Conversus Vitra

A Proportional-Integral-Derivative Loop controlled wine-glass instrument.

by

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Abstract

Conversus Vitra is a proportional-integral-derivative (PID) loop controlled continuous pitch hydrocrystalophone. It consists of four wine glasses, four motors to spin the glasses, four servos touching the glasses for friction, a MIDI keyboard, and four DC pumps to control the water level in the glasses. Conversus Vitra uses a proportional-integral-derivative (PID) controller to control the pitch of the wine glasses. As the player touches the MIDI keys, the pitches that are produced change by pumping or sucking water from individual glasses.

With any other glass instrument, the player would have to tune multiple glasses or bowls, and play them by rubbing fingers, or attaching the glasses or bowls to a spinner, and touch the glasses as they spin. These two types of instruments and human-instrument interactions have three things in common:

- Player must tune the glasses or bowls first.
- Player must touch the glasses or bowls.
- Glasses or bowls cannot be tuned dynamically on the fly.

With Conversus Vitra, the glasses constantly spin. When the player touches the MIDI keyboard, notes are translated into water levels using a PID loop by listening to the glasses, and water is pumped into or sucked out of the glasses as the user plays. With this approach, the player doesn't have to carry more than four glasses, and is not limited to set tunings of these glasses. Because the glasses can be tuned on the fly, new playing methods can be learned and applied. In addition to its portability, it makes playing wine glasses easier for everyone by reducing the time it takes to learn how to play. Being able to use MIDI as an input adds a few new properties to wine glass playing. For example, it allows the player to record a MIDI file of what’s being played, and have an exact replay of it, or the player can quantize the MIDI files and modify them digitally, without digital artifacts to the sound, as the sounds themselves are created physically.

Introduction

Conversus Vitra, taking its latin name from “Rotating or Conversing Glasses", is envisioned to be a modern update to Richard Pockrich's “Glass Harp”, and Benjamin Franklin's “Glass Armonica”. It is a proportional integral derivative (PID) loop controlled wine glass player with MIDI input. It's intended purpose is to reduce the time it takes to learn how to play wine glasses; to enable the player to record MIDI information and play back using the physical device and have minimum or in playback at all.

Conversus Vitra introduces different sounds and portability in the domain of wine glass playing. Consider the following scenario: you are a producer or recording artist seeking different sounds and you want to learn to play wine glasses; and want unique sounds to work with. You're excited to work on your project and rapidly test new sounds without dealing with the tuning of the glasses. You just want to play and don't want to worry about filling the glasses with the right amount of water, or touring stores trying to find the right wine glasses. Searching for new sounds sometimes can be a letdown and can impede motivation. If you're a touring producer or musician and you'd like to add some color to your live concerts, and you're sick of using samples to fill the FX parts that you need, you want to be able to control a physical instrument with the same MIDI keyboard you use to play your other digital instruments. Conversus Vitra is designed to address these problems. It's also introducing new techniques to wine-glass playing such as glissando (slide from one pitch to another), staccato (without worrying about knocking the glass over) and slide (quickly slide between notes for FX usage), which are hard to achieve or impossible to play by hand.

In addition to the problems listed above, the instrument solves a bigger issue with wine glass playing: multi-note chords. With a traditional Glass Harp, a beginner can't play more than 2 notes at the same time; more advanced players can play four notes at the same time; However any player, beginner or advanced can only play a limited number of notes as the two glasses have to be within the reach of one hand. In order to play a complex song the glasses have to be pre-tuned and arranged for the song specifically or the player would have to rearrange the glasses' order during the song. Conversus Vitra specifically solves this problem by being able to change the pitches of the glasses and address voices to different glasses using the input of the MIDI keyboard.

Related Work

Glass Harp (1741) - Richard Pockrich

The glass harp was created in 1741 by Irishman Richard Pockrich who is known as the first virtuoso of the musical glasses. The composer Christoph Willibald Gluck also played the musical glasses. He performed in London and Copenhagen. His instrument consisted of 26 goblets. The instrument was popular in the 18th century. It is a musical instrument made of upright wine glasses played by running moistened or chalked fingers around the rim of the glasses. Each glass was tuned to a different pitch either by grinding each goblet to the specified pitch, in which case the tuning is permanent, or by filling the glass with water before the performance until the desired pitch is achieved.

Glass Harmonica (1761) - Benjamin Franklin

Benjamin Franklin's treadle-operated glass harmonica was constructed of 37 bowls mounted horizontally on an iron spindle. The whole spindle turned by means of a foot pedal. The sound was produced by touching the rims of the bowls with water-moistened fingers. Rims were painted different colors according to the pitch of the note. A's were dark blue, B's purple, C's red, D's orange, E's yellow, F's green, G's blue, and accidentals white.[2] With the Franklin design it is possible to play ten glasses simultaneously if desired, a technique that is very difficult if not impossible to execute using upright goblets. Franklin also advocated the use of a small amount of powdered chalk on the fingers, which under some acidic water conditions helped produce a clear tone. Another supposed improvement claimed in ill-informed post-period observations of non-playing instruments was to have the glasses rotate into a trough of water.

Absolut Quartet (2008) - Jeff Lieberman & Dan Paluska

Absolut Quartet is an installation made by Jeff Lieberman and Dan Paluska as a part of the Absolut Vodka's Absolut Machines campaign. It is a web-based-interaction installation. The user visits the project website [absolutmachines.com] to interact with the machine. The main instrument is a ballistic marimba, which launches rubber balls roughly 2m into the air, precisely aimed to bounce off of 42 chromatic wooden keys. The second instrument is an array of 35 custom-tuned wine glasses, played by sticks touching them. Finally, an array of nine ethnic percussion instruments rounds out the ensemble.[7]

Instrument in Details

Overview

Conversus Vitra consists of eleven different parts: body, top plate, friction sticks, spinning plates & glass lockers, pumps, cooling, electronics mainboard, embedded software, controller software, MIDI keyboard, microphones. Each of these parts plays a critical role in how the instrument makes sounds and how it functions. These parts and their design processes will be explained in detail. This section covers their relationships and how these parts work together.

All structural and mechanical parts can be fabricated using a laser cutter. Pumps, tubes, electronic and electromechanical parts can be obtained from manufacturers and distributors; the main electronics controller board was custom designed for the instrument and ordered from a printed circuit board (PCB) fabrication service, and the wine glasses used for the instrument are from various retail stores.

During the design process, portability was one of the core features that led the design. Steppers, pumps, and power supply add weight to the instrument; and to compensate for this, the remaining parts are all laser cut so that the instrument can be modular, portable and lightweight. It is designed so that it would fit into a medium/large sized camera backpack when the glasses and friction sticks are unmounted from the body.

Electronics, except for the custom designed PCB board, are off the shelf components so that they can easily be replaced.

Here's a brief description of the parts used for the basic structure:

- The power supply is 12V 30A and most importantly it is fan-less to reduce noise.
- The controller is an Arduino Due which runs custom software.

The main-board PCB is custom designed to fit on top of an Arduino Due. It has four stepper motor drivers, eight logic level MOSFETs, it has screw terminals for the steppers, pumps, servos, main power. It is the central connection hub.

- Stepper motors are NEMA 17 hybrid-bipolar. They weigh 185 grams and have a holding torque of 3.7 kg/cm. It is important that these steppers are strong enough to carry the glasses when they're full, start spinning when the glasses are full, and be able to do all of this under the potential and variable stress generated by the arms touching the glasses. They have a 5mm shaft.
- Friction stick servos are slim radio controlled (RC) aircraft wing flap controllers, they are 10mm thick, weigh 28 grams, run with 5V and can lift 7kg/cm.
- Pumps are CPU cooling pumps that are non-primed, run under water and are very silent because of this. (< 38 dB), They are really light (85 grams) for their power (3.6 Liters/min or 68GPM @12V) and have a vertical lift of 3 meters.

The main body contains all of the electronics. - The power supply, Arduino controller, PCB main-board, four stepper motors. It is made of four sheets of acrylic. It is the base unit and it contains the brain of the instrument. Although it is modular and parts can be replaced/unmounted easily, it's designed so that can it can be carried as one piece. The walls, bottom, and the top plate are made of 0.22" thick acrylic, as it is the protective shell for all of the electronics. It is strong enough to carry around without being damaged and it carries all of the weight of the construction.

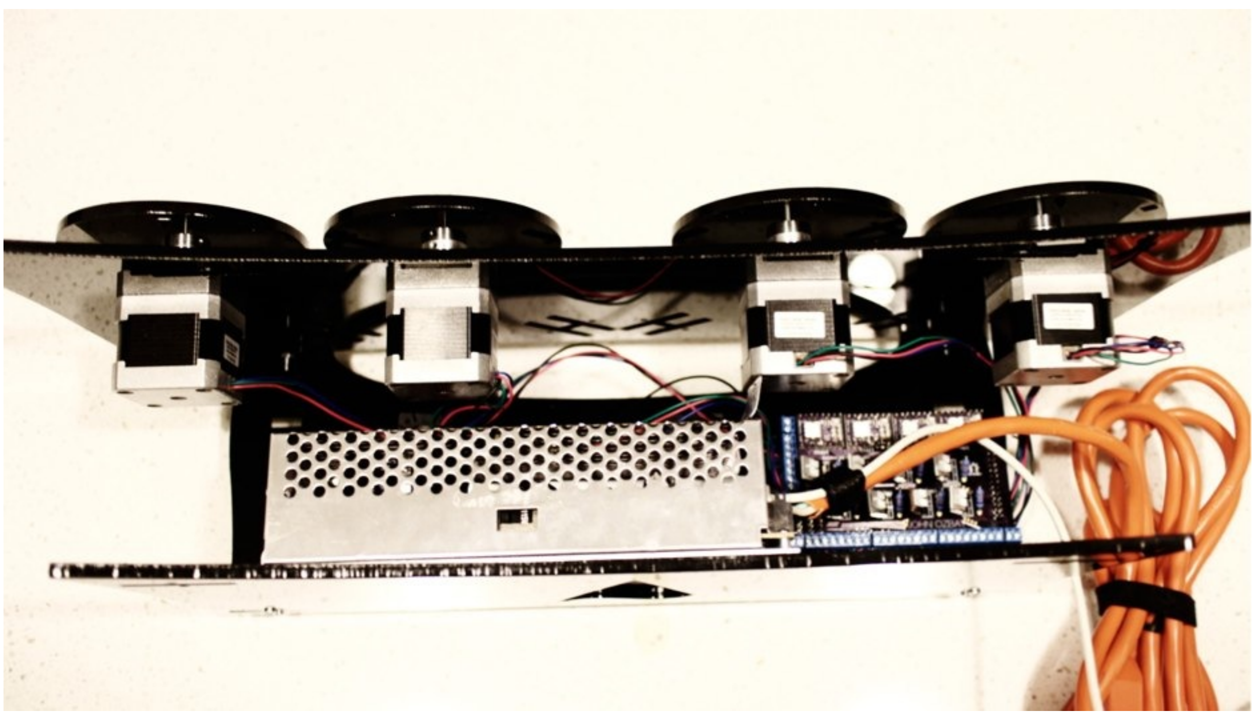

Photo - Main Body & Electronics

The top plate is the base mounting plate for the stepper bodies and the friction sticks. It's a part of the main body, the largest sheet of acrylic, and it is one of the most critical parts of the instrument as it needs to carry a lot of weight. It has four M3 screw holes and a shaft hole per stepper motor. The screw holes have rubber grommets to stop water from leaking into the steppers and to dampen the sound of the steppers to some degree. It has four friction stick connection points which are mounted on the top side.

Photo - Top Plate

The friction sticks, are 220 millimeters tall, and they're the most accurately created parts of the design. They carry the servo arms that are touching the glasses, route the tubes into the glasses; they are rigid. The construction of the friction sticks consists of two sheets of acrylic and with the servo sandwiched the between them. The top parts are screwed together and fixed in place with the servos and the bottom parts are screwed to the main plate. Also to pick up the best possible sound from the rims of the wine glasses, piezo microphones are attached to these friction sticks.

Photo - Friction Stick & Piezo Microphone

The spinner plates are attached to the shafts of the stepper motors using a 5mm mounting hub. The wine glasses sit on top of these spinning plates. To increase grip and reduce the motor vibrations from affecting the glasses, there is a thin layer of EPDM rubber in between the glasses and the spinner plates. Spinning plates are attached to the hub with 2xM3 screws. They have four locker holes on them and once these lockers are in position, there are two screw holes to fix the locker holes.

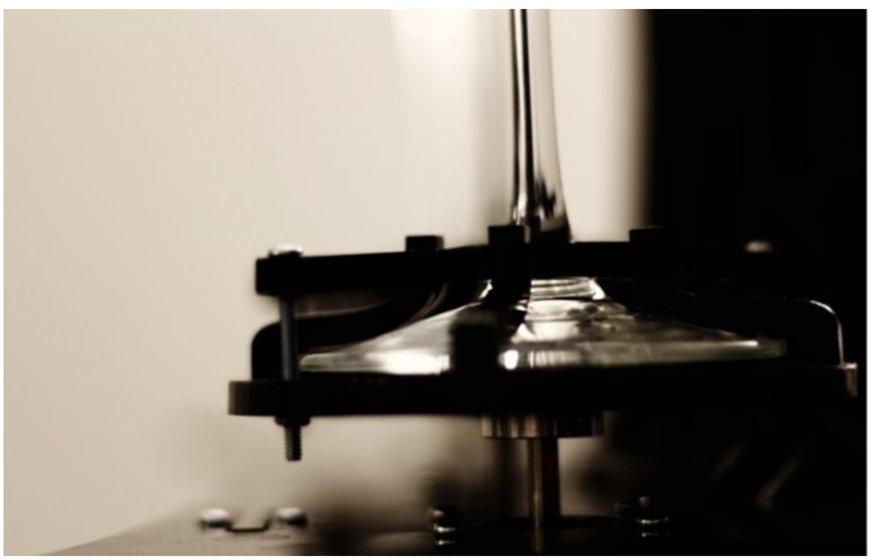

Photo - Spinner Plate Attachment

The glass lockers are small in size, but large in role. Four lockers position the wine glass on the plate and they must to be accurate to the millimeter to hold the glasses in position or the glasses would be unstable while rotating at full speed. Their accuracy reduces the shake and mechanical noise levels dramatically and they fix the glass in position so there won't be any accidental spills. They fit on four holes on the spinner plates and they're locked into position with a "C" shaped piece, which later screws onto the spinner plate with 2xM3 screws.

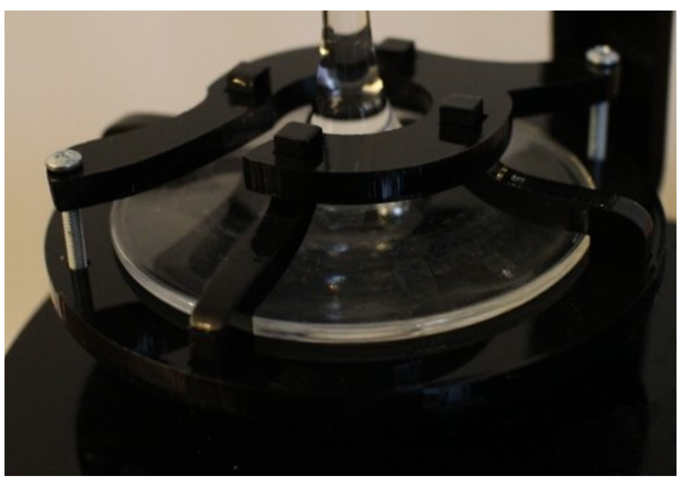

Photo - Glass Lockers

Photo - Wine Glasses

Wine glasses can be interchanged and the base-note of the glasses can be set in software, however after further experimentation, 20cc glass capacity is considered a fair maximum for the motors to be able to spin the glasses without any issues. This can be improved by replacing the motors with more powerful ones, however at this time the noise and heat becomes a big issue. Because the glass needs to fit onto the spinner there are some technical rules to consider when picking the right glass. The radius of the bottom base of the wine glass cannot be larger than 80 millimeters and can't be smaller than 50mm or it will be unstable. The radius of the rim should be between 60mm and 90mm for the arms to work. The body of the glass shouldn't exceed 100mm in width or it will touch the friction stick body. The glasses must be at minimum 180mm and maximum 230mm tall.

The controller software runs in MAX / MSP* and accepts MIDI inputs or reroutes from any Digital Audio Workstation (DAW). Piezo microphone signals are also processed here, and combined with the MIDI input signals they're translated into packages that are to be sent to the Arduino controller board, which are interpreted into pump on/off, stepper on/off, and servo position signals.

* MAX/MSP is a visual programming language for music and multimedia developed and maintained by San Francisco-based software company Cycling ’74. http://cycling74.com/products/max/

Design Challenges

Conversus Vitra has a lot of parts that need to be accurate and well crafted. Especially the parts that are directly related to the acoustics of the sound. The most important lesson learnt from the project is that water and electronics don't play well together. This was definitely the biggest challenge. But the second biggest challenge throughout the project was to pick the right components. Are there smaller / lighter ones? Are they waterproof? Are they quiet? If not, is it easy to dampen or cancel the noise without tinkering with the main design? These were the main types of problems. This section covers all design challenges and why some challenges are harder to address.

Water and electronics do not play well together and should not be mixed. The biggest challenge, as predicted, was keeping the water away from the electronics at high and unstable speeds. When a glass is more than half-way full, stopping and starting the stepper motor fast becomes a big challenge. The first batch of stepper motors (NEMA 14) were only able to handle 1kg-cm and they weren't powerful enough to start with so much weight. The only way to start them was to start slowly and ramp up, and slowly ramp down to stop, without damaging the motors or spilling water. This was good enough for sustained notes, but NEMA 1four motors fell short after a few other changes in the design.

Early prototypes had fixed, static friction sticks touching the glasses. However, as a glass started to get filled with water, because it got heavier, the pressure applied from the friction stick was not enough to resonate the glass. This mean that once a glass was 70% full, it became quieter. To address this issue, the first solution was to change the static friction sticks with servo arms (dynamic sticks), that could apply more pressure. This solved the issue to a great extent. However, like every other fix, this caused more issues on its own as well. The most important being the lockdown.

When a glass is full, it requires more pressure, which can be applied up to 7 kilograms with the latest design's servo arms. But as the arm started touching the glass, old steppers started to fall short. As soon as the friction sticks were lowered to touch the glasses, the pressure of the arms and the weight of a full glass stopped the old steppers. This required a change with the steppers. Replacing the steppers with the new powerful ones (NEMA17) solved the problem, but gave birth to another one. The locking mechanism wasn't strong enough to hold the glasses in position. Once the friction sticks were lowered to touch the glasses, the pressure of the arms and the weight of a full glass didn't cause the stepper to stop, but the glass itself stop spinning because it wasn't fixed well enough to the spinner plates.

To address the issue, the first solution was to change the locking mechanism and try to get better results. After 6 failed iterations (all of which are listed under Spinning Plates & Glass Lockers) in the 7th iteration, the lockers performed better. Although the glasses were absolutely locked with screws, nuts and bolts, the instrument started to lose its loudness with lower notes because of the smooth surface of the acrylic, which caused the glass to spin/stop independently from the mounted platform. Finally the issue was resolved after placing a thin layer of EPDM roofing rubber between the glass and the platform to fix the glasses. Which helped increase grip and reduce the motor vibrations from affecting the glasses negatively.[8]

Keeping the water away from the electronics got harder after switching to more powerful and faster steppers, as starting or stopping too fast with a glass full of water caused splashes. The solution to this issue was to go back to square one and apply the same technique used with the old stepper motors. With the old steppers, as they're not powerful enough, the only way to start and stop the steppers was to slowly and nonlinearly accelerate and decelerate. This technique temporarily solved the weak stepper motor issues, but more importantly because of it's gentle nature, it didn't cause any splashes. Thus was the most practical way to solve the splash problem.

Acceleration and deceleration helped the system function incredibly efficiently, however it caused many different issues, the most important one being the noise. As the steppers got more powerful, the stepper coil noise became worse. After investigating the issue and testing different mounting techniques, none stopped the noise as the problem wasn't a mechanical vibration noise, which can be dampened, but it was the noise of the coils being charged. After a few weeks of extensive testing, designing the system in such way so that the motor sounds would become a part of the instrument seemed like a better solution. Or a pseudo-solution.

The idea of utilizing the sounds of the motors and incorporating them in such way so that they would feel like a part of the instrument was a crazy one - also a hard decision to make. This was perhaps the most interesting hack of the whole project. Considering most of the motors don't have their noise levels listed on their data sheets, it was a hard decision picking the right motors. The final iteration of the system uses a Max/MSP patch to convert MIDI signals to base note frequencies, which are then converted to motor speeds, and pushed to the Arduino over a serial line to be used by the motors as soon as the player touches a key. Tuning the motors did help with the noise a lot, and although they're still audible, they do sound more like a part of the instrument now. It was a practical pseudo-solution to a problem rather hard to solve.

As the motors got quieter, the suction pumps became more audible and irritating. The earlier prototypes had two tubes leading into the glasses. One to suck and one to pump. The pumps that are used to pump the water are submersed and are absolutely inaudible mainly because of the water’s acoustic insulation. However, the suction pumps are self-primed, and they are not submersible; hence the noise. The suction pumps were a part of the original design due to the earlier versions of the PID control loop. Valves, due to their loud switching noise, were not a part of the design. Thus, if the pumping tubes were placed onto the bottom of the glasses, gravity would pull the water back as soon as the pumping was done. To prevent water from going back, the pumping-tubes were at the rim, and the suction tubes were at the bottom of the glasses. So water was pumped in and dropped into the glasses, and sucked from within the glasses. This approach was decidedly abandoned due to the noise of the suction pumps. The final design uses a single tube, which is aesthetically more pleasing and doesn't use a suction pump. It is used both for pumping and sucking water out of the glass using a single submersed pump.

Eliminating the need of a suction pump meant changing the PID control loop. The earlier designs would stop pumping once the glass reached the target note because the water level wouldn't be affected by gravity as the pumping-tubes were at the rim. The single tube came with its own problems the biggest being the gravity. As soon as the pumps stopped, gravity would to drain the water out. To address this issue the PID control loop had to be changed. In the new design, the water level is maintained by pumping water into the glasses and compensating for the amount of water gravity drained out. This solution eliminated the need of a separate loud pump to suck the water, and/or the usage of a loud valve.

Finally, with each different motor having different mechanical loudness properties, piezo microphones didn't work out of the box. NEMA14 and early NEMA17 motors can get mechanically too loud, and their noise could affect the wine-glasses' tuning accuracy. To address the issue, a potential system could use a laser microphone or a small electret condenser microphone aimed at the rim of each glass, eliminating the need to use mechanical pickups.

Hardware

Electronics

Conversus Vitra's internal electronics consist of 6 carefully selected main parts. An Arduino Due† Controller, a power supply, mosfets, a custom manufactured PCB controller, stepper motors and servo motors. This section covers all of the internal electronics, describes the criteria for selection, thoroughly explains the connections, circuitry and the custom fabricated printed circuit 22board (PCB).

For the instrument to work, a microphone or some sort of digital listening is mandatory and it has to be done in four independent channels, one for each wine glass. For this reason the project could have taken two directions: compact or optimized. The compact system would require the listening and sampling to take place inside the instrument, while the optimized system would have only the bare minimum components inside the instrument and have everything else, including the listening system, to be connected externally. For the sake of quicker iterative design and reliability of the proof of concept, Conversus Vitra uses an optimized system.

The decision to make the instrument not self-contained was made after careful consideration. The two most critical reasons were water exposure and reliability. Conversus Vitra could have used a Raspberry PI‡ computer and PureData for the PID loop, however, fitting such a system into the instrument itself would raise issues with water exposure, additional heat, noise and unreliability to the overall system. Another possible alternative to

† Arduino is a single-board micro controller.
http://www.arduino.cc/

‡ The Raspberry Pi is a credit-card-sized single-board computer developed in the UK by the Raspberry Pi Foundation.
http://www.raspberrypi.org

using a Raspberry PI would have been to use an Arduino Yún. Both of these devices have insufficient inputs for all of the required components and would have caused more issues than advantages.

Conversus Vitra uses an Arduino Due, which has a 32-bit ARM core that can outperform any other 8-bit Arduino micro controller boards for various reasons. It operates with 3.3V instead of 5V, has a clock speed of 84MHz, and has 5four digital input pins, which makes it the ideal board for Conversus Vitra. The final system uses 8 digital input pins on the Arduino for each stepper driver. (Direction, Step, Sleep, Reset, MicroStep1, MicroStep2, MicroStep3, Enable). In addition to 32 digital input pins used by the stepper motor drivers on the Arduino, the instrument also requires 1 digital input pin for each pump MOSFET, and 1 digital input pin for each servo arm. Which comes down to 40 digital input pins in total. Conversus Vitra greatly leverages Arduino Due's multithreading dual cores. While one core/thread is used for stepping the motors, the other thread is used for listening to the serial commands, controlling MOSFETs, and servos. The multithreaded nature and 84MHz clock speed of Arduino Due improves the response time of the instrument substantially in comparison to other controllers.

The instrument uses four NEMA 17 hybrid bipolar stepper motors, with a holding torque of 3.7kg-cm (51oz-in) at 1.7A per phase @ 2.8V. Which was ideal for the purposes of the instrument due to multiple reasons. Most importantly, the stepper motors needed to have enough holding torque to start the full glasses, and be able to spin while under pressure from the servo arms. Coupled with DRV8825 stepper motor drivers that can operate between 8.2 - 45V and can deliver up to 1.5A per phase without a heat sink or forced airflow, the stepper motors could run quite efficiently without overheating. Conversus Vitra could have used DC motors, and this would have eliminated most of the power and heat issues of the stepper motors, but considering the low budget, a powerful enough brushless DC motor that was silent enough for the purposes of this project was not the most economical choice. Therefore, because of their brushless nature, both noise-wise and economically, stepper motors were better fit for the instrument.

The friction sticks touching the glasses need to have a low profile servo motor in order not to physically obscure the glasses, and eliminate the need for a more complex mechanical structure. However with the size constraints in mind, finding the right servo required looking at a wide range of applications and determining the most similar use cases, where great power is required with the lowest footprint and the least amount of operating noise. The final system uses Turnigy TGY-S712G servo motors, that are normally used in hobby RC glider aircrafts' wings. Motors are 10mm (~0.4in) thick and 40mm (~1.5in) wide and tall with a holding torque of 7kg-cm (97oz-in) @ 6V.

Because the pumps used in the system are 12V pumps, and Arduino Due's digital outputs use 3.3V, a logic-level voltage MOSFET was required to switch the pumps on/off. The final system uses a N-Channel 60V 30A MOSFET (FQP30N06L), with very low resistance and logic-level gate voltage, that already has a charge pump circuit built inside which allows them to turn on/off even with the 3.3V that Arduino Due could provide. Again, heat dissipation was a big consideration while choosing the MOSFETs, and although these MOSFETs don't heat up with the voltages used by the pumps, to guarantee more efficient prolonged usage they use 0.25x0.25x0.13in aluminum heat sinks.

The main-board operates with 12 Volts and the overall system uses about 20A when the stepper motors are running and ~32A when the stepper motors are starting. To address the power requirements, a powerful but fan-less silent power supply was required. The final setup uses 2 fan-less 20A power supplies parallel connected to be able to provide the circuit with enough power when the stepper motors are starting up. Prolonged usage of the power supplies with limited amperages reduces their lifetime greatly. Therefore, to protect the fan-less power supplies from unexpected failure during high power operation and to prevent them from overheating after extended usage, the system uses two paralleled power supplies.

The custom designed PCB had multiple iterations. This was because the design of the instrument and the requirements changed as the instrument evolved. The PCB has sockets for four DRV8825 Stepper drivers and controller pins for four Servos on it. It also contains four MOSFETs for the pumps. The circuit operates with 12V from the power supply, and 5V from the Arduino Due. The board has screw-mounts for the motors' and pumps' wires, and it's designed to fit on top an Arduino Due, to make the connections easier, more reliable, and share the same physical footprint.

Body

Conversus Vitra's body consists of 2 sections: top of the base and bottom of the base. This section covers all design iterations, parts, placements, connections, fabrication and design considerations related to the bottom of the base. The bottom of the base contains all electronics and carries the instrument. In earlier designs, the bottom of the base consisted of two separate compartments, as the water tank was a part of the base in the first two designs, later it was removed and externalized for portability and ease of transportation.

The instrument has four stepper motors connected to spinning plates, which carry the glasses. Spinning plates are a 100mm wide, and each must have at least 25mm more for the curved body of the glasses on each side, so the motors are placed a minimum of 100mm apart from each other to prevent accidents and collision. All motors are mounted using M3 Rubber Grommets to dampen the mechanical noise, and to make the connections water-tight. The motors are 43mm square x 38mm tall, meaning the rest of the electronics must be placed at least 40mm apart from the top plate.

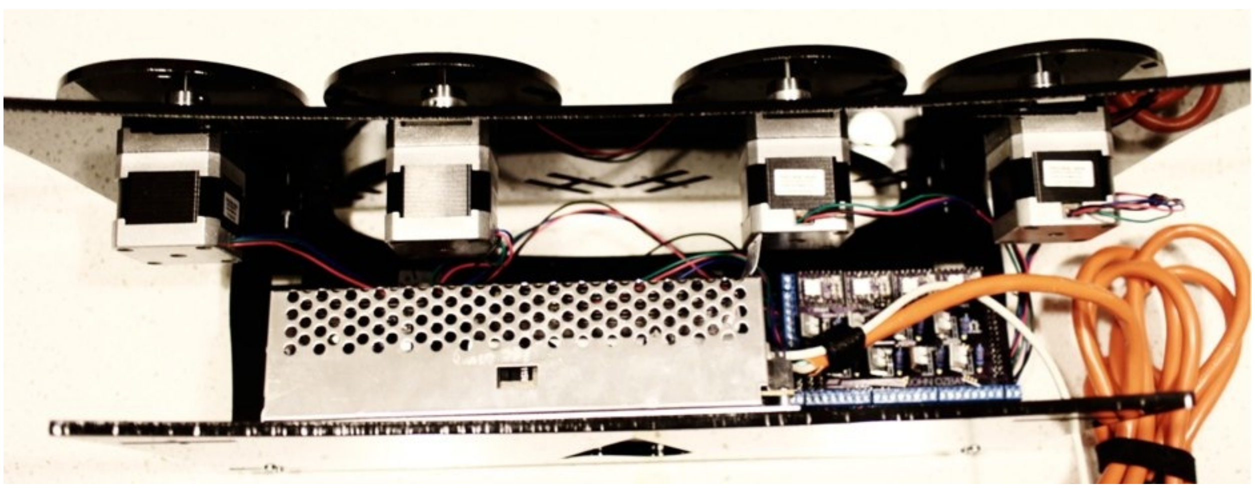

Photo - Main Body

The power supplies are 50mm tall and 110mm wide, they rest on the bottom plate of the instrument and dissipate heat from the holes on the top. The motors and power supplies have approximately 20mm space in between for air to circulate freely. This spacing is also used for most cables to be organized on the back plate using velcro cable ties. Right next to the power block, the Arduino Due is mounted on the back plate, raised 15mm from the bottom of the instrument, to protect the controller from potential water damage which can occur on the bottom of the instrument and to provide enough room to attach and screw the wires to the PCB. The Arduino Due is mounted 15mm below the motors for wires to be mounted easily and allow room for better heat dissipation, and is mounted to the back plate using 12mm M3 standoffs to protect the circuitry by allowing room for water to run through the back plate in case of a flood. All Arduino and power supply mounting connections have an M3 rubber grommet to make the connections water-tight.

The back and front plate has curved openings to allow more hot air to escape from the top and to allow better heat dissipation. The back plate has two small openings for the pump and servo cables to run through and to allow more organized cabling inside/outside the instrument. The front plate has a small logo-air hole for heat dissipation from the sides of the power supply where two transistors are mounted to the body of the power supply. The bottom plate is lifted from the ground using rubber feet and has a drain-hole to allow easier water movement. All plates are mounted using small holes for other plates to fit inside each other and they're tightened using a small laser cut piece fitting inside the plates.

Top Plate

Conversus Vitra's top plate consists of four motor connections, four friction stick mounting holes and four body mounting holes. All screws on the top plate are M3, and they're water-tightened using rubber grommets, which also provides dampening. This section covers all design iterations, parts, placements, connections, fabrication and design considerations related to the top of the base, and explains the assembly procedures thoroughly.

The top plate has four mounting holes for the friction sticks, which are locked and tightened into position using small acrylic cut pieces. When the glasses are spinning and servo arms are down, the friction sticks vibrate with the glasses, and if they're tightly mounted, their incapability of resonation affects the overall sound of the glasses and dampens the high frequencies. To prevent this, friction sticks' mounting holes are 1mm larger than the actual friction sticks to allow room for restricted movement and better resonation. It is important to keep in mind that the friction sticks have to be strong enough so that they can endure the pressure from the servo arms, but also allow the glasses to resonate. After careful testing and four iterations, spacing more than 1mm is observed to cause overall instability and less than 1mm is observed to dampen the high frequencies.

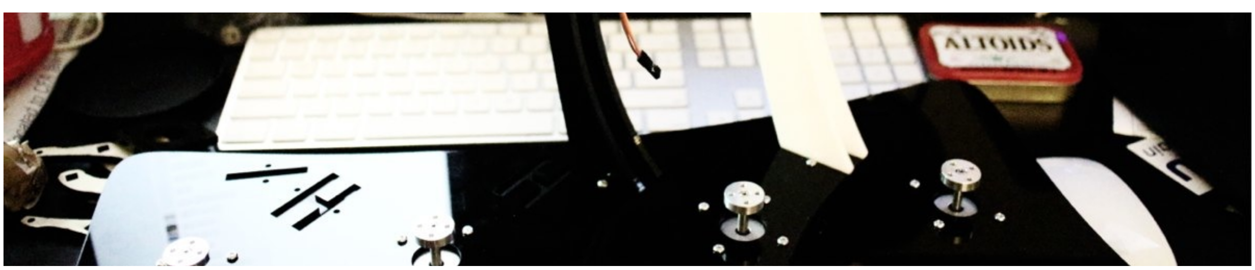

Photo - Top Plate

After the motors and friction sticks are mounted and all wires coming from the top plate are screwed to the main PCB, the top plate is connected to the front and back plates using the sockets on the sides using M3 screws and rubber grommets. Once the top plate is mounted, the spinners are connected to the 5mm universal hub on the steppers using #four screws and rubber grommets,and tightened. Once the spinners are in position, 50mm square EPDM rubber sheets are placed on the spinners and the glasses are placed on the spinners. After the glasses are in position, they're locked using the acrylic lockers and screwed in using 1" tall 3M screws. Finally, the acrylic servo arms are inserted onto the servo shafts, and mounted using M2 screws. Sponges are then mounted on the arms using zip-ties.

Friction Sticks

Conversus Vitra uses friction sticks to replace human touch onto the glasses. This section covers all design iterations, parts, placements, connections, fabrication and design considerations related to the friction sticks, how they're mounted, and the results of the iterative design process.

While the instrument was being designed, one of the biggest challenges was to create the friction sticks. To make them look aesthetically pleasing but rigid at the same time they needed match the glasses' curves. They had to have as few connections as possible or be a solid piece for better resonation, but they also had to function reliably even after transportation. While the earliest designs used a single piece of acrylic bent using a custom heating rig and vacuum forming, after testing the static sticks it was observed that the loudness was affected once the glass gets filled if they're not dynamic. Therefore, the final design uses friction sticks with dynamic servo arms, in order to apply more pressure when needed, and be able to contact the glass from different points.

Earlier designs had a 25mm square mounting surface on the lower side with 2x3M screw holes. They were as tall as the glasses plus 10mm to allow room for the sponge and an ~70mmx25mm contact surface for the glasses. These were made out of single sheets of acrylic and had small etched bending marks to indicate the bending lines. The sticks were then placed on a custom made wood rig and heated to 300 degrees F for about 7 minutes and bent from the bending lines. It was an effective method to fabricate " [" shaped sticks and was the fastest way to create solid, single piece sticks. They had 2 holes on them for the tubes to go into the glasses and the sticks were the mounting point for the tubes. However, as mentioned earlier, after many iterations, it was observed that this design wasn't good enough for lower frequency notes. This is because when the glass is full it requires more pressure to be applied to achieve audible sounds, and static sticks couldn't provide enough pressure.

Photo - Friction Stick

The new design is equally tall, more aesthetically pleasing, shares the same surface mounting area, and have a servo arm attached to them which allows them to dynamically change the amount of pressure applied onto the glasses. This eliminates the need for hand crafting friction sticks. They're made of two sheets of acrylic and a servo motor is sandwich-mounted between them using M2 screws. They also have a small extension on the top to let the tubes run through and screw holes to tighten and lock the tubes. Because the latest design uses only one water tube, the new friction sticks are more reliable than the old ones and are visually and aesthetically more pleasing when the tubes are mounted. Servo arms have a "Y" shaped tip, allowing the sponge to fit perfectly.

Spinning Plates & Glass Lockers

The wine glasses are mounted directly onto the motors using custom designed spinner plates mounted onto Pololu 5mm Universal Motor Hubs. This section covers all design iterations, parts, placements, connections, fabrication and design considerations related to the spinning plates, how they're mounted, and the results of the iterative design process.

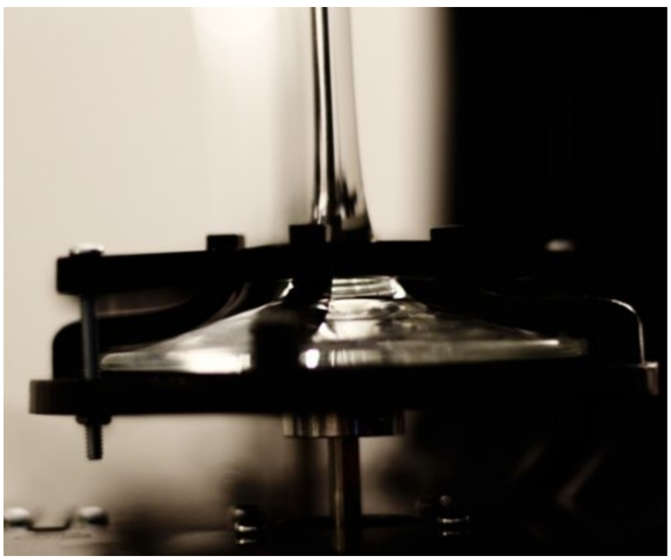
Photo - Spinning Plate

The design of the spinning plates changed 8 times as the instrument evolved and like the rest of the parts they're also modular. The plates are designed so that the glass-base would fit perfectly and have an extra 10mm on four sides to lock the glass onto the plate. While the plates haven't changed much in terms of size and function, the locking mechanism that fits onto the plates did. Earlier lockers were only small "L" shaped acrylic pieces attached to the plate from the outside of the glass to prevent the glass from moving on the plate surface. After the first two iterations of the instrument it became clear that mobility is greatly affected by this approach as the glass could move the lockers up and the glass would be released along with the lockers.

Photo - Glass Locker

Final designs have not just the "L" shaped acrylic pieces but also have a small locking plate that fits on top of the "L" shaped pieces. These smaller plates are screwed onto the spinning plates using 1" tall 3M screws. This approach not only stops the glass and the lockers from moving on the X or Y axis, but also on the Z axis when screwed down. Mobility becomes so much easier. The only thing that needs to be removed is the 5mm mounting hub and that separates the glass and the plate from the motors allowing the glasses to be carried separately. After switching to the new design and adding the smaller plates the "L" shaped locking pieces became "S" shaped as the small plate is mounted on top of them.

Software

Arduino

Conversus Vitra uses Arduino Due in its core fore development. What makes Arduino Due special is the multi-threaded nature of it and the amount of input and output pins it has available. Due has a 32-bit ARM core that can outperform any other 8-bit Arduino micro-controller boards. This section covers all the details of the software running on the Arduino.

The software uses three libraries. Scheduler and Servo, included in the standard Arduino Integrated Development Environment(IDE) distribution, and AccelStepper.[§]

Scheduler is the library that enables the Arduino Due to run multiple functions at the same time. This allows tasks to happen without interrupting one another. It is a cooperative scheduler in that the CPU switches from one task to another. The library includes methods for passing control between tasks. Although the scheduler library and the associated functions were experimental at the time of this project, they served greatly for the purposes of the instrument. The two main functions of the scheduler library used in the Conversus Vitra software are "startLoop()" and "yield()". "startLoop()" adds a function to the scheduler that will run concurrently with the main "loop()". "yield()" passes control to other tasks when called. For example, in "loop()" right after all stepper motor "step()" functions are called, or in the secondary loop ("loop2()") right after checking the serial port to see if there's any incoming data.

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§ A stepper motor library that provides an object-oriented interface for 2, 3 or 4 pin stepper motors. Written by: Mike McCauley.
http://www.airspayce.com/mikem/arduino/AccelStepper/

AccelStepper is a stepper motor library for Arduino, that's not a part of the standard Arduino IDE distribution. It has greater capabilities in comparison to the Arduino's included stepper library. AccelStepper significantly improves on the standard stepper library in several ways that are critical for Conversus Vitra to work:

- Supports acceleration and deceleration so that motors can start slowly with heavy load and stop with heavy loads.
- Supports multiple simultaneous steppers with independent concurrent stepping on each stepper.
- API functions never use "delay()" or block the flow of the code.
- Supports very slow and very fast speeds, which is heavily used in Conversus Vitra to tune the motors.
- It provides an object-oriented interface for the four pin steppers used in Conversus Vitra.

Servo library is the standard included servo library packaged with the Arduino IDE. It allows a variety of servos to be addressed by the Arduinos, and it's incredibly reliable.

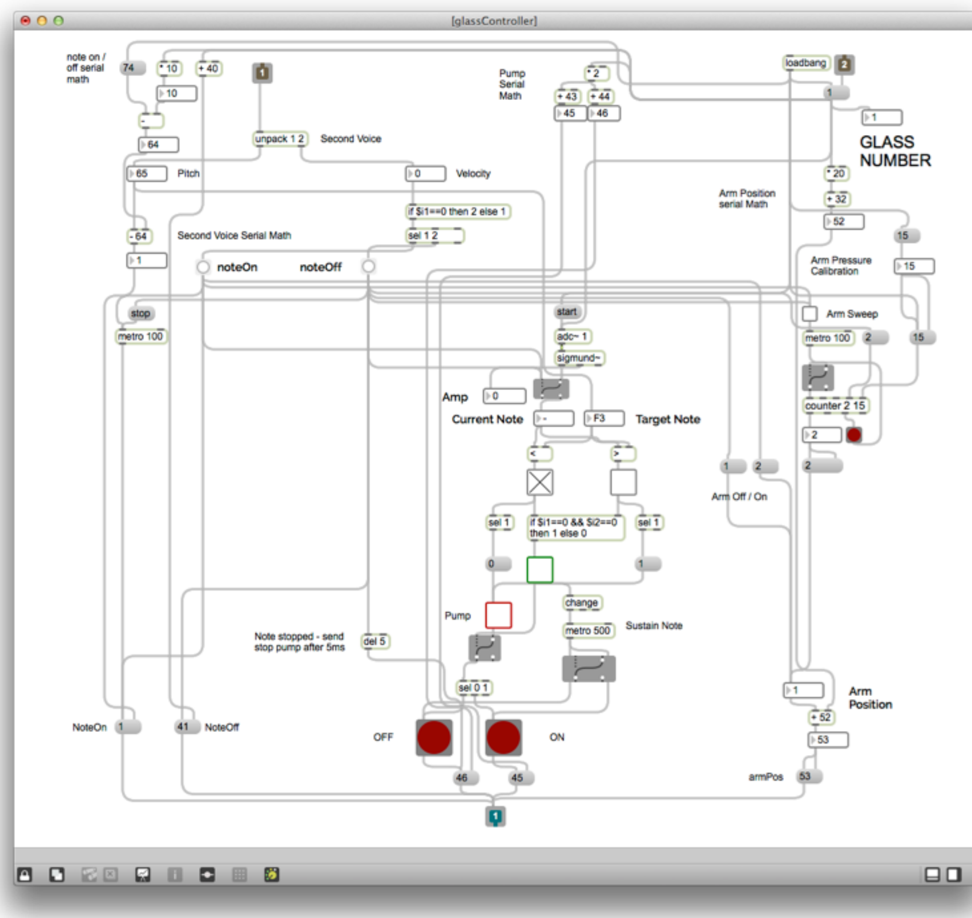
Conversus Vitra's software basically works as follows. “setup()” is used for digital pin assignments and to setup the sleep and reset pins of the stepper drivers. “loop()” is used for checking the serial port to see if there's any new data, and to write stepper running speed variables later to be used by “runSteps()” to control servos and pumps. “loop2()” is used to run the steppers, as the “runSteps()” function needs to be called as frequently as possible to achieve uninterrupted stepping. The multi-threaded nature of the Arduino Due, combined with the power of the Scheduler library, allows checking the serial inputs more frequently which enables greater speeds as a result in comparison to other micro controllers. This is an important feature for musical instruments as they need greater control speeds compared to other non-timed hardware projects.

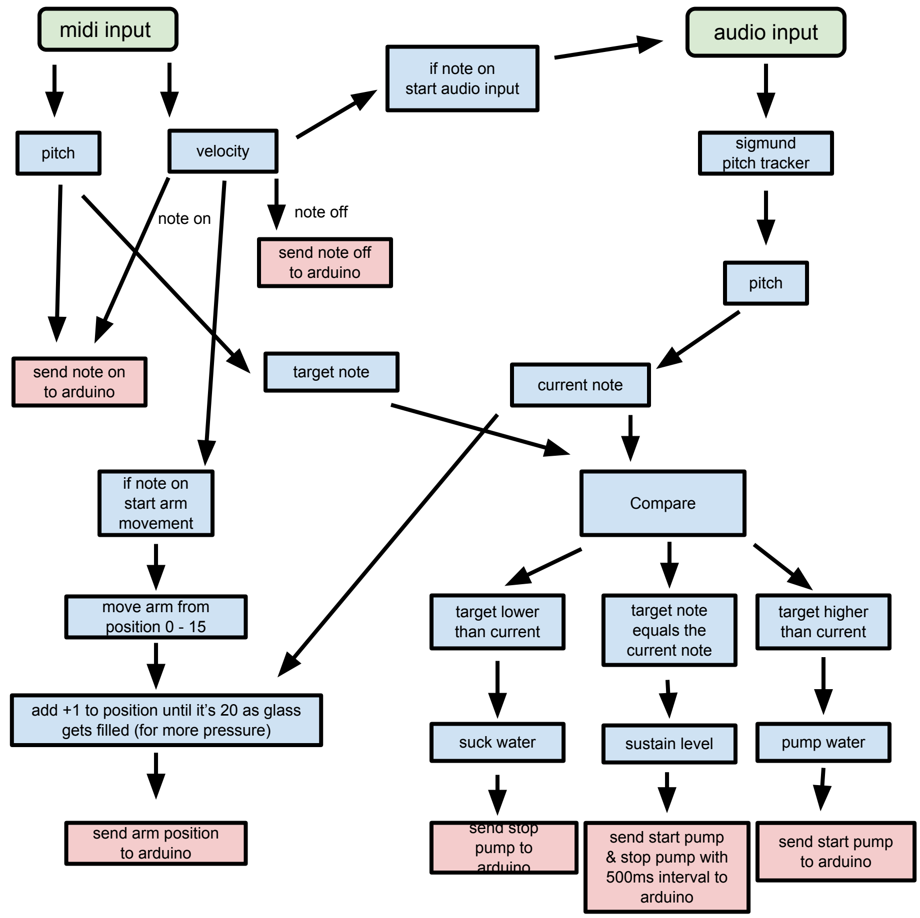
Each stepper motor has its own noteOn and noteOff function, allowing the enableOutputs and disableOutputs functions provided by AccelStepper to be called which puts the stepper driver circuits to sleep and lets them cool down. This was a critical function for heat dissipation as the drivers can natively provide 1.5Amps per phase without a heatsink and can drive into 2Amps - while the motors use about 1.7Amps. Shortly after the noteOn, the drivers start to get warm to touch and they cool down once noteOff is called.

Max/MSP

Conversus Vitra is built on top of Max/MSP, and it uses two custom made patches to control the servo arms and pumps. Most importantly the PID-loop that makes the instrument a possibility is built in Max. This section covers all the details of the software running in the Max/MSP environment.

Below is the screenshot and a block-diagram of a glass controller patch, that receives a MIDI note input from "Input 1", the number of the glass from the "Input 2" and outputs command numbers for the Arduino to interpret over serial port. Four controller patches like the one listed below controls the instrument.





The patch and block-diagram are annotated, but it is important to go through what each section does. Each patch receives its glass number input from "input 2", which is glass number 1 for this screenshot. It is then converted to note on and note off commands using math on the left side of the patch, and note off signals are detected by checking the MIDI velocity.

For example, the note on for glass one is "1", and note off is "41". The command list on the Arduino software goes as follows :

0 : Emergency Stop. (Stop pumps, glasses, arms, everything)

1 - 10 : Glass 1 Lowest Note On - Highest Note On

11 - 20 : Glass 2 Lowest Note On - Highest Note On

21 - 30 : Glass 3 Lowest Note On - Highest Note On

31 - 40 : Glass 4 Lowest Note On - Highest Note On

41 : Glass 1 Note Off

42 : Glass 2 Note Off

43 : Glass 3 Note Off

44 : Glass 4 Note Off

45 - 46 : Glass 1 Pump On - Off

47 - 48 : Glass 2 Pump On - Off

49 - 50 : Glass 3 Pump On - Off

51 - 52 : Glass 4 Pump On - Off

53 - 72 : Glass 1 Servo Arm Position 1 - 20

73 - 92 : Glass 2 Servo Arm Position 1 - 20

93 - 112 : Glass 3 Servo Arm Position 1 - 20

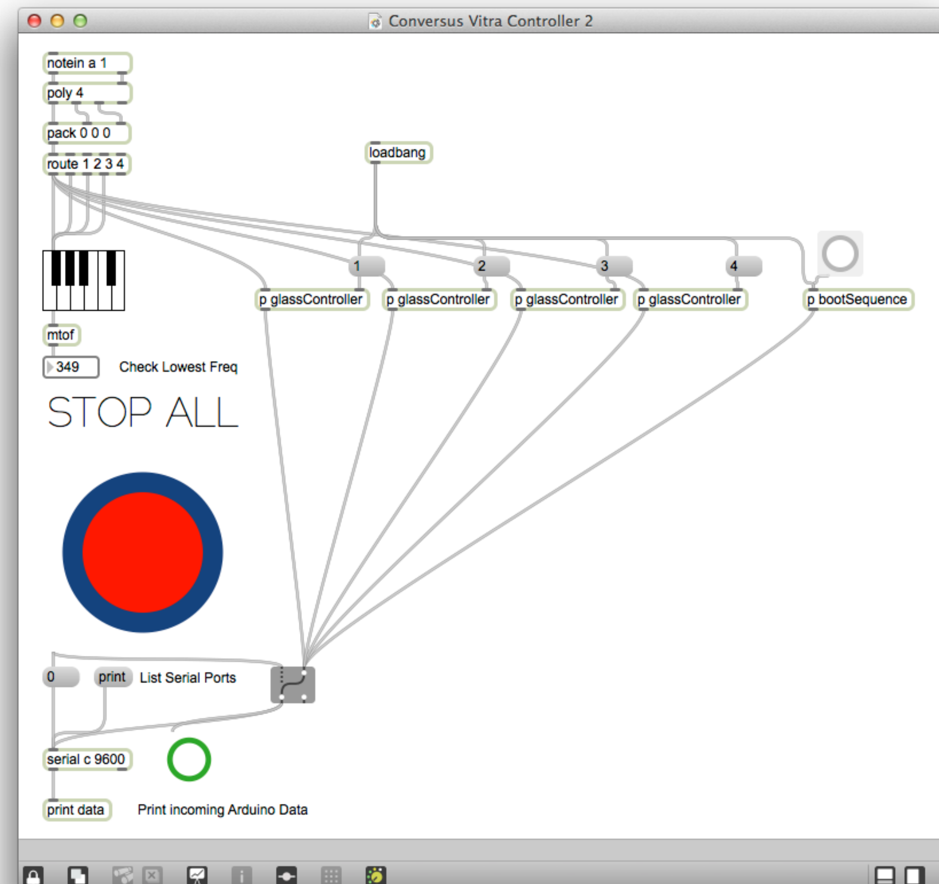
113-132 : Glass 4 Servo Arm Position 1 - 20

The glass number input is also used for the ADC input (audio input) object to select the input channel on the I/O for the patch. The audio signal from the selected input channel is directed into a "sigmund~" object where the audio goes through pitch detection.

The patch then compares the audio input pitch to the target pitch received from the MIDI keyboard and based on this either sends a “pump on” command, a “pump off” command, or sustains the note using pump on & off. The patch does this by sending a pump on / off signal every 500 milliseconds which is the time required to keep the pumps active just enough so that the gravity won't pull the water out or the pumps won't pump additional water into the glasses. It also creates an approximately 25 cents of vibrato on the lowest note and a maximum of 40 cents of vibrato on the highest note, while stopping right before the glass overflows.

On the right side of the patch, received “note on” and “note off” commands are also directed to servo arm control commands. The servo arms slowly sweep in and stop at a pre-defined pressure point. The pressure points are not necessary, but as each sponge attached to the servo arm is not uniform, often it is required to stop certain servo arms a few positions further than normal. The first 10 positions are 3 degrees, the next 10 positions are 2 degrees, and each degree is approximately 1mm. The sweeps are designed to make the sponge touch the glass relatively slower than the servo's original speed, which can be unstable for the glasses at high spinning speeds.

Also to send commands to the aforementioned glass controller patches, the instrument uses a main patch (screenshot below) to route the MIDI signals, collect all serial commands from all four patches, and run the boot sequence, which is just a pre-performance-test-run sequence that sends all serial commands with a second delay to check if everything's working.



Conclusions & Future Work

Using the same method, other continuous pitch instruments could be controlled as well. A great example would be a slide whistle, which also is a continuos pitch instrument that can relatively easily be controlled by a stepper motor/servo or even a trombone/buccin/sackbut coupled with a complex embouchure installation. The applications are not necessarily limited to continuous pitch instruments, but the method used in Conversus Vitra is best utilized for the specific case of hydrocrystalophones. This is mainly because constant rubbing and tuning can't be done at the same time, especially for multiple glasses, therefore making wine-glasses a perfect example to demonstrate how musical instruments can be improved using PID-loops.

Conversus Vitra was a great challenge and a great starting point for using small mechanical systems to create new instruments. It's been a great discovery as hydrocrystalophones were a bit of an uncharted territory. Unlike most instruments, they were perhaps the least modernized instruments that benefitted from technology. It is important to note that Conversus Vitra is perhaps only the beginning for a new way of creating hybrid hydrocrystalophones. It can certainly be improved in many ways in the future. Quieter motors, faster pumps, OSC wireless control, flex-sensor-gloves to control the pressure of the servo arms, silent valves to precisely maintain the notes and water levels and even staccato hits using solenoids. These are all possibilities, which can be improved in the future.

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This project wouldn't be possible without the support of my family. Thanks to them I grew up playing with electronics, hacking, tinkering, making and playing with things. I knew it was alright to void warranties, take apart my toys and build new ones.

The instrument exists today, thanks to Prof. Golan Levin. I've learned the most during the 2 years I've spent in Carnegie Mellon. His references, slides, jokes, and enthusiasm taught me so much, and made me feel home.

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While working on the instrument, I had to go through countless iterations and asked for help, ideas and guidance. I needed to laser-cut oddly shaped parts, find different ways to process materials, create better circuit boards and make better mechanical designs. My friends, colleagues and faculty were always with me, and Conversus Vitra wouldn't be possible without their help and moral support as well. So thank you; Prof. Ali Momeni, Prof. Aisling Kelliher, Prof. Tom Sullivan, Prof. Riccardo Schulz, Prof. Joshua Reiman, Abby Aresty, Charlotte Stiles, Adam Ben-Dror, Robert Kotcher, Dan Wilcox, Elijah Wood, Robb Godshaw, Haris Usmani, Carl Bajandas, Sarah Keeling, Patra Virasathienpornkul, Luke Schenker, Eden Weingart, Jake Marsico, Jorge Sastre Martínez and Madeline Gannon, without your support and friendship I wouldn't be able to survive through the hard 8 months.

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