Motors, Music and Motion

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ABSTRACT

Over the past four years the authors have conducted classes and workshops in design of systems for real-time digital synthesis of sound and haptic response. In response to current trends in Interaction Design education focusing on visual feedback and touchscreen interactions, the classes were developed to provide foundations for design students to leverage the potential of non-visual modes of interaction and provide them with tools and skills to develop complex multimodal, embodied experiences. These classes have been held in various institutions, have formed the basis for short workshops at conferences as well as provided tools for collaborations with external partners.

In this paper we describe for the first time the extent of the project and reflect on this particular field of Interaction Design education.

Author Keywords

Haptics; Interaction Design; Multi-modal; Toolkit; Hardware; Audio; Education

ACM Classification Keywords

H.5.2. Haptic I/O

INTRODUCTION

Having been involved with interaction design since the dawn of the discipline [10] and with work in Computer Research in Music and research in Haptics, Bill Verplank, together with David Gauthier, was invited in 2011 to start a course at Copenhagen Institute of Interaction Design (CIID) that fused the three fields.

Using The Hand [22] as a specific context of interaction students were asked in a one week workshop to prototype new experiences that combined sound synthesis and force-feedback through simple real-time physical modeling algorithms.

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Utilising Planks [20], Arduino boards, sensors and electrical components for driving motors, the students created projects that simulated flying a kite [5], for example, or the buoyancy of a block of ice [7] – see Figure 1. The resulting installations were then accompanied by audio synthesized in response to the interactions with Max/MSP.

For the two following years a dedicated Motors & Music hardware platform was developed that integrated microcontroller components with motor drive, sensor inputs and audio circuit that allowed for easy connections between the hardware components (Planks and motorized sliders) and more importantly allowed for self-contained projects that could function without being connected to a computer – see Figure 2.

Jakob Bak joined the project in 2012 with a lightweight basic audio synthesis engine developed for the Arduino platform [9] that allowed sound to be generated on-board in immediate response to sensor inputs and chosen force-feedback algorithms.

In 2013 we were invited to run workshops at TEI'13 [19] and at Resonate'13 [15], where short one-day, hands-on workshops introduced the platform to a range of designers and technologists from academia and industry with great feedback for the project and introducing the platform to an external research project.

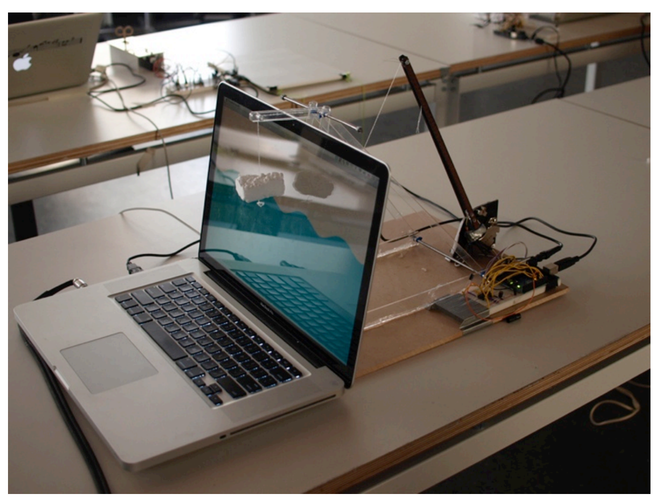

Figure 1 - Student setup from first Motors & Music class

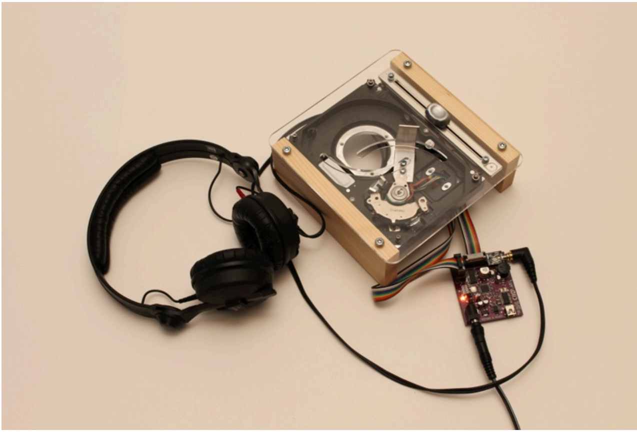

Figure 2 - Second iteration of hardware platform

In addition to the yearly class at CIID the project did a one-week workshop with interaction design students at Umeå Institute of Design (UID) in Sweden, testing a new version of the hardware running on the Arduino compatible Teensy 3.1 microcontroller platform [18]. This new version of the hardware was used again in 2014 with extensions to its audio library – see Figure 3.

MOTIVATION FOR THE PROJECT

The Motors & Music project originated from Stanford's CCRMA course "Physical Interaction Design for Music." This course was mainly targeted to music students with the aim to teach them to design haptic interfaces for musical expression. The motivation of Motors & Music, however, differed from the Stanford course in two key ways. Firstly, its targeted student population was interaction design students at the Copenhagen Institute for Interaction Design (CIID) who required little to no musical or technical expertise. Secondly, the project consisted of a one-week workshop, instead of a full semester. This could in some cases be seen as a limiting factor for the course, but in this case, rather than being a constraint, these differences helped focus the main objectives of the project: to teach students basic techniques and require them to produce prototypes quickly, without too much theory. As such, the class spans basics in haptics and digital audio synthesis, as well as offering a basic introduction to algorithmic modeling of simple physical systems, all within the general teaching framework of fast, iterative, design-led, studio culture education.

There are a number of other projects that share common aspects with Motors & Music. On the one hand, projects [1] and [3], for example utilize the same motorized slider device that is employed in Motors & Music, yet are not specifically tailored as material for teaching haptics to design students, but rather focus on the production of musical instruments. Simple haptics projects such as [11] [12], on the other hand, share the common goal of Motors & Music of producing design materials suited for interaction design students. However, the Motors & Music project differs from this project as it focus on dynamic force feedback devices with higher temporal resolution than the ones utilised in this project. Most similar to Motors & Music are projects relating to the Haptic Paddle described in [13], [4] and [16], leading to Stanford's Hapkit [6]. As does Motors & Music, these projects feature educational material aimed at introducing haptics to graduate students. The main difference with this initiative relates to its focus on educating mechanical engineering students. Motors & Music's focus is centered on the design of haptic experiences within a particular context while the Hapkit focuses on the science and techniques of motorised feedback and physical simulations.

The prime motivation behind the Motors & Music project is introducing a dedicated course in design of non-visual interactions with a focus on programming and physically prototyping cross-modal feedback systems. These foundations are then embedded in a classic interaction design process (iterations of context analysis, concept generation and experience prototyping), which emphasizes the experience of the user rather than the technical functioning of the system.

PROJECT MATERIALS

Below we will introduce in detail the various elements that come together in the classes; Hardware, Software and the didactic format employed. The most recent version of the platform can be accessed at the code repository Github [8].

Hardware

For the first iteration of the Motors & Music classes the main design materials consisted of a set of electronic components (mainly an H-Bridge and connected passive components) arranged on a breadboard, which then connected to an Arduino microcontroller board. The Arduino board was programmed from a connected computer, and through the Arduino's serial port the students triggered Max/MSP patches to play back samples or synthesize audio in response to the behavior proposed by the students' design of the system.

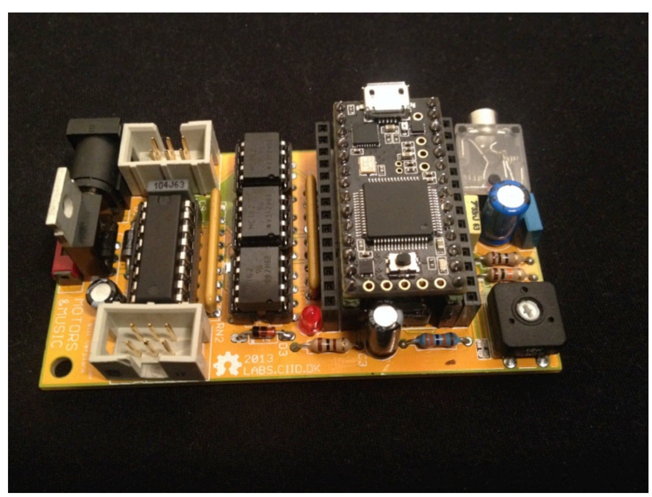

Figure 3 - Third iteration of hardware platform

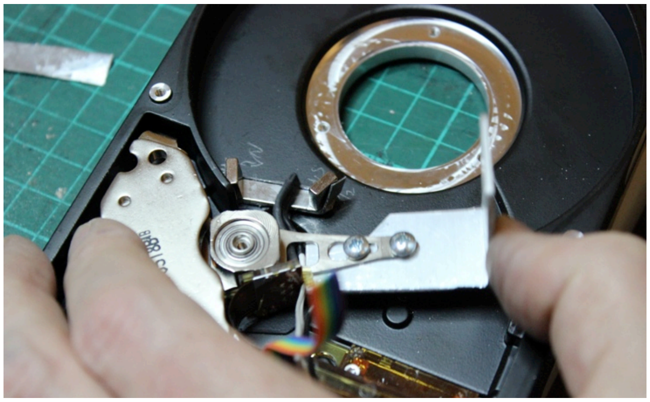

Figure 4 - Hall-effect sensor on Plank

As their first haptic interface the students were introduced to the Plank [20]. The Plank is a repurposed hard disk drive, where the motor coil of the reading head has been connected to the outputs from the H-Bridge. Connecting a PWM signal from the digital outputs of the Arduino board to the inputs of the H-Bridge, one can obtain real-time adjustable voltage outputs and hence finely controlled current output to the motor coils. With a Hall Effect sensor fixed to the reading head, and placed between two Neodymium permanent magnets, an analog input of the Arduino board can read the position of the reading head and adjust the PWM output to the H-Bridge in a real-time feedback loop, providing precise control of position and directed force of the interface. Physically interacting with the reading head (see Figure 4) creates a force-feedback loop, which can be controlled by simple physical modeling algorithms, e.g. mass-spring-damper systems.

As a one-degree of freedom interface the Plank is surprisingly versatile, with a resolution of its force output that enables the user to feel pressure feedback over a broad range. In some setups the Plank is further equipped with a pressure sensor at the point of interaction, allowing the force-response to be tied to the orthogonally applied force from the user.

The second iteration of the hardware focused on integrating the used components into a single surface mount PCB – adding an on-board audio circuit consisting of a 12bit DAC and a headphone amplifier. The components used corresponded to surface mount versions of the Arduino board with H-Bridge and surrounding components (see Figure 5). This made it possible for the authors to stay within the Arduino IDE for programming which the students were familiar with.

In addition to the Plank the second iteration of the classes saw the use of motorized sliders, commercially available at reasonable costs, allowing for a different type of user interaction (linear, rather than arched, and with a longer throw).

Both types of interfaces was wired up with ribbon cable and connectors that allowed for easy connection to the M&M board, creating a unified interface for the students who could then concentrate on designing the surrounding materials and program the dynamic behavior of the system.

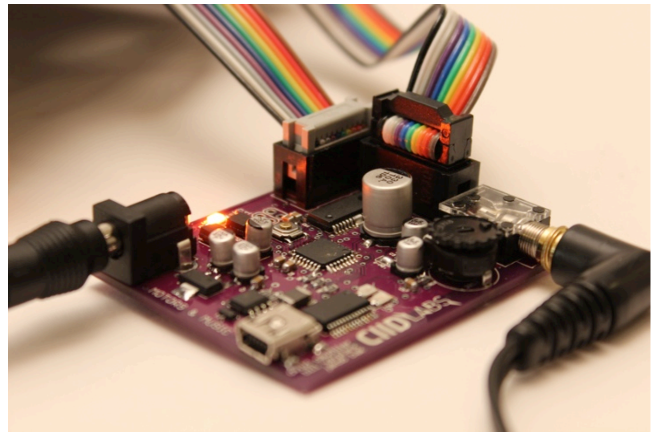

Figure 5 - Close-up of surface mount M&M board

The move to a single integrated platform for both audio and haptic feedback generation meant a severe decrease in available synthesis methods for sound especially, and issues with a limited amount of cycles for computation of outputs for both modalities. The audio synthesis engine developed for the platform (see section Software) was therefore kept intentionally simple and lean, to allow for enough overhead to run physical modeling code.

This turned out to be a welcome restriction, in that the available synthesis method was then simple enough for the students to get a sufficiently in-depth understanding over a short period of time and was able to experiment with it. It also meant that the overall developed projects could be stand-alone installations, disconnected from laptops or other computational equipment, maximizing their experiential impact and encouraged tighter integration between sound and haptic interactions.

The integration also meant that the board size itself could

Figure 6 - Stand-alone student project containing M&M board, Plank, motorized slider and speaker

be considerably smaller than the first iteration of the platform, essentially enabling all functional components to fit into confined spaces (see Figure 6).

The third iteration of the hardware platform (see Figure 3) saw the move back to through-hole components for increased ability for interested parties to produce the hardware themselves. The project embraces an Open Hardware approach to its designs and wish for students as well as other developers to experiment with building their own instances of the platform.

For increased computational capacity we chose to employ the Teensy 3.1 platform as the microcontroller unit in the system. Based on a Freescale Cortex M4 processor, the Teensy is programmable through the Arduino IDE, but being 32 bit and running at up to 96MHz, allowed for additional overhead that enabled a broader range of synthesis possibilities. Having a dedicated microcontroller board to plug into the platform also meant we could source a critical component of the platform from the outside without compromising its functionality.

Software

The software side of the platform has developed substantially since its inception. While the first iteration of the class employed writing all code in the Arduino IDE (using a couple of generic libraries), and creating Max/MSP patches for audio synthesis, the second iteration platform employed custom-made libraries that handled audio synthesis and output at fixed interrupts, as well as simple functions for controlling the force and direction of the motor outputs [9]. Physical modeling code was still written directly in the Arduino IDE as the focus of the class was developing the students' understanding of programming the cross-modal interactions, while audio synthesis could be approached as setting a range of parameters.

For the audio part, the engine developed initially was a simple three-oscillator, 15KHz sample-rate, wavetable synthesis setup with no filtering. Functions for individual frequency, gain and waveform selection, note triggering, a simple audio-rate ADSR envelope and final mixing stage, provided a conceptually simple framework for the students to experiment with (see Figure 7). Sixteen 8-bit waveforms were available as well as a 12-bit sine-wave option, which provided less noisy output.

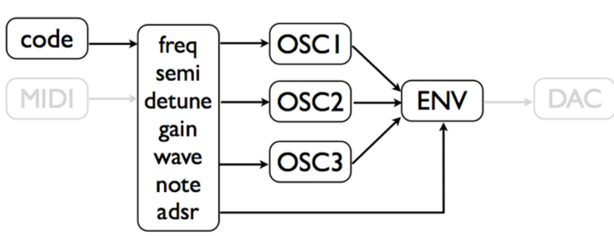

Figure 7 - Overview of first version of audio engine

Addition of a basic MIDI implementation (through serial communication with a Processing sketch on a connected computer) let the students explore from external software the sonic possibilities the limited set of parameters provided. As can be seen in Figure 7 though, the intention with the audio part of the class was to strengthen the students ability to write procedural code that would control the various parameters of their sound design without the use of externally connected software.

The Motor part of the software consisted of a set of functions with microcontroller level C code that would enable the student to write simple commands to the attached actuators. The line, for example,

```
MotorA.torque(-512);
```

will make the Plank push backwards with the maximum force, without having to worry about which pins were connected to which inputs, etc. The internal microcontroller resolution of the PWM output was bi-directional 9-bit (-512 to 511), allowing for very fine-grained control of the H-Bridge outputs, although the mechanical resistance and inertia of the Plank and motorized sliders in effect resulted in a lower physically experienced resolution.

In addition to these libraries a number of tutorial Arduino sketches demonstrating the capabilities of audio synthesis, motor control and physical modeling was included with the project's codebase to help the students get started quickly.

Finally a Processing sketch visually demonstrating the concept of a mass-spring-damper system was developed to facilitate the introduction of physical modeling and the effect of changing parameters in the equations governing its dynamic response (see Figure 8).

The third iteration of the hardware platform saw changes mainly to the audio engine. With the increased performance of the Teensy microcontroller there was now amble room for more complex calculations. This has resulted in FM capability of all three oscillators with an additional

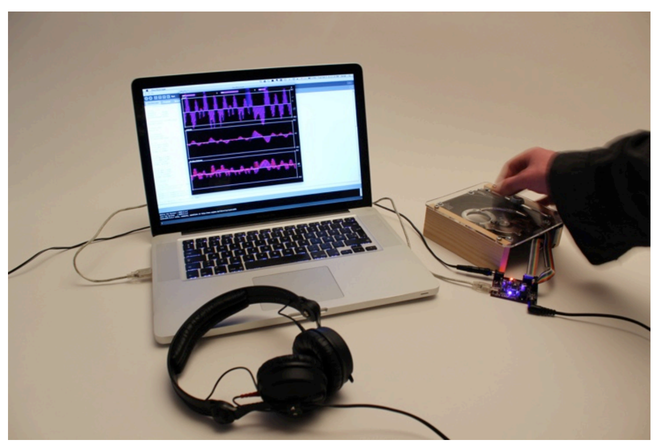

Figure 8 - Processing sketch visualising mass-spring-damper system running on M&M board in real-time

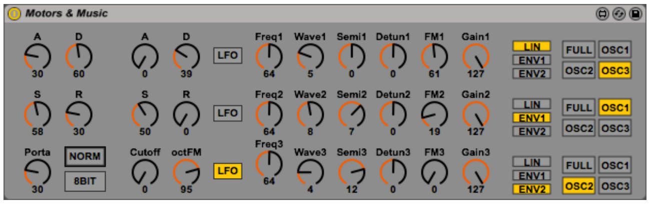

Figure 9 - Max For Live interface to the Motors & Music platform

envelope, and a FM routing scheme that lets each oscillator be modulated by any of the others, including itself. Additionally LFO capability and portamento has been introduced to provide greater sonic design possibilities (see Figure 9).

The lack of a dedicated floating point ALU on the microcontroller though means the FM implementation is fairly light on the processor's resources, resulting in some rather idiosyncratic behavior that, combined with 8-bit waveforms, can give a certain rugged identity to its sonic output.

The motor control and physical modeling implementation has been ported to the new platform but essentially remains the same.

For the fourth class at CIID in 2014 the audio engine has been extended with an a set of digital filtering techniques as the platform pushes forward into more elaborate DSP territory [8]

Workshop Format

The class and workshop formats put forth in this project adhere to both a focused one-week class and one-day workshop. Despite the short time frames (compared to classes running a full semester), the sprint-like format lends itself amiably to the hands-on and studio based nature of the design process. Rather than extensively covering the foundational theory underpinning the science of motorized haptics, Motors & Music articulates fragments of theory and practice, where core concepts of haptics design are exemplified through exercises and tutorials. Presentations are interspersed with 'live coding' sessions, where code examples are developed on-screen in front of the participants, to facilitate a "learning-by-doing" process.

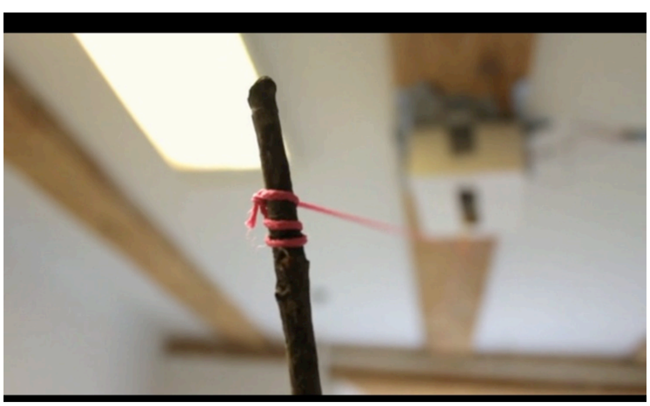

Figure 10 - Gone Fishin' by Marthinus Oosthuizen and Harsha Vardhan Ramesh Babu

The syllabus is segmented into three main parts entitled Motors, Music and Motion. In the Motor part of the workshop, students learn how to drive both the voice coil of the Plank and the DC motors of the sliders while being introduced to the theory of dynamic force-feedback. The Music part focuses on examples and descriptions of digital sound synthesis, with an emphasis on synthesis performed on embedded microcontrollers. Finally, the Modeling part of the class focuses on developing simulations of physical models such as pendulums and spring-based systems. The Motors and the Music parts of the workshop can work as standalone separate topics, while the Modeling part fuses topics of both Motors and Music. In doing so, students are asked to put into correspondence both motor driving logic and sound synthesis, with the aim at creating sound based haptic prototypes (such as the sound of friction for example, or the pluck of a string).

After the introductions to the general framework of the project, participants are given a design project brief from which they develop their own prototypes, fusing in the best way possible haptics, sound and an engaging experience design. In one-week classes the introductions usually take 1.5 days, with 2.5 days of dedicated prototype development time and 0.5 day of student presentations. In the one-day workshop format the introductions are compressed down to half a day, and the design phase consist of a more free experimentation session to make a unique interactive instrument.

Throughout each design phase the teachers are present to help troubleshoot or further elaborate on the available resources to enable the participants to steer the developing concepts towards a meaningful and illustrative prototype.

SELECTED PROJECTS

Below we present a selection of projects from classes to illustrate some of the potential of the course so far.

Gone Fishin'

This project [14] was developed during the first Motors & Music class in 2011 and consisted of a playful interaction with a fishing rod connected through a Plank to model of a fish. Trying to raise the fish out of the water the participant will feel the resistance of the fish accompanied by a reactive sound composition done in Max/MSP. See Figure 10.

The Mutic Box

The Mutic Box [21] was also developed during the first Motors & Music class in 2011 and recreated the feel of a mechanical music box through digitally synthesized haptic and audio feedback. A DC motor provided rumble as force feedback and played back piano samples from MAX/MSP as the central wheel passed conductive elements past a sensor. See Figure 11.

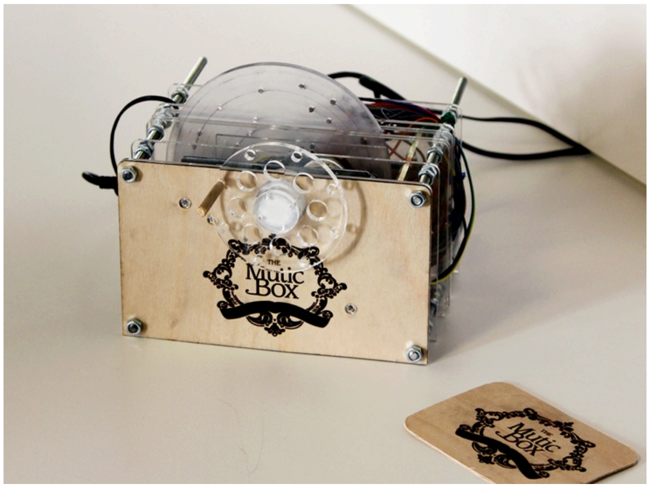

Figure 11 - The Mutic Box by Daim Yoon and Yufan Wang

Duojam
Developed during the second Motors & Music class in 2012, Duojam [2] explores what happens when two musicians are playing the same instrument. The instrument has one tone whose frequency is determined by an average of two motorized sliders. Each player's distance from the average slider position is output in their slider as increasing force feedback and thereby elicit the two players to engage in a negotiation which alternates between collaboration and playful resistance as they try to 'jam' with the playback of a musical composition. See Figure 12.

Hapticket
The 2013 class of Motors & Music focused on 'micro interactions' and designing decoupled, but meaningful tangible interfaces for them with digitally synthesized audio and haptic feedback.

Hapticket approached the transport ticket validation micro-interaction and infused it with a haptic response, which subtly but intuitively indicated a payment by slightly resisting the move of a transport card through a slot. See Figure 13.

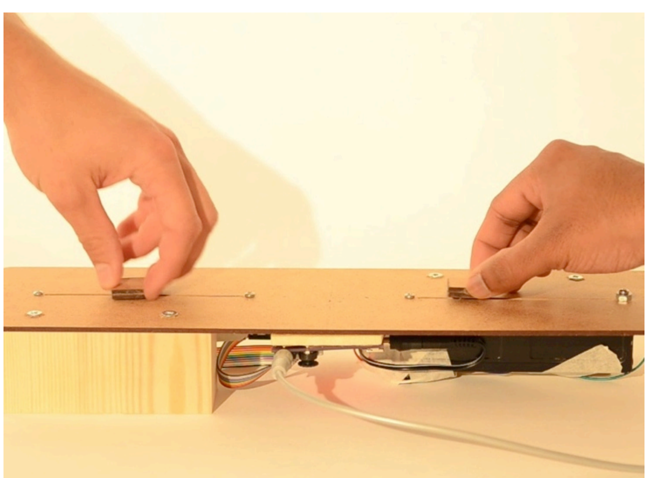

Figure 12 - Duojam by Martin Malthe Borch and Umesh Janardhanan

Figure 13 - Hapticket by Jane Kate Wong and Ankkit Modi

"As the user swipes their card through the slot, the resistance increases towards the bottom, providing immediate indication that a larger amount is being debited from their card. Soft "bumps" are felt in the hand as the card passes downwards in the slot, which correspond to the levels of money being charged. The addition of audio feedback through incrementing notes for each payment level further assists users to understand that the transaction has been made." [23]

Aether
For the 2014 class of Motors & Music the topic was on fully autonomous vehicles and redesigning the driving experience when direct control has been removed from the people being transported.

Aether focusing on the "vehicle as a membrane to the surrounding environment" designed a way for the passengers of an autonomous vehicle to experience and reconnect with the airflow around the vehicle through a tangible interaction with a digitally controlled simulacrum. See Figure 14.

"We chose to shy away from using a fan in our prototype as it would have been too much of a one-to-one association. Instead we experimented with different materials that might create the same tickling or vibratory sensations typically associated with the action. By attaching strips of straws to 'The Plank' that would vibrate and move according to a slider, the user could control the speed of the car in motion.

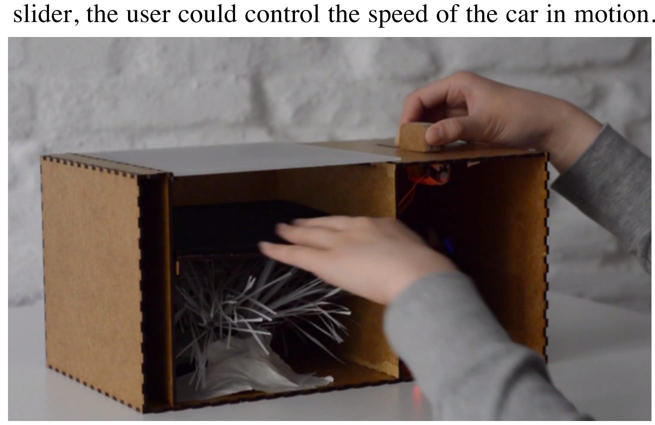

Figure 14 - Aether by Akarsh Sanghi, Bethany Snyder, Chia Yu Hsu and Myoungeun Kim

The more the user 'accelerated', the faster the motor vibrated which in turn generated a wind noise provided by a Max patch. This all worked in tandem with a Servo motor that adjusted the angle of a screen located above the straws to guide the user in the wave-like pattern we aimed to replicate." [17]

CONCLUSION

Motors & Music brings together two different domains that hitherto have had little connection, and the conjunction of which elicits reflection. As a technological domain, haptics has a long history of highly specialised techniques which each have carved out interesting fields for future technological research and development. These fields though come with demands of highly specialised knowledge and technological acumen, demands that can be hard for designers to meet. Design, on the other hand, brings a range of sensitivities that help develop new perspectives within established structures, new ways of using touch and haptic technology that may lie outside of the current technological focus of the domain.

In fusing the two fields, we have focused on teaching and developing new, easy to access prototyping materials that minimize the learning curves and background knowledge needed to engage with haptics research and practice. We have carefully structured hardware, software and curricula and made trade-offs in resolution, force and precision to allow for prototyping materials that fit the cognitive, temporal and financial limitations of short introductory level classes in haptic design.

Through the four years of teaching Motors & Music, we have developed and produced:

(1) introductory material for learning active force-feedback and simple audio synthesis, (2) hardware and software platforms (plank and fader) that are Arduino compatible and easy to work with, (3) sets of exercises and tutorials tailored to each platforms and addressed to interaction design students, and (4) designs and prototypes demonstrating the potential of our platform.

Part of the learning expectations we set ourselves for the project was for students to develop a critical perspective on tangibility in regards to the development of user interfaces and products. In retrospective, this goal was achieved in many ways as students are able to question current products claiming to address the sense of touch (smartphones, tablets, surfaces, etc.). Motors & Music has equipped them with basic haptics and sound synthesis vocabulary to evaluate such products and claims while provided them with enough knowledge and know-how to carry out haptic design and research work that can challenge the status quo in the design of tangible interfaces.

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