Fluid Samplers: Sampling music keyboards having fluidly continuous action and sound, without being electrophones

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ABSTRACT

Present-day sampling music keyboards are electronic instruments that fall under the last (5th) category of the Hornbostel Sachs musical instrument classification scheme. Conversely, we first propose an entirely acoustic/mechanical mellotron-like sampling keyboard instrument that neither uses nor involves electricity in any way. Instrument voice/voicing is changed by replacing mechanical storage media similar to Edison phonograph cylinders, gramophone disks, or vinyl records that were commonly used from 1870 to 1980. We next propose a fluid version of our instrument in which hydraulic (water) action is used to fluidly index into the mechanically stored samples, again, without the use of electrical components. Finally, we present a computerized version of our instrument in which digital signal processing is used to obtain fluidly continuous control of musical sampling from a hydraulic keyboard in which each key is a water jet. The final result gives rise to new musically expressive capabilities for continuously flowing manipulation of music samples. Moreover, we propose versions of the computerized instrument that derive the initial sound source from the water itself, such that the instrument is not an electrophone.

Categories and Subject Descriptors

H.5.2 [**Info. systems**]: Info. interfaces and presentation—*User Interfaces*; J.5 [**Computer applications**]: Arts and Humanities

General Terms

Design, Experimentation, Human Factors, Performance

Keywords

Fluid-user-interfaces, fluid sampling, tangible user interfaces, water-based immersive multimedia, hydraulophones, interactive art

1. BACKGROUND

Musical instruments are traditionally grouped into three categories: strings, wind, and percussion, as for example, by de Brossard's Dictionaire de musique, which, in 1703 had the top level categorization:

1. ENCHORDA (strings);
2. PNEUMATICA (wind);
3. PULSATILIA (beaten instruments).

Each of these three top levels was further subdivided, e.g. string instruments are further devided 1.1 plucked with fingers; 1.2 bowed, etc.[3, p158].

In the 19th century, a newer system was devised as a "classification scheme to cover and identify all instruments the world over... for contemporary needs."
[3, p162]

The first classification system specifically designed to encompass all of the world's instruments was developed in 1893 by organologist and acoustician Mahillon. It had four top-level classes, denoted by Roman numerals:

- Class I **Autophones** (self-sounders: sound is produced by elasticity of instrument's body, not by any tension);
- Class II **Membranophones** (sound produced by tightly stretched membranes);
- Class III **Aerophones** (contain a column of air);
- Class IV **Chordophones** (sound produced by stretched strings).

In 1910, Galpin also proposed four classes of instruments and added a 5th class in 1937, as follows:

- A sonorous substances (autophones = self-vibrators);
- B vibrating membranes (skin-vibrators);
- C stringed instruments (string-vibrators);
- D wind instruments (wind-vibrators) [Galpin 1910, C and D reversed; what is shown here is the ordering proposed in 1937].
- E electrophones (electric vibrators)[1, pp29-30].

Galpin was the first to add a category for instruments in which sound was produced electrically, e.g. by oscillations in electric valves[3, p176]. The term "electric valves" referred specifically to vacuum tubes, but more generally (and more recently) can be understood to encompass devices like transistors (whether discrete or in the form of integrated circuits, chip-level firmware, or executing software) that perform a similar function.

In 1914, ethnomusicologists Horbostel and Sachs proposed a taxonomy "to be able to order all existing and conceivable instruments in a manner independent of space and time (for 'all nations and all times')... they wanted it to be logically exhaustive..."[3, p169].

They adapted Mahillon's scheme, renaming the first of Mahillon's four top-level categories as "idiophones", and re-ordering the four top-level categories (Galpin had C and D reversed in 1910) as follows:

- 1. **idiophones**: instruments sounded by the "substance of the instrument itself, owing to its solidity and elasticity... without requiring stretched membranes or strings"
- 2. **membranophones**;
- 3. **chordophones**;
- 4. **aerophones**.

Further numbers were used to subdivide this classification scheme at each stage, much like the Dewey Decimal System of Classification.

In 1940, Sachs added a 5th category he called "electrophones"[5] for instruments involving electricity.

Present-day organologists and ethnomusicologists have come to a mutually agreed-upon understanding that this classification scheme should depend only on how sound is initially produced in the instrument.

Thus it is now generally agreed that the 5th category, namely "electrophones", should only be used for instruments such as the Theremin, ondes martenot, and, of course, the modern synthesizer, that actually generate the sound signal source itself, electrically.

For example, a pipe organ is still an aerophone regardless of whether the wind source is an electric motor or hand-operated blower, and regardless of whether the valves delivering wind to the pipes are mechanically, electrically, pneumatically, or hydraulically actuated.

An interesting case, for example, is the Greek Hydraulis (invented by the hellenistic scientist Ctesibius of Alexandria, in the 3rd century BC) an early pipe organ that used the dynamic energy of water ("hydor") as a source of power to generate air pressure to blow air into organ pipes having valves that were mechanically actuated. Thus the source of power is water (hydraulic). The source of actuation (to open the valves) was mechanical. However, it is still an aerophone because the pipes are wind-driven.

The diversity of musical instruments and how they are controlled (i.e. that which comes before the initial sound production mechanism) and how they are post-processed (that which comes after the sound production mechanism), highlights the importance of better understanding the physics behind sound production.

In 1932, Andre Schaeffner developed a new classification scheme that was "exhaustive, potentially covering all real and conceivable instruments"[3, p176]. Schaeffner's system has only two top-level categories denoted by Roman numerals:

- I: instruments that make sound from vibrating solids
  - I.A=no tension;
  - I.B=linguaphone (fixed at only one-end); also known as lamellophone or lamellaphone;
  - I.C=strings (fixed at both ends)
- II: instruments that make sound from vibrating air.
  - II.A=ambient air;
  - II.B=free cavities;
  - II.C=air column.

2. PHYSICS-BASED ORGANOLOGY

In this paper, we propose new musical instruments that organologically challenge our pre-conceived notions of existing instruments. We also problematize the existing taxonomy while attempting to broaden the space of known instruments across all states of matter.

Although previous classification schemes attempted to exhaustively cover all possible and conceivable instruments, we have recently proposed a number of new instruments, some based on liquid and some based on plasma, as well as some based on combinations of liquid and plasma. Since liquid (or plasma) is neither solid nor gas, these new instruments forced us to re-consider the above categorizations.

Along with proposal of these new instruments, we have also proposed 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", like the top-level of the Andre Schaeffner classification system.

However, unlike the Andre Schaeffner classification system, we also include a top-level classification for the other two states of matter: liquid and gas, resulting in the following scheme:

1. "Earth"/Solid:
   (a) chordophones (strings): stretched solids that are essentially **1-dimensional**, i.e. their cross section is much less than their length;
   (b) membranopones: stretched solids that are essentially **2-dimensional**, i.e. their thickness is much less than their surface area;
   (c) idiophones: solids that are essentially **3-dimensional** — no tension.
2. "Water"/Liquid: hydraulophones;
3. "Air"/Gas: aerophones (wind instruments);
4. "Fire"/Plasma: ionophones,

giving the four states of matter as the top-level categories.

In addition to adding two new top-level categories, we attempt to "deconstruct" or problematize Sachs' fifth category (Electrophones), through the construction of new musical instruments that synthesize sounds, or play back sound samples, but that either do not involve or use electricity, or involve and use electricity merely for control purposes (as with a pipe organ) or to post-process acoustically generated sounds (as with the electric guitar).

This challenge attempts to force us toward a possible re-thinking of the fifth category, perhaps requiring that it be broadened to include instruments that synthesize sound or process sound samples by way of mechanical computing, optical computing, or any other physical embodiment of code/ software/ computation whether or not it is based in whole, or in part, on electricity.

3. THE "HARMELLOTRON"

The world's first sample-playback keyboard, was the Chamberlin, consisting of a piano-style keyboard mechanically linked to an array of magnetic tape players, one tape and tape player for each key on the instrument. A similar instrument, called the Mellotron, was then produced by a competing company, in Birmingham, England in the early 1960s, founded by a former Chamberlin associate.

Chamberlins and Mellotrons, as they are known, have largely been replaced by modern sampling keyboards.

While modern multimedia technology has replaced magnetic tape as a sound storage, sampling, editing, and manipulation medium, the vinyl record, among certain artists of the Hip Hop generation, has held on longer, even in the face of modern computational manipulation tools.

Turntables and vinyl records are regarded by some as highly expressive "musical instruments" in which their mechanical physicality lends themselves to the creation of new kinds of music.

Such "musicians" are referred to as a "turntablists". Indeed Miles White describes the phonograph turntable as "a manual analog sampler" (http://www.research.umbc.edu/eol/2/white/, (See also Bakan et al 1990, "Demystifying and Classifying Electronic Music Instruments," Selected Reports in Ethnomusicology Vol. 8. Ethnomusicology Publications. UCLA. In fact, a new kind of musical instrument called a "scratchophone" has recently emerged [http://www.scratchophonic.com].

Many turntablists refer to "flow", as if to suggest a liquid or fluidic quality to music. Indeed, the turntable and vinyl record may be thought of as a fluidic sampling mechanism of sorts.

Figure 1: Consider an entirely mechanical sound recording medium for use as a friction idiophone! Using this crude medium as a musical instrument in the way that turntablists do (i.e. as a friction idiophone for "scratching", or the like), emphasizes the physicality and acousticality that is possible. [Image from Wikipedia, under General Public License (GPL)].

4. MUSIC SAMPLERS THAT ARE NOT ELECTROPHONES

When a turntable is used as a musical instrument, it may be regarded as a friction idiophone. Some writers erroneously refer to the turntable instrument as an electrophone, even though the electricity merely amplifies sound that is acoustically generated by "scratching" a mechanical pickup device in a mechanical groove.

As a matter of artistic purity, let us consider the use of earlier entirely mechanical recording devices, as illustrated in Fig 1, for this purpose.

Phonograph cylinders were known as "records" during their pupular usage from around 1888 to 1915, whereas the gramophone disk later became the dominant commercial audio medium in the 1910s and commercial mass production of phonograph cylinders ended in 1929 [http://wikipedia.org].

In some ways the move from cylinders to disks was a step backwards:

1. Gramophone disks were for consumer-playback only, whereas the earlier phonograph cylinder system allowed the end user to record as well as playback prerecorded sounds;

2. Starting in 1906 cylinder records became available in indestructible hard plastic and could be played thousands of times without wearing out, and were the most durable form of analog sound recording medium ever produced (compared with all later media such as vinyl disks, audio tape, or the like).

F. B. Fenby was the original author of the word phonograph. An inventor in Worcester, Massachusetts, he was granted a patent in 1863 for an unsuccessful device called the "Electro-Magnetic Phonograph". His concept detailed a system that would record a sequence of keyboard strokes onto paper tape, and is often seen as a link to the concept of punched paper for player piano rolls (1880s), and as Herman Hollerith's punch card tabulator (used in the 1890 census), a distant precursor to the modern computer.

Thomas Edison's phonograph was the first device to record and reproduce sounds. (US Pat. 200,521, February 19, 1878). This device was publically demonstrated November 21, 1877 [http://wikipedia.org].

4.1 An entirely mechanical mellotron-like instrument

We propose a keyboard or keyboardlike musical instrument made from a plurality of non-electrophonic sound-sampling media.

Deliberately playing or recording records at the wrong speed has been previously used. It has been, for example, noted that:

> playing the song "I'm on Fire" from Bruce Springsteen's LP at a 45 RPM speed gives the singer a falsetto singing voice that sounds very much like Dolly Parton. Subsequently, playing a 45 rpm recording of Dolly Parton at 33 RPM gives her voice a husky, almost masculine tone. ... Canadian musician Nash the Slash also took advan-

tage of this speed/tonal effect with his 1981 12" disc Decomposing, which featured four instrumental tracks that were engineered to play at any speed (with the playing times listed for 33, 45 and 78 rpm playback).

[http://wikipedia.org]

Consider 12 separate turntables, each playing a portion of a song like Donna Summer's "Dim All The Lights" (a song that sent the world record for longest single note held), or perhaps a test record in which the whole record is just a 440Hz test tone. Modifying each turntable to play at a slightly different speed, along with careful choice of each of these speeds, will give us a set of tone generators, each making one note of the musical scale.

However, for the purposes of proving our point beyond any shadow of doubt (i.e. proving that we can make a sampling keyboard that is not an electrophone), we choose, instead to use an entirely mechanical recording medium

Consider, for example, an array of entirely mechanical phonographs (Fig 2), arranged in a row, in which each player has a recording of a single note that lasts the entire length (4 minutes) of the recording.

Since the cylinders spin in unison, they can share a common shaft, requiring only a single crank, rather than requiring 12 people to separately turn each crank. The musician turns this single crank in one hand, while pressing keys on the keyboard with the other hand. Each key is linked to one stylus (needle) in such a way that it modulates the needle by pressing it closer to the record when the key is pressed harder. The result is a displacement-senstive (rather than velocity-sensitive) keyboard instrument in which a note gets louder as the key is pressed further down, and quieter or completely silent as the key is released sufficiently.

This instrument can be made using mechanical action (mechanical connection from each key to the corresponding stylus/needle), or it can be made with electric action, pneumatic action, or hydraulic action.

For the purposes of proving our point (i.e. that we can make a sampling keyboard that is not an electrophone) beyond any shadow of doubt, we choose a non-electric action. Since we wish the flexibility of being able to move the keyboard around and the option to position the record players elsewhere, we choose fluid-action so that there are 12 flexible hoses that link the keyboard to the record players. In choosing whether to use compressible fluid (air) versus incompressible fluid (water), we note that the responsivity of the instrument is greatly enhanced by using noncompressible fluid (e.g. water), resulting in virtually instantaneous key action.

Since we are inventing a completely new instrument we might as well choose a completely new kind of keyboard, rather than the traditional plastic or wooden keys of a piano keyboard. In particular, we note that almost all piano keyboards seem to lend themselves best to velocity-sensitive usages, and we seek a different kind of user-interface that would be more suitable for the fluidly flowing nature of our new instrument.

Whereas velocity sensitive keyboards concentrate mainly on the "striking" of something (as in a real acoustic piano as well as synthesized striking in electronic keyboards), our new instrument affords a certain kind of fluidity not available on a piano. For example, if one wishes to let the volume of a note gradually build up, drop down a little, go up some more,

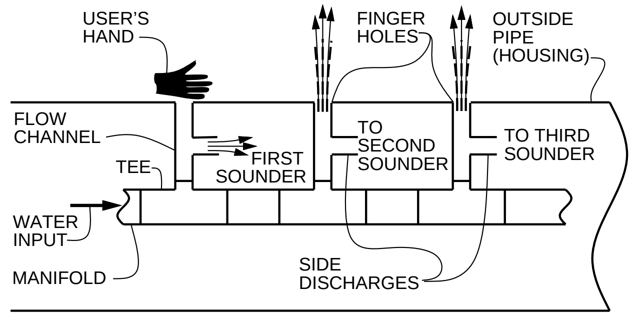

Figure 3: Keyboard in which each key is a water jet: pressing down on a given key supplies water to a sound-producing mechanism. The water can, for example, be used to modulate a phonograph needle in our mechanical sampling keyboard.

and so on, it is very easy to do with our new instrument. The musician can literally ride the sound level of any note up and down at will, totally independent of the other notes.

This feature goes beyond the notion of polyphonic aftertouch that existed on a limited number of high end keyboards such as the Roland A-50. Rather than aftertouch as an afterthought to the production of a note, we have fluidly continuous control over each note from the outset. We have intricate touch control before, during, as well as after a note is established. We might therefore refer to our new keyboard as possessing the property of polyphonic "beforetouch", polyphonic "duringtouch", and polyphonic aftertouch.

The resulting sound has a fluidity much like that of a strings section, but controllable by a single musician, such that the musician has control as to whether particular notes start abruptly, or whether they more fluidly flow into one another in various ways.

Although true tracker-action on certain pipe organs can provide a similar effect, it is not possible to partially press down an organ key and have the pipe sound properly, because pipes are meant to operate at a certain wind pressure. However, since our keyboard is a sampling keyboard, it plays perfectly at any amount of key action, so keys can be depressed halfway and held there for as long as desired.

4.2 Hydraulic keyboard

The fluidity of the new mechanical sampling instrument suggests the need for a new kind of keyboard that itself is fluid. Ideally it would have keys that have a much longer key travel, and that also convey, artistically, the fluidity of the instrument.

For this purpose, we decided to build a keyboard in which each key is a water jet (Fig 3 and 5).

4.3 A new perspective on hydraulophones

Hydraulophones are instruments in which a player blocks water jets to force water into a hydraulic sound-producing mechanism. In previous publications we have described hydraulophones in which the sound is produced by the water itself. Presently, with the sampling hydraulophone (hydraulogram), we desire that the water play a more central role in the production and shaping of the sound.

To achieve this, we replace the phonograph stylus/needle with a fine jet of water. Since there are no electrical com-

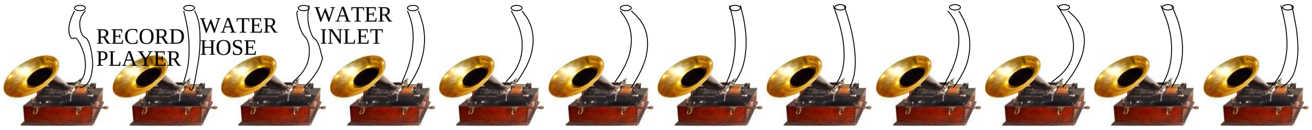

Figure 2: Consider a linear array of 12 phonographs, each having a record of a single note played for its entire duration. The needles can be separately modulated by hydraulic action, so that the instrument can be played from a 12-key keyboard console.

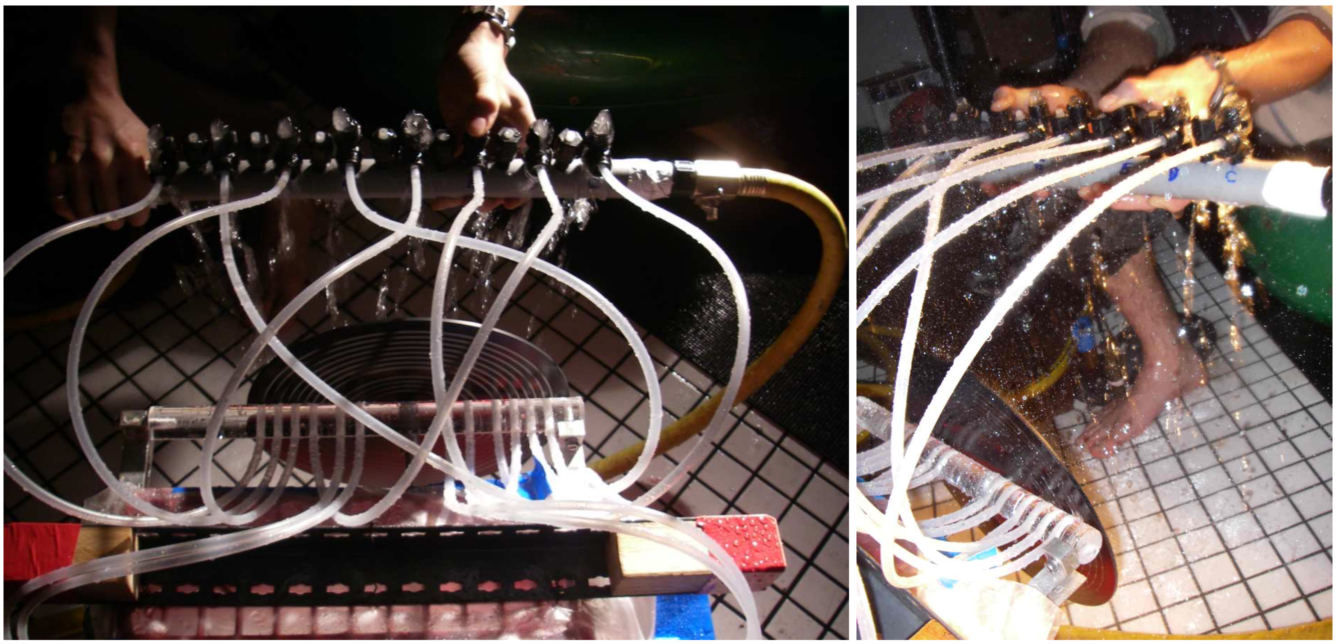

Figure 4: Hydraulogram: mechanical sampling keyboard instrument with hydraulic action. A special kind of vinyl record can be polyphonically "scratched" and sampled with 12 water jets, each jet either controlling, or actually being a stylus on the vinyl record.

Figure 5: Keyboard in which each key is a water jet: the result is a fun-to-play keyboard instrument (playing it is like playing in a fountain) that can even be played underwater, if desired.

Figure 6: Underwater testing one of our hydraulic gramophone disks: After laser-cutting our record, we tested it by spraying water into the grooves. The result is a completely mechanical sound sample storage media that's playable with a stylus consisting of a water jet (in this picture we've put some air into the water jet to make it visible underwater).

ponents in our system, all we need do is make everything out of water-resistant materials (housings made of plastics instead of wood, etc.).

Because the stylus is a water-jet, the sound vibrations come directly from compressions and rarefactions of water. Thus we might be able to argue that the instrument is no longer an idiophone, i.e. that the water is at least as much responsible (if not more so) for the sound than the solid matter from which the instrument is made. In this sense, it could be regarded as falling under the new hydraulophone category rather than under the idiophones category.

Most interestingly, our instrument will still play when completely immersed in water, thus making underwater concerts possible. Indeed, we have done a number of underwater concerts and underwater performances (Fig. 5 (b)).

When played underwater, we have an interesting situation in which a sampling keyboard exists with no need for either air or electricity. When the listeners position themselves underwater, with their ear canals full of water, no air need be involved in the sound production process, or the delivery, since there are bones inside the ear that conduct sound from the eardrum (which is in direct contact with the water) to the fluid-filled portion of the inner ear.

4.4 Disk-based hydraulophones

Just as Edison's cylindrical record gave way to gramophone disks (still totally mechanical at first — electric amplification did not come until much later), we also chose to migrate toward making hydraulophones in disk form, primarily for reasons of manufacturing ease.

Fig. 6 shows an underwater test of a disk that we cut from acrylic sheet, using a CNC laser-cutter (computer-controlled laser cutting system).

4.5 Parallel grooves

A number of unusual gramophone records have been produced in which parallel grooves record more than one song interlaced into the same space on the disk. Some records such as Jeff Mills' "Apollo" were manufactured this way, using a process called "NSC-X2" from National Sound Corporation in Detroit. With these records, song selection appeared random, depending on which groove the needle fell into at the beginning of the record. As a futher technique with parallel grooves, we can also cut our record so that the tracks are concentric, rather than spiralled. Using these techniques, we can record all 12 (or more) of our samples on one disk, where all or any samples can be accessed at the same time. Furthermore, the way each sample is played, by varying the pressure on the stylus (and even shape or flow rate of the stylus, if the stylus is made of water), can be done continuously, fluidly, and independently for each sample.

When cutting all the samples into one disk, we prefer to put the high notes toward the outside where the linear velocity (velocity with respect to the water-jet stylus) is highest, and low notes toward the center. See Fig. 7.

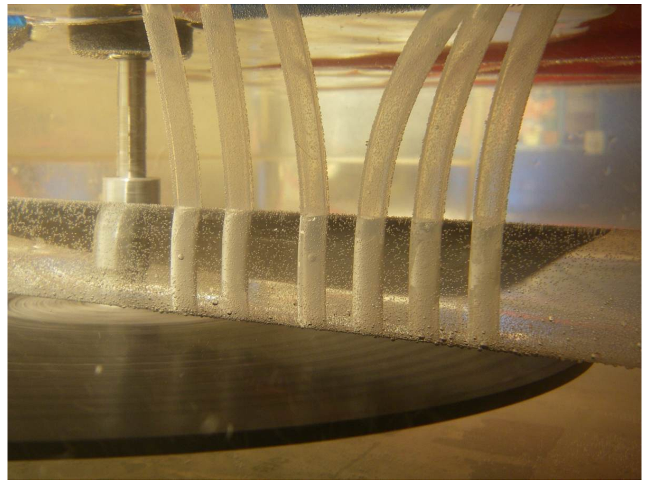

Figure 7: Underwater record with 12 parallel grooves: Our staggered design has the six even-numbered tracks each sprayable with a water-jet stylus on the right side (shown in the picture), and odd-numbered tracks sprayable with a water-jet stylus on the left side (not shown in the picture). As a result, a stylus does not run into the adjacent one.

5. COMPUTER-BASED IMPLEMENTATIONS OF FLUID SAMPLING

We now consider the use of water to index into samples stored as sound files in a computer. For this purpose, we use a water-jet keyboard in which a hydrophone (specialized underwater microphone) is placed in each jet, to pick up the sound of the water flowing in the jet. The sound from the water is then used to fluidly control the playback of samples from the computer. Initially we used a computer having 6 PCI slots, and inserted 6 stereo sound cards, giving a total of 12 inputs, one for each of the 12 hydrophones. One input thus corresponded to each water jet.

Subsequently we put together a specialized computer system having 80 audio inputs, so that we could build an instrument having up to 80 water jets.

Each audio input controls a virtual phonograph record, where the sounds produced by the water cause a virtual stylus/needle to flow through the virtual phonograph record.

The use of the computer allows the recorded sample to be manipulated by the water jet in a much more intricate and expressive way. Velocity-sensitive keyboards allow samples to be played back at different volume levels depending on how hard a key is hit.

With our displacement-sensitive keyboard, we control the volume by how far down we press a given water jet. This gives us greater control over the sound shaping, because we can continuously adjust the volume of the sample while it is playing.

However, we wished to be able to change the manner in which the sample played back. In particular, we wished to create a system in which pressing down on a water jet very quickly would produce a clear playback of the sample, whereas pressing down slowly would produce a temporally smeared version of the sample. So if, for example, the sample is recorded speech of the word "HELLO", it will be played back as-is, when the water jet is pressed quickly, but will be played back more like "HELLO HELLO HELLO" when the water jet is pressed slowly.

This emulates the effect of a violin, in the sense that it can be bowed abruptly to make a note with a very precise onset (eg. an accented note), versus a legato note, with gradual onset and slurred performance. For the accented notes, we wish to hear a highly intelligible sample, wheras for the legato notes, we wish to hear a slurred (smeared out) sample. Obviously we can attain anything in between by varying the how quickly we press down on a given water jet. Moreover, variations in the shape of our attack profile on the water jet are to result in a wide range of variations in how the sample gets played.

In our simplest implementation, we envelope-detect the sound from the water, $w(t)$, to obtain $v(t) = f(abs(w(t)))$, where f is a simple moving-average filter. This resulting time-varying voltage, $v(t)$, is known as a *restrictometric quantity*[4], i.e. it provides a measure of the degree to which the user is restricting the flow of water coming out of any particular water jet. Our paper [2] gives a different method.

We then differentiate the resulting restrictometric quantity, to obtain an audio blurring kernel, $b(t) = dv(t)/dt$, which we then convolve with the sample as it plays out. This process happens continuously in realtime, within the obvious constraints of a causal system.

This process is illusrated in Fig. 8.

On this basis we ultimately generalize the concept of an Attack Decay Sustain Release (ADSR) envelope from the usual binary on/off conceptualization (i.e. a note is either present or not present, with hard start and end points), to a more fluidly flowing continuous implementation. Additionally, we add a Proportional Integral Deriviatve (PID controller) to handle displacement, presement (the integral of displacement) and velocity (the derivative of displacement). The result is a highly expressive instrument that responds to the derivative and integral of displacement in a flexibly limitless re-configurable way.

5.1 Fluid stylus

Fluid sampling allows us to generalize the notion of a phonograph stylus. We can imagine a stylus which is able to grow and cover more than just a single spatial point on the record (ie. more than just a single point in time in the sample).

For example, a water-jet stylus can be built so that the

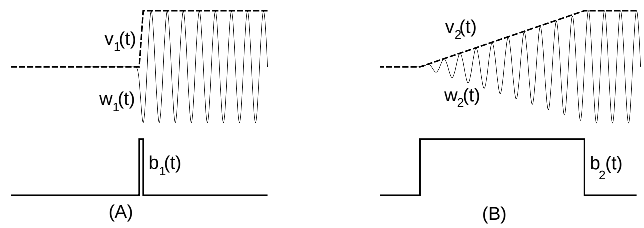

Figure 8: Fluid sampling: Sounds from the water are picked up by hydrophones (special underwater microphones) in the water jet streams. These sounds are represented as waveform $w(t)$, having envelope $v(t)$. (a) During a quick stoccado note onset, i.e. when pressing the finger down on a water jet abruptly, $b_1(t) = dv_1(t)/dt$ is approximately a Dirac Delta measure. Convolving $b_1(t)$ with the sample will result in a sample that is essentially unchanged. (b) During a slow legato passage, the finger comes down on the jet slowly, so that $b_2(t) = dv_2(t)/dt$ is quite broad. Convolving this with the sample "smears" the sample. If the sample is speech, this smearing makes it is largely unintelligible. If the sample were from a violin, the result would be something that sounds like a strings ensemble rather than just one string.

jet transitions between being a fine line of spray and being a thin plane of spray. See Fig. 9.

Furthermore, by making the shape of the fluid stylus follow the user input (or be affected by the acoustic sound inside the pipes of a hydraulophone), the fluid stylus becomes a means of acheiving fluid sampling without any electronics.

Unlike many conventional record-based musical instruments (as used in hip-hop music, etc.), this record advances steadily in space and time. It is now the stylus which becomes the dynamic element in the instrument.

5.2 Enunciated vs. Fluidized

When playing music on an instrument, *slurring* is a technique of moving from one note to the next in a fluid manner, so that it is difficult to tell exactly when one note ends and the next note begins. The opposite is to abruptly transition between notes.

The action of the stylus is suggestive of "articulation mimicking". Derivative-based fluid sampling is perhaps the most basic, fundamental way of mimicking the musical articulation of a note. In derivative-based fluid sampling, a clearly enunciated note leads to a clearly enunciated sample. For example, if the sample is a spoken word, such as "hello", the derivative means that a note with a clearly articulated abrupt onset leads to the word "hello" being clearly enunciated.

"Articulation mimicking" might suggest that the output sounds predominantly like the sample, and is only incidentally related to the input. This occurs in a MIDI keyboard in the sense that the synthesizer mimicks the motion of a finger based on the points in time that it activates a key. However, in fluid sampling, the original sound (eg. from water flow in a hydraulophone), remains present to a large degree in the final sound output.

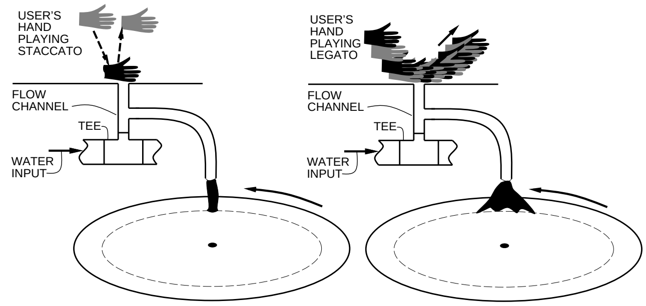

Figure 9: Fluid sampling analogy for our computer program: One can imagine a fluid stylus which would change shape depending on the way that a user manipulated a hydraulophone water jet. A profile of user interaction over space and time would affect the profile of the stylus over space and time, which in turn would hydraulically sound the record. Unlike many conventional record-based musical instruments (as used in hip-hop music, etc.), this record would advance steadily in space and time. The stylus would become the dynamic element in the instrument. Left: the user plays clearly enunciated note (clearly enunciated in the temporal sense), which leads to a spatially compact stylus, and sounds a clearly-played sample. Right: user plays a slurred note, causing the stylus to widen, and leading to a smeared-out playing of the sample.

5.3 Is the computerized hydraulogram an electrophone?

With the initial sound in hydraulograms (and all other 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 our hydrophones, extends beyond the range of human hearing. Our hydrophones are responsive from DC up to 50 MHz. The sound controlled by the user can be richly expressive in the subsonic, sonic, and ultrasonic ranges.

By having the initial acoustic sound of the instrument strongly passed through the fluid-sampling processing, our aim is to preserve the acoustic nature of the instrument. Indeed, by having the subsonic and ultrasonic sounds contribute to the overall sculpting of the output sound, we give the listener access to acoustic content they would not otherwise hear. Thus we create a hyperacoustic instrument, which is even more acoustic than a fully acoustic instrument having no electronic post-processing. The result is an instrument having a larger space of controllability that the user can access, and also hear (ie. closing the human interface feedback loop).

Furthermore, we found that the output of the fluid sampling still sounded acquatic. In this way an acoustic instrument augmented with fluid-sampling not only remains classified as an acoustic (non-electronic) instrument, but it also sounds like an acoustic instrument.

6. SCRATCHING RECORDS WITH YOUR FINGERS

By moving the samples from concentric rings on a disk into grooves around the outside of a cylinder, we created a sampling instrument where the fluid stylus is a human hand. Something as small as one human fingernail can touch the cylinder, almost acting as a single-point stylus). Alternatively, larger surfaces of a finger, several fingers, or entire hands can be used (Fig. 10).

The finger-stylus can not only expand and contract, but change shape to form a variety of intricate continuous two-dimensional pressure profiles that can vary:

- **circumferentially** across the time range of the sample (spatially around the circumference of the cylinder); and
- **longitudinally** (side-to-side across multiple sound sample tracks); or
- **both**, i.e. in any of a variety of combinations of these, including some that are not dimensionally separable.

Circumferentially (i.e. along the time-axis), human skin can put various pressure profiles that can smear the time-axis in a wide variety of different ways. For example, this time-smearing can be a gently-varying pressure profile with no sharply-defined beginning or end, or it can be very localized, or it can be anything in between. It can even be doubly localized (i.e. gripped with widely spaced thumb and index finger and nothing in between), resulting in a kind of slap-back echo of the time axis instead of the more slurred temporal smearing that might result from wrapping the whole hand around the cylinder.

Longitudinally, the finger-stylus can continuously move side to side, along the cylinder, parallel to the axis of rotation, and therefore can smoothly transition between different samples, or smear different samples together but at the same point in time.

In addition to fluid sampling, we have experimented with other types of signal-processing operations which, when used to process the sound from acoustic instruments, still allow for fluidly continuous action and sound on the instrument, and preserve the quality of the instrument as being acoustic.

7. HARMELODY

A certain genre evolved around the new capability afforded by fluid sampling.

In particular it arose out of the desire to play harmony along with a distinctly audible melody, overlapping within a limited compass.

Harmelody is the combination of overlapping harmony and melody, in which the melody is embedded within the accompaniment, by way of continuous volume variations in the individual notes of the accompaniment, independently adjusting each note's volume.

A harmelodic technique is to play a chord in which one note of the chord, corresponding to the melody note, is made to become louder than the other notes in the chord, and then, while sustaining that same chord, the loud note is made quieter and a the next melody note in that same chord is made louder, and so-on, dynamically, to follow along the course of that portion of the melody that falls within the chord.

Figure 10: Polyphonic friction-idiophone as a continuously variable sampling surface for morphing stylus: A spinning aluminum cylinder with a specially textured surface produces sound picked up by a wireless contact microphone inside the cylinder.

Often the emphasized melody notes within a chord are further modulated in amplitude, to create rhythmic emphasis within the melody.

Being able to play harmelody effectively requires an ability to skillfully and continuously update the volume (amplitude) level of notes while they are sounding.

7.1 Notation for fluid sampling

The unique ability of the hydraulophone to produce notes that continually vary in amplitude, pitch, timbre, etc., requires a new form of musical notation.

Fig. 11 shows a new musical notation featuring variations on a well known children's song played in "harmelody" style.

On a piano, though, all notes decay after being struck, and therefore they must be re-struck every time the pianist wants to update the volume level. Unlike a piano, the hydraulophone can sustain its notes for as long the jets are fingered, and continuously responds to the manner in which they are blocked with the player's fingers.

In fluid music notation, continuously changing notes are drawn as a continuous function of time on the musical staff. The change is drawn as a varying line thickness. The line always lies with its centre over the correct pitch on the staff. This notation is a type of time-frequency (e.g. spectrogram) density plot (intensity mapped to line thickness), in which the frequency axis is logarithmic.

Fluid music notation is useful for any fluidly varying instrument or user-interface. Most notably, fluid music notation reflects the continuously-variable, free-flowing nature of playing the hydraulophone's tactile user-interface.

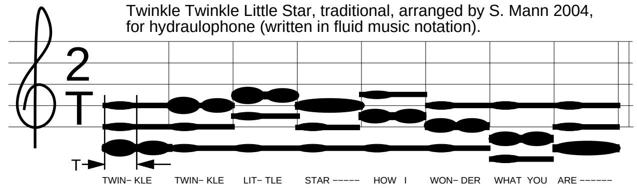

Figure 11: Example of harmelody represented using "Fluid music" notation. Notes change continuously in volume, in order to combine harmony and melody within the an overlapping compass. The fluidly flowing change in volume lends the music a uniquely expressive quality. Moreover, components of the harmelody throb in volume, to gently convey a flowing sense of rhythm. Note the time signature, where the denominator, T, of the fraction is an arbitrary ("undigital") analog quantity of time, as set forth by the continuous (fluid) nature of the musical process. In particular, notes need not necessarily be discretized in duration. Here, the low C is sustained for the first six bars, and acts as a harmelodic drone. In other harmelodic compositions, all of the notes on the keyboard drone softly in the background, for the duration of an entire song.

8. RELATED WORK

8.1 On hydraulophones

The hydraulophone is a highly expressive and fun-to-play musical instrument, well suited for sound sculptures and musical instruments in public spaces because the water jet forms a self-cleaning user-interface that can be shared with strangers without the usual risks of cross contamination that might occur if an interface like a pushbutton, lever, or other actuator were left out in the middle of a park. There's no need to wash your hands when you're playing in a fountain!

The hydraulophone is currently being installed in public spaces. Since one plays the instrument by playing in the fountain, the usage of the instrument is a form of aquatic play. We are therefore working with manufacturers of aquatic play equipment to produce hydraulophones for installation in public parks, pools, beaches, and the like.

8.2 Underwater oscillations due to vortex shedding, and turbulence

Fluid flow creates an exciting range of acoustic possibilities, especially with water, which has unique turbulence and vortex shedding properties as compared with the air of ordinary woodwind instruments.

The wake produced by an obstacle in water flow gives rise to a number of well-known effects, such as the Strouhal instability and in particular, the *Von Karman Vortex Street.* (http://en.wikipedia.org/wiki/Von_Karman_vortex_street – gives a short introduction.) The Karman vortex street is a series of eddies that can be created underwater, close to a cylinder. Various instabilities occur in water flow, giving rise to oscillations and vibrations that are too weak to be useful in an unamplified instrument, but that provide some exciting possibilities to explore in amplified instruments. Thus we experimented with water whistling through small openings, and past various structures, to create different sounds.

Having experimented with various hydraulophone designs, it was found that many of the resulting instruments were highly expressive, and allowed the player to "bend" the pitch over a wide range. For example, one was able to play a C-major chord by blocking the "C" (jet number 3), the "E" (jet number 5) and the "G" (jet number 7) at the same time, and then move the finger that was on the "E" in such a way as to make it slowly move down one semitone, while keeping the other two notes constant. Thus one could gently and continuously glide from major to minor.

With the water spray, each note is a time-varying sculpture, in which pitch, timbre, and volume changes manifest themselves as visible changes in the water spray pattern experienced by both the player and his or her audience.

8.3 Hydraulic musical instruments

Water and music have had a long-standing relationship.

Hydraulics is the branch of engineering and science pertaining to mechanical properties of liquids, and fluid power. The word "hydraulics" comes from the Greek word for "water organ", a musical device consisting of hydraulically blown wind pipes used to imitate the chirps ("songs") of birds [http://wikipedia.org/wiki/Water_organ]. The Hydraulis was also a water-powered but air-based pipe organ, in which water power was used to blow air into organ pipes.

Both the Greek "water-organ" as well as the Hydraulis were water-powered wind (air) instruments, the difference being that the "water-organ" worked like a player piano (i.e. played itself), whereas the Hydraulis was a keyboard instrument (the world's first keyboard instrument), played by pressing down on wooden keys or levers. [http://wikipedia.org/wiki/Hydraulis].

In 1832, a musical instrument designer made a "steam trumpet" (later to be known as a train whistle or steam whistle). Such steam whistles had long been used on steam locomotives.

Later, Joshua C. Stoddard of Worcester, Massachusetts came up with the idea of using an *array* of these previously known steam whistles.

Stoddard's invention, which he patented October 9, 1855, was basically a pipe organ that used steam whistles instead of regular organ pipes, although Stoddard referred to his invention as a "steam piano". Note that Stoddard did not invent the steam whistle, but merely used multiple instances of an existing invention to make a well-known signaling making device into a musical instrument.

9. CONCLUSIONS AND SUMMARY

We have described a number of new musical instruments that use real physical processes to interact with sound samples. Some of these instruments are friction idiophones that work in a manner similar to the way a disk jockey "scratches" a needle/stylus through a record groove to creatively produce sound. However, our instruments use multiple record players, or multiple mechanically stored tracks on one multi-track cylinder or disk to emulate the effect of multiple record players. Each record player (or track) is used for a different note of a scale, i.e. each corresponds to one key on the keyboard. The result is a fluidly flowing and highly expressive instrument similar to a mellotron, but much more versatile and much more physical.

We also found that a suitable keyboard for controlling the new instrument could be made from an array of water spray jets, with each jet functioning as a key on the keyboard. The result was a fully acoustic sampling keyboard with hydraulic action that was: (1) instantaneous due to the incompressibility of water; (2) expressive due to the intricacy and subtlety of water as a user-interface medium; (3) expository due to the fact that the water spray is easy to see and learn from.

Additionally, we presented variations of our non-electric sampling keyboard in which a water jet was used as the stylus for each groove in the record (i.e. a separate water jet for each note on the keyboard). This provided a simple and intuitive connection, i.e. each water jet on the keyboard controlled a corresonding water stylus on the record.

Pressing down on one water jet (i.e. stopping the water from coming out of one of the holes) forced it into a hose and out a nozzle at the record, thus "scratching" the record in proportion to the degree of restriction of the water jet.

Some variations of the instrument using electric amplification were presented. In one embodiment, the fingers of the musician were placed directly on a special record designed to be "scratched" with fingernails or with the meatier part of the fingers or hand. This embodiment allowed for both temporal as well as track to track smearing of samples, by use of an entire fingertip rather than just the fingernail.

Finally, a computerized embodiment was presented in which similar smearing of samples was implemented using convolution with the time-derivative of a watersound envelope. In this embodiment, the original sound in the instrument comes from underwater microphones (hydrophones) thus putting this instrument into the hydraulophone category (rather than the electrophone category more typical of computer-based instruments).

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