User-Interfaces Based on the Water-Hammer Effect: Water-Hammer Piano as an Interactive Percussion Surface

Steve Mann, Ryan Janzen, Jason Huang, Matthew Kelly,* Lei Jimmy Ba, Alexander Chen
University of Toronto
email: hydraulophone at gmail dot com

ABSTRACT
Water hammer, a well known phenomenon occurring in water pipes and plumbing fixtures, is generally considered destructive and undesirable. We propose the use of water hammer for a musical instrument akin to hammered percussion instruments like hammered dulcimer, piano, *etc.*.

In one embodiment, the instrument comprises an array of mouths each for being struck with the open palm or fingers, each mouth connected to a separate hydraulic resonator. In another embodiment, we use a basin or pool of water as a multitouch user-interface where sounds made by water are acoustically sensed by an array of hydrophones (underwater listening devices).

Using water itself as a touch surface creates a fun and playful user interface medium that captures the fluidity of the water's ebb and flow.

Author Keywords
Absement, Filterbanks, Hydrophone, Hydraulophone, Hyperacoustic, Musical Instrument, Natural pitch notation, Nessie(TM), Nessonance, Nessonator(TM), Presement, Sensory Table, Shifterbanks, Tangible User Interface, Water Drum, Water Hammer, Water Table, WaterDrum, WaterHammer-Drum, WaterTouch(TM), Waterplay

ACM Classification Keywords
H.5.2 Info. systems: Interfaces—*Haptic I/O; Auditory feedback; Input devices; User-centered design*; J.2 Computer apps.: Physical sciences & engineering; J.5 Computer apps.: Arts & humanities—*Music*

General Terms
Design, Experimentation, Human Factors, Theory

INTRODUCTION

Background and related work
Water has a history of use in human computer interaction [18], public sculpture [16], and water therapy [15].

*Thanks to the Human Media Lab at Queen's University.

TEI'11, January 22–26, 2011, Funchal, Portugal.

Water is a natural "element" (element as in Earth, Water, Air, Fire), that can form a natural and fluid tangible interface.

Water has also been used in hydraulophones [13], which use pressurized jets of water as a tactile user-interface. In some sense, the hydraulophone may be regarded as an ORGANic user-interface [19]. Tangible user interfaces have proven themselves in many types of human-computer interaction. Ishii's bottles [6], and the Music Cube [1] form notable examples of tangible interfaces applied to the domain of music.

THE WATER HAMMER PIANO
Musical instruments are generally classified according to the manner in which the initial sound production occurs[8][17].

Previously known acoustic musical instruments make their initial sound from vibrations in solid (strings and percussion) or gas (woodwinds and brass).

Plumbing fixtures such as toilets, faucets, showers, and the like, often make strange noises, and sometimes even make sounds that are almost musical (or at least oscillatory). With the advent of sensor-operated electronic plumbing fixtures, such phenomenona are more prevalent than ever!

We're all familiar with the clanging sounds made by pipes when a solenoid actuated valve abruptly turns off the water to an automatic faucet when the user's hands are taken away, or the thump of an automatic flush urinal or toilet.

In many situations, these sounds originate, at least in part, by matter in its *liquid* state.

Ordinarily water hammer is very destructive, and plumbers go to great lengths to silence bathroom fixtures. There is a large aftermarket for products such as water hammer arresters or water hammer suppressors, as well as delayed valves, and the like. These products aim to suppress vibrations, resonances, and sounds made by pipes and plumbing fixtures.

But what if we could use this violent water-hammer phenomenon creatively to make a new musical instrument? We have made a variety of musical instruments that produce sound from matter in its liquid state. For example, Fig 1 shows two embodiments of the waterhammer piano.

The instrument is made from a dozen Type 316 stainless steel pipes each having extremely thick walls. Whereas most water pipes are Schedule 10, or at most Schedule 40, we

Figure 1. (left) Whereas a traditional piano uses hammers to strike strings, the water hammer piano creates sound by acoustic disturbances that originate as water hammer in any of its 12 pipes (a separate pipe for each note of the musical scale). The instrument is played by suddenly stopping the flow of water, resulting in a hammering effect similar to that observed in solenoid operated valves (e.g. automatic sensor operated faucets). Hydraulic resonance occurs at various notes due to the varying lengths of the pipes. (right) a single-note "Nessonator^{TM}" comprises a Bordeaux wine bottle encased in concrete (foreground). In the background is a 12-jet hydraulophone named "Nessie". The word "Nessonator" is a portmanteau formed from the words "Nessie" and "resonator".

made our water-hammer instrument from pipes having a wall thickness of Schedule 160, the highest wall thickness standardly available.

Water emerges through the opening of each of the 12 pipes. The instrument is played by striking the ends of the pipes (where the water emerges) with rubber mallets, or, simply, by blocking the water jets with the fingers, in an abrupt fashion. This sudden increase in water pressure produces a violently forceful acoustic impulse, which resonates within the pipe, as a water column.

This instrument has a range from 3A to 4E, as expressed in hydraulophone pitch notation, also called natural pitch notation. The lowest note of a hydraulophone, like the piano, is an "A".

Frequencies and natural pitch notation

We propose Natural Pitch Notation (NPN) to overcome the following 5 problems with previously proposed notation [20] (IPN, International Pitch Notation) [1] :

- **IPN reverses significant digits**, e.g. middle C is denoted C4 where the least significant digit "C" (the one that increments faster) is to the left while the most significant digit, "4", is on the right;
- **leftmost digit starts counting from three:** in counting, the "carry" occurs on the third letter (i.e. "C"), not the first letter (i.e. "A") of the alphabet.
- **reference frequency is non-integer:** "A440" is the standardized reference frequency, and every A from 55 CPS and up is an integer frequency. But IPN is C-centric, so every time the octave counter increments, it does so at a non-integer frequency.
- **leading zeros appear in the middle,** e.g. the note after B09 = B9 is C10; the new "1" digit jumps into the middle of the digit sequence, even though the "1" is now the most significant digit;
- **least significant symbol in the middle:** the sharp (♯) or flat (♭) is the least significant parameter, but improperly appears between the digits, e.g. between the "B" and the "4" of B♭4.

[1] There is confusion as to the terminology; e.g. International Pitch Notation (IPN); so-called "scientific" pitch notation; "scientific pitch", which is also a term for a special version of middle C at exactly 256 CPS, which itself is inconsistent with the widely recognized ISO 16 standard A pitch at exactly 440 CPS.

For example, in the existing IPN system, a frequency of 8.176 cycles per second is denoted "C-1". The negative sign appears between the two digits, rather than to the left, as should be the case.

Natural pitch notation, though, works like the odometer on a car: the rightmost digit or symbol moves fastest. Also the letters occur in their *natural* order, starting with the first letter of the alphabet. We use the word "natural" here as a double entendre, because it also refers to the *natural minor* scale, rather than the major scale that goes from "C" to "c". One reason this notation is natural for hydraulophones is that all hydraulophones are manufactured on a minor scale.

Moreover, the "tens" (i.e. the numbers with the rightmost digit being lowest), fall on integer frequencies once we get to 55 CPS and above:

Note	**Freq/CPS**	3A	110	8A	3520
-1A	6.875	4A	220	9A	7040
0A	13.75	5A	440	10A	14080
1A	27.5	6A	880	11A	28160
2A	55	7A	1760	...	...

Thus, for example, the first 12 white keys of the piano (which are exactly 2 octaves down from the 12 jets of the hydraulophone) are: **1A, 1B, 1C, 1D, 1E, 1F, 1G, 2A, 2B, 2C, 2D, 2E**. Sharps and flats now properly appear at the end. For example, -2B♭ is 3.642 CPS. Likewise, saying B♮ is like placing a zero after the decimal point, analogous to saying "2.0"; i.e. writing "2.0" is more specific and implies more precision than "2". In summary, the minus sign is on the left side, followed by the most significant digit, then the least significant digit, and finally the sharp, flat or natural sign.

Water-Hammer Piano Construction

To cause the water in each pipe to resonate at the desired frequencies, several types of resonators can be used. Fig 1(right) shows a single-note from a set of 12 "Nessonator^{TM}" hydraulic resonators. Each note is made from an appropriately modified (cut down to a selected length or the like) Bordeaux wine bottle encased in concrete. The concrete protects the bottle from being broken by hydraulic waterhammer forces, and also ensures the sound is influenced purely by vibrations of water and not of the solid container.

Another embodiment of the waterhammer piano is shown in Fig 2. In this embodiment there are 12 rigid toilet tubes each connected to an elastic hose of equal length, initially (until tuning begins). The hoses were connected to a manifold to supply water into all of them. One prototype embodiment of this was later built into a Spaberry hot tub.

In some embodiments, one or more hydrophones (underwater microphones) listen to the sound made by the vibrating water. The outputs of the hydrophones are electrically amplified, and sometimes various auditory effects processors are used, or other processors are used to generate other multimedia effects, not necessarily limited to auditory effects.

Figure 2. An early embodiment of the waterhammer piano comprised of rigid pipes connected to elastic thick-walled rubber hoses. The instrument was fine-tuned by trimming away the rigid pipes, or the rubber hoses, to raise or lower the resonant frequency of each note to the correct pitch.

In another embodiment of the invention, a user-interface comprises a dozen or so 3 inch pipes (approx. 76cm in nominal diameter), of various lengths, each connected to an identical rubber elastic medium, each of which has a filling nipple. The pipes are supplied by a gentle stream of water that maintains a meniscus that is concave downwards. The instrument is played by slapping the meniscus with the palm of the hand. The resulting shockwaves, water-hammer, or the like, sets a column of water into transient disturbance such that it settles into an oscillatory motion that decays exponentially, like that of a struck string on a piano. Oscillations occur due to the interaction between the inertia of water in the pipe, and the elasticity of the end cap on the bottom of each pipe (i.e. like a mass-spring oscillation).

We can relate a mass-spring resonator to a capacitor-inductor (C-L) resonator, using the force-current analogy. We define a quantity analogous to capacitance as follows:

$$C = \rho l / A \tag{1}$$

where ρ is the density of the fluid, typically in units of kg/m^3, and l is the length of the pipe leading from the elastic hose to the user-interface port, and A is the cross sectional area of the pipe and its user-interface port.

Capacitance, C, of Equation 1 is in units of

$$\frac{\frac{kg}{m^3} m}{m^2} = kg/m^4. \tag{2}$$

The eLastic hose or buLb of the bottle forms the spring part of the mass-spring arrangement that gives hydraulic resonance ("Nessonance"). The eLastic part is denoted by the letter "L" and is analogous to inductance. For example, a volume of water in the buLb of the bottle has eLasticity:

$$L = V\beta = V/K, \tag{3}$$

where β is the compressibility given by $\beta = -\frac{1}{V} dV/dp$, whose reciprocal is the incompressibility, K, given by $K = -V dp/dV$.

Inductance L is in units of:

$$\frac{m^3}{\frac{kg}{ms^2}} = \frac{m^4 s^2}{kg}. \tag{4}$$

The resonant frequency of each note is given by:

$$f = \frac{1}{2\pi\sqrt{LC}}. \tag{5}$$

In the case of the concrete-clad Bordeaux wine bottle, this is approximately:

$$f = \frac{c}{2\pi}\sqrt{\frac{A}{Vl}}, \tag{6}$$

where c is the speed of sound in the water, $c = \sqrt{\frac{K}{\rho}}$, A is the area of the user-interface or neck, l is the length of the neck, and V is the volume of the bulb.

WATER HAMMER WITHOUT PIPES: 3-DIMENSIONAL VOLUMETRIC INTERACTIVE SURFACE

We desired a more volumetric medium of interaction than our 1-dimensional pipe interface of Fig 1 (rightmost) (actually 0-dimensional since the ability to expressively control the hand's linear position is lost in order to abruptly move toward the end of the pipe).

A 3-dimensional body of water can be touched, hit, and swirled side-to-side in a variety of ways. We thus took the waterhammer effect and made use of it in a tangible 3D interface inspired by a very old method of interaction.

The Baka People and *Liquindi*

Ancient traditions of the African rainforest, particularly of the Baka people, have used water as a tangible interface. The Baka have a practice known as *liquindi*, or water-drumming, whereby women and children use their hands to slap, beat and strike the water surface in various ways to produce complex rhythms as a group [14].

Typically the sound is produced by a person standing in water, hitting the surface of the water with her hands cupped to trap air in the palm when the surface is slapped.

The resulting sound cannot be produced with water alone, since it requires a solid-water or air-water boundary to sustain the sudden impact. As a result, the sound is not purely hydraulophonic [12].

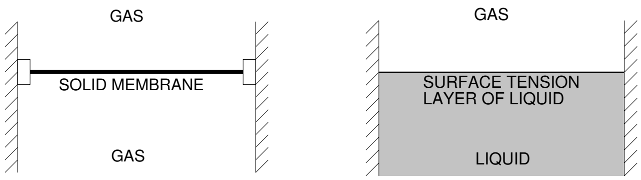

Figure 3. (left) Membranophones are solid percussion instruments, with a 2D membrane under tension. Examples include tabla, timpani, and snare drum. (right) Now the membrane is created by surface tension, becoming a percussion surface between water and air. In this case, the membrane itself (surface tension layer) no longer plays its exclusive role in determining the type of vibration, but instead becomes part of the surrounding media in doing so.

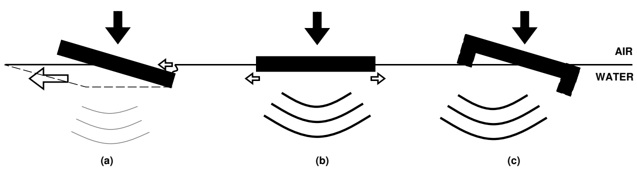

Figure 4. Simplified explanation of hand impact on a water surface: (a) Weak sound from off-angle impact, due to transverse water escape. (b) Co-planar impact produces a stronger acoustic wave. Less water escapes on impact, creating a better acoustic coupling and higher-pressure acoustic pulse. (c) Cupping the hand traps air which allows an uneven surface (or hand) to be impacted more uniformly, producing more sound than in (a).

3D Percussion with Amplification, Electronic Processing

Our work strives to reverse the trend toward electronic MIDI triggering drums by, instead, using sound that is produced acoustically, and merely passing these sounds through various continuously-responding filters (i.e. not merely triggering sound events). The result is an expressivity that comes from interacting with a tangible, richly tactile medium on the surface (e.g. slapping) as well as volumetrically (e.g. moving the hands through the water to create a more continuous sound). We use sound itself that is directly created in a physical medium, so that by swishing, splashing, *etc.* in the water, those complex sounds are not lost in the final sound. In this way, our instrument is a physiphone[11]. In particular, rather than merely triggering samples to be played back as discrete events, the ebb and flow of the water, no matter how subtle, is always present. The hydraulophone is another musical instrument—an underwater version of a pipe organ—that uses the highly expressive qualities of interacting directly with water [13]. As with the hydraulophone, our WaterDrum surface makes sound with musical notes or other sounds that have no beginning or ending, but ebb and flow for all time as long as the instrument is operating.

Touching the Surface-Tension Layer

Water makes an interesting tangible surface because it affords additional expressive capabilities not found in solid interfaces. Turbulence carries a rich set of information from the exact way it was instigated (and can even reveal a unique signature about the conditions around it, such as temperature [7])).

In this work we convert the solid boundary of a membranophone to a liquid surface tension boundary. See Fig. 3.

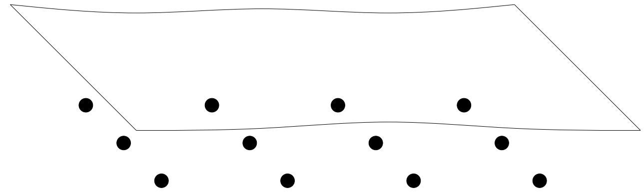

Figure 5. Pattern for 8 to 12 hydrophones under the water surface.

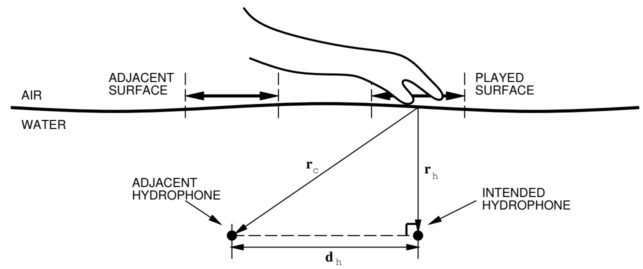

Figure 6. Reducing crosstalk between different playing areas of the waterdrum.

On this surface, a type of water hammer effect can be created once again (in addition to the other more gentle, expressive types of interaction). A sudden impact against the water boundary creates a high pressure pulse since the body of water cannot change its velocity instantaneously. A similar effect can occur with electricity flowing through an inductor. In each case, water current (equivalent to electrical current, *i.e.* motion of electrons) cannot change instantaneously, leading to a large surge in pressure (equivalently, a surge in voltage). If the hand impact Mach number were above 1, there would be shock wave generated in the water. Even in the case of a normal acoustic wave, the power of the pulse can be quite damaging, as is often seen in industrial accidents caused by the water-hammer effect.

In our case, we use hydrophones (underwater microphones) to pick up the sound of the pressure surge as it transforms to an acoustic wave and propagates through the water.

HYDROPHONES ARRANGED UNDER THE WATER DRUMMING SURFACE: THEORY

Hand impacting water directly

To properly set up the waterdrum to achieve its sound consistently, we considered near-field acoustic effects from the impact zone.

Let us consider the effects along a centre axis extending underwater below the hand, considering one frequency component of the impact spectrum. If the hand moved in a pure sinusoidal pattern, wave fronts originating from the centre of the hand (the direct wave) and the edge of the hand (the edge wave) lead to interference patterns as in Fig 7—a series of maxima and minima in front of the hand. Fortunately, at a certain distance away from the hand, the wave becomes more consistent, attenuating monotonically. This point occurs at the last maximum, which is positioned at a depth of:

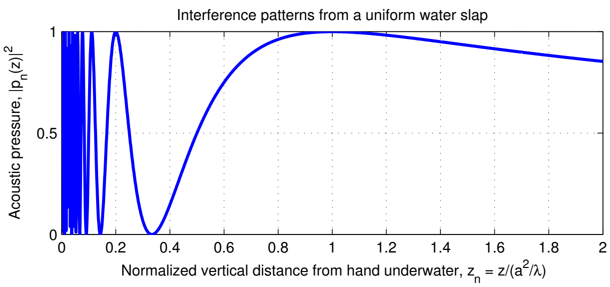

Figure 7. Sound radiation interference pattern from an ideal uniform water slap (covering radius a), as heard from various depths under the point of impact at the water surface. Past the right side of the graph, the sound level forever continues to monotonically decay to zero. Each wavelength λ out of the total frequency spectrum has its own scaled version of this interference pattern.

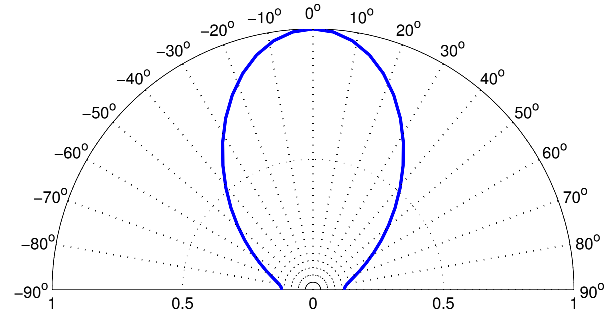

Figure 8. Sound radiation from an ideal uniform water slap, as heard from various angles under the point of impact at the water surface. This is a graph of angular directivity, illustrating how the intensity decreases compared to its maximum. The sound is strongest along the centre axis directly under the hand ($\theta = 0°$). The shape of the curve varies according to frequency.

$$z = \frac{a^2}{\lambda} = \frac{a^2 f}{c} \tag{7}$$

For example, taking $c = 1500$m/s in water, with the hand's maximum clean contact dimension as 0.08m, and stipulating that we want the system to detect impact frequencies up to 8kHz, produces a last maximum at z=0.034m. Thus, to avoid near-field effects, we preferred to position the hydrophones at approximately 5cm below the drumming water surface.

Note that diversity in the hand impact apodization (from a moving and uneven water surface) aided in making the wave fronts heard clearly at the hydrophones.

Hand impacting water with an air pocket

As the hand cannot form a perfectly flat surface, coplanar with the water surface, water can escape from under part of the hand without producing a wave front.

Cupping the hand as done by the Baka tradition helps to solve this problem. Cupping traps an air pocket inside the palm (Fig. 4c), and can help produce a strong wave front by synchronizing a pressure impulse across an irregular hand-water or air-water interface.

One consequence is that the frequency spectrum is generally lower with cupping (Fig. 4c) than with a direct flat impact (Fig. 4a) because the air pocket softens the impact and reduces the acceleration (and thus frequency) of the pulsing motion in the water.

Avoiding cross-talk between waterdrum areas

We experimented with having multiple sensitive areas on the same water surface, each with a separate hydrophone. Acoustic waves inevitably interfere with neighbour hydrophones to some extent; however, they will be attenuated if the areas are spaced far enough apart. If we want crosstalk to be C_{dB} decibels weaker than the desired drumming signals, we can carefully choose the hydrophone separation d_h as shown in Fig. 6. Approximating a spherical wave whose $\frac{1}{r}$ decay[2] dominates over lossy attenuation near the source, then the hydrophone separation is:

$$d_h = \sqrt{r_c^2 - r_h^2} = r_h\sqrt{\left(\frac{r_c}{r_h}\right)^2 - 1} \simeq r_h\sqrt{10^{\frac{C_{dB}}{10}} - 1} \tag{8}$$

where r_c is the nearest crosstalk distance and r_h is the direct distance to the hydrophone for the local drum region being played. Choosing a crosstalk attenuation of -12dB and a depth of $r_h = 5$cm as before, gives a hydrophone separation of at least 19cm. We built one prototype with 20cm spacing to experiment with very fast, intricate water drumming enabled by the close spacing of the drum regions.

The actual amount of crosstalk will be equal to or better than this first-order approximation because diffraction effects create the strongest sound at an angle directly under the hand (main lobe) and a weaker acoustic field at increasing angles from this centre axis (side lobes). The exact field profile can be found from Rayleigh's integral, Huygens principle[2][3][9], Rayleigh-Sommerfeld theory[2][3][5][9], the Kirchhoff formulation[2][3][5][9], and the angular spectrum model of plane waves[4][9]. A simple example is to model the hand as a perfectly round disk, in which case the angular directivity would be:

$$D(\theta) = \frac{2J_1(ka\sin\theta)}{ka\sin\theta} \quad \text{with} \quad k = \frac{2\pi}{\lambda} \tag{9}$$

where J_1 is a Bessel function of the first kind. A maximum occurs directly under the hand ($\theta = 0°$), as shown in Fig 8.

WATER AS A 3D EXPRESSIVE TACTILE MEDIUM

Water makes additional expressivity possible which is not found on a solid drumming surface. Beyond just drumming, a user can touch, splash, swirl, and stir the water in various ways.

For this reason, we made the original physical sound have a strong role in the final output sound, rather than simply causing drum samples to be triggered. As a result, the user can expressively play the instrument.

Spraying a jet of water into the drum areas gave the effect of "bowing" the drum as one would bow a violin, except with an infinitely long bow.

[2]In acoustics, field quantities obey a $\frac{1}{r}$ law for a spherical wave, whereas power intensity decays as $\frac{1}{r^2}$.

FILTERBANKS TO TRANSFORM ONE PERCUSSIVE SOUND INTO ANOTHER

An array of filterbank effects processors were designed, consisting of various bandpass filters, convolutions, *etc.*, created for each drum region on the water surface. Each region was processed separately to create a multitouch surface.

Implementation of WaterDrum kit

To acheive unique, compelling output from our system we adopted technology that would allow us to rapidly prototype new signal processing methods and sounds. With twelve hydrophone outputs from the WaterDrum kit, connecting them directly to a single PC for processing was not a flexible option. Instead, we ported the leads from the hydrophones directly to a audio mixer board for preamplification before the signals were processed. This allowed us to process on multiple disparate PCs in a dynamic configuration. After processing on the PCs, the signal was sent back to the mixer for amplification and output (through speakers).

To achieve a natural and metaphor free experience to the users of the WaterDrum kit, we chose to retain the texture of the input signals. By doing so, we would capture the natural sound of the water-hammer effect in the output signal. One method included an array of high-Q bandpass filters, one for each input signal, with various tuned frequencies. This allowed some of the original signal to pass through while allowing the user to expressively play the water surface as if it were tuned like a xylophone or timpani.

The second method of signal processing that captured the expressive texture of the input signal was realtime convolution. By interfacing an M-Audio Delta 1010 input/output device to a PC, we then processed the signal within Puredata-extended. By using the *partconv* external in Puredata, we were able to convolve samples of percussion (and other) instruments with the water hammer input signals. In this way, the acoustic sound is continuously filtered according to an individual filtering process for each hydrophone.

Do filterbanks turn an acoustic instrument into an electronic instrument?

Our water-hammer piano uses filterbanks that post-process acoustically generated sounds from hydrophones.

It is an example of a hyperacoustic instrument or physiphone[11]. Physiphones typically use one of:

- geophones, contact "microphones", or the like (sound pickups for solids);
- hydrophones, or underwater "microphones" (sound pickups for liquids); or
- microphones (sound pickups for gases).

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[10] in which position sensors, or the like, add synthetic sounds to an acoustic instrument, hyperacoustic instruments use the original sound as their primary computer input, with other sensors 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 acoustic nature of the instrument (e.g. using computer vision sensing body motion to position the setting of an analog guitar pedal connected to a vacuum tube amplifier).

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

We believe, therefore, that hyperacoustic instruments are not members of the Hornbostel Sachs 5th Radiophonic / Electrophone category [17] any more so than is an electric guitar with effects pedals, or a Steinway grand piano that's been electrically amplified.

WaterDrum as a hyperacoustic musical instrument

Inherent in the WaterDrum system is the complex response produced by intricate interaction with fluid dynamics.

Many of these dynamic disturbances are below the range of human hearing, but are nevertheless acoustic in nature, at least insofar as they are the natural sounds of water. Although the total sound is audible, a great deal of the frequency spectrum extends below the range of human hearing. We chose to embrace these sounds by capturing them, and shifting their frequencies up to desired notes on a musical scale. In this way, our WaterDrum system, when used as a musical instrument, is a hyperacoustic instrument.

To make this hyperacoustic instrument as expressive as possible, we wished to bring 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 downshifted 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 the frequency distribution of human perception. [12]

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

In the WaterDrums, we have shifted ultra-low frequencies (of which a musician gains very detailed control [7]) into the audible range by means of a frequency-shifter imple-

Figure 10. (left) Sensory Tables such as this product manufactured by Jonti-Craft are used in the classrooms at many child care centres. A basin is built into a table on wheels. There is a drain to empty the water into a bucket at the end of each play session. There are no sensors in a Sensory Table, but if we equip the table with sensing apparatus, it can be easily be made into a computational multimedia interface. (right) WaterDrum being played by two people at once: slapping the water surface with hands, and spraying a jet of water into different 3D drum regions to create a more smooth and continuous sound. The slapping is analogous to plucking a guitar, and the spraying is more like the bow of a violin.

mented on a computer having a broadband analog to digital converter, i.e. an A to D converter that responds all the way down to 0Hz (DC), and up to about 40kHz.

What we have done is brought the subsonic (as well as ultrasonic) frequencies into the audible range, as is commonly done with electric hydraulophones [12] (underwater pipe organs).

WATERDRUM FOR PUBLIC PERFORMANCES

We arranged 8 to 12 hydrophones (underwater listening devices) in an array underwater to create a multitouch haptic surface, located near the water surface, as shown in Figs 5, 9.

The hydrophone mounting frame was designed so it could be submerged in any body of water, just under the surface. For portable use on land, we used a product called a “Sensory Table” manufactured by Jonti-Craft. Sensory Tables are commonly used in child care centres such as nursery schools and day cares. The product consists of a transparent acrylic tub with a stand on wheels, as shown in Fig. 10 (leftmost). It can be filled with sand or water, to allow children to experience a variety of sensory input as they touch the and or water. Sensory Tables are also sometimes known as “Water Tables” or “Sand Tables” depending on the material they are filled with.

The name “Sensory Table” arises because the sand or water are used to stimulate the senses, not because the table has any sensors in it. But we can easily add sensing apparatus, to make the Sensory Table into a human-computer interface.

The instrument, seen in Fig. 10 (rightmost), was used in a variety of public performances.

For more information, pictures, and video, see
http://glogger.mobi/s/waterhammer

Figure 11. Various public performances, lectures, workshops, *etc.*, were based around the WaterHammer Piano and WaterHammer drum percussion surface.

Performances, lectures, and workshops

Over the Summer of 2010, we used this new interactive water surface in a wide variety of performances, lectures, and workshops. For example, we used it in a series of performances, ranging from a performance for the National Capital Commission in the nation’s capital, to performances at various schools and street fairs.

In one of our workshops, the Department Head of the school commented: “That was the best field trip we had...”.

One theme we taught was renewable energy and sustainable development, to raise awareness of natural resources, water, and energy. See Fig 11.

CONCLUSIONS

We successfully implemented and demonstrated a “WaterDrum” kit, water-hammer piano, etc., a user-interface based on a Sensory Table (Water Table). The apparatus was equipped with hydrophones that resulted in a water-based touch surface and volume. As a result, the user could provide expressive input by interacting with the natural physicality of the water, producing water waves, ripples, bubbles, and similar phenomena, all of which affect the resulting sound.

Figure 9. LEFTMOST: WaterDrum surface, with array of 8 to 12 hydrophones arranged underwater (in this figure, 8 hydrophones are shown, for a single octave compass); CENTER: Interactive art installation; four participants engaged in the experience; RIGHTMOST: Street performance, playing some jazz and classical reperetoire.

We also did a series of public performances and workshops for various schools and other organizations, and found that the our new user-interface had a positive effect on people from many diverse backgrounds and age groups.

ACKNOWLEDGEMENTS

Our thanks to Dr. Roel Vertegaal, founder of the Human Media Media Lab at Queen's University, to the NCC (National Capital Commission), Ottawa, Canada, and to Jonti-Craft, Inc. Wabasso, MN, for their assistance.

REFERENCES

1. M. B. Alonso and D. V. Keyson. *MusicCube: making digital music tangible*. ACM CHI, 2005.
2. E. B. Baker. *The Mathematical Theory of Huygens Principle*. Oxford Univ. Press, London, 2 edition, 1950.
3. C. Bouwkamp. Diffraction theory. *Rep. Prog. Phys.*, 17:35–100, 1954.
4. P. Clemmow. *The Plane Wave Spectrum Representation of Electromagnetic Fields*. Pergammon Press, London, 1966.
5. J. W. Goodman. *Introduction to Fourier Optics*. McGraw-Hill, New York, 1968.
6. H. Ishii. Bottles: A transparent interface as a tribute to mark weiser. *IEICE Trans. on Info. and Systems*, pages Vol. E87–D, No. 6, pp. 1299–1311, June 2004.
7. R. Janzen and S. Mann. Arrays of water jets as user interfaces: Detection and estimation of flow by listening to turbulence signatures using hydrophones. In *Proceedings of the 15th annual ACM international conference on Multimedia, September 24-29, Augsburg, Germany*, pages 505–8, 2007.
8. M. J. Kartomi. *On Concepts and Classifications of Musical Instruments*. Chicago Studies in Ethnomusicology (CSE). University of Chicago Press, 1990.
9. E. W. M. Born. *Principles of Optics*. Cambridge University Press, Cambridge, 6 edition, 1997.
10. T. Machover. Hyperinstruments: A composer's approach to the evolution of intelligent musical instruments. In W. Freeman, editor, *Cyberarts*. Spartan Books, San Francisco, 1991.
11. S. Mann. Physiphones... In *Proc. New Interfaces for Musical Expression*, 2007.
12. S. Mann, R. Janzen, R. Lo, and C. Aimone. Inventing new instruments based on a computational "hack" to make a badly tuned or unpitched instrument play in perfect harmony. In *Proc. International Computer Music Conference, ICMC '07, August 27-31, Copenhagen, Denmark*, volume 1, pages 105–112, 2007.
13. S. Mann, R. Janzen, and M. Post. Hydraulophone design considerations: Absement, displacement, and velocity-sensitive music keyboard in which each key is a water jet. In *Proceedings of the 14th annual ACM international conference on Mu ltimedia, October 23-27, Santa Barbara, USA.*, pages 519–528, 2006.
14. V. D. Mark Ellingham, Orla Duane, editor. *World Music: The Rough Guide (Africa, Europe and the Middle East)*. London: Rough Guides, Ltd., dist. by Penguin, 1999.
15. D. K. R. D. B. NK. Effects of a water-based program on women 65 years and over: a randomised controlled trial. *Australian Journal of Physiotherapy*, 52(2):102–8, 2005.
16. P. Richards. *The Wave Organ*. Exploratorium, http://www.exploratorium.edu/visit/wave_organ.html, Accessed 2005-8.
17. C. Sachs. *The History of Musical Instruments*. Norton, New York, 1940.
18. K. van Mensvoort. *Datafountain: Money translated to water*. Online documentation by the inventor, http://www.koert.com/work/datafountain/, 2005.
19. R. Vertegaal and I. Poupyrev. Organic user interfaces. *Communications of the ACM*, 51:26–30, 2008.
20. R. W. Young. Terminology for logarithmic frequency units. *J. Acoust. Soc. Am.*, 11(1):134–139, July 1939.