Hydraulophone Design Considerations: Absement, Displacement, and Velocity-Sensitive Music Keyboard in which each key is a Water Jet

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ABSTRACT

We present a musical keyboard that is not only velocity-sensitive, but in fact responds to absement (presement), displacement (placement), velocity, acceleration, jerk, jounce, etc. (i.e. to all the derivatives, as well as the integral, of displacement).

Moreover, unlike a piano keyboard in which the keys reach a point of maximal displacement, our keys are essentially infinite in length, and thus never reach an end to their key travel. Our infinite length keys are achieved by using water jet streams that continue to flow past the fingers of a person playing the instrument. The instrument takes the form of a pipe with a row of holes, in which water flows out of each hole, while a user is invited to play the instrument by interfering with the flow of water coming out of the holes. The instrument resembles a large flute, but, unlike a flute, there is no complicated fingering pattern. Instead, each hole (each water jet) corresponds to one note (as with a piano or pipe organ). Therefore, unlike a flute, chords can be played by blocking more than one water jet hole at the same time.

Because each note corresponds to only one hole, different fingers of the musician can be inserted into, onto, around, or near several of the instrument's many water jet holes, in a variety of different ways, resulting in an ability to independently control the way in which each note in a chord sounds.

Thus the hydraulophone combines the intricate embouchure control of woodwind instruments with the polyphony of keyboard instruments.

Various forms of our instrument include totally acoustic, totally electronic, as well as hybrid instruments that are acoustic but also include an interface to a multimedia computer to produce a mixture of sounds that are produced by the acoustic properties of water screeching through orific plates, as well as synthesized sounds.

Categories and Subject Descriptors

H.5.2 [**User Interfaces**]; H.5.5 [**Sound and Music Computing**]; J.5 [**Computer Applications**]: ARTS AND HUMANITIES—*Fine arts*

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General Terms

Measurement, Performance, Design, Experimentation, Human Factors, Theory

Keywords

Fluid-user-interface, tangible user interface, direct user interface, water-based immersive multimedia, FUNtain, hydraulophone, pneumatophone, underwater musical instrument, harmelodica, harmelotron (harmellotron), duringtouch, haptic surface, hydraulic-action, tracker-action

1. INTRODUCTION: VELOCITY SENSING KEYBOARDS

High quality music keyboards are typically velocity-sensing, i.e. the notes sound louder when the keys are hit faster.

Velocity-sensing is ideal for instruments like the piano, or the celeste, because the tones of the instrument decay after they are struck. Whether one is playing on a real acoustic piano which is velocity sensitive, or one is playing on a velocity sensing electronic keyboard that synthesizes or otherwise emulates a real acoustic piano, velocity sensing works well as a way of initiating a tone to begin at an initially selected sound level and to then die out over time.

Other instruments, like the organ, have lingering tones that need not decay, but instead can sound for as long as a key is held down. Real acoustic pipe organs and electronic organs, tend to have keyboards that are not velocity sensing.

Moreover, with organs, notes often turn on and off in a binary fashion, rather than by degrees as with a piano. However, some modern electronic organs, especially high quality synthesizers that have organ settings, sometimes have keyboards which are velocity-sensing. This means that when you press the key faster a note sounds louder and when you press the key down more slowly the note sounds quieter. Since organs can produce lingering tones, if a musician is holding a note for several seconds, he or she is unfortunately stuck with the note volume that was established by the initial velocity that the key was hit with. Therefore, although the velocity sensing keyboard allows an increase in musical expression, it would be nice if there was an ability to continuously update the musical expression of each individual note, or at least vary the sound level of the note, while the note continues to sound.

Although some organs provide expression pedals, such as a volume pedal, these pedals affect more than one note at the same time, and do not allow individual notes to be continuously updated in volume while they are sounding. Electronic keyboards with channel aftertouch also provide a single global modification across all the notes being played.

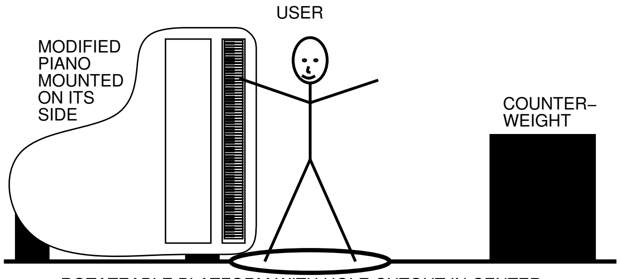

Figure 1: **The "PIANOrgan", a make-believe instrument that combines the expressivity of a piano with the organ's ability to sustain notes for as long as desired:** Imagine a piano that had infinite key travel. Perhaps this could be achieved by keys traveling in a cylindrical (endless) path, using a "treadmill" platform. As the platform rotates around the user, the keys of the specially modified piano could be pressed down continuously deeper and deeper without ever reaching bottom. The piano would have to be modified so that the notes would continue to ring out for as long as the keys were pressed. Ideally, perhaps this might create a very "fluid" and continuous musical experience. Obviously it may be impractical or impossible to achieve this situation.

It would be nice to be able to individually (independently) control the volume of each note in a chord continuously, over time. Some electronic keyboards, such as the Roland A50, implemented polyphonic aftertouch, but only with limited success. In fact, presently, no keyboards with polyphonic aftertouch are being manufactured any more. The only kind of aftertouch that exists on currently manufactured keyboards, channel aftertouch, once again acts globally across all notes being played.

Moreover, when polyphonic aftertouch did exist, it involved the initial creation of a note, followed by updates to its expression. Rather than construct a note at a certain initial keypress velocity, and then attempt to later modify it, it would be nice to be able to continuously adjust the expression of each note in a flowingly fluid way. We use the term "duringtouch" to refer to this ability to continuously update one or more attributes of a note at all times before, during, and after it is sounding.

If a velocity-sensing keyboard could be made in such a way that it had infinite key travel (i.e. so that keys would never bottom-out), it would be possible for the musician to be able to continuously and dramatically shape each note, independent of the other notes. This ability to shape each note would last for as long as the notes lasted; i.e. as long as a note was sounding, it could be shaped up or down in volume, pitch, timbre, etc., in various ways.

A piano affords some very nice and subtle ways to change the way notes sound, but pianos have limited key travel, after which a key bottoms out, and cannot be pressed any further, so it is impossible to maintain a constant velocity on a piano key, or to continuously modify the velocity.

Imagine, instead, a piano that had infinite key travel, so that it would continue to sound for as long as you wanted, i.e. for as long as you kept pressing the keys further and further down. One way to achieve this endless key travel might be to turn the piano sideways and put it in an endless cylindrical "treadmill" as shown in Fig. 1.

Of course mounting the piano sideways in a cylindrical treadmill platter, along with some mysterious modifications might seem totally absurd. Even if it could work, you could not readily press individual keys at different velocities without soon extending beyond the reach of your hand-span, so you would be limited to playing only one note at a time, if you wanted to attain complete and continuous expressional control. Conversely, what we desire is the ability to have continuous independent expressive control of each note in a musical chord (or of each note in any other group of simultaneously sounded notes).

However, the idea of an endless "key" is certainly possible. If you rub your finger around the rim of a wine glass (or the end of a verrophone) the note can continue to sound for as long as you keep your finger moving around the rim. Since the glass is circular you never reach the end of the sounding path. Thus the tone can linger for as long as you keep moving. Moreover, you can continuously put expression into the sound. But it is very difficult to play complex chords on a set of wine glasses, or on the glass pipes of a verrophone.

1.1 A keyboard-like instrument with continuously flowing keys

Playing a set of wine glasses (or a verrophone which consists of glass pipes open at both ends) you have to keep your fingers moving around in a circle. Benjamin Franklin observed that all we need is relative motion between the finger and the glass, so in 1761 he invented a new instrument that he called the armonica or "glass harmonica". Franklin's armonica consisted of a spinning metal shaft, upon which were mounted, concentrically, the tops of variously sized wine glasses, or other glass disklike objects similar to the tops of wine glasses.

To play the instrument you simply pressed wet fingers against the moving glass "keys". One could play up to ten notes at once, by pressing one finger against each disk. The instrument produces a celestial bell-like sound, but the glass bells can be made to ring continuously, for as long as the musician continues to press on them. Moreover, the musician has total control of the sound envelope, and can, for example, create tones that grow, decay a little, and grow some more, etc., rather than merely the decaying tones of a piano. This fine control over musical expression can be done individually for each note in a complex musical chord, greatly increasing the virtuosity of the instrument.

Thus very rich and full chords could be played with virtuoso complexity.

The armonica had a celestial softness that was simultaneously pleasant and haunting, allowing it to produce soulful melancholy sounds.

Unlike electro-mechanical instruments, like the chamberlin or mellotron, where magnetic tapes are manipulated indirectly by keys, or optical variations like the optigan, where sounds from an optical disk are accessed by a keyboard, the glass harmonica has a more direct user-interface because the fingers are touching the glass directly, rather than being mediated through the mechanics of a keyboard. Thus, compared with similar instruments like the mellotron, the glass harmonica allows the musician greater ability to continuously and independently affect some very subtle changes in expression, as notes are sounding.

2. THE HYDRAULOPHONE: USING WATER INSTEAD OF GLASS FOR CONTINUOUSLY FLOWING KEYS

We propose a keyboard instrument that uses the continuous flow of water. Each "key" is a water spray jet. Like Franklin's glass harmonica, each "key" of our new instrument is endless (assuming either an unlimited supply of water, or a means such as a trough or catch basin, to capture and re-circulate the water).

Unlike the glass harmonica, our instrument uses hydraulic action of the fluid, into a sound-producing mechanism. Some variations of our instrument are totally acoustic, where the sound-producing mechanism consists of fluid screeching through small orifices or disks or hydraulic sounding pipes. Other versions of our instrument use the optical properties of the water and work like an optical variant of the tonewheel drawbar organ. We also built some that use electrical properties of water, and some that are completely electronic [4][6], or are simply "hydraulic-action" or hydraulectric-action consoles.

We refer to our new instrument as the hydraulophone, combining the Greek term "hydraulics" and "phone" (sound).

Our hydraulophone, in many forms, is a hydraulically actuated organ that is played by direct interaction with the hydraulic fluid (usually water). This direct interaction with the hydraulic fluid provides a wider range of, as well as finer control over, the musical expressivity of the instrument than would have been possible had we simply used keys made of solid matter, to indirectly press down on the hydraulic fluid.

2.1 Example of hydraulophone

We have designed and built a number of hydraulophone prototypes, many of which are human-powered and entirely acoustic, and others which are electrically powered, water-pressure powered, or natural-gas powered, as well as still others which have been electro-acoustic, opto-acoustic, as well as some that are completely electronic.

Hydraulophones usually include a user-interface that comprises an array of water jets that each function like a key on a keyboard instrument. Hydraulophones are usually played by touching, diverting, restricting, or obstructing the water jets in the array. Often the jets are arranged in a row, like the keys on a piano, so that the instrument is played by pressing down on one or more of the water jets in succession.

Of our purely acoustic hydraulophones, some are built using active water-choppers or spatial water modulators. For simplicity, we often use a single chopper wheel for all of the notes. A fifteen-note (two-octave) diatonic design is shown in Fig 2.

An example of a hydraulophone which can operate underwater, or in air, is shown in Fig 3.

The hydraulophone has a row of fluid jets which can be played with one's fingers to create musical notes. The more one's finger blocks a jet, the more fluid that is diverted to the sounding mechanism. When more fluid is diverted to the sounding mechanism the sound changes in various ways. For example, it becomes louder, and brighter in timbre. However, most importantly, the note stays in tune, regardless of the quantity, pressure, of other flow changes in the hydraulic fluid.

Therefore, unlike even a true tracker organ, which gives the musician some control over the attack envelope, the hydraulophone gives continuous and far greater control over both the attack envelope and the steady state sound (volume, timbre, etc.).

2.2 The hydraulophone as an instrument with continuously flowing expression

Many woodwind instruments have a row of holes, wherein, to achieve each note, there is a particular somewhat complicated fingering pattern that must be remembered. Since the holes are used in various combinations of this sort, these instruments are purely monophonic.

Our hydraulophone, however, associates one hole to each note. The hydraulophone's holes can be (and usually are) arranged in a pattern akin to a piano-style keyboard, as shown in Fig. 4.

Another side-effect of the fact that each jet, together with its sounding mechanism, corresponds to only one note, is that the instrument is able to play chords, unlike wind instruments such as flutes, clarinets, saxophones, and the like.

Additionally, while woodwind instruments allow a musician to continuously vary the expression of only one note at a time, the hydraulophone allows each note in a chord to be given an independent continuously-varying expression. It is then possible to play the hydraulophone in such a way that the harmony can be played softly in the background, overlapping in the same space as the melody, a combination that we call "harmelody".

This 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, as shown, by way of example, in Fig. 5.

Hydraulophone technique allows a musician 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 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.

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

To play the hydraulophone, a musican forms a hydralic bond between their finger(s) and one or more of the hydraulophone's water jets, to restrict, divert, obstruct, or modify the flow of the water. This action on the water flow diverts it elsewhere inside the instrument to make a sound that varies widely depending on the manner in which the restriction, obstruction, diversion, etc., is performed.

Because of the abililty to play harmelodically, we sometimes refer to the hydraulophone or pneumatophone (hydraulophone run on compressed air instead of water) as a "harmelodica", and to its electric counterpart as the "harmellotron".

2.3 Hydraulophones in public spaces

Because the hydraulophone can be housed inside a heavy stainless steel pipe, it is suitable for installation in a public park, as a form of publically accessible art. Unlike the glass harmonica (armonica) which is very fragile, the hydraulophone's keys are much more durable because they are made of water (water replenishes itself). Even a piano left unattended in a public park could be easily damaged, whereas the hydraulophone presents new possibilities for bringing music to everyone in public spaces, even those who are not fortunate enough to have a piano in their homes.

In addition to creating installations in public places, we have also made a number of portable hydraulophones that re-circulate the water into a bucket, so all that one needs in order to play in any location is a pail of water and a hand-operated (or electric) bilge pump, as shown in Fig. 6 and 7.

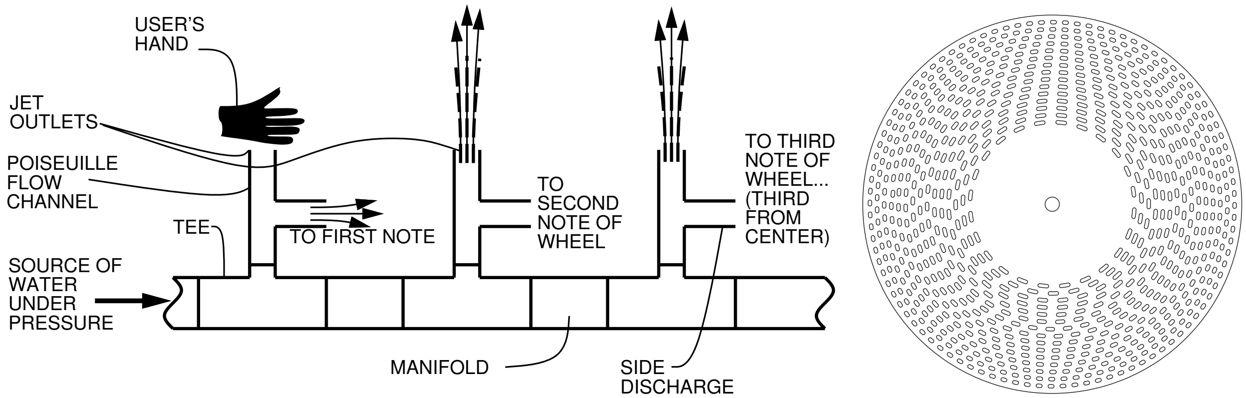

Figure 2: **Acoustic hydraulophone:** (a) Fluid User-Interface: blocking a jet diverts hydraulic fluid, such as water, to a sound-producing mechanism. For simplicity only three jets are shown, although the number of jets might more typically be 88 (e.g. similar to a piano). The first jet is shown in a blocked state, where hydraulic fluid exits through the side discharge to the sound-producing mechanism. The other two jets are shown in an unblocked state where, by way of the Bernoulli principle, a vacuum is drawn on the side-discharge pipe, to silence the corresonding sound. (b) the sound-producing mechanism for use with a 15-jet hydraulophone is a perforated wheel that spins at high speed. When diverted, hyrdraulic fluid from the first side-discharge is directed against the innermost circle of holes, to sound the lowest of the 15 notes by way of pulsating water jets that can be heard either underwater, or above the water's surface. Outer circles of holes are for higher notes.

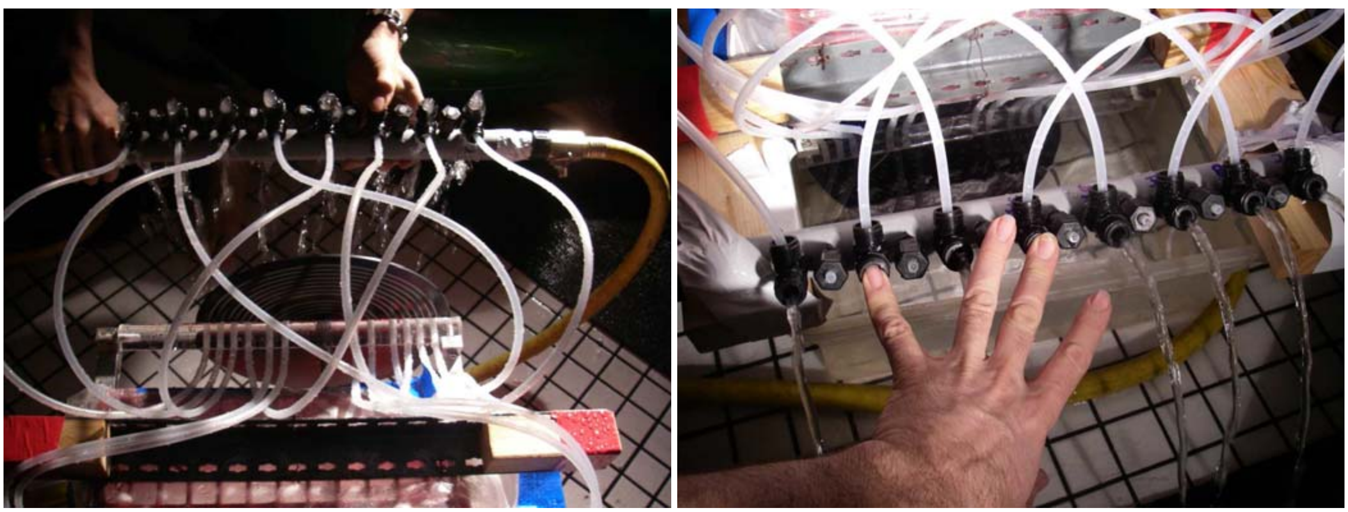

Figure 3: **An entirely acoustic hydraulophone:** Sound is produced by water jets being made to pulsate at very high frequencies through modulating the stream of diverted water by a spinning disk with a series of holes. (a, leftmost figure) Water jets spray through the air; (b, rightmost figure) A water reservoir collects water and the disk is immersed further underwater as the water level builds up. This provides a time-integrating effect in which the sound changes as the water level in the reservoir rises. A small drain in the reservoir allows the level to slowly fall when the water supply is removed.

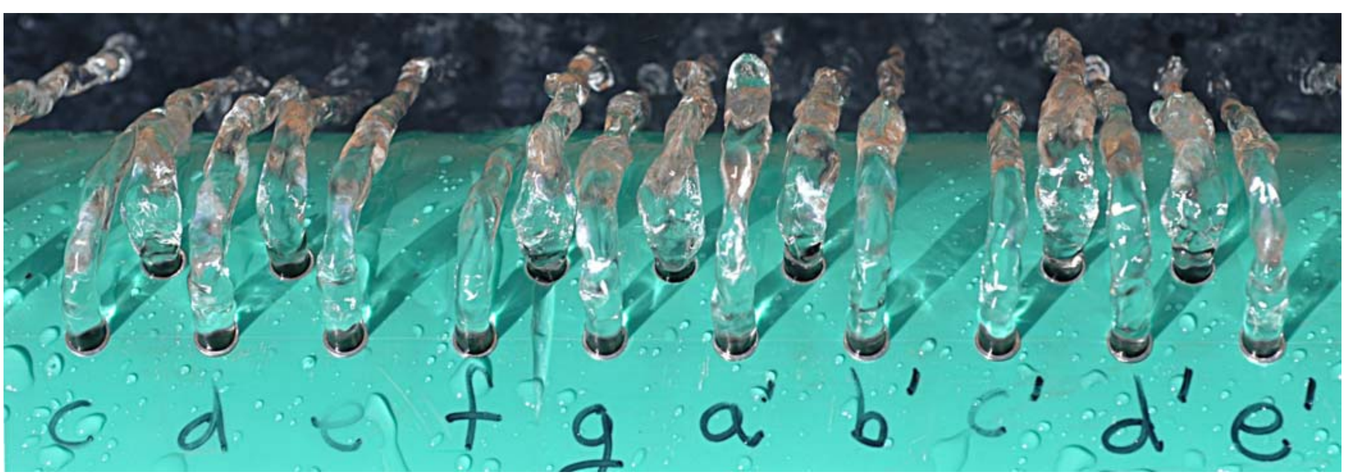

Figure 4: Example of piano-style layout of hydraulophone jet outlets.

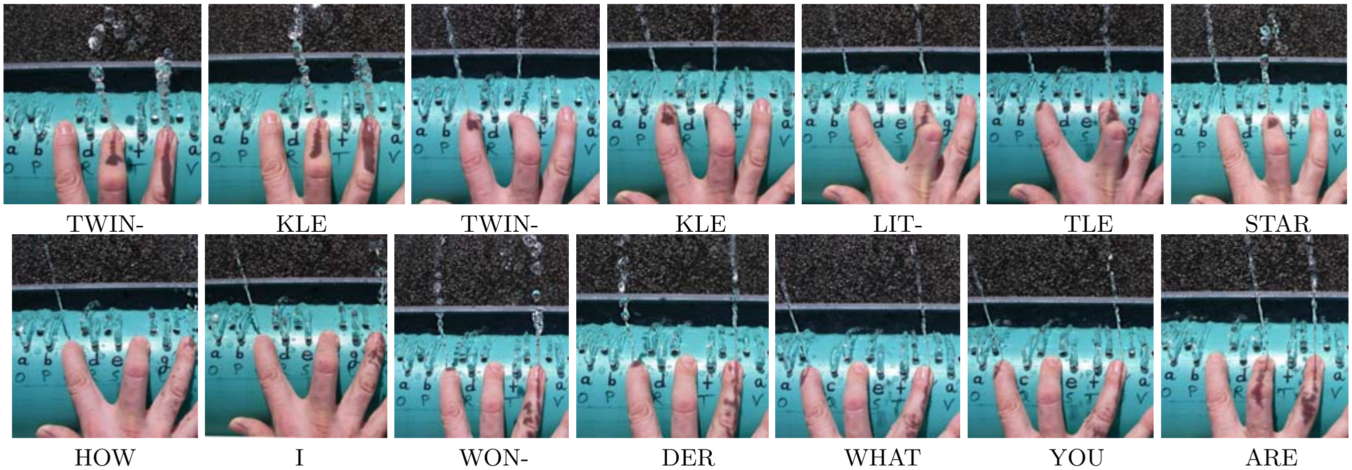

Figure 5: Example showing the two phrases “Twinkle twinkle little star” and “How I wonder what you are” being played with overlapping harmony and melody. A unique aspect of the hydraulophone is that the individual fine control over the sound of each note is visible, unlike other instruments that use air. Being able to see this “finger-jet embouchure” of the instrument’s many “mouths” simultaneously, makes it easy to learn, and useful for teaching the finger-expression control technique. Consider the upper leftmost two of the 14 figures. Here we see a C-major chord being played with emphasis on the first note of the melody, C (the flow of the C-jet is fully restricted), while the E and G jets are being partially restricted. In the next two figures, the same three jets are being blocked, but the emphasis is shifted fluidly and continuously toward the G jet, without any disruption in the harmony.

Figure 6: Portable lightweight 45-jet hydraulophone made from IPEX PVC pipe, with catch trough to recirculate the water into a bucket.

2.4 Displacement, and Velocity sensing keyboards

One interpretation that fits both Franklin’s glass harmonica as well as our hydraulophone, is that these instruments are both velocity-sensing “keyboards” that have endless “keys”.

However, another possible interpretation is that they are displacement-sensing (or pressure-sensing) keyboards, because if we ignore the movement of the keys, and just measure finger position, the sound gets stronger as the finger comes closer to (or presses harder against) the moving glass or the moving water.

Ignoring, for a moment, that the glass or water flows (at some velocity) past one’s finger, it is really the position of the finger with respect to the glass or water that matters the most.

As was suggested in Fig 1, the hydraulophone may be thought of as combining the expressivity of the piano with the non-decaying tone of the organ. The organ may be regarded as a keyboard instrument with keys that respond to displacement rather than to velocity. Consider just one key, in the keyboard that is illustrated in Fig. 8

For the organ keyboard depicted in Fig 8(a), a natural place to put the origin is at the resting place of the keys when they are not being touched by anyone. From there, we draw a downards-facing arrow to indicate the direction of increasing displacement. With this choice of coordinates, pushing down on a key (increasing the displacement) thus activates the tone corresponding to that particular key on the keyboard.

In the case of the hydraulophone, the water jets have no particular well-defined resting place when they are not being pressed down by a musician. Because the uppermost peak of the water jet is somewhat random, there is no convenient place to define an origin for the uppermost extremity of the “key” (water jet) travel. Moreover, the instrument is often operated at a variety of different pressures and flow rates, so the key travel may range anywhere from one millimeter to one meter. Thus the only reasonable place to define as the origin (the point at which the displacement equals zero) is the hole from which the water jet emerges.

When the instrument is being played, the sound typically gets louder, brighter, and a little sharper in pitch, as the finger comes closer to the hole from where the water jet emerges. Thus, with displacement defined as distance from the hole, as the displacement increases, the activation of the note is decreased. This inverse relationship between displacement and note volume is shown in Fig. 9(c).

Our original hydraulophone design operated at very high pressure, so that even a person of exceptional physical strength could not obstruct the fluid entirely. In fact, total obstruction would typically result in damage to the instrument, so we regarded total obstruction as an “infinite” (i.e. never-reached) condition. Therefore it made sense to think instead of reciprocal **dis**placement, which we referred to as “placement”:

$$\text{placement} = 1/\text{displacement}. \quad (1)$$

Figure 7: Portable hydraulophone set up for public performances at the annual Kensington Market Water Festival, 2006. Leftmost: Performance by Fernan Enriquez; Middle: Performance of "Rock Christina" (a song intended for being played by two people) by S. Mann. Unlike other musical instruments, because the hydraulophone is also a fountain, it is self-cleaning, and thus lends itself well to being played by hands as well as feet, providing the whole-body experience similar to what one might get by running through a fountain or frolicking in a pool (Middle picture photo credit: Ron Miyanishi). Rightmost: Performance by Christina Mann (age 4).

Placement of the fingers on the instrument results in increased note volume as the placement increases. When the musician places his or her fingers more firmly down against the hydraulic fluid pressure, the note volume rises with increasing placement, as shown in Fig. 9(d).

Let us again compare the hydraulophone with the piano: Recall that a velocity sensing keyboard is an instrument that has its default or "zero" state at the point where no key is in motion. The range of interaction with the velocity-sensing keyboard is then defined by how hard and fast the keys are pressed from this zero state, as shown in Fig. 9(a).

For an organ, the zero (no key action) state has to do with position rather than velocity. We might say that the zero state of an organ keyboard is simply the resting position when a key is not being pressed. In this state the note is off. The note comes on when the key is pressed with downwards displacement, as shown in Fig. 9(b). Recall that the organ responds to displacement rather than to velocity. Note also that the organ responds abruptly, i.e. it comes on suddenly after the displacement exceeds a certain threshold.

Recall that for hydraulophones displacement becomes a difficult variable to work with, because there is no easily defined unactivated resting point on a water jet because the jet is contstantly active, foaming, bubbling, etc., and never at rest.

Therefore, the most natural place to define the origin is the base of the water jet, where the water comes out through the hole. But this base is where the instrument "blows up" (either damages itself or at least saturates to full volume) if the jet could ever be pushed down this far (fortunately humans lack the strength to do so).

The positions of the jet outlet channels are very clearly defined, even though it is not possible (due to high water pressure) for a user to ever put their finger right at that point. Thus the bottom, rather than the top, of the "key" (water jet) travel is the natural place to define a displacement origin, thus creating the inversalism for using placement rather than *dis*placement.

3. THE RESERVOIR HYDRAULOPHONE

Another type of hydraulophone is the reservoir hydraulophone. This form of the hydraulophone has a much more celestial or spiritual kind of sound that builds up slowly, producing lingering tones very similar to Franklin's glass harmonica. This variation of our hydraulophone design uses perforated water wheels that each receive water from a separate reservoir for each note. When a water jet is first pressed down, it takes a while for the note to begin sounding. The reservoir has an integrating effect on the downward displacement of the water jet. Thus the height, h, of the water in the reservoir (which controls approximately the note volume) is approximately equal to the integral of placement:

$$h(t) = \text{note volume} \approx \int_{-\infty}^{t} p(\tau) d\tau, \qquad (2)$$

where $p(\tau)$ is the placement as a function of a time variable τ.

We refer to this time-integral of displacement as presement. When the user's finger is present, pressing down on a jet, for an extended period of time, the note reservoirs slowly fill up, resulting in a gradual increase in note volume. Presement is the presence of the user's fingers for an extended time period.

When the user takes their fingers away, notes die down slowly again.

4. HYDRAULOPHONES THAT RESPOND TO BOTH PLACEMENT AND PRESEMENT

Our most expressive hydraulophones respond to both placement (inverse displacement) and presement. Our design is depicted in Fig. 10. One component of the sound comes from water passing through an opening in the side-discharge of a Bernoulli jet that draws vacuum under idle conditions but receives varying amounts of positive pressure under various conditions of water jet blockage [4]. The other component of the sound comes from an integrating reservoir. The reservoir supplies a water-based tonewheel that has a sound very similar to a glass harmonica. These lingering tones build up slowly, and provide a background to the more fast response of the Bernoulli jet component.

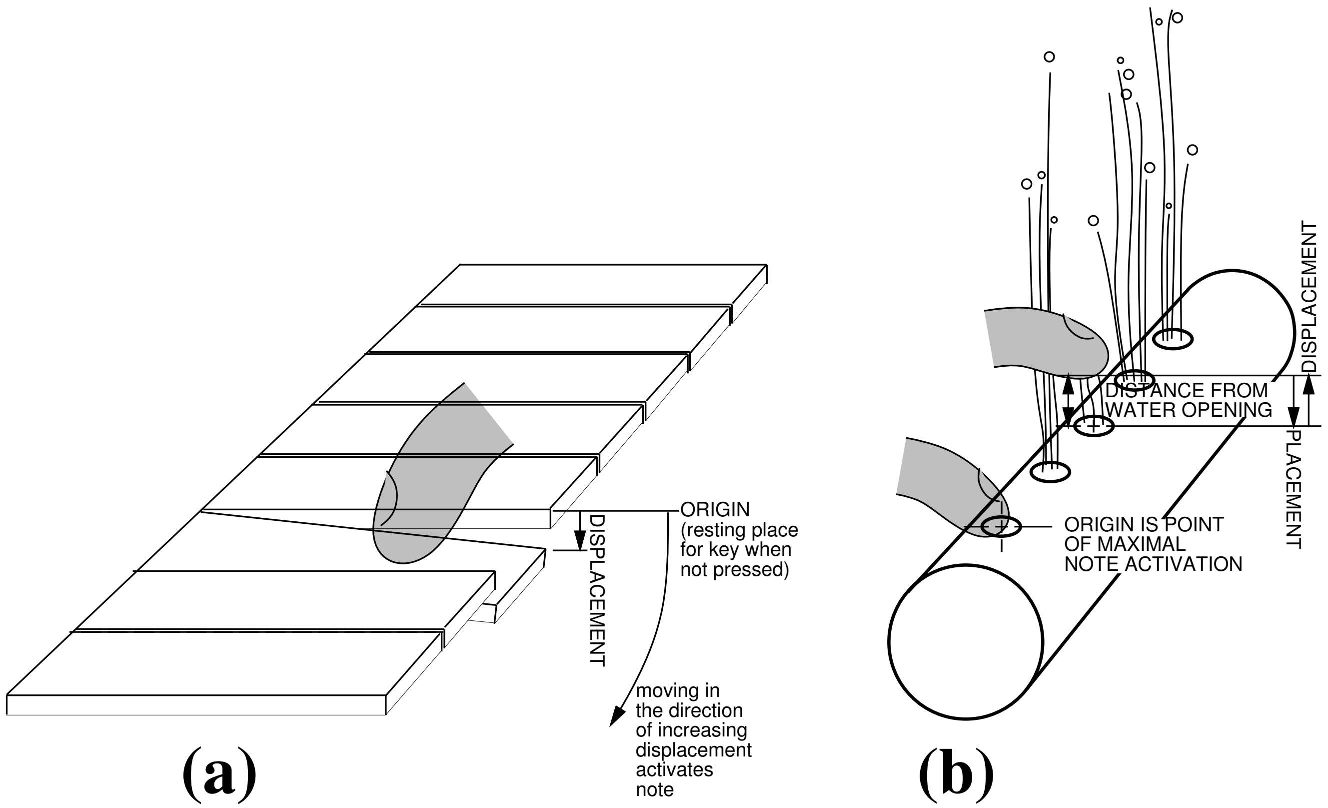

Figure 8: **Interpretation of hydraulophone as displacement-sensing "keyboard"** (a) Organ keyboards are displacement-sensing keyboards. A natural point of origin is the resting point when a key is not pressed (i.e. when a note is not sounding. As the downward-displacement increases past some threshold, the note turns on. (b) Hydraulophone "keyboards" have "keys" that area each made of a water jet. Since the jets do not end at a particular well-defined point in space, the natural orgin is the place where the water emerges from. This point is a point of maximal note activation. As the finger moves back from this point, the note is more weakly activated. The strength of the note varies approximately as the inverse of the displacement so-defined. As the finger approaches the point where the water emerges from, the note activation increases without bound, although there is some theoretical maximum activation beyond which damage to the instrument occurs. To capture this inverse relationship, we consider "placement" (reciprocal displacement) which increases without bound as we approach the water jet origin.

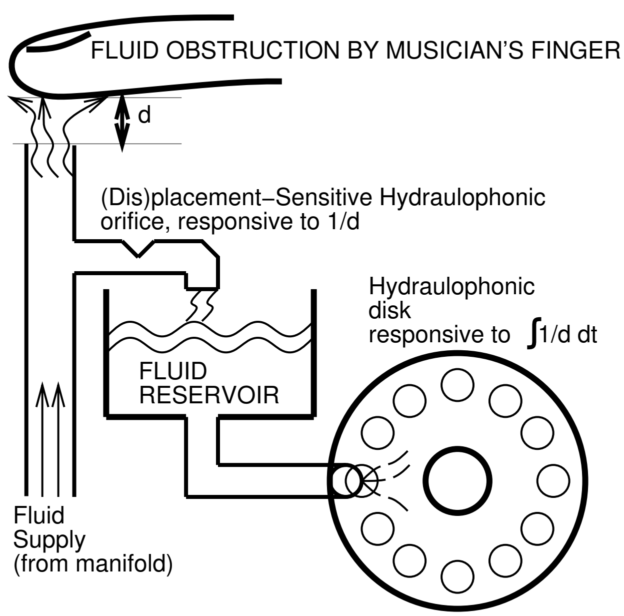

Figure 10: **Hybrid hydraulophone that responds to both displacement and the time-integral of displacement.** A Bernoulli jet screeches as water is forced through it when the main jet is blocked. Additionally, a reservoir fills with water and supplies water to a water tone wheel.

4.1 A poetic narrative for absement/presement

The most melancholy element of the hydraulophone comes from the presement/absement response. To understand presement/absement in terms of a metaphor from real life, consider absemence as when spending some time away from a loved one. With absement being a product of time and displacement, the more time, and the farther away from home, the more absement one feels. Borrowing from a common saying, we might say that "absement makes the heart grow fonder". Being two hundred miles from home for one day, produces approximately the same feeling of absement as being one hundred miles from home for two days.

As another example, consider a long-distance phone bill based on a time-distance product. Units of absement are the product of time and distance. Whereas velocity is measured in meters per second, absement is measured in "meter seconds".

5. WHY WE DESIGNED THE HYDRAULOPHONE TO HAVE A SOOTHING MELANCHOLY SOUND

Canoe songs (recall, for example "My paddle's keen and bright; Flashing with silver; Follow the wild goose flight; Dip, dip and swing") are usually in a minor key, and convey the lonesome sense of longing brought to mind in the water. See, also, The Great Canadian Tunebook, "Land of

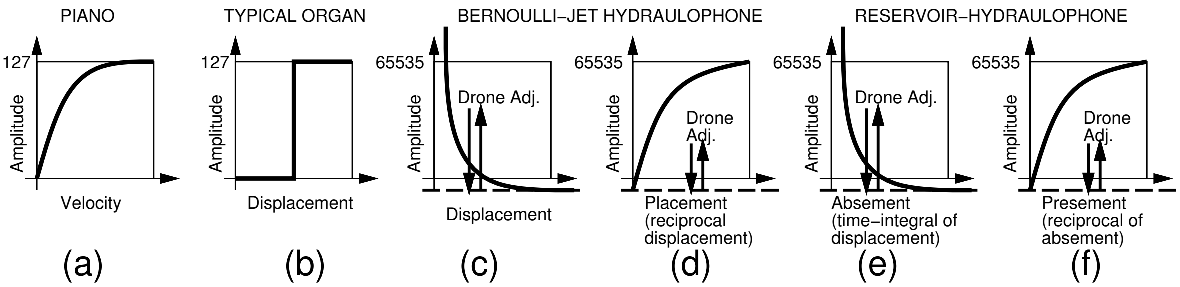

Figure 9: **Velocity-sensing versus displacement-sensing keyboards:** (a) Most high quality keyboards are velocity-sensing, as is a real acoustic piano. In the case of electronic MIDI keyboards, the amplitude (volume) of a note goes from zero (or some low value) when the zero velocity is zero, up to a maximum value of 127 (defined by seven bit precision) for maximum velocity. (b) A typical organ responds to displacement rather than to velocity. When a key is pressed down from the displacement origin (indicated in Fig. 8) the note turns on (in electronic organs "on" typically corresponds to some fixed value such as 63 or 127). When the key is released (displacement goes back to zero) the note goes off again. (c) The Bernoulli-jet hydraulophone responds to displacement like an organ, but instead of the organ's abrupt on/off, it has a continuously variable expression curve, as does a piano. Note volume increases as the user's finger gets closer to completely blocking the water jet. The upper limit of note amplitude is never reached until some hydraulophone damage threshold that is typically well beyond the force limit of what a human user can exert. In an electronic hydraulophone or a hybrid (acoustic and electronic) we typically use 16-bit precision, so that at some small value of displacement, maximum note volume of 65535 is reached. (d) It makes more intuitive sense to think of reciprocal **dis**placement which we call "placement". As the user **places** his or her fingers down onto the water jet, the volume increases with increasing placement. Infinite placement (zero displacement) would require astronomical force beyond human capability (and would result in damage to the instrument), but some time before that point a sufficiently high note volume level is reached. (e) A reservoir hydraulophone works similarly, except that it responds to the time-integral of displacement which we call absement. When the user's finger is absent for an extended period of time, the note reservoirs slowly drain, resulting in a gradual decrease in note volume. When the user's fingers are less absent (closer) for an extended period of time, reservoirs slowly fill, resulting in a gradual buildup of note volume. (f) It also makes sense to think of absement in the reciprocal sense, which we refer to as presement. Presement is the presence of the user's fingers for an extended time period. (a,d,f) Note how the PIANO, the BERNOULLI-JET HYDRAULOPHONE, and the RESERVOIR-HYDRAULOPHONE all have the same shape of curve, but respond to velocity, the integral of velocity, (i.e. (displacement or placement), and the double integral of velocity (i.e. absement or presement), respectively. One important difference between the piano and the hydraulophone is that hydraulophones always have some background activation level for all of the jets through which fluid is flowing. Thus when there is no one playing the instrument, it still makes a drone sound in which every note is playing softly in the background at the same time. In some hydraulophones this drone level can be adjusted (Drone Adj.) down to (and sometimes even less than) zero, as indicated by the dotted baseline.

the Silver Birch", e.g. "...My heart cries out for thee, hills of the north Blue lake and rocky shore I will return once more....". Both these songs are in pentatonic minor (i.e. a soothing minor key that emphasizes consonance rather than dissonance).

Hydraulophones are usually in the key of A-minor for just intonation (to emphasize perfect consonance, in at least one key), and, in the case of an equally tempered hydraulophone, the compass is usually still defined to give the most range for playing in the key of A-minor. In particular, the lowest whole[1] note on a hydraulophone is almost always "A" and the highest note is almost always "E", so that the lowest and highest chords played in root position (non-inverted) are both A-minor. Pipe organs usually start on "C", and electronic keyboards usually start on "C", or "G", or "F". Interestingly, the standard piano keyboard begins on "A".

Starting on "A" re-defines the musical alphabet so that it starts on "A" rather than "C", i.e. the first eight "white jet" (whole) notes of the hydraulophone, A, B, C, D, E, F, G, a, define the **natural minor** scale. This is the musical scale that a child may likely have learned as a baby, by way of a lullaby sung by a parent every night, drawing their tears into sleep with the sad, soothing, and comforting sound of "Hush a Bye[2]", "Rock Christina", or perhaps Gershwin's 1935 lullaby, "Summertime". The minor scale is thus perhaps metaphorically connected, in a baby's mind, to the watery comfort of the womb.

Interestingly, there are 26 "white jet" notes on the standard 45 jet hydraulophone, making notational sense to continue the alphabet, i.e. call the second highest "A" an "H", and continue up to the highest "E" and call it "Z". Since most children's songs are played entirely (or mostly) on "white jets", the notes in these songs may be written down uniquely by a list of letters. Additionally, children quickly learn the alphabet in a natural way, (i.e. starting on "A" rather than "C").

In addition to our emphasis on playing in minor keys, the timbre and expressivity of the hydraulophone has evolved toward an introspective melancholy sound. The range of sounds was inspired by the wailing cry of the steam calliope, once upon a time heard on riverboats and at circuses, as well as the call of a lonesome loon, the melancholy sound of panflutes and blown bottles, and the introspective sounds of string-pipes.

String-pipes can create the sound of a strings ensemble, but with wind-blown pipes rather than vibrating strings. String-pipes are found in many large pipe organs, where multiple pipes slightly out-of-tune with one another are sounded together to obtain a more rich and full sound. We achieve similar effects with reservoir hydraulophones having multiple tonewheels slightly out of tune with one another.

String sounds appropriate to playing in a minor key include, for example, the soothing sound of the strings ensemble in Gershwin's Summertime, or the melancholy sound of a mellotron's "sad strings". Our hydraulophone sound sculpting was inspired by instruments like the chamberlin, the mellotron, and Benjamin Franklin's glass harmonica. These kinds of sounds form the presement/absement (time integral of displacement) part of the hydraulophone's sound.

However, we didn't want to merely emulate the sound of a strings ensemble, but, rather, we wanted to emulate the sound of pipes trying to emulate the sound of a strings ensemble. Thus what we really wanted to do was emulate

[1]Some hydraulophones have A as the second lowest note, with the lowest note actually being G-sharp, so that one can change from A-minor in root position for the "I" chord to an inversion of E-major for the "V" chord.

[2]All the Pretty Little Horses

the sound of a church organ that is trying to emulate the sound of strings, rather than to emulate the sounds of strings directly.

The reservoir portion of the hydraulophone re-creates a sound quite similar to the sound created with an ensemble of Celeste de Viol, and Viol d'Orchestre organ pipes.

5.1 The Haunting Cry of the Lonesome Loon

Nothing captures the spirit and serenity the Northern wilderness like the haunting soulful cry of the loon across the water. A loon's wail is an almost wolflike cry with the tenor of a bassoon in its upper ranges, or of a strong wind whistling through railway telegraph wires across the Canadian North.

The Common Loon is the national bird of Canada and is depicted on the Canadian one-dollar coin, which has come to be known affectionately as the loonie. It is also the official provincial bird of Ontario, which is where we are installing most of our outdoor hydraulophones.

Some of our hydraulophones are in parklands adjoining wilderness areas, and thus provide a cry in the wilderness, like the eerie, haunting call of a loon echoing across a lake.

The sound of a loon is so much like a human in anguish that the Ojibwe have a legend that departed souls call back to us through the loon.

With the hydraulophone we attempt to embody the melancholy wailing sound of the violin, but in a way that sounds appropriate for coming from a pipe, rather than from an orchestra's strings ensemble.

The cello, which falls more in the range of the human voice, also evokes the soulful melancholy sound of the departed Ojibwe. However, the sounds of Vox Humana pipe organ stops are even more closely in keeping with the spirit of the distant cry of the lonesome loon, as a source of inspiration for the sound of the hydraulophone.

5.2 Cry of the Calliope

We have evolved the "lead" (melody) displacement- responsive portion of the sound of the hydraulophone toward the wailing cry of the steam calliope, once upon a time heard on riverboats and at circuses, with some fill-in from presement/ absement responding "string pipe" sounds for accompaniment.

5.3 Other spiritually introspective woodwinds

The hauntingly beautiful mournful soul-searching sound of a shakuhachi (Japanese bamboo flute) is said to replicate the sound of nature, and brings the mind into spiritual thought.

The duduk (Armenian flute) also has a unique exotic, melancholic, and nostalgic sound that provided inspiration in the evolution of the hydraulophone.

5.4 Wind in the reeds

Tribal peoples, attuned to their environment, have been aware of the haunting sound made by wind blowing across broken hollow-stemmed bamboo, reeds, or river cane. Thus the enigmatic panflute (6000 year old indigenous instrument of Andes) is appropriate, since reeds grow near bodies of water (lakes, ponds, rivers, coastal regions).

See for example, Roman poet Ovidius Naso's Metamorphoses: "Sitting on the riverbank, Pan noticed the bed of reeds was swaying in the wind, making a mournful moaning sound, for the wind had broken the tops of some of the reeds. Pulling the reeds up, Pan cut them into pieces and bound them together to create a musical instrument, which he named 'Syrinx', in memory of his lost love".

Thus an element of the sound sculpting in our acoustic hydraulophones, as well as our hybrid and electronic hydraulophones, has been to include these "earthy" sounds in the displacement-responsive portion, together with the chiff of the pan flute in the velocity-responsive portion. Velocity, acceleration, jerk, and jounce components of hydraulophone response borrow more from the inspiration of introspective woodwinds, whereas the presement/absement components of hydraulophone response borrow more from the celestial sounds of the most "stringy" pipes in a pipe organ.

5.5 Earth, wind, water, and fire

Some pan flutes, used in religious ceremonies, resemble a bird's outstretched wings, and are symbolic of the phoenix, the legendary fire-bird that represented life, death, and resurrection.

Socrates described the panflute as rustic, carnal, and elemental. (in contrast to stringed instruments like lyre and harp of the intellectuals and cultural elite).

One of our recent installations at the Ontario Science Centre in Toronto, Canada (a permanent hydraulophone installation measuring 10 metres in diameter, and 20 feet high[3]) is based on the theme of earth, wind, water, and fire. Displacement response symbolizes earth, the lonesome presement/absement concepts symbolize water, velocity responsive elements symbolize wind, and jerk, jounce, and higher derivatives of displacement symbolize the sounds of fire.

6. CREATING PLACEMENT AND PRESEMENT COMPUTATIONALLY

In many of our hydraulophones, we wanted to add some computationally synthesized sounds, and for other installations we wanted to build some completely electronic hydraulophones. In these hybrid (acoustic and electronic) as well as completely electronic versions, we wanted to maintain the same response to various time-derivatives and to the time-integral of displacement, present in their fully acoustic counterparts. Most notably, we wanted to maintain the absement/presement component characterized by lingering tones that build up over time, and give the instrument its wonderful spiritual/celestial sound.

We also wished to maintain the instrument's response, i.e. displacement sensing, velocity sensing, acceleration sensing, jerk sensing, jounce sensing, etc., which we did by way of a generalized Proportional Integral Derivative (PID) controller acting on each note.

The PID's proportional component is most related to placement (displacement). The integral component is most related to presement (absement). Our presement algorithm is based on simple differential equations which deal with the long-time variation of the volumes for each note. The integral/presement signals control their own sounds which are synthesized softly. This causes slow, "celestial" tones to build up and decay smoothly.

The derivative components are related to fast interaction with the instrument. They are determined computationally, based on derivatives of presement. The resulting "D" sound components can be especially heard when pressing a jet suddenly with a high velocity, resulting in a "chiffing" sound similar to that made in an organ pipe when air is suddenly forced through it. Blocking a jet slowly or softly on the hydraulophone deemphasizes this chiffing effect.

[3]The 20 foot height comes from starting on "A" rather than "C" which would have given a height of 16 or 32 feet.

The P, I, and D components are combined to affect volumes and pitches in various ways, sculpting the overall sound with influences from the call of the loon, etc.. A number of computational "reservoirs" are introduced similar to our acoustic reservoir hydraulophone.

7. OTHER RELATED WORK

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].

The original idea for the hydraulophone came from the screeching sounds made by defective faucets, and other valves with liquids passing through them, giving rise to the discovery and exploration of various water-based multimedia devices such as musical instruments based on pressurized hydraulic fluid [4]. In particular, various underwater musical instruments were made from simple devices (some hand-cranked or pumped like an accordian, others motorized) that rapidly turned water jets on and off, or forced water through resonant orifices, and other water-based musical instruments such as organ pipes with water actually flowing through the pipe and fipple mechanism, were explored [4].

Tangible media [2][3][1][8] have been demonstrated in various forms. Our arrays of water jets as a new multimedia interactive design element, could be considered an example of tangible media.

Peter Richards, 1986 Artist in Residence at the San Francisco Exploratorium, created a Wave Organ that similarly used water power to push air through organ pipes [5]. The wave-organ has no user-interface.

Other fountain installations consist of fountain jets that can be aimed by users but do not use direct interaction with the jets as a user input.

Fountains have often been used as output devices. Koert van Mensvoort's data fountain [7] is one such example. Fountains are often used as information displays, sometimes in synchronization with music (e.g. the fountains in front of the Bellagio hotel in Las Vegas). What is novel about the hydraulophone is the use of fountains (arrays of pressurized water jets) as both input and output devices.

Other related user-interfaces such as the Theremin, that also give continuously changing control quantities, do not provide any tactile feedback. What is unique about the hydraulophone is the soft tactile feedback that falls nicely somewhere between the tactility of hard plastic keys and the absolute absence of tactility of the Theremin.

8. CONCLUSIONS AND SUMMARY

Fluid user-interfaces were explored. In particular, it was found that an array of water jets formed a new and useful input device that functioned like a "soft" and expressive keyboard, by way of responsivity to the time derivatives and time integral of displacement.

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