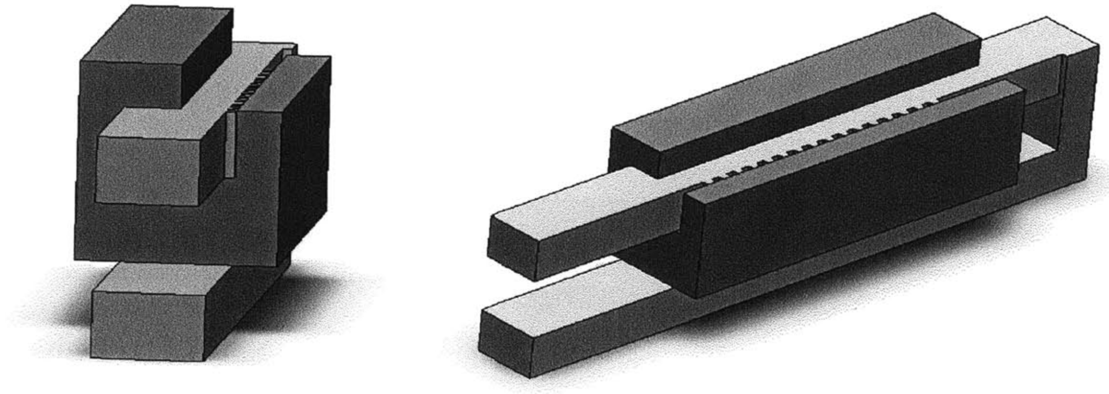

Figure 4. E-Joint Frame Around Sliding Rack

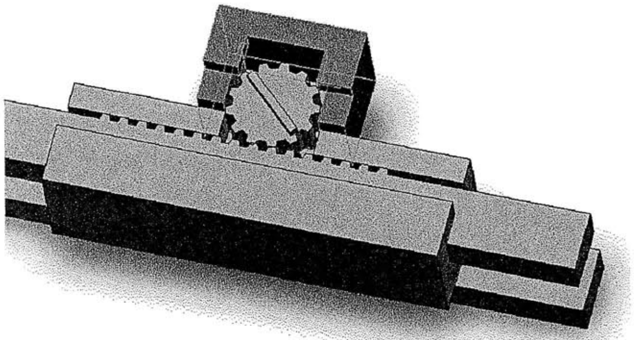

Figure 5. E-Frame Housing for Gear

As companion to the rack, a gear is located alongside the sliding part; it is housed by an extension of the E-frame, but free to rotate within that designated volume. The housing extension simply constrains the gear from slipping out of a mate with the rack's teeth.

It is the rotation of the gear that turns side A of the thumbwheel potentiometer and in turn outputs a digital signal. Of course, in order for the potentiometer to produce a voltage-reading signal, one half has to rotate relative to the other; therefore, the frame of the E-joint has a slight extension on its side, which houses the potentiometer and keeps its side A motionless (Figure). The design capitalizes on the shape of the potentiometer's non-circular half; the E-frame uses a flat vertical surface to stand flush against the flat side of the potentiometer so that the a voltage reading can be attained.

This frame serves as the central housing unit of the module, from which all the other parts extend. Its walls were designed to be 0.10" because this ensures that the frame is durable as the most weight-bearing part. As the E-frame takes up slightly less than half the length an individual Sound Strand module, its length was set to be 1.5", just under half of the maximum desired length of 4". A reasonable length for the rack was chosen to be 2.5", so that it has an extra inch of length over the frame length, which can be free to slide back and forth.

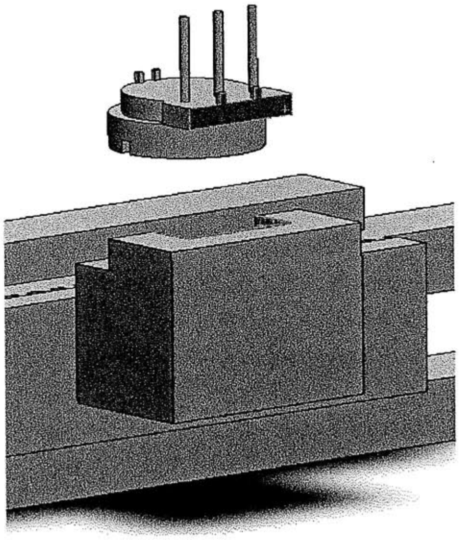

Figure 6. E-Frame / Potentiometer Constraint

Gear teeth extend for 1" on the rack so that the entire span of the thumbwheel potentiometer can be reached. With a gear diameter of 0.35", the system needs a minimum length of 0.83" to spin the potentiometer its full 270 degrees. This translates to about three-quarters of the way around the circle, which requires:

$$(0.35\pi)*0.75 \approx 0.83"$$

To ensure that the rack does not run out of teeth in unforeseen circumstances, the rack has an additional tolerance of about 0.3", running teeth along the rack for 1.15".

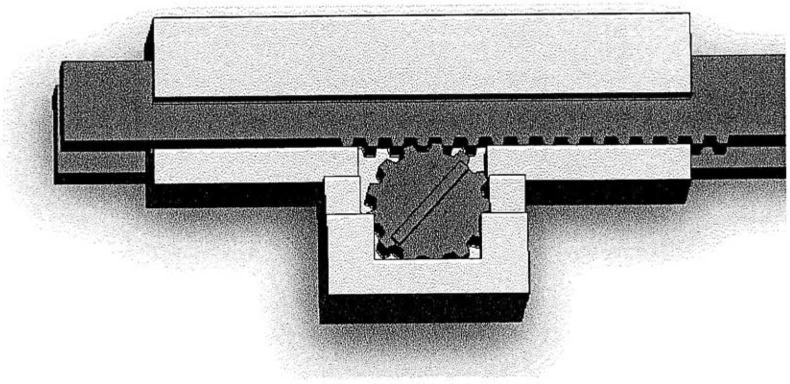

Figure 5. Rack & Pinion Assembly of E-Joint

Joined with the rack and pinion assembly is the potentiometer; side A of the potentiometer is coupled with the gear, so that the rack's elongation can be read digitally. On the top face of the gear, the extruding rail fits snugly into the potentiometer's slot. This feature of the gear forces the gear and potentiometer to act as one; essentially, the potentiometer's side A becomes the pinion of the rack and pinion assembly. As seen in Figure , the extended housing on the E-frame provides a flat vertical surface, flush against the highlighted flat edge, keeping side B in place while side A rotates with the gear.

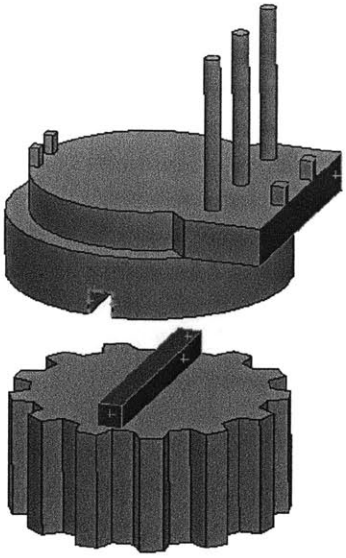

Figure 6. Gear / Potentiometer Mate

4.2. Bending Joint

Size of B-Joint
Volumetric Space of B-Joint = 1.75" x 2.00" x 2.00"
Length of B-Arm = 1.55" | Thickness of B-Arm = 0.15"
Diameter of B-End = 2.00" | Diameter of Pin = 0.09"

The main challenge of the B-joint was its attachment to the rest of the module. A method was required to read its bending motion, but it was not reasonable to rely on the potentiometer itself to be the weight-supporting structure of the joint. In the face of rough handling or too much force applied to the B-joint, the joint itself still had to maintain its structural soundness.

The solution is a pin that slides through the two arms of the B-frame, as the arms sandwich the main elongation frame as seen in Figure 9. A pin of 0.09" diameter serves as the axis of rotation around which the arm swivels. Tolerance was given for ease of motion with 0.01" difference in diameter between the holes in the B-arm and E-frame, and the pin itself. This difference leaves enough space for the pin to spin freely and without resistance, but nonetheless, is still tight enough for the pin to spin without wobbling.

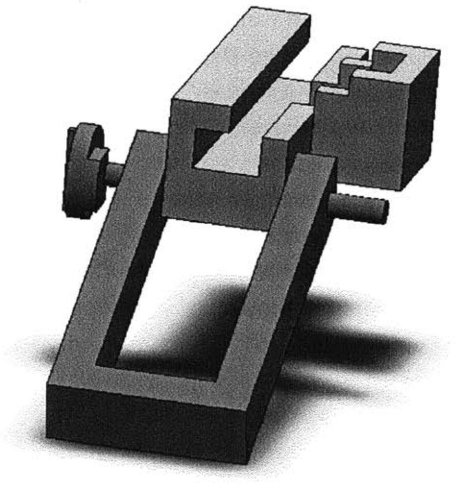

Figure 7. B-Joint Arm & Pin Assembly

In order to eliminate extraneous parts, this design capitalizes on the B-frame's pin joint to double as both its axis of rotation and its own signal to the potentiometer. An initial iteration consisted of the B-arm coming to a rounded end with gear teeth, which would mate with a gear that jointly spun with a potentiometer, while attached to the E-frame for stability. However, the numerous loose parts put the mechanism at risk of failure at many points, so the B-joint was later designed such that the joint itself doubles in functionality for structure and encoding. This required that the pin and B-frame rotated in sync, moving as one.

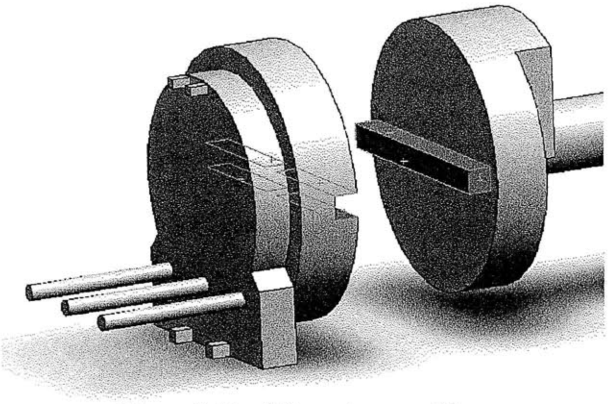

Figure 8. Pin / Potentiometer Mate

The solution is almost identical to that of the gear/potentiometer connection from the E-joint. From the surface of the pin head, a thin guiderail extrudes in the exact shape to fit into the female screwdriver slot of the potentiometer. This protruding line that stretches across the diameter of the pin head acts as the male half to the potentiometer's side A, which, when fitted together, forces the pot to spin with the arm and pin (as seen in Figure 10). While the pin body holds the B-frame to the E-frame, the pin's head directly turns side A of the thumbwheel potentiometer.

Since the pin and arm are two separate parts, a critical design challenge to solve was how to join the pin and arm so that they would move together, but be feasibly constructed and assembled. Building the entire arm, including the pin, as one piece would not be feasible assembled, since the part would be shaped like a closed loop, with no opening through which to attach it to the E-frame. Thus, the pin had to have some characteristic that would align its motion with the arm's swiveling. The solution was to design a male-female mate on the back face of the pin head and the outside face of the b-arm (Figure 11). An inset on the outside face of the B-arm houses a matching shape that protrudes out from the back of the pin head, securing the two pieces' motion together.

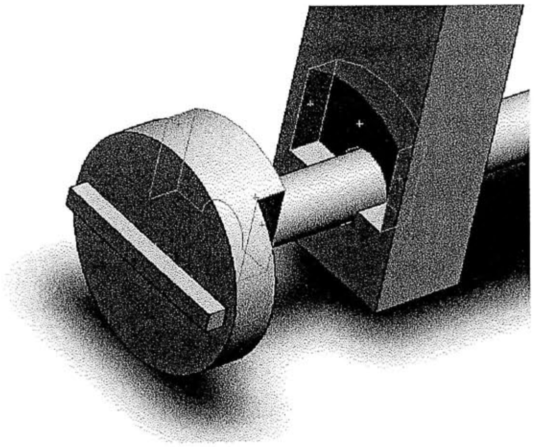

Figure 9. B-Joint Pin / Arm Mate

Once the pin, arm, and the potentiometer's side A had all been designed to move together, a fixture was constructed to keep the potentiometer's side B in place, such that side A and B could rotate relative to each other and produce a digital output. That is the intent of the overhang on the E-frame in Figure 12. The flat surface holds the potentiometer's side B in place while side A, the B-arm, and pin are spinning. As a force-sustaining structure, the overhang is formed in a triangular shape, intending to serve as a truss. When side A of the potentiometer spins, the rotational moment felt by side B will be countered by the truss.

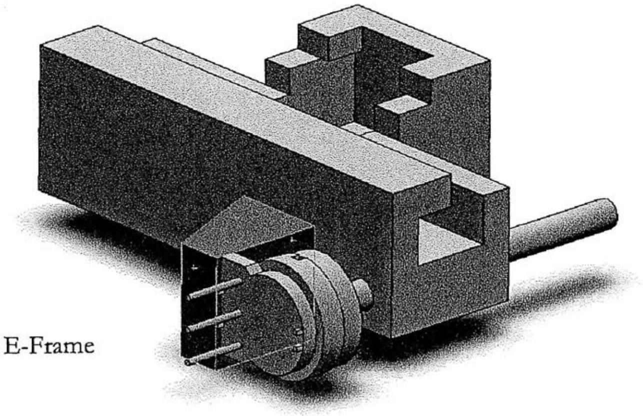

Figure 10. Truss Extension from E-Frame

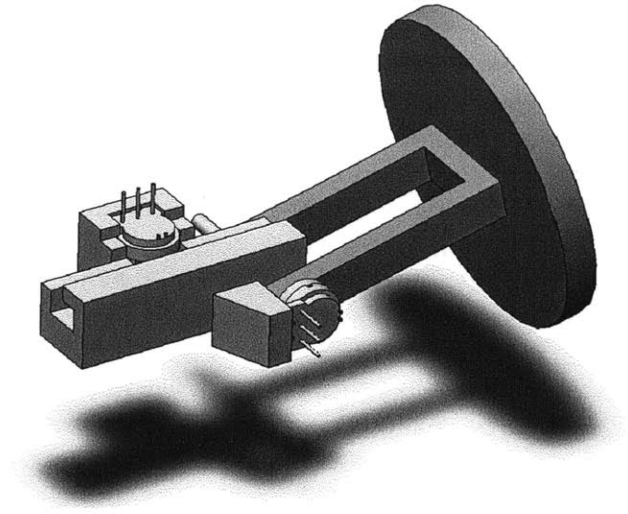

Figure 11. Final Bending Joint

To form one end of the Sound Strand module, the Bending joint draws to a close in the form of a circular disk; this disk serves as the module's end piece with which the user interacts. As a child or adult's hand should easily grip and manipulate this disk, the diameter was chosen to be 2" with a thickness of 0.10". This structure, after construction, was rigid enough not to warp under pressure, but also conserved 3D printing material by its compact size. While large enough to grip with a hand, it is also small and nimble enough to attach onto other modules (thus creating a strand of these modules) without becoming too bulky.

4.3. Rotational Joint

The final joint of the Sound Strand module is the rotational joint, responsible for enabling twisting around the central axis. Without adding unnecessary bulk to the overall module, the R-joint was designed to double as both the rotational structure and the end cap of the module.

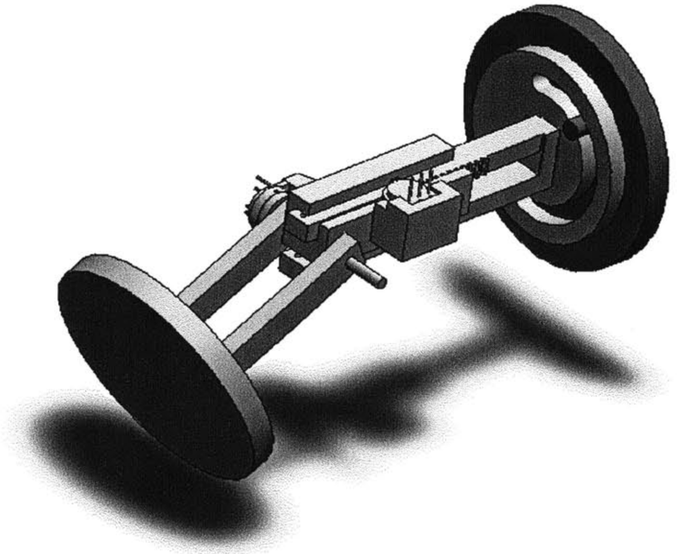

Figure 12. Final Rotational Joint in Assembly

Critical design challenges for this component included:

a) How to attach this end onto the rest of the apparatus, while maintaining its ability to spin freely

b) How to force the potentiometer to read the end's rotational motion without adding gears, gear trains, or other superfluous features

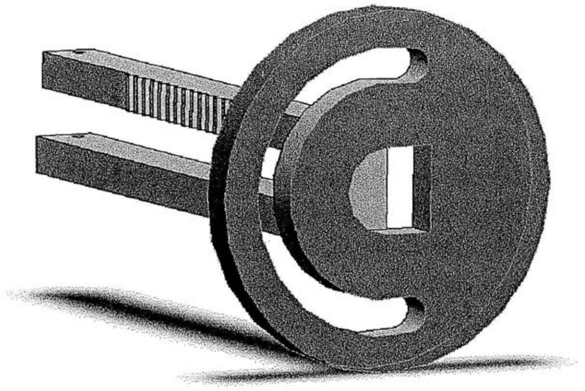

Figure 13. R-Mount Attached to E-Rack for R-End

To avoid adding extra components onto the R-joint, this design called for the end disk to be attached somewhere other than its center. This would leave the center of the disk free to turn the potentiometer with its extruded rail, as seen in Figure 16 below. For easy attachment, a mount for the R-end was built onto the end of the E-rack; the rack and mount became a single piece to minimize loose joints, so the mount is designed to never conflict physically with other parts of the E-joint. As the concentric end disk and its disk-like mount rotate relative to each other, a pin slides along the circular rail (concentric to the R-end and R-mount), ensuring that the two disks stay concentric, and that the potentiometer is not turned past its 270° allowance.

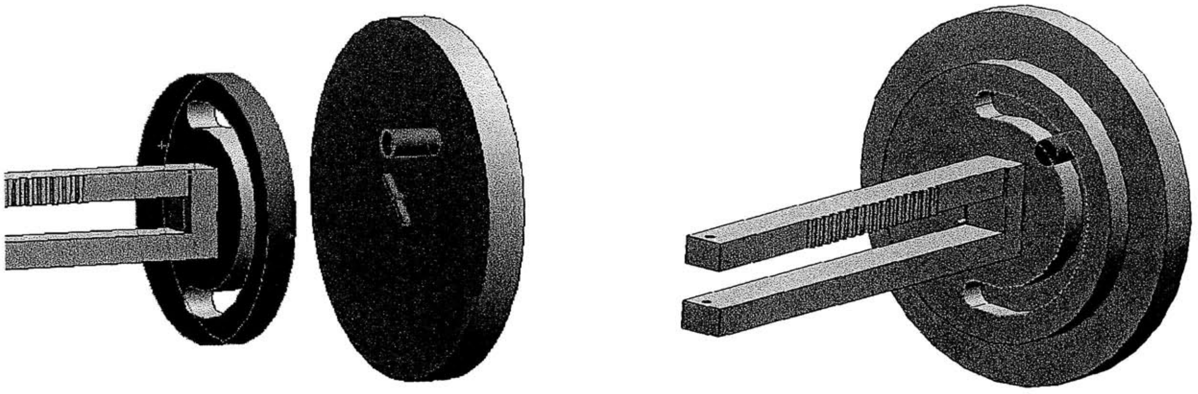

Figure 14. R-End & R-Mount Assembly

Figure 17 below illustrates how the thumbwheel potentiometer is secured between the R-mount and R-end. Side A attaches to the extruded rail on the R-end, while side B fits snugly into the cutout of the R-mount.

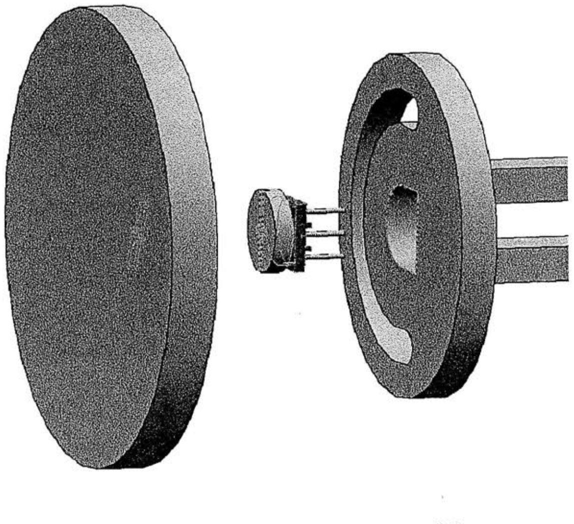

Figure 15. R-Joint & Potentiometer Mate

5. Evaluation and Next Steps

5.1. Final Assembly

The Sound Strand's final assembly consists of five separate 3D printed parts:

1. E-Frame
2. E-Rack/R-Mount
3. R-End
4. B-Arm/B-End
5. Pin (for joining B and E)

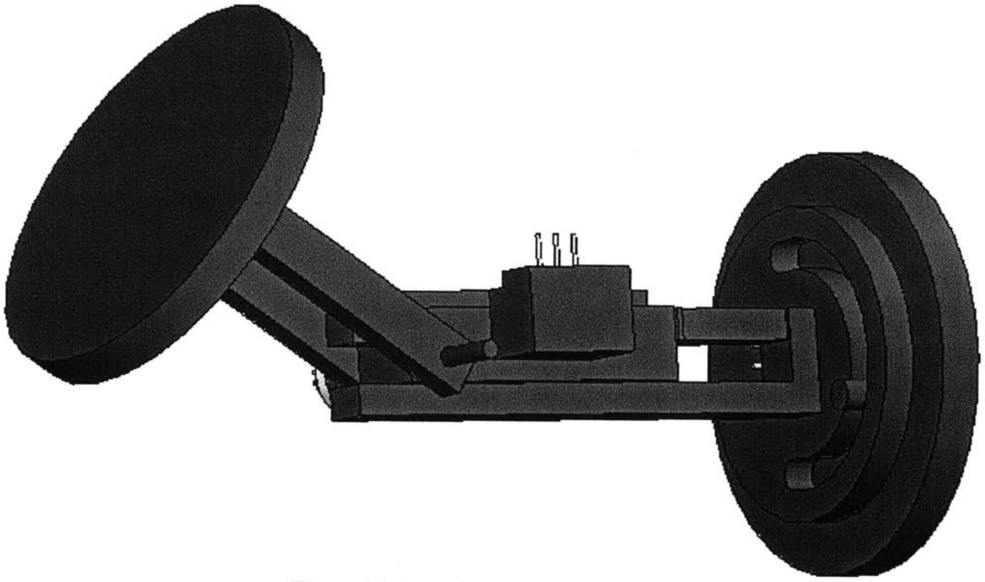

Figure 16. Sound Strand Design - Front

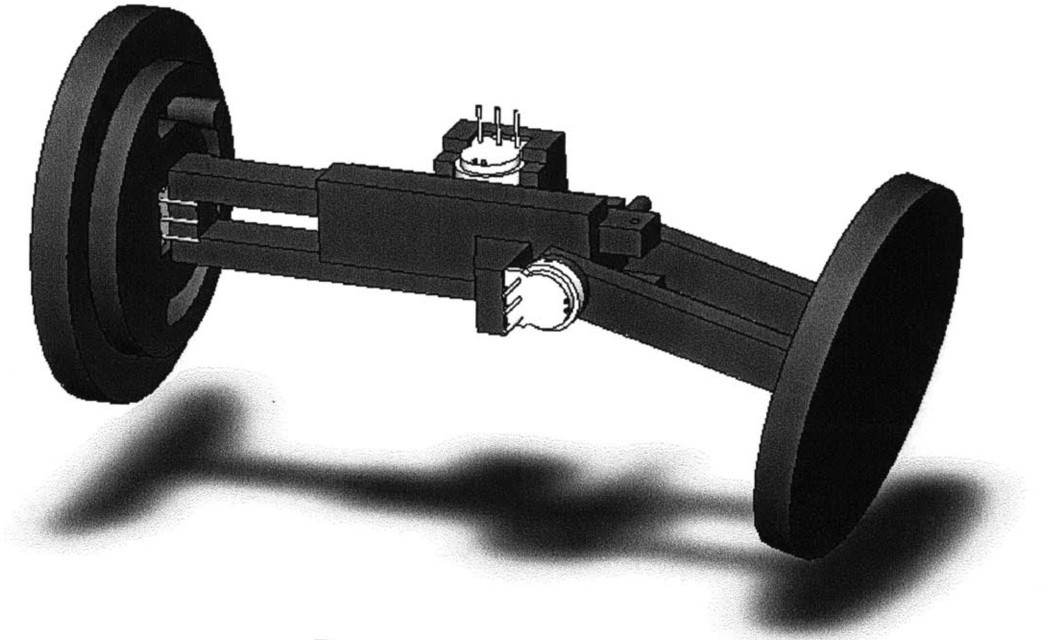

Figure 17. Sound Strand Design - Back

5.2. Assessment of Project Goals

All of the primary project goals mentioned in Section 2.4 were met with the final design.

1. Space Constraint

The final assembly amounts to a volume that fits within the 2x2x4 in^3 space, conforming to the size constraint. Its two circular end disks make the overall module easier and more comfortable to grip, serving appropriately as the handheld, portable easily manipulated "toy" it set out to be.

2. Easy Digital Accessibility

A potentiometer was coupled to each joint (elongation, bending, rotation), reading physical changes and outputting a digital signal. Because the potentiometer leads need to attach via wire to electronics that exist alongside the mechanical components within this space, this design also minimizes the movement of side B of each potentiometer (the side from which the circuit leads extend); it is usually side A that moves with the loose parts. This will improves the connection between mechanics and electronics, and minimizes risk of failure.

3. Structural Self-Sustenance

The goal of making joints self-sustaining, such that their structural soundness and attachment does not rely on the potentiometer, was also met by this design. All of the joints rely on some feature of its own to keep the part intact (E-joint by its frame; B-joint by the pin; R-joint by the sliding handle along rail), without putting extraneous force on the potentiometers. Handling the parts by hand did not damage or break parts, and the 3D printed material provided enough sturdiness to maintain its form under slight pressure. Given that no excessive force was applied directly along any part's weakest direction

5.3. Future Goals and Development

Mechanically, the system delivers overall smooth and stable performance. Joints move well within the module, and the parts stay firmly together. Originally, the intent was to introduce tolerance gaps between the moving parts, so that motion could be effortless and unburdened. However, even without tolerances (or with very slight gaps of 0.01" between parts), the 3D printed pieces move uninterrupted by friction. Compared to the original plan, the module's overall size seems small in hand, but is actually appropriate in size considering the numerous modules that must be assembled in order to create a musical composition. Though small intricate parts can be more difficult to grip than imagined, these printed pieces provide enough surface area and thickness to firmly grasp.

Improvements to be made to this system lie mostly in the housing apparatus for the potentiometers. The potentiometers, though theoretically held in place by its side A attachment to a mobile piece and its side B alignment against a static backboard, occasionally slip out of place. Using adhesive to permanently join side A and its corresponding part (e.g. gear, pin, disk) does not ensure 100% reliability, so this may be a point of further development. The gear in the rack and pinion assembly can also be modified so that it spins more naturally along the rack; the E-joint offers the greatest risk of failure because of its tricky dependence on gears. If teeth become misaligned or the pitch diameter of the gear is off even slightly, its rotation and movement along the rack is bumpy and unreliable. More investigation into the gear and rack assembly can benefit Sound Strand's design.

Now that joints *within each module* have been designed and constructed, next steps move the project toward outer shell design and module-to-module joint design. To house each module's internal mechanics, an outer "shell" must enclose the joints detailed in this paper; likewise, the hardware that enables modules to string together also require research and development. Initial ideas for the outer casing or "shell" of the joints designed in this project point towards flexible casing using malleable material; the fluidity of music would be represented through the adaptable shape of the modules' shells. Potential paths to pursue include rubbery latex material, cloth, or other fabric. These materials would enclose the module into one cohesive unit, but adapt easily and effortlessly to its changing shape.

Drawing again from the concept of *affordances*, the connecting joints between modules should express something about the fluidity of music, moving from one bar to the next while maintaining assured bonds with each other. Music, however, can always be altered; one particular motif does not necessarily follow another, so bars of music –in this case, the motifs represented by each module– can be added on, de-assembled, and re-assembled as the user desires, each time creating a new composition. Joints between modules should be based on the desired outcome of connecting modules, that is, that the link itself is static, strong enough to avoid unintended detachment, and able to carry a digital signal through the ends. Potential design concepts to explore include using Velcro to join module ends, a twist-on twist-off assembly, and snap-fit ends.

Alongside hardware development is electronics development. On the electrical/digital side, Sound Strand requires analog-signal communication (voltage readings of the potentiometers) both within each module and between modules. The electronics that read and translate the joints' movements are in development by Eyal Shahar, who will continue to progress this project past its hardware stage. His contributions to developing the final product are crucial, defining directional and conceptual end goals.

Musically, Sound Strand has much to learn as it becomes a more intelligent system; future development could look into having the system recognize features such as repetition, movements, harmonies, phrasing, dynamics, etc. and being able to product them as modules are added on to a composition. Directionally, this project could also move beyond its concept as an instrument or toy to explore other topics within the area of digital sound manipulation. Within the same structure of joining sound bytes together in a linear fashion, Sound Strand's framework and system could be expanded in the future to represent other processes of creation. For example, instead of music, modules could embody word fragments to be strung in a sentence. Alternate uses of Sound Strand's framework could innovate new learning tools in several other fields.

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