Spherical Harmonics: Novel Musical Instrument Development at the Yale Center for Engineering Innovation and Design

ISAM 2019 Poster No.: 23

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Introduction

The Directionally Nuanced Orbital (DNO, pronounced "Dino") was created as a final project for ENAS 344/ MUSI 316 Musical Acoustics and Instrument Design, a hands-on class taught at the Yale Center for Engineering, Innovation, and Design (CEID). The course explores the principles of acoustic and electronic musical instruments and culminates in the design and construction of an original instrument by each student[1]. ENAS 344/ MUSI 316 was co-taught by Larry Wilen and Konrad Kaczmarek, faculty in Mechanical Engineering and the Department of Music, respectively. The DNO was designed and built by Antonio Medina, a student in the class, who is now a Design Fellow at the CEID.

Motivation

Antonio, a mechanical engineering major, was also a saxophonist. Inspired by the saxophone's assortment of keys and fingering chart, he wanted to create an electro-mechanical instrument that incorporated an array of buttons that mapped to discrete musical pitches. The performer, however, would rotate the orb in space, so Antonio also wanted to actively measure the instrument's physical orientation in the user's hands through a combination of motion sensors.

Instrument Overview

The course instructors encouraged students to embrace of design challenges as opportunities to inspire creative elements and innovative surprises that might lead the instrument into a new direction. The design and construction of the DNO indeed faced several challenges, such as the limitations of available audio hardware that ultimately led to an exciting implementation of wireless solutions. The resulting device was a spherical Musical Instrument Digital Interface (MIDI) controller built with intentional programmability and stylish visual aesthetics capable of producing modifiable polyphonic control mappings. This poster will detail the critical design components of the DNO and discuss how the iterative making process often changed the implementation of those components. I hope to demonstrate the DNO's unique musical capabilities and illustrate how a student project can utilize nearly every resource available at a space like the Center for Engineering Innovation and Design.

Electronic Components

Students working on projects with digital control systems were encouraged to use the Teensy microprocessor[2], a breadboard-friendly development board with a much smaller footprint than an Arduino. For the DNO, the Teensy was an optimal choice for the project for its high number of GPIO pins, its ability to emulate USB-MIDI communication, and the availability of add-ons like the Prop Shield, which can add 10 DOF motion sensors and a 2-watt audio amplifier. These features would allow for the DNO's desired button-to-pitch mapping, ability to send or receive audio signals, and capability to measure physical orientation, respectively.

Figure 1: The Directionally Nuanced Orbital (DNO).

An early goal of the project was for the DNO to be completely handheld and wireless. Therefore, the incorporation of the Teensy Prop Shield was also originally done so with the intention of using the built-in audio amplifier to generate tones directly from the DNO itself. However, this early design objective came with added challenges and limitations. To produce sound from the device would mean incorporating a speaker into its construction. Experimentation with the prop shield's amplifier demonstrated that even with a large 2-watt speaker, the device would not be able to produce sound at the desired volume level. Furthermore, the Teensy's audio programming interface was not as robust as other computer music programming platforms in terms of producing a variety of timbres or using motion sensors for control. These constraints led to a shift in the architecture of the device's core electronic components. Rather than using one Teensy to process input data *and* output music through a built-in speaker, the DNO would utilize two Teensy controllers that interact with each other via wireless radio communication. By connecting each Teensy to an NRF24 radio module, a 'transmitter' Teensy in the DNO processes button input along with roll, pitch, and yaw data from the prop shield. This data is converted into byte form and sent to a 'receiver' Teensy, which decodes the data and converts it into MIDI signals. Those signals are then sent via USB to a computer running a music synthesis program. With this solution, the DNO is now

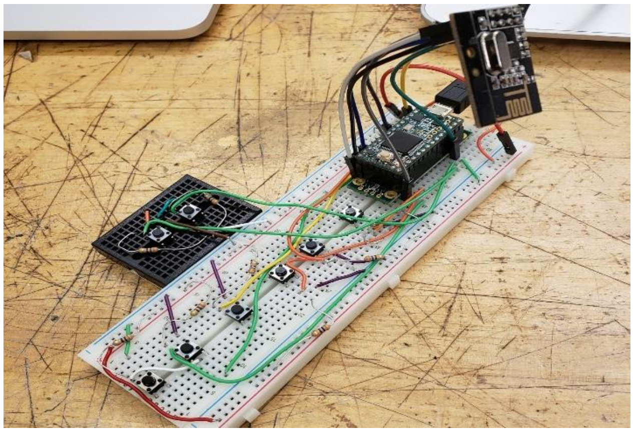

Figure 2: Electronics prototype. A Teensy microprocessor with a mounted prop shield link to a NRF24 Radio module. Eight black pushbuttons simulate the keys of the DNO's input interface.

able to generate high-quality, modifiable tones that can draw from immense libraries of built-in sounds ranging anywhere from flute and guitar to car horns and sci-fi bass.

Physical Components

A. *Mechanical Buttons*

At the end of the semester, each student was expected to perform a song on their original instrument. With that in mind, the physical interface of the DNO was designed to be relatively easy for a saxophonist to use. On a saxophone, four fingers from each hand are responsible for covering over 20 tone holes through a combination of keys and levers. One thumb controls an octave key, which alternates between the upper and lower octaves of the instrument. Several of the Teensy GPIO pins were used for the prop shield and the radio module, so the DNO had a limited number of digital pins available to connect to physical buttons. To solve this problem, an array of six mechanical pushbuttons was used to map to the 12 pitches of a chromatic scale. Instead of one octave key, two pushbuttons were used to represent an 'octave up' and 'octave down' key. This resulted in a key mapping that resembled a traditional saxophone fingering chart with a more economical number of buttons and the ability to span any number of octaves, not just two. An additional pushbutton was added to allow additional features to be programmed into the instrument's capabilities.

B. *Enclosure*

The DNO was designed to have a spherical form factor to resemble the various spherical degrees of freedom captured by its motion sensors. This design goal created an interesting manufacturing challenge. An original prototype was designed with CAD and 3D printed in the CEID. The prototype enclosure was comprised of two hemispheres that clasped together. While the printed prototype was useful for brainstorming button placement and electronics installation, it also demonstrated the limitations in size and quality of 3D printed parts. As a creative solution, the body of the DNO was created by modifying two large wooden salad bowls[3]. A threaded nylon rod was inserted through the center of each

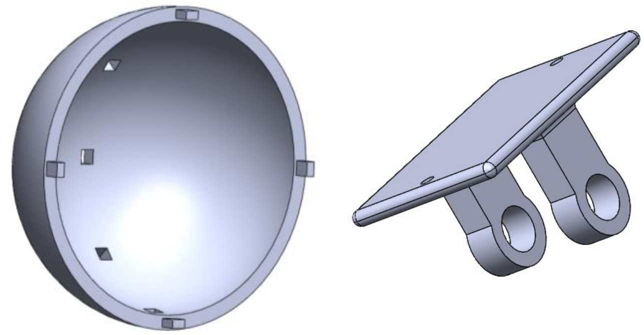

Figure 3: CAD Models of the hemispherical enclosure prototype (left) and the electronics mounting platform, manufactured on the CEID 3D printers.

bowl and the two hemispheres were held together into a bowling ball-sized sphere using two aluminum end caps manufactured in the CEID machine shop.

The teensy, prop shield, and radio module were mounted onto a solderable breadboard, which was assembled in parallel with the enclosure construction. The electronics were mounted on a custom designed, 3D printed platform. With so many wires enclosed into a spherical container, care had to be taken to bundle them in such a way that they did not interfere with radio communication by accidentally creating a Faraday cage. Finally, the 'receiver' teensy was installed inside a subtle black project box with a USB cable to connect to a computer with a music synthesis program.

Conclusion

As a MIDI controller, the DNO can both make its own sounds through digital music synthesis programs and act as a controller for other devices that communicate with MIDI signals. As an experiment, the DNO was used to control another student's digital wind chime instrument, to entertaining results. The development of the DNO served as an exceptional hands-on learning experience that emphasized making through iterative design, where challenges present opportunities to adapt and come up with innovative solutions. This experience would not have been possible without the resources provided by the Yale CEID.

References

[1] L. Wilen, K. Kaczmarek, A. Medina, S. Gertler, "Music in the Making at the Yale CEID." In *Proceedings of the 4th International Symposium on Academic Makerspaces* (2019).

[2] https://www.pjrc.com/teensy/

[3] https://www.ikea.com/PIAimages/0712885_PE729156_S5.JPG?f=l