Explorator Genus: Designing Transportable Mechatronic Sound Objects for Outdoor Installation Art

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ABSTRACT

The Explorator genus is a set of hardware and firmware systems, artistic motivations, and physical construction methods designed to support the creation of transportable environmentally-responsive mechatronic sound objects for exhibition outdoors. In order to enable the realization of installation scenarios with varied cochlear needs, we developed a generalized hardware and firmware system that can be reused between projects and which supports the development of purpose-built feedback mechanisms.

We introduce five distinct hardware instances that serve as test cases for the Explorator genus. The hardware instances are introduced as Explorator "species". Each species shares core hardware and firmware systems but uses distinct soundscape augmentation feedback mechanisms to support unique installation scenarios. Initial subjective and objective observations, findings, and data are provided from fieldwork conducted in four American states. These initial test installations highlight the Explorator genus as a modular, transportable, environmentally reactive, environmentally protected, self-powered system for creating novel mechatronic sound objects for outdoor sonic installation art.

Author Keywords

soundscape, soundscape augmentation, sonic art installation, soundscape-specific, natural soundscape, natural sounds, musical mechatronics, mechatronic soundscape augmentation

CCS Concepts

•**Computer systems organization** → Realtime systems; **Embedded and cyberphysical systems;** •**Applied computing** → *Sound and music computing;*

NIME'23, 31 May–2 June, 2023, Mexico City, Mexico.

1. INTRODUCTION

Recent publications have highlighted the artistic potential of using natural sounds and sonic environments as an artistic focus for sonic installation art [6], to encourage environmental listening [10], and design sonically pleasant public spaces through soundscape augmentation [20]. While the majority of this work has utilized loudspeaker-based systems to mix sounds onto existing sonic environments for public enjoyment, or as a method to create sonic installation art, in recent decades, some researchers have used alternate technologies to achieve these goals.

Among the alternate technologies is the use of mechatronic actuators including solenoids and DC motors. This interest has been supported by the increased availability of high-quality, lower-cost microcontrollers, sensors, actuators, and batteries and is an active topic of research for several academic programs and individual members of the NIME community [2, 23, 22, 17, 12].

Our research focus is creating installation scenarios that encourage listening to, and physical exploration of, in-situ natural sonic environments. To address this high-level artistic objective, multiple hardware projects and installations have been developed. Our prior related work focused on audio and environmentally responsive non-cochlear[1] feedback to highlight the vocalizations of a specific cicada species [21], while the Explorator project introduced in this paper expands on this research by pursuing kinetic non-cochlear and mechatronic cochlear feedback to augment a broader range of sonic environments than previously investigated. Explorator hardware instances are exhibited following a soundscape-specific pop-up exhibition strategy where the installation location and exact placement of artifacts are determined at the time of the exhibition according to the in-situ sonic environment (Figure 1).

2. MUSICAL MECHATRONICS

There are numerous reasons artists pursue mechatronic sound-producing mechanisms over loudspeaker systems [9]. Some take advantage of the "audiovisual materialism" generated by actuator movements that provide tangible correlations between sounds and the actions that generate those sounds [25]. Some are attracted to the complex acoustic

[1]We use the terms cochlear and non-cochlear as developed by Seth Kim-Cohen in [5] where cochlear refers to the physical experience of sound waves as they pass through the ear and are translated into neural impulses, while non-cochlear refers to the perceptual experience of sound as interpreted by the brain, which includes cultural, social, and psychological factors.

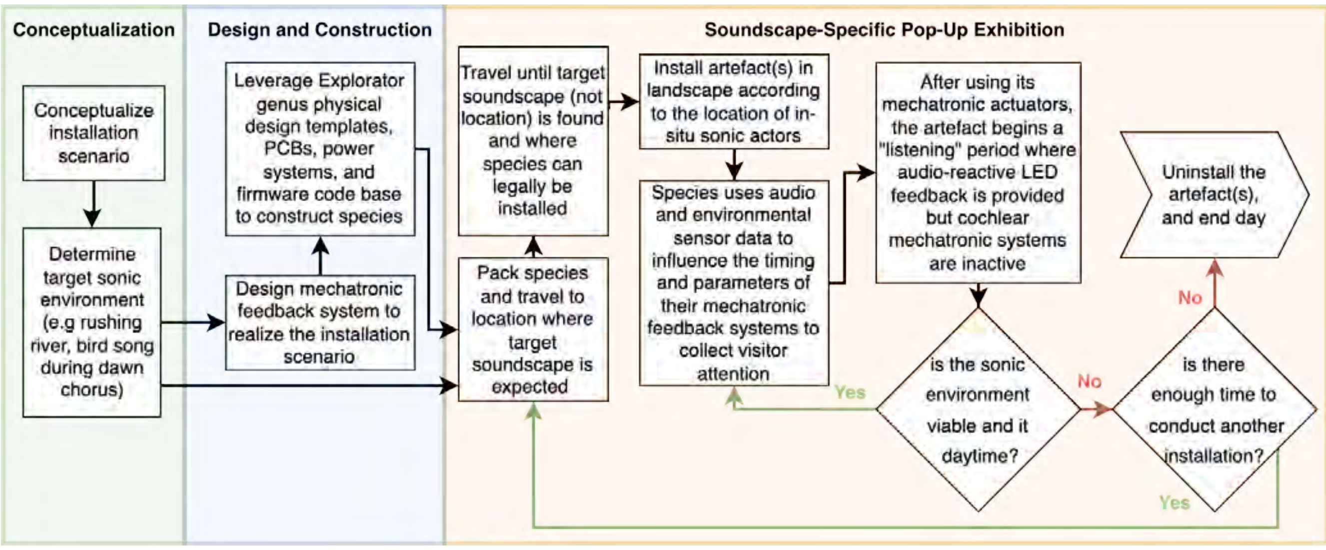

Figure 1: Conceptualization, design, and exhibition process for Explorator artifacts along with the fundamental framework for our installation scenarios.

properties of the omnidirectional real and authentic sounds produced by mechatronic sound objects and how they interact with the physical environments [18]. Others believe that the cause-and-effect characteristic of musical mechatronics can support more engaging audience experiences than purely acousmatic approaches [7]. As noted in [11], “there can be no doubt that for artists and composers interested in exploring localization and spatialization in manners not afforded by loudspeakers, musical robotic systems will continue to be a means by which new music and sounds can be explored”.

2.1 Modular Musical Mechatronics

The inherent technical and physical characteristics of mechatronic instruments and sound objects often led to the development of hardware systems to realize specific installation scenarios which are often exhibited in a predetermined location [19, 1, 8]. Alternatively, some artists and researchers have adopted a more frugal approach by adopting modular design philosophies to encourage the reusability of hardware, firmware, and physical design elements between installations.

By leveraging its small unit size and flexible mounting system, Achim Wollscheid’s *clapper system* (1993-1998) can quickly adapt to new site-specific installation scenarios [24]. The system’s adaptability is realized through a flexible mounting mechanism that allows the devices to be mounted to a broad range of surfaces and by building numerous identical hardware instances. These features allowed the system to be used for several installations in physically distant and distinct locations.

While also implementing a modular surface-mounting system, Eric Singer’s *ModBots* (2001) extends the flexibility of Wollscheid’s *clapper system* by supporting variable physical configurations which each featured distinct vocalization mechanisms supported by a single channel of DC motor- or solenoid-control. Singer noted that “because of their small size, versatile mounting capability and minimal cabling required for installation, ModBots can be configured in limitless arrangements” [18].

Modular design principles have further been adopted in instruments designed primarily for realizing musical performances as demonstrated by some of the KarmetiK Machine Orchestra’s instruments including *Modulets* (2016) and *MalletOTon* (2016) [3, 4]. *Modulets* adopt a similar approach as the *ModBots* by leveraging multiple centrally controlled individual solenoids to produce spatialized percussion while *MalletOTon* uses arrays of independent actuator mechanisms to modify the instrument’s key, pitch range, and timbre. Directly supporting our exhibition methodology and research objectives, Kapur et al. describe the benefits of modular design as including “flexibility and ease of deployment” [4].

When the same piece of hardware is expected or desired to be displayed repeatedly, these modular musical mechatronic systems demonstrate distinct advantages over systems designed for one specific artistic application or physical configuration. As noted by Kapur et al., “while other avenues of mechatronic instrument development focus on the development of increasingly complicated apparatus and interfacing techniques, the utility in a ‘real-world’ environment of a rapidly-installable instrument is undeniable” [4]. This is especially true for projects such as Explorator where variations of similar systems are needed to realize several installation scenarios. As our research involves the exhibition of multiple pop-up installations within a single day, the characteristics of rapid installation and development demonstrated by modular design principles are particularly useful for addressing our research objectives.

2.2 Outdoor Mobile Musical Mechatronics

While most sonic installation art is exhibited in indoor venues, for nearly as long as the artform was formalized in the mid 20th century, artists have been drawn to exhibiting work in outdoor locations to take advantage of the variability, unpredictability, sonic complexity, and dynamism of these environments. A number of sonic installation art pioneers presented works in outdoor locations including Max Neuhaus’s *LISTEN: Field Trips Thru Found Sound Environments* (1966) which stamped the hands of participants with the word “LISTEN” before leading them through a silent soundwalk through an urban location during nighttime [1].

The mechatronic creations of Godfried-Willem Raes and Trimpin both independently take advantage of mobile design principles as many of their creations include casters that allow for easy transportation of instruments between performance venues [19, 16]. Raes’s writings indicate that some instruments such as *Toetkuip* (1987), *Klankboot* (1987), and *Le Grand Coucou* (1997) were explicitly conceptualized and constructed for outdoor exhibition [15, 14] with design features supporting mobile exhibition including a lead-acid battery-based power system. However, the mobility of these artifacts is limited as *Toetkup* and *Klankboot* weigh 180 kg and 240 kg while their electronic systems are largely exposed to environmental conditions. Our research addresses these transportability limitations through the use of environmentally-protected electronic enclosures to allow for exhibition in adverse weather conditions and by prioritizing artifact transportability and size to ensure a single person can conduct installations.

3. EXPLORATOR GENUS

For Explorator we investigate the viability of using musical mechatronic systems to augment outdoor natural landscapes with the aim of directing attention to the in-situ sonic environment. For this objective, mechatronics provides the distinct advantage of simultaneously supporting non-cochlear kinetic feedback mechanisms and cochlear sound-producing mechanisms and therefore serves as a natural extension of our prior work [21].

3.1 Design Considerations

The Explorator genus is a set of hardware, firmware, and physical construction templates which support the creation of novel mechatronic soundscape augmentation artifacts. The Explorator genus takes advantage of a modular design strategy similar to Singer's *ModBots* and the self-power capabilities of Raes' instruments. Furthermore, as Explorator is explicitly created to support the exhibition of artifacts in outdoor natural locations, self-power, robust electronic enclosures, and transportability are important design considerations along with the inclusion of environmental sensors to direct attention to in-situ environmental conditions. In summary, the Explorator genus adopts the following design priorities:

- **Modular** hardware, firmware, and physical design templates to expedite the design and construction of novel soundscape augmentation artifacts.
- **Self-Power** to support exhibition in remote natural environments for 16 hours on a single charge.
- **Transportable** enough for transportation, configuration, and installation by a single person on foot.
- **Environmentally reactive** hardware and firmware that can respond to in-situ conditions in real-time.
- **Environmentally resistant** with an approximate ingress protection (IP) rating of IP54 to protect electronic systems from exposure to adverse weather conditions.

3.2 Hardware Systems

To save time, the Explorator project utilized many of the successful hardware systems developed for the Speculātor non-cochlear soundscape augmentation artifact, which shared identical design considerations. This includes a Teensy 3.2 microcontroller that manages sensors, actuators, and DSP processing (Figure 2). Likewise, a MEMS microphone, ambient light sensor, and a combined temperature and humidity sensor provide environmental sensing capabilities for increased flexibility when creating new hardware instances, Explorator's electronics are distributed between the electronics enclosure, the mainboard PCB, and a breakout PCB.

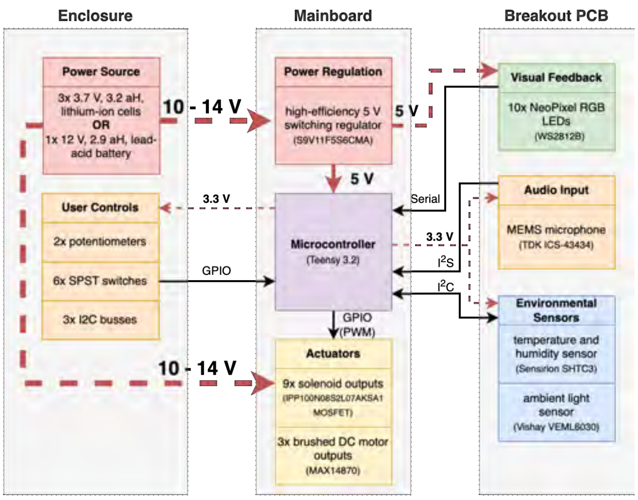

Figure 2: Explorator hardware system integration.

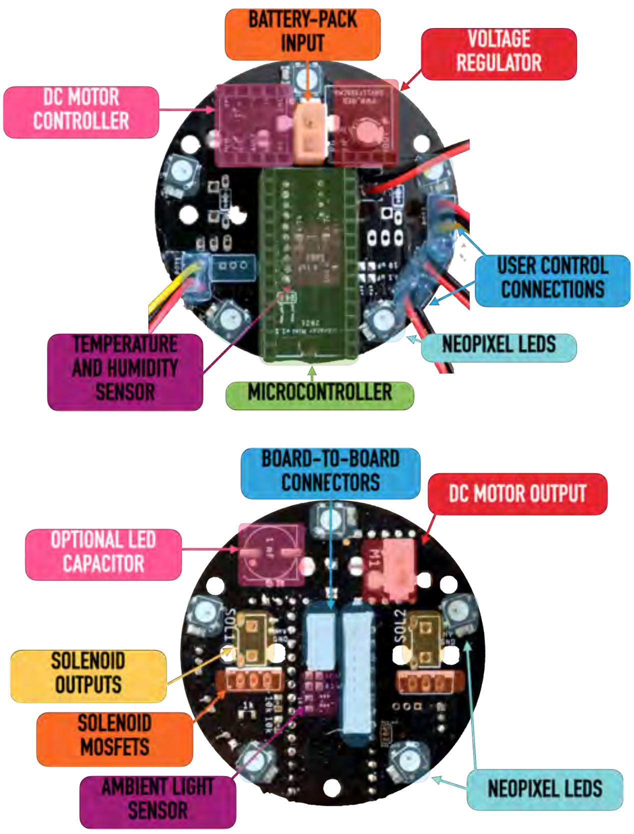

Figure 3: The smaller 58 mm diameter Explorator mainboard PCB top (top) and rear (bottom) sides.

The mainboard PCB is available in two variations, the larger variant features nine MOSFETS and three DC motor drivers. The smaller mainboard PCB supports less ambitious Explorator designs with two solenoid channels, one DC motor driver, and an array of RGB LEDs around the board's perimeter (Figure 3). The 40 mm diameter breakout PCB houses the ambient light sensor and microphone.

As hardware modularity and transportability are primary concerns, an off-board battery pack is used to power Explorator artifacts while the voltage regulator accommodates input voltages ranging from 2 to 16 V. This combination allows for easier sourcing, transportation, and the support of a broader range of battery chemistries, sizes, and cell numbers within battery packs. In the interest of promoting collaboration and advancing the NIME community, the hardware is open source and available under the MIT license at `https://github.com/nathanshaw/Explorator`.

3.3 Firmware

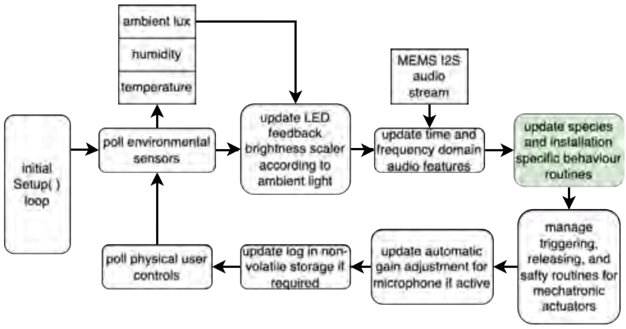

Figure 4: Default firmware operation for Explorator genus.

As an extension of prior research creating non-cochlear soundscape augmentation artifacts, the Explorator project saved development time by leveraging code from the Speculātor project to handle the operation of the majority of the artifact's operations including audio system routing, LED management, ambient light sensor polling, temperature and humidity polling, physical user control polling, and miscellaneous microcontroller responsibilities (Figure 4) [21]. The open-source Explorator firmware code base, available under the MIT license at `https://github.com/nathanshaw/Acropolis_Family_Firmware`, builds upon successful hardware and software systems developed in the prior Speculātor project. We encourage interested parties to utilize and contribute to the code base to advance research in non-cochlear soundscape augmentation.

3.4 Physical Construction

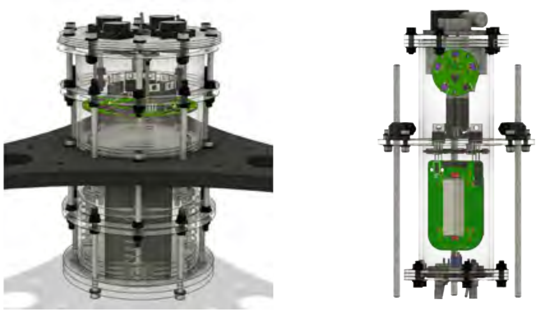

Figure 5: 3D models of *Explorator chipper* (left) and *Explorator winder* (right).

A combination of rapid prototyping techniques, readily available raw materials, and consumer-available components are used to construct Explorator hardware instances. To promote modularity and reduce development time, all Explorator artifacts use similar electronic enclosures, bodies, legs, and feet. This design is adjusted using CAD modeling software, and is then applied to the construction material of choice and scaled based on the physical requirements of the specific artifact's mechatronic actuator.

To protect the electronics from the environment, the enclosures are constructed from plastic pipe segments with top and bottom caps. It is attached to a "body" structure, which is held above ground with the electronics enclosure by three legs, which are equipped with modular plastic feet that hold the artifact in place during installation (Figure 5).

3.5 Reusable Systems

The hardware components of the Explorator project are designed for flexibility and reusability in future mechatronic-based sonic installation art. Two general-purpose mainboard PCBs are utilized to accommodate artifact instances of various sizes and actuation needs. The mainboard PCBs feature a suite of environmental sensors, including a combined temperature and humidity sensor, user controls such as DIP switches, and hardware components like robust MOSFETs and DC motor drivers to support a wide range of actuator configurations. In addition, a breakout PCB houses an ambient light sensor, microphone, and LEDs. These hardware components, along with the shared use of a Teensy 3.2 microcontroller, significantly reduce development time while providing easy adaptability and application to new installation scenarios.

In terms of physical construction, the project offers 3D models that can be parametrically scaled for different-size artifacts, as well as shared components such as fasteners, stainless steel legs, and modular 3D printed feet for different terrains.

The project's firmware features a single code base for all species, with a configuration.h file used to select compilation parameters such as the Explorator species, installation scenario, user control mappings, and other important species-specific and generalized hyper-parameters. The firmware includes unified and shared functions for artifact behaviors such as audio routines, environmental sensor mappings (temperature, humidity, light, sound), LED feedback mappings, and the management of solenoid and DC motor-based vocalizations.

Overall, the use of these generalized hardware, physical construction, and firmware systems greatly reduces the de-

Name	Installation Scenario	Target Sonic Environment	Mechatronic Actuators
Chirper	responds to bird-song produced by in-situ sonic actors	high levels of avian biophony	3x pitched bells struck by solenoids with solenoid-powered dampening mechanisms
Chipper	mimics sonic characteristics, rhythmic patterns, and destructive behavior of woodpecker pecks	cochlear woodpecker activity	1x solenoid-powered ceramic chisel pecking mechanism and 1x DC-motor powered rotating wooden roundtable
Clapper	produces snap or clap-like vocalizations to demonstrate environmental acoustics	distinct acoustics, preferably with echo	1x solenoid directly striking metal container fixed to artifact top
Spinner	produces noise-like geophonetic inspired vocalizations capable of extended sustain envelopes	location with high levels of geophony produced by water, or location void of geophony	1x spinning cabasa controlled by a geared DC motor and optical encoder
Winder	produces anthrophonetic (sounds produced by humans) pitched vocalizations	low anthrophony but high biophony and geophony	1x music box wound and unwound using geared DC motor and optical encoder

Table 1: Installation scenario, target sonic environment, and feedback mechanism for each species.

velopment time for new mechatronic-based sonic installation art projects. This approach allows for easy adaptation and application to new installation scenarios. The potential for reusability of these systems offers significant benefits to the NIME community, and we encourage their use and further development.

4. EXPLORATOR SPECIES

Five hardware instances, or species, as they will be referred to hereafter, have been designed, constructed, and exhibited using the Explorator genus (Table 1). The species were created using shared core hardware, firmware, and physical design templates, but each feature distinct feedback mechanisms tailored to address low-level artistic objectives. As their physical design was informed by the artistic motivations of a specific installation scenario, the artistic objectives for each species are first introduced, followed by an overview of the mechatronic feedback system designed to realize that particular installation scenario. In our installation scenarios, most species use an environmental sensor mapping inspired by the behavior of poikilothermic (cold-blooded) animals where high humidity, bright light, and high temperatures increase vocalization chance over low humidity, dim light, and low temperatures.

4.1 Explorator chirper

Figure 6: *Explorator chirper.*

The artistic objective of *Explorator chirper* (colloquial name Chirper) is to approximate sounds to draw attention to rhythmic and tonal variations in animal vocalizations. Chirper aims to initiate and engage in call-and-response interactions with in-situ sonic actors. In realizing this objective, Chirper does not aim to directly mimic the sounds it hears, but rather to deconstruct those sounds into their fundamental elements of pitch, length, and amplitude, and then use that abstracted data to produce the parameters for its vocalizations[2]. The target sonic environment for Chirper installations contains high levels of avian biophony[3] and low levels of human and environment-produced sounds.

Desk bells were chosen for Chirper's vocalization mechanism as they are weather-resistant, have a small size, are physically durable, are pitched, provide an opportunity to easily adjust timbre, and demonstrate long-enough sustain envelopes for our purposes. Three vocalization mechanisms were constructed, each with a variable-sized bell to represent low, middle, and high-pitched sounds. Generic, widely available, low-cost, push-pull solenoids are used for the striking mechanisms. Larger push-pull solenoids with extra-thick compression springs and rubber-capped plungers serve as the dampening mechanisms. While providing flexibility for the cochlear feedback system, the dampening mechanisms also support experimentation with non-cochlear feedback through mappings such as silently releasing the dampeners during listening periods in reaction to loud sonic events.

4.2 Explorator chipper

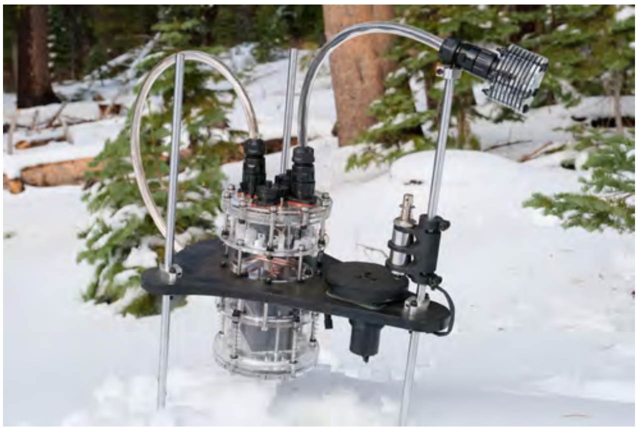

Figure 7: *Explorator chipper.*

Explorator chipper (colloquial name Chipper) investigates a vocalization mechanism inspired by the sounds produced by North American pileated woodpeckers. Two characteristics of these birds' pecking activities informed the design of Chipper's feedback mechanisms. The first characteristic is sonic and consists of the percussive, beak-on-wood timbre of the woodpecker's pecks. The second characteristic is physical and consists of the environmental (and property) destruction these birds cause through their pecking.

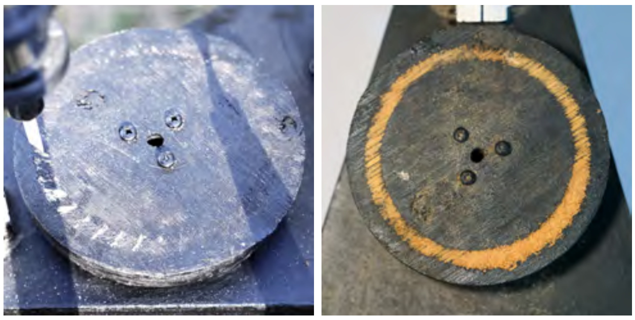

Figure 8: *Explorator chipper*'s wooden turntable showing minor(left) and major (right) damage.

With these two targets, Chipper's woodpecker mechanism consists of two actuators acting in tandem: a solenoid-powered pecking mechanism and a wooden turntable rotated by a DC motor (Figure 7). Chipper is designed to interact with woodpeckers during exhibitions, and therefore, the target sonic environment for this installation scenario includes woodpeckers pecking with low levels of geophony and anthrophony[4].

[2]In this research we refer to any sounds produced by Explorator species as vocalizations to anthropomorphize the artifact instances and distinguish from non-cochlear feedback.

[3]Biophony is a soundscape ecology term used to describe all sounds produced by non-human biological organisms [13].

[4]Anthrophony and Geophony are terms from soundscape

The turntable mechanism serves to rotate a wooden disk to reveal a fresh section of wood for the pecking mechanism to destroy. This disk serves as a visual score of the installation through its destruction. While sound and music can be considered to be an ephemeral phenomenon that does not have a direct impact on the physical world, this installation challenges this assumption by inviting reflection on the physical actions which cause the sounds we hear and the impact those actions have on our environment. When installed, Chipper triggers its pecking mechanism according to ambient lighting, humidity, and temperature, and highlights "real" woodpeckers by responding directly to their cochlear activity by increasing LED activity and vocalization chance.

4.3 Explorator clapper

Figure 9: *Explorator clapper.*

Instead of focusing on the in-situ sonic environment, *Explorator clapper* (colloquial name Clapper) explores its acoustic environment using short percussive vocalizations in quick succession. In order for Clapper to perceive its echoes, its vocalizations must exhibit brief attack and release envelopes. This installation scenario is best realized within sonic environments with distinguished acoustic characteristics but which contain low levels of environmental sounds. Alternatively, Clapper can be installed in sonic environments with rhythmic sonic events (e.g. waves breaking onto a shoreline) to reinforce those sounds.

Clapper's vocalization mechanism consists of a single solenoid that strikes a small, hollow three-sided aluminum box. The container and striking solenoid are bolted to the top of the enclosure to reduce artifact size and dampen mechanical vibrations. The solenoid generates a sharp and rapid transient, characterized by a combined attack and decay time of 50 ms. Accounting for the approximately 25 ms period of resetting, the mechanism allows for sustained vocalizations to be produced at a rate of 13 Hz.

4.4 Explorator spinner

Inspired by geophony and ever-changing non-cochlear environmental conditions, *Explorator spinner* (colloquial name Spinner) is designed to serve as a mechatronic noise generator whose vocalizations are constantly influenced by real-time changes in ambient light, temperature, and humidity. Spinner aims to create a nearly continuous wall of noise akin to the sounds produced by a waterfall, stream, or gust of wind. There are two target sonic environments for Spinner. The first contains little to no geophony while the second contains water- or wind-based geophony that can be augmented using Spinner vocalizations.

Figure 10: *Explorator spinner.*

To encourage reusability when more percussive noise-based vocalizations are desired in future artistic use cases, Spinner's vocalization mechanism is constructed from a cabasa (a Latin American concussion idiophone) which is rotated by a geared DC motor fitted with a magnetic encoder to support closed-loop control of the cabasa's relative position. Spinner is able to constantly adjust the rotating speed of the cabasa to ensure the metal beads continue to chafe the perforated metal core to produce a relatively consistent timbre for periods longer than a minute.

4.5 Explorator winder

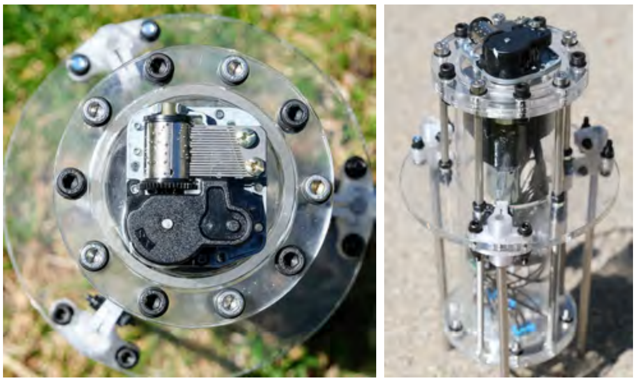

Figure 11: *Explorator winder.*

The fifth species, *Explorator winder* (colloquial name Winder) produces anthrophonetic-inspired sounds with a focus on tonality to contrast Clapper's non-tonal clap- and snap-inspired vocalizations. The *Explorator winder* is a compact device (135 x 135 x 248 mm, 1060 g) that generates anthrophonetic, tonal, and musical vocalizations using hand-cranked music boxes. A geared DC motor fitted with an optical encoder provides closed-loop control of the music box winding and unwinding process (see Figure 11). Winder's target sonic environment contains low levels of anthrophony. To provide more ample soundscape relocation opportunities, the location has once had a greater human impact than at present (e.g. ghost town, abandoned mine, etc.).

ecology used to categorize sounds based on their origin. Anthrophony refers to all sounds produced by human beings and their creations. Geophony describes all naturally occurring sounds produced by a habitat, excluding sounds made by living organisms [13].

5. INITIAL FINDINGS

In-situ test installations were conducted using the five artifacts between August 23rd, 2020 and April 17th 2021. While originally intended for in-situ enjoyment by large public audiences, due to pandemic restrictions, this work has largely been experienced by the public through digital image and video captures of real-world fieldwork. The objective findings shared in this paper include metrics for transportability, self-power, and environmental resistance. Subjective observations including notes concerning our shift in artifact design priorities through the iterative development process.

5.1 Transportability

Species	Weight (grams)	Dimensions (mm)	Setup Time (minutes)	Dismantle Time (minutes)	Travel Restrictions
Chirper	5622	405 x 355 x 431	10 - 20	5 - 10	size and weight
Chipper	4890	292 x 330 x 304	10 - 15	3 - 5	size and weight
Clapper	1844	200 x 200 x 215	5 - 10	1 - 5	lithium batteries
Spinner	2280	200 x 200 x 273	5 - 10	1 - 5	lithium batteries
Winder	1060	135 x 135 x 248	5 - 10	1 - 5	lithium batteries

Table 2: Explorator genus transportability

While exhibitions with other soundscape augmentation artifacts were conducted with Chirper and Chipper, considerable bulk prevented their exhibition with more than a handful of other artifacts. Alternatively, the final three species (Clapper, Spinner, and Winder) were small and light enough to easily be transported all together with their size, weight, and form easily supporting multiple-artifact installations. The size and weight of each species varied, but all were transportable enough to be displayed by a single facilitator alongside other artifacts (Table 2).

5.2 Self-Power

Species	Battery Chemistry	Battery Model	Qty.	Nominal Voltage	Total Capacity (Wh)	Battery Weight (grams)	Mean Power Use (mWh)	Typical Run Time (hours)
Chirper	lead-acid	Battery Mart SLA-12V2-9	1	12.6	34.8	1082	1333	21.87
Chipper	lead-acid	Battery Mart SLA-12V2-9	1	12.6	34.8	1082	958	30.45
Clapper	lithium-ion	Panasonic NCR18650GA	3	11.1	35.5	145	640	47.15
Spinner	lithium-ion	Panasonic NCR18650GA	3	11.1	35.5	145	1858	16.24
Winder	lithium-ion	Panasonic NCR18500A	3	11.1	22.2	99	663	28.46

Table 3: Power and runtime data for Explorator devices, including battery capacity and power consumption, are presented in units of Watt hours (Wh) and milli-Watt hours (mWh) for easy comparison across devices with different voltage potentials and battery chemistries.

Following the lead of Godfried-Willem Raes's pioneering mobile mechatronic instruments, the first two hardware instances use lead-acid batteries to increase artifact stability while the later three hardware instances take advantage of advancements in contemporary battery technology to optimize artifact size and weight by using lithium-ion battery packs (Table 3).

In the absence of many power-saving firmware routines or re-optimizing the hardware power consumption, Explorator species can be expected to run from 16 hours for Spinner to 47 hours for Clapper. This significant variation in runtime can be attributed to the vocalization mechanism and programmed behavior of each species. Since Spinner uses a DC motor for its vocalization mechanism and its installation scenario requires nearly constant vocalizations, it consumes significantly more energy than Clapper's less-active intermittently triggered solenoid vocalization mechanism.

5.3 Environmental Resistance

Enclosure	Initial IP	Modifications	Final IP
Chirper	IP51	improved connection between top-cap and outside mounting hardware, tightened and added sealant to user-controls and fasteners	IP54
Chipper	IP52	permanently sealed acrylic tube with enclosure bottom, added sealant to user-controls and fasteners	IP54
Breakout	IP31	created membrane to cover slots when precipitation is expected, patched stacked acrylic with sealant	IP54
Clapper	IP12	covered breakout PCB access port with membrane, sealed acrylic tube with enclosure top and bottom, added sealant to user-controls and fasteners	IP53
Spinner	IP21	covered breakout PCB access port with membrane, permanently sealed acrylic tube with enclosure bottom, added sealant to user-controls and fasteners	IP43
Winder	IP30	added sealant to reduce open space where music box mounts to the enclosure, applied sealant to bottom-cap, inverted orientation so music box faces downwards	IP32

Table 4: Explorator genus approximate environmental resistance ratings. The approximate IP rating is inferred from in-situ performance and artifact performance during staged IP testing which consisted of a 10-minute exposure to a measured flow rate of 7 liters per minute directed at the species at a 45-degree angle.

The Explorator species performed well in in-situ exhibitions as no species experienced noticeable liquid or particulate ingress. However, during tests manufactured to simulate sustained torrential rain, initial performance was below the original objective of IP54 which equates to being protected against particulate ingress with no harmful deposits and being protected from water splashed from all directions. Nonetheless, as a result of upgrades to the originally exhibited species, higher IP ratings were achieved with the final approximate ratings ranging from IP32 to IP54 (Table 4).

5.4 Subjective Observations

From facilitating multiple in-situ installations with five Explorator species, one of our primary observational findings was the effectiveness of using closed-loop DC motors and solenoids to support a broad range of kinetic and cochlear vocalization mechanisms. Furthermore, we observed that during exhibitions periods of cochlear inactivity were helpful in allowing attention to naturally shift from the artifact to the in-situ environment.

While the cochlear augmentations produced by artifacts generally satisfied our expectations and served the artistic objectives of their installations, we subjectively found that the species which were able to leverage kinetic feedback provided the most artistic promise for investigation in future work, while the audio-reactive LED-based visual feedback system benefited most installation "listening" periods by directing attention to in-situ sonic actors.

The Explorator genus provided short development times for new species; Clapper's design and construction took only three days, while Spinner and Winder took approximately one week. While the Explorator genus demonstrates that mechatronic sound objects can be created within a relatively short period of time to support novel installation scenarios, they still require a degree of planning, customization, and prototyping that cannot easily be reduced. We have found this lead time limiting for soundscape-specific pop-up exhibitions as this exhibition strategy sometimes requires very quick conceptualization, design, and in-situ realization periods in order to utilize seasonal or otherwise fleeting sonic environments. However, as most exhibition strategies aren't as time-sensitive and support a longer development period, this strategy can likely be more successfully implemented in projects that do not focus on targeting specific sonic environments.

5.5 Shifting Priorities

Through the process of conducting fieldwork with existing hardware and creating new species, our design priorities gradually shifted away from the use of multiple actuators, overly robust physical construction, and environmental protection in favor of visual aesthetics, transportability, and single actuator vocalization mechanisms (Figure 12).

While conducting test exhibits with the earlier species, it was discovered that transportability was the most significant limitation when implementing previously unplanned installation scenarios. Moreover, IP ratings decreased from the first to the final species due to our experience that most installation scenarios do not require IP ratings as high as IP54 as long as each artifact's IP limitations are known beforehand, and species can be quickly uninstalled to protect hardware should adverse weather conditions occur.

6. CONCLUSIONS

Five Explorator species were designed using differing low-level artistic and technological motivations to simplify the design of novel mechatronic-based soundscape augmentation artifacts. Each species was tested within a unique installation scenario where their mechatronic vocalization mechanisms were designed to collect and direct attention to natural sonic environments using kinetic visual feedback and mechatronic cochlear feedback.

This project has found that mechatronic soundscape augmentation in outdoor natural environments is a challenging endeavor that must overcome a broad range of unique logistic, artistic, and technological challenges. Mechatronic-based sonic installation art has inherent downsides that could limit the adaptability of the Explorator genus to new installation scenarios. However, prioritizing the unique properties of mechatronic vocalization within installations can create listening experiences that would be prohibitively difficult to realize using other technologies. As a result, there is ample opportunity to construct installations that offer unique and compelling soundscapes.

Furthermore, the hardware and firmware developed for the Explorator genus were designed with reusability in mind, allowing for easy adaptation and application to new installation scenarios. This approach contributed to the success of the project. From an artistic perspective, Explorator's purpose-built actuators support a distinct category of installation scenarios while from a technological lens, the genus-species development strategy was shown to significantly reduce the development time for new artifacts and to be capable of supporting several distinct vocalization and feedback strategies.

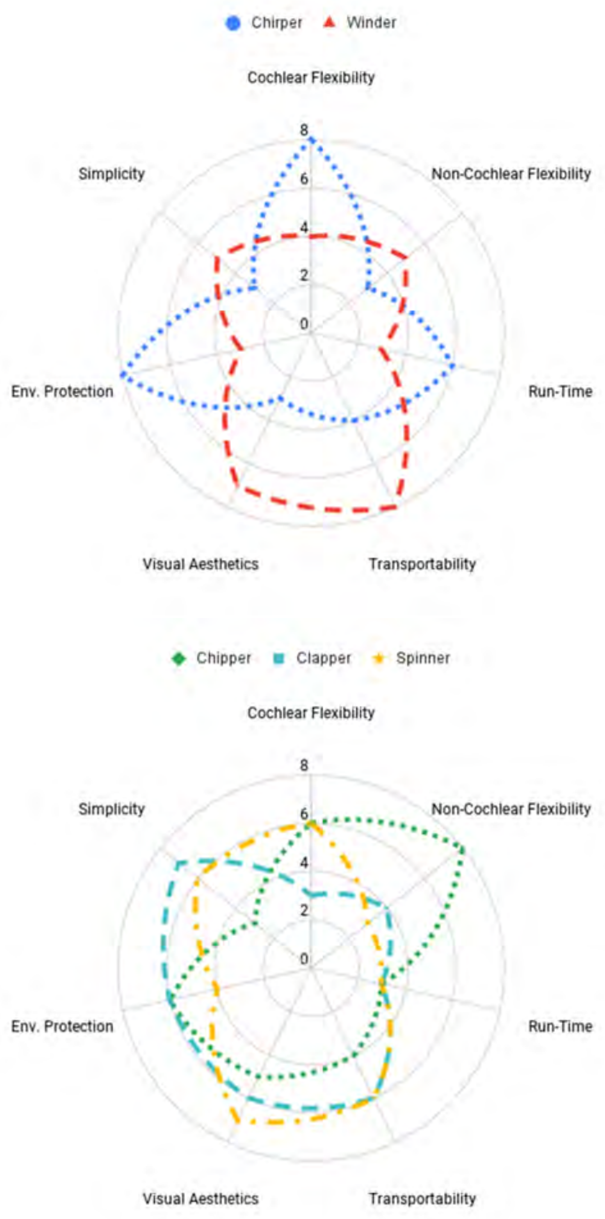

Figure 12: Comparison of Explorator design priorities for the Chirper and Winder species (top) and the Chipper, Clapper, and Spinner species (bottom). Each species allocated 35 points between the seven primary design priorities of Cochlear Flexibility, Simplicity, Environmental Protection, Visual Aesthetics, Transportability, Run-Time, and Non-Cochlear Flexibility. These ratings were used as guidelines during the design process to inform specific hardware, firmware, and physical construction implementations.

6.1 Future Work

As the favorable transportability of Explorator species provides ample opportunity to investigate installations with multiple species interacting with each other, future work will include realizing installations that leverage multiple artifact species. However, foremost, as the Explorator project was conceptualized before COVID-19, its fieldwork has had to adapt to external pandemic restrictions which have limited our ability to collect subjective evaluation data from the public. Therefore, future work includes evaluating the effectiveness of different cochlear and non-cochlear soundscape augmentation strategies.

7. ETHICAL STANDARDS

This research was conducted in adherence with the ethical standards of the Victoria University of Wellington, including guidelines for the ethical treatment of animals and the protection of the environment. To minimize potential negative impacts on the environment and its inhabitants, we took careful measures during the design, installation, and use of our hardware. Specifically, expeditions were conducted for short periods of a day or less, with a focus on leaving the environment cleaner than we found it. We also ensured that our interactions with animals were conducted in a responsible manner, and that the impact of our presence was similar to that of a loud hiker or camper.

The installations were all installed legally on public land or private property with explicit permission, and we made a concerted effort to minimize the risk of environmental pollution resulting from the use of our hardware by ensuring all equipment is accounted for and transported out of installation locations. Our research team remained vigilant in ensuring ethical and responsible conduct throughout the course of our work. We welcome further discussion on these important ethical considerations.

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