# INVENTING NEW INSTRUMENTS BASED ON A COMPUTATIONAL "HACK" TO MAKE AN OUT-OF-TUNE OR UNPITCHED INSTRUMENT PLAY IN PERFECT HARMONY

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## ABSTRACT

We begin with a case-study of one of our public art installations, a large waterflute, which is a member of a class of water-based instruments that we call "hydraulophones". Hydraulophones are like wind instruments but they use matter in its liquid state (water) in place of matter in the gaseous state (wind). The particular waterflute in question has the unique property that it has never been tuned, and, additionally, due to what would appear to be a theft from an underground vault just before the main public opening, a number of important parts went missing. Additionally, due to some errors in the installation, we had to use some creative and improvisational computation in order to make the instrument "sing" in perfect harmony.

What we learned from this case-study, was a specific technique that allows computation to be used to make almost any out-of-tune, broken, or quickly built/improvised instrument play in perfect harmony, as long as a separate acoustic pickup can be used for each note. Our method uses a filterbank in which sound from each pickup is processed with a filter having a transfer function that maps the out-of-tune or otherwise "broken" sound to the desired sound at the desired pitch (optionally with acoustic feedback to excite the original acoustic process toward the proper pitch) without losing too much of the musical expressivity and physicality of the original acoustic instrument. We also propose the use of other techniques such as computer vision to relax the requirement of having separate pickups for each note, while maintaining the physicality of an acoustic instrument.

## 1. HYDRAULOPHONES

The hydraulophone is a musical instrument that works like a wind instrument but uses fluid in its liquid rather than its gaseous state-of-matter. The instrument looks like a giant flute, with water coming out of a row or array of finger holes. It is played by blocking the holes, which forces water back inside the outer housing, into a space between the outer housing and the inner housing, as illustrated in Fig 1. Some hydraulophones are hyperinstruments, equipped with MIDI outputs and networked on the Internet, whereas others are stand-alone units. Some are entirely acoustic, whereas others either require, or at least include a capability for electric amplification.

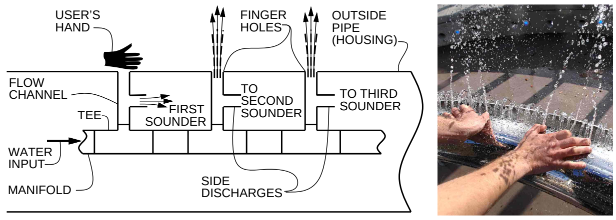


**Figure 1**. Hydraulophones are like wind instruments but they run on water rather than air. They look like giant flutes, but unlike a concert flute, each note has its own sounding mechanism, so the fingering is very easy. The instrument is played by blocking the FINGER HOLES, forcing water out the SIDE DISCHARGES. There is a one-to-one correspondence between finger holes and notes so blocking the first FINGER HOLE forces water out the first SIDE DISCHARGE to the FIRST SOUNDER, sounding the first note. Blocking the second FINGER HOLE sends water out the second SIDE DISCHARGE to the SECOND SOUNDER, sounding the second note, and so-on. By blocking more than one hole at the same time, one can play chords, and can also put expression into each member of the chord independently, in a fluidly, continuously flowing manner.

There are four kinds of hydraulophones currently available for installation in public parks, beaches, pools, and the like:

- The Sirenessie/harmellotron (TM), a mechanical hydraulophone that behaves similarly to a mellotron, in the sense that it is a sampling hydraulophone. It essentially plays back samples from mechanical disks or cylinders spinning underwater. The only electrical components are one motor to turn the cylinder or disk, and another motor to run the pump. A single motor can perform both functions. The device can also be hand-cranked in which case there is no need for any electrical components in the instrument. Each recording is played back by water spraying at a mechanical track, groove, or the like. To change the sample in this sampling device, the player switches to one or more different disks or cylinders, using water valves;
- The Waterflute (TM), a reedless instrument in which sound is produced by vortex shedding, and amplified by special hydrophones that we manufacture ourselves. The hydrophones have a unique feature of a small entrance port, to pick up minute spatiotemporal oscillations inside the instrument, underwater;
- The Clarinessie (TM), a single reed instrument in which sound is produced by an underwater reedlike element;

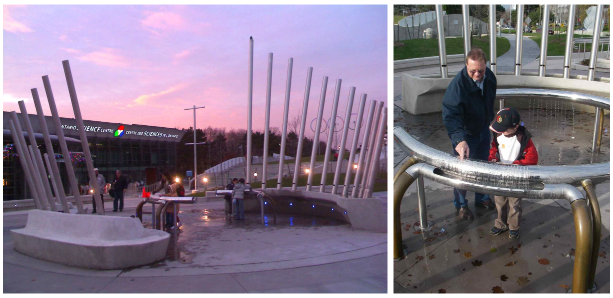

**Figure 2**. The main architectural centerpiece in front of Ontario Science Centre is a fountain that is a hydraulophone, approximately 10 metres in diameter and 20 feet high. This hydraulophone is reedless, but other hydraulophones include the Clarinessie (single reed), the $H_2$Oboe (double reed), and a wide variety of underwater orchestral instruments. (Leftmost picture 'glog captured by James Fung)

- The $H_2$Oboe (TM), an instrument having more than one reed associated with each note.

All four of these embodiments of the hydraulophone have the same user-interface, namely a row or array of water-bearing finger holes in which a player obstructs the water in order to make sound. Any of them can be supplied with hyperinstrumentation, MIDI output, or hyperacoustic output.

### 1.1. World's largest hydraulophone

Presently, the world's largest hydraulophone is the main architectural centerpiece out in front of the Ontario Science Centre (Fig.2), one of Canada's landmark architectural sites. It is designed to run 24 hours a day, for members of the public to freely play. Sound, produced by water, is picked up, underwater, inside the instrument, by specially manufactured hydrophones. Organ pipes, also filled partially with water, reproduce the sounds through a combination of pneumatic, hydraulic, and forced mechanical action. The instrument receives water from three water pumps, each connected to a 3-inch diameter supply line. Water is re-circulated, through the instrument, and is then collected and returned to the water intake of the pumps, for treatment (filtration, etc.), and ultimate re-use by the hydraulophone. Each pump is capable of producing 140 gallons per minute (GPM) of water. Additionally, compressed air is supplied by three Ingersoll Rand air compressors. Each compressor has four-cylinders and a 25 horsepower motor, and produces an air pressure of 93 pounds per square inch (PSI). Stable high and low pressure air is then achieved using two separate pressure regulators.

Our role in this installation was that of artist, responding to a call for art in the theme of Earth, Water, Wind, and Fire (the ancient Four Elements that correspond to what we now know as the states-of-matter: solid, liquid, gas, and plasma).

Our work was selected by a peer-review process, in response to a worldwide call for artist submissions in September 2004. There were submissions from 230 artists and designers from around the world. These submissions were narrowed down to 40 semi-finalists, in a first round of review. Another review narrowed these down to 10 finalists, from which the hydraulophone was eventually selected.

## 2. CASE STUDY AND NARRATIVE ON COMPUTATIONALLY CORRECTING FOR AN IMPROPERLY INSTALLED INSTRUMENT

The hydraulophone installation was part of a larger project that included the design and construction of a $4700m^2$ public exploration plaza. Consequently, numerous contractors and various architecture and design firms were involved, leaving many aspects of the project beyond our control. Our role as artists/sculptors was limited to supplying a piece (our instrument), to be installed by onsite contractors (not hired or managed by us).

Due to problems associated with the larger project, the hydraulophone installation was never able to be fully completed or properly tuned. For example, it was supposed to run year-round, right through the harsh Canadian winter. A large water heater was acquired to achieve this, but never installed and now sits idle in the sub basement of the main mechanical building.

Our limited access to and control of the larger project made our task very difficult. For instance, the type of water supply was completely uncertain to us, right up to and including the day of the grand opening (at which Canada's Minister of Culture and numerous other officials were present). On the morning of the opening, the instrument was actually run from a garden hose hookup, rather than a properly plumbed system. Additionally, errors in the installation equipped the instrument with drain pipes that were as small as the supply pipes (against our specifications which called for a drain pipe approximately four times the diameter of the supply pipe), such that major flooding occurs when the instrument is run at optimal flow rates and pressures. The the instrument currently runs at much less water flow that what we originally designed it to run at.

Another interesting twist occurred due to a contracting error: the underground vault housing our process control equipment, etc., turned out to be 5.5 feet high instead of the 6 foot height that we and the others agreed on. As a result, none of our hydropneumatic control systems would fit in the vault. This problem was compounded by a strange disappearance of our tuning mechanisms and various test equipment from the undergound vault on the morning of the grand opening. As a result the instrument has never been tuned.

### 2.1. A computational approach to solving the problem

We looked to a computational approach to ensure that the instrument would continue to work in the face of disasters beyond our control. However, we wanted to make sure that the introduction of computing did not change the fact that the hydraulophone is an acoustic instrument (i.e. we did not want it to become an electronic instrument).

In order to address the need to get good tonal stability from an instrument running on unknown and unpredictable water temperature, pressure, or flow rate, our approach was to fit each water whistle with a hydrophone to separately pick up the sound from the water, and then run the output from each hydrophone through a separate bandpass filter. Each filter was constructed such as to allow a note's fundamental and some desired harmonics through. We also incorporated acoustic feedback in order to help excite the original acoustic process back toward proper pitch.

Moreover, we had to locate the whistles in the FLOW CHANNEL rather than the SIDE DISCHARGE, for a variety of reasons, one being that the underground vault had no reliable drain (a sump pump was later installed but not, at-first, connected). Fortuitously, this means that the water jets all produce sound even when the finger hole is not blocked.

As a backup plan we installed an overhead camera on the tallest of the organ pipes (Fig 2, leftmost). The overhead camera, with high resolution optics, can be used to analyze the flow of water from each finger hole, so that, if desired, the instrument can begin producing sound as soon as a finger touches any of the water jets. Because the water is making sound at all times, this allows an acoustically originated sound to be allowed, disallowed, or modified, via the computer.

The hydrophones also pick up the water sound from the whistle in each jet. Although these are presently "blanks" (i.e. they would normally be tuned by hand), the sound made by the water still gives a relatively good range of expressive capability, once filtered to become the desired note.

Each bandpass filter in the filterbank basically must map the sound coming from the water into each musical note, and make it sound correct. Nevertheless even in this untuned form, the instrument is still an acoustic instrument, with a relatively high degree of expressivity, in at least the same way that an electric guitar retains a high degree of expressivity as compared with an electronic instrument like a keyboard synthesizer.

Our improvisational approach at recovering from some unfortunate events illustrates the power of modern signal processing technology, i.e. that the right signal procssing can force-tune a hydraulophone with a missing heater, erratically variable and inadequate water supply, stolen parts, and absent any form of tuning.

This was an important lesson, and one thing that we learned is that with the right kind of signal processing and computing power, one can take any instrument, no matter how badly out-of-tune it is, and make it play in perfect tune, without much loss in expressive capability.

## 3. HYPERACOUSTIC TRANSFORMATIONS

With the initial sound in hydraulophones being produced acoustically (ie. non-electronically), a wide variety of physical phenomena are at play which determine the acoustic sound texture — friction effects, resonances, as well as vortex shedding and stochastic turbulence.

Sound comes from turbulence in the pressurized water as it flows through the instrument's pipes. This sound, as picked up by hydrophones, extends beyond the range of human hearing, and indeed can be richly expressive in the subsonic, sonic, and ultrasonic ranges.

### 3.1. Logarithmic Superheterodyne Filterbanks

To make the instrument as expressive as possible, we wished to bring these subsonic and ultrasonic sounds into the audible range by way of signal processing of the acoustically-generated signals. In a way similar to (but not the same as), superheterodyne radio reception, signals can be down-shifted and upshifted by means of using an oscillator in the process of frequency-shifting and various forms of selective sound filtration. However, unlike what happens in a superheterodyne receiver, we prefer to scale frequencies logarithmically rather than linearly, in order to better match human perception.

This digital signal processing is, in a general sense, a filtering operation, which may be highly nonlinear in certain situations.

As an example, we have shifted ultra-low frequencies (of which a musician gains very detailed control, when playing on our hydraulophones [Mann et al., 2006]) into the audible range by means of oscillator-based filterbanks using MIDI devices. An array of parallel MIDI devices serves as a collection of oscillators to perform frequency-shifting. In this way, the frequency band from 0 to 20 Hz in the subsonic range is brought into the audible range. (Non-MIDI based filters are obviously required to process the higher frequency audio acoustically picked up from from the water's sounds.)

Note that rather than triggering a sample or MIDI note as has been often done in computer music, we retained the acoustic property of the instrument by simply passing each of the parallel sound signals (numbering 12 on the North fountain and 45 on the South fountain) through a bank of nonlinear filters.

By implementing some of the filterbanks (the filterbanks corresponding to subsonic input audio) in a hydraulophone using MIDI-based oscillators, we needed to communicate a large bandwidth of information over MIDI channels. Our method was tested as compliant with the MIDI standard, and was successful on several MIDI compliant devices, but, interestingly, it produced erratic behaviour in a great many MIDI devices even though these devices worked fine for more conventional applications.

### 3.2. Duringtouch (FLUIDI)

A curious side-effect of using MIDI-compliant oscillators to implement acoustic filterbanks led to something we call *duringtouch*. Duringtouch is the use of MIDI signalling for a smooth, near-continuous processing of audio from a separate microphone, hydrophone, or geophone for each note on an instrument such as a hydraulophone.

Normally MIDI is used to *trigger* notes using a note-on command, at a particular velocity, perhaps followed by *aftertouch* (channel aftertouch or polyphonic aftertouch).

With duringtouch, however, the idea is to get a MIDI device to become a sound processing device. With our hydraulophone, there is no such thing as a note-off command, because all the notes sound for as long as the instrument is running (especially when the whistle of each note is located in the FLOW CHANNEL, as shown in Fig.1). Indeed, all notes on a hydraulophone have some level of background activity from the continuing water flow and turbulence, even when no note is being played. (The gentle "purring" of the instrument is a soothing sound that many people enjoy while sitting in a park eating their lunch.)

All notes are sounding **before**, **during**, and **after** the user **touch**es the water jets (i.e. all the time). The sum of this sound over all notes is called the hydraulophone's "compass drone". (We call this sound the "compass drone" of the instrument because it makes audible the compass spanned by the instrument.) Signals from each of the jets on a hydraulophone can be processed to enhance, reduce, or modify the compass drone. When done via duringtouch, we are left with a computer-modified "duringdrone".

The first stage of duringdrone processing (before hyperacoustic processing) is an affine (gain and bias) function of the initial sound. More detail is given in our other paper to appear in these proceedings, entitled, "The electric hydraulophone: A hyperacoustic instrument with acoustic feedback".

An example of this processing takes place inside a microprocessor-based affine duringdrone processor we created. It is able to handle signals from twelve audio inputs (eg. hydrophone pickups on twelve notes of a hydraulophone). The processor nicely accounts for vacuum effects in the hydraulophone pipes due to the bernoulli effect when the water flow is turned up.

The duringdrone gain and bias can be tuned differently for each note. In fact, great care in hydraulophone installations is taken to adjust the compass drone to create a certain character of sound for compositional purposes, and to affect the environmental ambient sound when the instrument is not being played. Often, the parameters are adjusted to emphasize certain notes so as to create a faint a minor-ninth chord. This is an artistic, rather than technical decision that we make, based on our desire to create an introspective tension when people first walk up to the instrument and perceive it merely as a sound sculpture before they begin to play.

At some installations, a number of people, completely unaware that a hydraulophone was a musical instrument, would walk to it and sit down next to it to enjoy the soothing sound of the re-emphasized compass drone.

The fact that notes "play" before anyone touches the instrument gives what we might call "beforetouch". Thus, philosophically, the instrument tries to go beyond the idea that a note must come into existence and then be modified by aftertouch.

The concept of duringtouch does not exist within the MIDI standard. As a result, we had to find MIDI devices that could be "hacked", "hijacked" or repurposed into what we termed "FLUIDI" (using MIDI oscillators to achieve a filterbank). As well, we used existing MIDI commands to transmit data relevant to the filtering process, but the speed could have benefitted if there were MIDI commands specifically for duringtouch – that is, messages for smooth variation of sounds (not based on Note on/off). Our experiments were on a variety of MIDI devices, including the Korg OASYS, the Open Labs Neko. Presently the most successful use of duringtouch was with the Yamaha PSRE303.

We have also made circuits that downgrade from duringtouch to regular MIDI so that the hydraulophone can be used as a MIDI controller. But then the sound no longer comes from the water, because the MIDI is no longer being used as a filter. Thus we prefer to use a "hacked" PSRE303 rather than converting to standard MIDI to ensure that the instrument is operating acoustically (i.e. whereby sound originates in the water) and not merely as a user-interface.

Our use of a hydraulophone as a MIDI controller has been reported in http://createdigitalmusic.com/2006/07/26/

## 4. USING OUR HYDRAULOPHONE SIGNAL PROCESSOR TO MAKE OTHER HYPERACOUSTIC INSTRUMENTS

Much of computer music concerns itself with the generation or composition of music in which the resulting computer-based instrument (or computerized hyperinstrumental extension) would rightly be classified as an electrophone (Hornbostel Sachs 5th category[Sachs, 1940], as currently practiced[Kartomi, 1990]).

However, as we noted with our "broken hydraulophone" fix, computers may also be used for digital signal processing as applied to acoustic instruments, without changing the fundamental categorization of the resulting hybrid. For example, an electric guitar, whether running through traditional analog guitar effects pedals, or digital effects (e.g. software pedals, waveshapers, etc.) is still a chordophone — the fact that the effects are digital rather than analog (as in a traditional guitar effects pedal) does not necessarily change the hybrid computer plus guitar into an electrophone.

Just as with the case of fixing the "broken" hydraulophone, we wish to use computers in this sense, in order to facilitate the creation of other new instruments that remain in Horbostel Sachs categories 1 to 4 (i.e. the non electrophone categories), and that also define new categories (categories 1-4 of our co-pending submission to ICMC 2007, entitled "physics-based organology..."). In particular, we approach the computer as a tool to help us overcome some of the inherent limitations in making acoustic instruments work better with —or under— water.

### 4.1. Underwater xylophone

Many instruments from the Earth/Solids category (xylophones, drums, violins, etc.) will work underwater to some degree, apart from eventual deterioration (e.g. wood rot, rusting of metal parts, dissolving of water-soluble glues, etc.). This does not change the fact that they are still from the first category, because we distinguish between

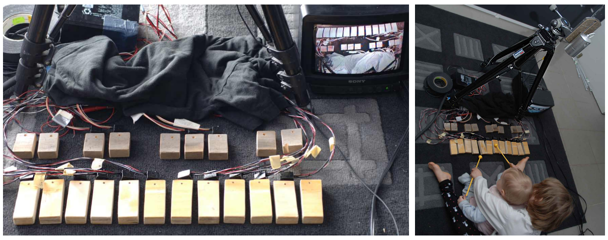

**Figure 3**. **Making a bell-like sound from a dull thud:** An array of wooden blocks is setup on a carpet. Each one is fitted with a separate acoustic transducer fed to a separate bandpass filter having transfer function equal to the quotient of the desired bell sound and the sound made by actually hitting the block.

the medium of sound production and the surrounding medium in which the sound is produced. Thus an underwater glockenspiel is no more a hydraulophone than it is an aerophone when it is operated in air (i.e. above the water's surface).

Over a roughly 3 year period, from 2004 to 2007, we held a series of weekly underwater concerts/performances, and the like, using acoustic musical instruments. One problem with the use of Earth/Solid instruments in water rather than in air is that the sound decays very quickly due to the higher damping of the water (water is approximately 1000 times more dense than air). For example, a tubular glockenspiel that we made out of 19 rustproof (aluminum) pipes sounded more like a xylophone (Xylo is Greek for wood, and denotes an instrument using wooden blocks) than a glockenspiel. While this "woody" sound was desirable in some cases, there were other situations in which we wished to be able to have a more bell-like sound quality.

To address this need, we attached a hydrophone/geophone (a form of underwater contact microphone that we custom-manufactured ourselves) to each of the 19 pipes in the glockenspiel, and routed these 19 signals through a digital signal processing system, and then back into the pool through underwater speakers.

As with duringtouch, we did not simply trigger a sample or MIDI note according to the way a pipe was struck. We retained the acoustic property of the instrument by simply passing each of the 19 sound signals through a filter having transfer function $H(f)$, where we computed $H$ based on taking ratios of sound recordings made from real tubular bells and our instrument when it was underwater.

### 4.2. Making a bell-like sound from a dull thud

Our problem of clarifying the underwater glockenspiel basically amounted to getting a dull thud to ring out as clear as a bell, while maintaining all the nuances of how it was struck.

To demonstrate this newly invented instrument in a simple way, we set up a version of it outside the pool, using a more familiar setting of an array of wooden blocks each fitted with a separate audio transducer (Fig 3).

Note that the range of expression is much more diverse than merely velocity-sensitive triggering of a recording of a bell sound where amplitude varies with strike velocity. For example, rubbing the sticks against the blocks (rather

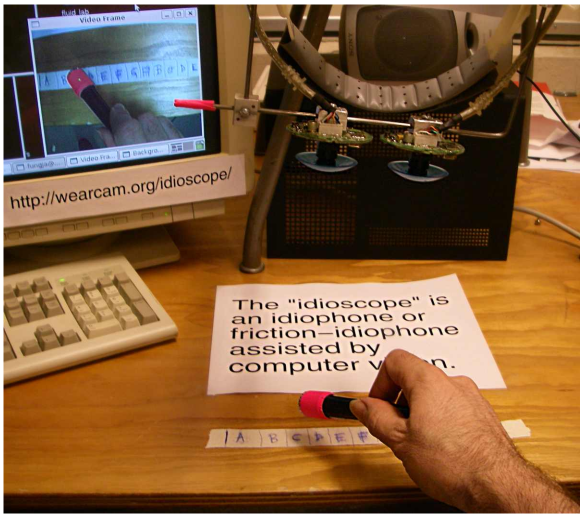


**Figure 4**. **Making a bell-like sound from hitting a desk:** A computer music system that is not an electronic instrument. Sound originates acoustically, and the role of the computer is merely for post-processing (much like a Wah Wah pedal on a guitar). The center frequency of the filter's passband varies with position, as detected by the overhead camera rig. Note the wearable stereo camera rig hanging from a fixed location. The cameras can be mounted to a tripod, or worn by the player.

than striking the blocks) produces a sound similar to that obtained by rubbing sticks against a real bell.

The wooden blocks can be varied in size so they produce the correct note to begin with, or they can all be the same size (as shown), so they all produce the same note prior to entering the bandpass filter for selection of the correct note.

Optionally, the audio transducers can be mounted in sticks, mallets, or the like, while an overhead camera allows the computer to see which block is struck. This has the advantage of allowing the computer to slightly modify the transfer function depending on where the block is struck, allowing pitch bend, timbral variation, etc..

This computer vision is similar to the use of vision in the O.S.C. hydraulophone, to expand the range of expression that is already present where and when the acoustic sound is initially created through direct contact.

With an overhead camera focused on the underwater xylophone, we can eliminate the need for a separate audio pickup in each block, and instead mount an audio pickup in each mallet or stick, thus reducing the required number of pickups from 19 down to 2, as well as reducing the required number of microphone inputs from 19 down to 2 (thus using a standard stereo sound card rather than a specialized multi-channel analog to digital converter).

With an overhead camera, we can also eliminate the separate blocks, and simply use a single surface as the playing surface, as shown in Fig. 4. The result is a glockenspiel having continuously variable pitch.

For the computer vision we used the Intel OpenCV image library, but any standard computer vision system, known to anyone skilled in the art, may be used. Improvements to speed of processing can also be implemented using the OpenVIDIA libraries.

We decided to use a stereo wearable camera rig to give

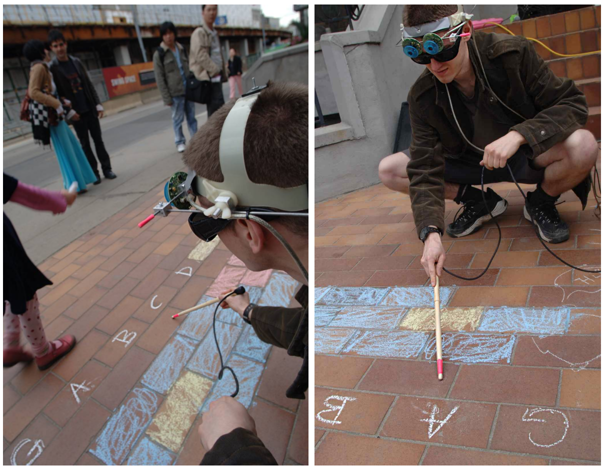

**Figure 5**. **Sidewalk bricks or pool tiles cum tubular bells:** Cyborg street performance using wearable camera rig and computer vision to control the transfer function of virtual effects pedals. A Wah-Wah like virtual effects pedal filters the acoustic sound of sticks hitting concrete. Filter transfer functions can be changed to achieve sounds of church bells, glockenspiels, piano, etc., but the sound all originates acoustically, thus remaining in the idiophones (not electrophones) top-level.

the player the option of either hanging the camera rig from a tripod (or similar mount above a desk), or wearing it. When worn, the player has the benefit of an infinitely large playing area, by simply assigning different transfer functions to a limitless library of real physical objects.

For example, in some of our cyborg street performances we used a vast expanse of sidewalk space to create a giant tubular glockenspiel (Fig 5). The result is an infinitely large glockenspiel having continuously variable pitch.

We ported our latest version of this software to run on a camera phone, so that, plugging the special stick into the microphone input of the phone, one can use the instrument while listening to headphones (Fig:6). Our program will run on underwater camera phones, such as a UTStarcom Underwater GzOne Cell Phone, using wireless bluetooth microphones, combined with a SwiMP3 (TM) earpiece.

We made some other versions that work underwater, in which the player wears underwater cameras and hits, rubs, or scratches the tiles on the bottom of a pool in various ways. Thus an underwater "cyborg" musician can use the bottom of the pool as a giant glockenspiel or other instrument.

In this way, the signal processing makes it possible for the idiophones to sound clear as a bell when underwater, while maintaining all the subtle variations and acoustic textures associated with being underwater.

### 4.3. Underwater friction idiophone having polyphony combined with continuously variable pitch

It was Benjamin Franklin's love of water that led him to invent the glass armonica (sometimes also referred to as glass harmonica), a glass harp consisting of a row of glass goblets all mounted to a single spinning metal shaft.

While playing glass harp underwater, we found that the water imparted some nice attributes to the sound, but we wanted some additional versatility, and the option to have a high Q-factor (less damping) at certain times during our

**Figure 6**. **A 12-bar idioscope running on a camera phone:** One or two drumsticks or mallets with contact microphones plug into the headset input of a standard cameraphone. While listening to earphones, the player strikes an object in view of the camera. There are 12 vertical zones, each defining a separate note on the musical scale. The player can walk down the street and strike street signs, lamp posts, and the like, as part of a live performance webcast in real time. Here the player is locating a fire extinguisher through one of the 12 zones defined in the camera phone view and hitting the extinguisher with the mallet. Whatever pitch is produced by the sound of hitting the extinguisher is filtered and frequency-shifted to the desired note, so that all 12 notes can be produced by hitting this one fire extinguisher or other similar everyday objects.

performances. In order to achieve this, we used a spinning cylinder, which produced sound continuously along its entire length.

The sound is picked up by a contact microphone in the cylinder, and transmitted wirelessly to a computer. A computer vision system also connected to the camera takes note of where the rod is touched (positions, orientations, and contact geometry of all fingers in contact with the rod).

This information is used to control the attributes of one or more (depending on the number of fingers touching) bandpass filters. The instrument was used in a variety of public performances (street performances, underwater performances, etc.). See Fig 8.

### 4.4. The evanescope: An underwater friction idioscope based on total internal reflection

We constructed a variation on the friction idioscope that uses a special glass cylinder immersed in a liquid having approximately the same refractive index as the special glass. With this matching of refractive indices, the glass cylinder appears almost invisible in the water. Using underwater cameras looking upwards, at an angle less than the critical angle of total-internal-refraction, the image of the fingers is strongly enhanced, such that the camera can much more easily pick up the fingers while ignoring everything else in the scene (Fig 8). Additionally, microscopic water waves produced by the sound vibrations are visible, so that the camera can actually pick up some of the ripples from the sound waves in the scene.

**Figure 7**. **Polyphonic friction-idiophone having continuously variable pitch:** A spinning aluminum cylinder with a specially textured surface produces sound picked up by a wireless contact microphone inside the cylinder. The sound is fed to one or more (depending on the number of fingers touching the cylinder) bandpass filters controlled by computer vision. The instrument can be used above or below the surface of the water.

**Figure 8**. **An underwater friction-idiophone based on total-internal reflection:** Underwater (plus optional overhead) cameras "look" at a glass cylinder. Placing the camera further underwater than the cylinder, and having it look up at an angle, makes it possible to see the fingers as they disturb the evanescent wave of total internal reflection. This gives rise to a hyper-sensitivity in the image plane, making visible subtle sound-induced ripples in the water that occur from sound vibrations in the glass cylinder. With carefully constructed computer vision, the camera can thus function as an optical pickup of acoustic phenomena, much like an electric guitar having an optical pickup. Together with an array of geophones, hydrophones, and microphones, this provides a multiply acoustic instrument having a richly acoustic physicality.

## 5. DO FILTERBANKS TURN AN ACOUSTIC INSTRUMENT INTO AN ELECTRONIC INSTRUMENT?

Instruments like the idioscope use computer vision and computation to adjust coefficients in a filter that post-process acoustically generated sounds from microphones, hydrophones, geophones, or the like. Such a "hyper-acoustic" instrument makes it possible to bring subsonic and ultrasonic acoustic vibrations into the audible spectrum and add to the richly physical experience of playing a real acoustic instrument.

Unlike a hyperinstrument[Machover, 1991] in which position sensors, or the like, add synthetic sounds to an acoustic instrument, the proposed hyperacoustic instruments use sound as their primary computer input, with vision affecting the processing of this sound.

We also constructed some variations of these instruments using mechanical resonators, as well as analog electric resonators (such as a computer-controlled Cry Baby (TM) Wah Wah pedal), to convince even a skeptic of the acousticality of the instrument (e.g. using computer vision to position the setting of an analog guitar pedal connected to a vacuum tube amplifier).

However, we feel that regardless of whether these post-processing effects are mechanical, analog, or digital, the instrument, in whole, remains an idiophone, since the initial sound production comes from solid three dimensional physical matter in the real world, also giving a fundamentally tactile and "real" playing experience.

We believe, therefore, that instruments like the idioscope are not members of the Horbostel Sachs 5th Radiophonic/Electrophone category [Sachs, 1940] any more so than is an electric guitar with effects pedals, or a Steinway grand piano that's been electrically amplified.

## 6. STATES-OF-MATTER: A PHYSICS-BASED INSTRUMENT TAXONOMY

The form of computer music that we present in this paper makes it possible to fashion a wide range of musical instruments from various physical processes that have traditionally not been associated with music.

Many of the newly presented instruments do not fit well within existing ontologies of musical instruments, and thus require a broadening of existing musical categories, or introduction of new ones. For example, the hydraulophone either requires a broadening of wind instruments to include all fluids (water or air), or the introduction of a new category of instruments where sound comes from water.

The Clarinessie/harmellotron is a sampling/informatic instrument that uses entirely mechanical computation to produce sound. This suggests that the fifth Hornbostel Sachs [Sachs, 1940] category (Electrophones) should be broadened to include all sound synthesis, whether the computation is optical, mechanical, or electric (i.e. broadening computer music to include even some instruments that involve computation without electricity).

We thus propose a physics-based musical instrument classification scheme, re-arranging the first three top-levels of the Hornbostel Sachs system (those in which sound is produced by matter in its solid state) as sub-categories, under the top-level "solid", and the fourth top-level of the Hornbostel Sachs system (in which sound is produced by matter in its gaseous state), under the top-level "gas", and adding two new top-level categories, "liquid" and "plasma".

It also makes sense to present the four states-of-matter in increasing order of energy: Earth/Solid first, Water/Liquid second, Air/Gas third, and Fire/Plasma fourth. At absolute zero everything is a solid. then as things heat up they melt, then they evaporate, and finally, with enough energy, become a ball of plasma, thus establishing a natural physical ordering as follows:

1. "Earth"/Solid (ordered in increasing dimension, from 1d to 3d):
   - 1.**1** chordophones (strings): stretched solids that are essentially **1-dimensional**, i.e. their cross section is much less than their length;
   - 1.**2** membranophones: stretched solids that are essentially **2-dimensional**, i.e. their thickness is much less than their surface area;
   - 1.**3** idiophones: solids that are essentially **3-dimensional** — no tension;
2. "Water"/Liquid: hydraulophones;
3. "Air"/Gas: aerophones (wind instruments);
4. "Fire"/Plasma: ionophones;
5. "Quintessence"/Aether/Idea/Informatics: instruments in which sound is initially produced by computational means, whether optical, mechanical, electrical, or otherwise.

The new classification scheme also mates well with the range of acoustic transducers that exist: **(1) geophone** for Earth/solid; **(2) hydrophone** for Water/liquid; **(3) microphone** or **speaker** for Air/gas; and **(4) ionophone** for Fire/plasma.

## 7. CONCLUSION

In using computers to recover proper sound from an improperly installed hydraulophone, we uncovered a unique approach to computer music, namely the use of a bank of filters, one for each note, of a polyphonic woodwater instrument (like a woodwind but using water instead of wind).

This approach was shown to also work for a variety of newly invented instruments, a number of which were presented and described. The method was shown to work in situations where there is a separate sound-producing mechanism for each note, which can be captured with a separate pickup (microphone, hydrophone, geophone, or the like) for each note. We also found that the requirement of a separate microphone for each note could be relaxed using other sensing technology such as computer vision.

Computer processing, digital filtering, and the like may be applied to acoustic instruments, without changing the fundamental categorization of the resulting hybrid. For example, our underwater and above-water idioscopes use digital signal processing and computer vision, but the fact remains that the sound originates acoustically. Tracing back to the original source of sound is true to the spirit of the Hornbostel-Sachs organology, as typically practiced. The unique ability of this form of computer music to regularize or "tame" the "baddest" of instruments allows us to venture into states-of-matter ordinarily off-limits to musical usefulness, namely water and plasma, with rock-solid reliability even in the face of improperly installed instruments. Our computational approach can be used to create instruments that produce sound from physical processes, as based on matter in any of its four states: solid (Earth), liquid (Water), gas (Air), plasma (Fire), even under some of the most adverse conditions of improper installation, neglect, theft, sabotage, or simply the use of media that was never meant to be used for musical instruments.

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