THE HYDRAULOPHONE: INSTRUMENTATION FOR TACTILE FEEDBACK FROM WATER FOUNTAIN FLUID STREAMS AS A NEW MULTIMEDIA INTERFACE

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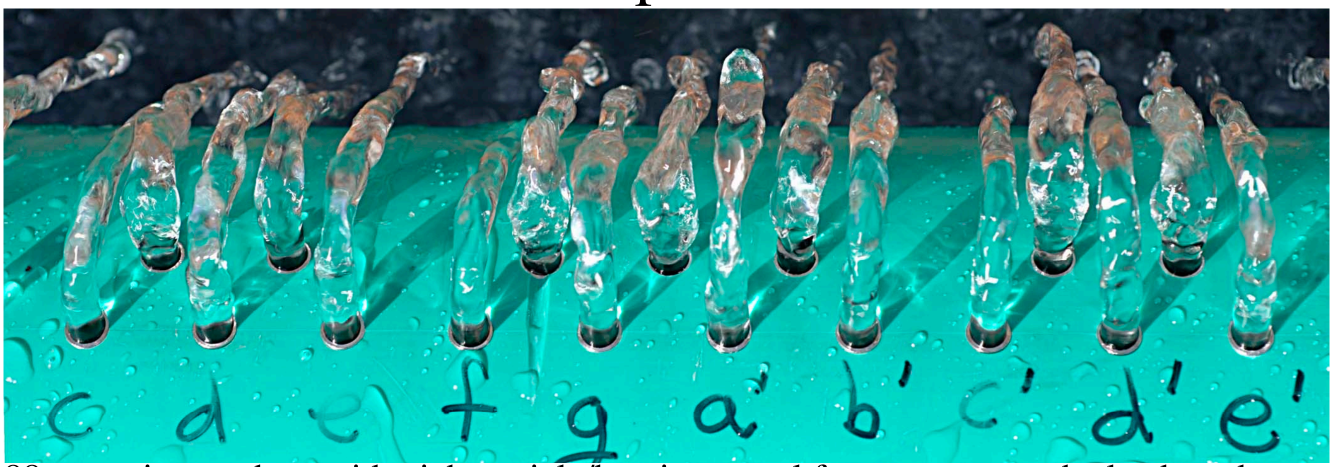
This water fountain is a piano!



88 spray jets each provide rich tacticle/haptic control for one note on the keyboard.
Each note sounds different depending on how you press (from above, versus from one side, the top, etc.).

ABSTRACT

Water fountains can become haptic/tactile surfaces that respond when people touch, block, or restrict the flow of the water jets, triggering any audiovisual or other multimedia event. This new “fluid-user-interface” metaphor is based on the “hydraulophone” (alternative spelling: “hydrauliphone”), a musical instrument played by direct interaction with a pressurized hydraulic fluid that emerges from an array of finger holes, where hydraulic sounding mechanisms are located upstream of the point at which human contact with the hydraulic fluid is made.

The hydraulophone is like a keyboard, made from a water fountain, but each jet of the fountain is a soft key that can be pressed in infinitely many different ways to obtain intricate and independent control of the volume, pitch, and timbre of each note, when sounding multiple notes simultaneously.

Usually the hydraulic fluid is non-compressible, although some “wet/dry” hydraulophones have been designed for use with either air or water, and some “pneumatophones” (alternative spelling: “pneumatiphone”) have been designed to work exclusively on air. In their purely acoustic form, pneumatophones are woodwind instruments similar to flutes except that they can play chords, and there is a rich space of variations in tone, volume, timbre, etc., that can be independently applied to each note when more than one note is sounded together.

This paper describes the construction of a MIDI interface that can be attached to an acoustic hydraulophone, or pneumatophone, or to an ordinary water fountain, or air fountain. This allows the fountain to be used as a haptic/tactile control surface or highly expressive fluid keyboard that provides gentle, soothing (soft) tactile feedback quite different from either the hard (solid) feedback of plastic keys, or the total lack of tactile feedback inherent in camera-based, vision-based, or proximity-sensing user-interfaces.

We describe some of the difficulties in constructing such a multimedia input device, and some system architecture and signalling protocol considerations. In particular, we describe a modular self-healing architecture for fluid-based user interfaces. The architecture uses small microcontrollers, strung together, to obtain a large number of analog inputs in a small size low-power distributed system that is long and slender and can be easily waterproofed and sealed inside water pipes, manifolds, fluid chests, or fountains.

1. INTRODUCTION

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. A similar device was the Hydraulis, a water-powered pipe organ, in which water power was used to blow air into organ pipes. To the extent that waterfalls are often now used to produce the electricity that runs the air compressors and blowers in modern pipe organs, a modern pipe organ is a water organ in the sense that a waterfall such as Niagara Falls turns a turbine that produces the “hydro” to run the blower fan. The term “hydro” is slang

1-4244-0367-7/06/$20.00 ©2006 IEEE

for electricity, and we often speak of the "hydro meter" when we refer to our electricity bill, and to the electricity we use to power modern pipe organs.

2. THE HYDRAULOPHONE: A TRULY HYDRAULIC MUSICAL INSTRUMENT

Both the Greek "water-organ" as well as the Hydraulis were water-powered wind (air) instruments. What we propose is a truly hydraulic instrument that uses an array of pressurized water jets as the user interface and/or sounding mechanism.

The hydraulophone, a water-based musical instrument, was invented by S. Mann in the 1980s. The inspiration for this invention came from the screeching sounds made by defective faucets, and other valves with liquids passing through them [1]. The hydraulophone may be defined precisely as a musical instrument that is played by direct human contact with a fluid emerging, under pressure, from a plurality of holes, where sound is caused by one or more hydraulically actuated sounding mechanisms located upstream of the holes. An approximate informal definition is that you have water coming out of some holes, and you play the instrument by obstruction of the water, which causes some action to take place upstream of where the blockage occurs. When you block one of the water holes, the fluid is usually forced somewhere else to produce sound at a pitch corresponding to the note associated with that particular hole.

An interesting property of the hydraulophone is that it can be played underwater, resulting in music that occurs without the involvement of air, if the listener is also underwater, such as when the instrument is played in a pool. Pool water touching the eardrum conveys sound through the bones in the middle ear, to the cochlea which is filled with cochlear fluid.

An example of a totally acoustic hydraulophone that can be played above or under the water, is shown in Fig. 1(b).

In addition to the purely acoustic version of the instrument, the same concept of a "fluid-user-interface" can be generalized to trigger other multimedia events.

Our use of water as a new multimedia interactive design element, and water-sprays as user-interfaces, creates an example of what Ishii might refer to as tangible media. Ishii constructed a bottle metaphor [2], in which he senses that bottles are being opened, and plays back sound recordings when the bottles are opened. As he describes the metaphor, "you open up the bottle to let the sound out". Our fluid-user-interface metaphor is similar: you block the fluid jet to "press down" on a key, thus "keying" a particular multimedia event. Each jet is a rich and intricate "key" because of the infinitely many ways in which it can be touched, blocked, obstructed, or restricted by a human user. Sensing the way in which the jet is blocked, allows for considerable variation in the multimedia event space that is triggered by blocking the jet.

2.1. The hydraulophone as a new category of musical instrument

Traditionally musical instruments are broadly classified, by their scientific names, as either wind instruments (aerophones, from the Greek words "phonos" = sounding, and "aero" = wind), or solid instruments (self-sounding instruments in which solid matter vibrates to then cause the surrounding air to vibrate). Solid instruments are further subdivided into idiophones (three-dimensional solids, e.g. xylophones), membranophones (two-dimensional solids, e.g. drum membranes) and chordophones (one-dimensional solids, e.g. stringed instruments like pianos and guitars). The hydraulophone suggests a new category of instrument, in which liquid is the sounding mechanism, rather than solid or gas (See Fig. 1).

The traditional scientific classification of musical instruments is based on how they output (make) sound, but if we go to a music store to purchase a musical instrument, we will find that they are usually categorized by input (user-interface). Thus the keyboard instruments, like pianos, accordions, organs, and synthesizers, will all be together, perhaps on the main floor. Upstairs you might find the instruments that you blow into (flutes, woodwinds, brass), and downstairs you might find all the instruments that you play by hitting them (drums, xylophones, etc.).

Classification based on both input (user-interface) and output (sounding mechanism) suggests a possible new space of water-based instruments that includes also the use of liquid also as a user-interface. The hydraulophone, in its purset form, exists at the center of the classification space (i.e. water is both the input and output medium).

However, other uses of fluid-user-interfaces are possible. For example, a musical instrument that used water as the input device, but not for output device, was the Pool Piano, created by S. Mann, consisting of a fountain in a pool, with a row of water jets, each jet activating a MIDI output to play a real grand piano that was located near enough to a swimming pool to hear it while activating it from within the pool [1].

Regardless of the actual sound-producing mechanism (whether acoustic or electronic), people of all ages from six months to 100 years, enjoyed the interaction with water as the input mechanism. There is something very soothing and physical about touching fluid jets instead of plastic or wooden keys, and the various prototypes were met with a strong welcome at numerous public pools, and day care centers (Fig. 1(c)) as well as for combining music therapy and water therapy for the elderly at various retirement homes.

3. MIXING ELECTRICITY AND WATER: THE FUNTAIN AS A NEW MULTIMEDIA INTERFACE

We now describe the construction of a 128-jet interactive water fountain that we call the FUNtain (TM). (See http://funtain.ca for more background on the FUN fountain.)

One of the problems with purely acoustic versions of the hydraulophone was the difficulty in keeping the instrument in tune, as well as the limited number of notes. Children seemed to want to explore the ends of the frequency spectrum, and when presented with the 88-note Pool Piano, they seemed to like to play the lowest and highest water jets to push the instrument to its limits.

We therefore wished to make a longer water-based MIDI "keyboard" having 128 water jets as the keys instead of the 88 jets that would map to the keys on a piano. The number 128 was chosen because that is the maximum number of keys within the MIDI standard, although no other keyboard (other than ours) having all 128 keys, exists, to our knowledge.

Thus our fountain might actually be the world's longest MIDI keyboard.

We also wished to maintain the soulful melancholy sound of the real acoustic hydraulphone, which results from its unique ability to independently and continuously modulate individual notes by way of the very expressive "finger embouchure" holes, i.e. because there are infinitely many ways that the water jet can be blocked, restricted, or touched.

The mournful cry of an acoustic hydraulophone, like the sound of a haunting call of loons in the wilderness, was something that users had really connected with, so we wanted to maintain that same melancholy sound in the electronic hydraulophone.

To create this fluid and flowing sound required 128 analog inputs, not just the key switches of a traditional velocity sensing key-

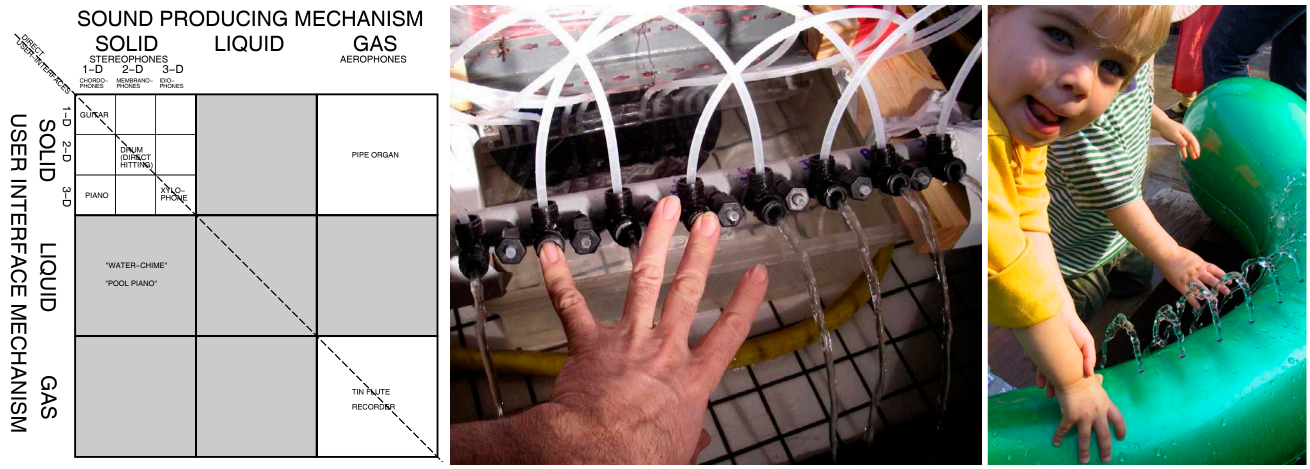


Fig. 1: (a) Categorization of musical instruments by both their input (user-interface) and output (sound-producing mechanism) suggests the possibility of some new instruments within the shaded regions. (b) A totally acoustic 12-note hydraulophone which can be played above the water or underwater. It is played by blocking the water jets in various ways, to force hydraulic fluid (water) back into the sounding mechanism. This instrument, invented by S. Mann, was built by S. Mann and C. Aimone, as a teaching tool to illustrate the principle of the hydraulic fluid-user interface. (c) Christina Mann (age 3), performing on a hybrid (acoustic and electronic) hydraulophone, at University of Toronto's early learning center, in 2005. This hydraulophone, made by S. Mann and C. Aimone, is designed to resemble a sea monster named Nessie.

board that measures the time of downward flight of a key, and then possibly (later) adjusts the note volume with polyphonic aftertouch.

In a sense, what we required was a kind of "duringtouch" in which note amplitudes and frequencies could continuously vary based on flow properties at each of the 128 water jets.

Building a compact reliable, stable (drift-free) waterproof (and fully submersible) interactive multimedia system with 128 analog inputs presented us with some interesting challenges. For example, when pushed underwater the changes in pressure and temperature might otherwise cause drift, as the instrument is moved from the cold pool to the hot tub, etc..

3.1. Modularized System Architecture

To allow an expandable, reliable, and cost-effective architecture, rather than using a personal computer with 128 analog inputs, and trying to make it waterproof, we decided to use the Atmel Atmega48 Microcontrollers for the hydraulophone project.

The Atmega48 provides us with built-in analog inputs, with reasonably reliable serial communication data ports, small size, low power consumption and the lowest per-note cost for making very long keyboards.

It was important, for example, that there be no moving parts, such as computer hard drives, so that the computational elements could be embedded in epoxy, and sealed within the tubular enclosure of the FUNtain's body.

With the Atmega48 Microcontrollers, we are able to propagate analog data serially, from one chip to the next. This allowed generality of the system, as we could expand the number of analog inputs quite easily.

Turning a fountain into a FUNtain is easy: all that is needed is a restrictometer [1] for each jet, together with the data collection system that we now describe.

Each of the microcontrollers is also located physically close to a group of restrictometers [1], on a group of adjacent fountain jets and each microcontroller is connected to the restrictometers in the group. Close proximity leads to better signal-to-noise ratio and stability.

Using our technique of passing analog data down through a series of microcontrollers, we are able to filter the data stream as it travels along. In particular, the constant highly expressive MIDI updates on 128 notes results in a tremendously high bandwidth. To mitigate this problem, we can, for instance, filter out all but the notes having the highest volumes. Another advantage was that we are able to use a distributed neural network running on each of the microcontrollers, to provide intelligent adaptive filtering in order to optimally manage the bandwidth problem.

Additionally, during debugging, we can display the array of data on a 128-trace oscilloscope that we also made from a microcontroller and LCD display. There are a myriad of other applications for using a stream of analog data. In the FUNtain system, we used it to display the finger-embouchure (aspects of the fingering on each note) independently for each note, on a debugging screen.

3.2. General Module Interface

To allow the flow of data through our series of microcontrollers, we used a protocol that transmitted the array index, followed by the data corresponding to that index. Transmission was continuous for each and every allocated index. This allowed the microcontrollers to keep the flow going endlessly, allowing updated data to get propagated down the data stream.

3.3. Self-healing system architecture and protocol

When the user is playing notes on the instrument, in the FUNtain project, he/she expects that a note be sounded whenever finger-embouchure is applied to the water jet. Now let us consider the error state which the system enters when a note continuously sounds without the user applying pressure, e.g. if a restrictometer becomes clogged with foreign debris. What we desire is that the system will heal itself by ignoring that jet, rather than continuing to make the annoying sound of a note that is stuck on. This process was achieved by a distributed neural network in which the system learned usage patterns and made an inference as to whether or not a note was being played, versus simply a clogging of one of the jets. When a jet became clogged, the system would reduce the sensitivity to that jet, to adapt to a state that made reduced use of that sensor, and to make sure that a change or drift in one sensor did not adversely affect the sounds produced in respone to the other restrictometer inputs.

4. AUTOMATIC CALIBRATION OF RESTRICTOMETERS USING A DISTRIBUTED ADAPTIVE FILTER (NEURAL NETWORK)

Monitoring fluid-flow restriction sensors (restrictometers) in a system of variable flow is an effective way of recognizing and measuring real changes in the obstruction of flow over an array of jets, which serve as a fluid user-interface [1]. Depending on the context, the usefulness of the flow information as ascertained by these restrictometers relies strongly on a very precise calibration process. In particular, a good FUNtain with jets that shoot up high can provide wet "keys" that have a very long key travel, and thus provide a much more expressive input than plastic or wooden keys, because the player can either press the key down, or "slice" the finger through the key, to shorten the water column abruptly. There are infinitely many ways of obstructing the water jet, rather than just the one-dimensional way of pressing a wooden or plastic key down along a single axis of movement. However, to benefit fully from this new expressive fluid-based medium, the system must be calibrated very carefully, because the change in restriction when the jet is blocked far away from the opening is very minute.

A sophisticated calibration process is used to determine the range of possible measurements associated with the restrictometers between a maximum value (ceiling) and a minimum value (floor).

In so doing, calibration allows for values taken from the restrictometer to produce effects related to their relative location within the range (from floor to ceiling). A change in flow is monitored and processed in order to adjust the volume of a musical tone (note) associated with the flow at that location. Calibration is necessary in this context since, at a minimum value across the restrictometer (floor), it is desired that notes not sound loud and at maximum (ceiling) it is desired that notes sound loudest. The calibration must be automated and on-going since environmental stimuli (such as water temperature fluctuations) that affect the impedance-pressure characteristics of the pressure-sensitive elements in the restrictometers and blockage of the actual flow at different locations in the system, will adversely affect the maximum and minimum readings associated with minimum and maximum flow.

The solution developed is a distributed adaptive filter that makes inferences about whether or not the instrument is being played, and also learns the unplayed floor value for each jet and subtracts that value from the sampled array of restriction values measured across the array of jets. Copies of the adaptive filtering code are run in parallel on serially connected Atmega48 microcontrollers that handled various aspects of sampling and processing for groups of restrictometers. By adjusting two parameters, the "learning rate" and the "step size", the convergence properties of the adaptive filter were established. The learning rate must be slow enough so that deliberate changes in flow (such as when a note is played for a long time) are not confused with a rising floor value. In particular, it was found that children would often sit on the instrument, or lay down on it, blocking a large number of jets, and it was desired that this be considered as a valid form of musical expression. Thus such prolonged clusters ("butt chords") should not be filtered out in the same way as would be actual clogging of the jets with small particulate debris.

The adaptive filter must also be fast enough so that unintentional fluctuations in the properties of the restrictometers and flow of the system are adequately handled by the learning algorithm in adjusting the floor weights.

Designing the adaptive filter to monitor the ceiling values is more complicated than the adaptive filter designed to track the floor values. In the floor adaptive filter, we have the advantage of assuming that when a note is not being played, which is more often than not, the corresponding restrictometer will show values at the current floor. With this assumption we can essentially adjust the floor weights of the adaptive filter by low pass filtering the measured values of the notes, after gating with a usage inference decision (i.e. during times when the instrument or a region of it is not played). This can be done for each note with only a few lines of code that involve only multiplication, addition, and therefore minimal supplemental processing time. The only draw back is that notes played for a long time in comparison to the learning rate will start to die out as the floor is slowly tracked to reach the note's amplitude. However, in the ceiling case we must first determine whether a note is being played near or at its maximum. Only then can current note volumes be used to adjust the ceiling weights of the system. The ceiling adaptive filters that have been created thus far have resulted in a total adaptive filter (floor and ceiling) with a significant increase in the total processing time required.

Since the smooth operation of the current system depends on timely serial communication between the different nodes, too much processing at each location disrupts the system's "fluid" (continuous) feel. This is true even though the adaptive filter code for each group of 6 notes functions in a distributed and parallel fashion. The floor adaptive filter is a the most useful part of the adaptive filter since it involves little supplemental processing at each node and handles the most aggravating of the possible scenarios of hardwired floor and ceiling values which results in notes sounding loudly when no one is playing them.

This asymmetry in importance suggested that most of the processing time should be devoted to running the floor's adaptive filter system, and the ceiling updates should run in the background at a slower update rate, since it is less critical.

5. CONCLUSIONS AND SUMMARY

This paper outlined some of the architectural considerations in the construction of a system, signaling protocol, and implementation of a 128-note fluid-user-interface. In making a very sensitive and expressive essentially analog musical instrument interface, with continuously and individually adjustable note volume ("duringtouch") and pitch (wailing melancholy sound like the call of a loon in the wilderness), the use of water jets as keys on a keyboard instrument made the instrument very expressive and fun. Each time a key was pressed, it could be expressed differently (for example, pressing straight down versus pressing to one side). Many problems arose due to slight changes in water temperature, clogging of jets, and the like. It was found that an adaptive neural network could be used to correct these problems. Moreover, a distributed self-healing system architecture was put in place to ensure system stability. With this, we gave birth to a smart, fun, and entertaining water instrument, the 128-note FUNtain, in the form of a very sensual user-interface.

6. ACKNOWLEDGEMENTS

We thank Chris Aimone for collaborating with us on various design aspects of the hydraulophones. We also thank Anurag Sehgal who worked with us on what became the winning entry of the Coram International Sustainable Design Award. Additionally we thank Fabian Wauthier for working with us on the 128-channel oscilloscope that is built into many of the instruments as a diagnostic tool.

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