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Wireless Interactive Sonification of Large Water Waves to Demonstrate the Facilities of a Large-Scale Research Wave Tank.

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Abstract: Interactive sonification can provide a platform for demonstration and education as well as monitoring and investigation. We present a system designed to demonstrate the facilities of the UK's most advanced large-scale research wave tank. The interactive sonification of water waves in the 'ocean basin' wave tank at Plymouth University consisted of a number of elements: ocean wave generation,

acquisition and sonification of ocean wave measurement data, and gesture controlled pitch and amplitude of sonifications. The generated water waves were linked in real-time to sonic features via depth monitors and a motion tracking of a floating buoy. Types of water wave pattern, varying in shape and size, were selected and triggered using wireless movement detectors attached to the demonstrator's arms. The system was implemented on a network of five computers utilizing MaxMSP alongside specialist marine research software, and was demonstrated live in a public performance for the formal opening of the Marine Institute building.

The Sound-Wave system is an interactive sonification system (Degara, Nagel and Hermann 2013) that controls and sonifies a large scale wave tank for high emotional impact demonstration purposes, for a scientific and commercial audience. A wave tank is a body of water incorporating some method for generating waves or turbulence which allow experiments to be run in a controlled environment, as opposed to say in the open sea. The particular wave tank for which the Sound-Wave system for designed – the ocean basin housed in the Marine Institute building at Plymouth University – will be described in greater depth in a later section.

On the day that the Marine Institute building was opened by HRH The Duke of Edinburgh – on 30th October 2012 – a 15 minute demonstration of the swimming pool-sized wave tank was given using the interactive sonification system. This was essentially a form of performance, and led to an emotional impact of a far greater intensity, than a simple linear wave demonstration.

Related Work

The Sound-Wave system utilizes computer music techniques to create the basis of the sonification. Water-based sonification has been designed in the past which does not require such technology. Non-interactive examples are the Croatian Sea Organ, the San Francisco Wave Organ, and the Blackpool High Tide Organ (Bašić 2005)(Richards and Gonzalez 1986)(Telegraph 2004) – which all generate sound based on the live behavior of the sea, which they are located in or next to. An interactive system is the acoustic Hydraulophone (Mann, Janzen and Post 2006) which is played by blocking holes from which water is streaming, leading to a hydraulic effect that can be turned into sound mechanically.

The non-interactive use of computers in such water-based sonification can be dated back at least to 2002 (Sturm 2002) with the sonification of ocean buoy spectral data. Initially this had a scientific motivation, and the idea of creating a musical performance came later (Sturm 2005). The buoy sonifications were located in an 8 channel field according to their physical locations. 266 minutes of data was recorded to make the final 40 minute piece. Further ocean sonifications are described in

(Bednarz, Bokuniewicz and Vallier 2011) these were an attempt to capture the seismic signature of ocean surf in sound to detect hazardous conditions, for example rip currents. Sound files of 1-3 minutes were produced where data representing one hour of ocean-wave seismic recordings was mapped directly to audible pitch in the range of 600-1200Hz. It was reported that differences between storm and calm conditions could be detected in the sound.

A more interactive example of sonification of water waves is found in the Tüb installation (Erlach, Evans and Wilson 2011). A small circular tub was filled with water illuminated from above, with a webcam looking down on it. Installation visitors could excite the water to create waves and ripples. The real-time image from the webcam was used in what is reported as an implementation of scanned synthesis. The audio output of the system was based on scanning the surface of image in two adjacent elliptical paths, and mapping the brightness in the scans directly to amplitude over time.

Research Wave Tank.

Coastal Ocean and Sediment Transport (COAST) laboratory, located in the Marine Institute building at Plymouth University, have a number of hydrodynamic capabilities. The COAST laboratory combine wave, current and wind power to create a dynamic 'theatre' appropriate for device and array testing, environmental modeling and coastal engineering. The equipment can generate short and long-crested waves in combination with currents (traveling in any direction with respect to the waves), sediment dynamics, tidal effects and wind. Unlike the situation when testing designs at sea, these scientific research facilities can accurately recreate the specified wave conditions to be able to re-run controlled experiments.

Fig. 1. The Ocean Wave Tank at COAST laboratory, with stationary paddles in view.

The ocean wave tank basin is 35m long, 15.5m wide, and is operable at different depths (with a raisable floor) to a maximum of 3m. It has 24 wave making paddles (seen in Figure 1), able to produce waves of up to 0.9m in height. The COAST laboratory include a suite of instruments that allow detailed and comprehensive acquisition of data including Particle Image Velocimetry (PIV) and Laser Doppler Anemometry (LDA), 3D Laser scanning for accurate measurement of surfaces, and a six degrees-of-freedom video motion capture system for floating structures. The final of those, based on Qualisys hardware and software, was used in the demonstration. The other sensors that we used were wave-height gauges comprising probes connected (via amplifiers) to a National Instruments analogue-digital converter, and to the LabVIEW software running on one of the COAST computers.

Interactive Sonification System.

The interactive sonification consisted of a number of elements: ocean wave generation, acquisition and sonification of ocean wave measurement data, and gesture controlled pitch and amplitude of sonifications. These elements will now be described in more detail.

Sound-Wave Control System.

At the heart of the gesture control system, was a wired network of computers (LAN) using MaxMSP to interface a range of specialised softwares. An overview of the interaction network – illustrating the configuration of interconnections and data-flow between the various hardware and software elements of the system – is shown in Figure 2.

The demonstrator stands on a gantry from where most of the wave tank can be seen. The gantry is a large metal bridge-like structure that spans the width of the ocean basin. This moveable gantry is positioned so as to give the audience a clear view both of the waves in the wave tank and of the gestures being made. The demonstrator faces the wave paddles – located at the other end of the tank – for most of the demonstration, and wears sensors for gestural control.

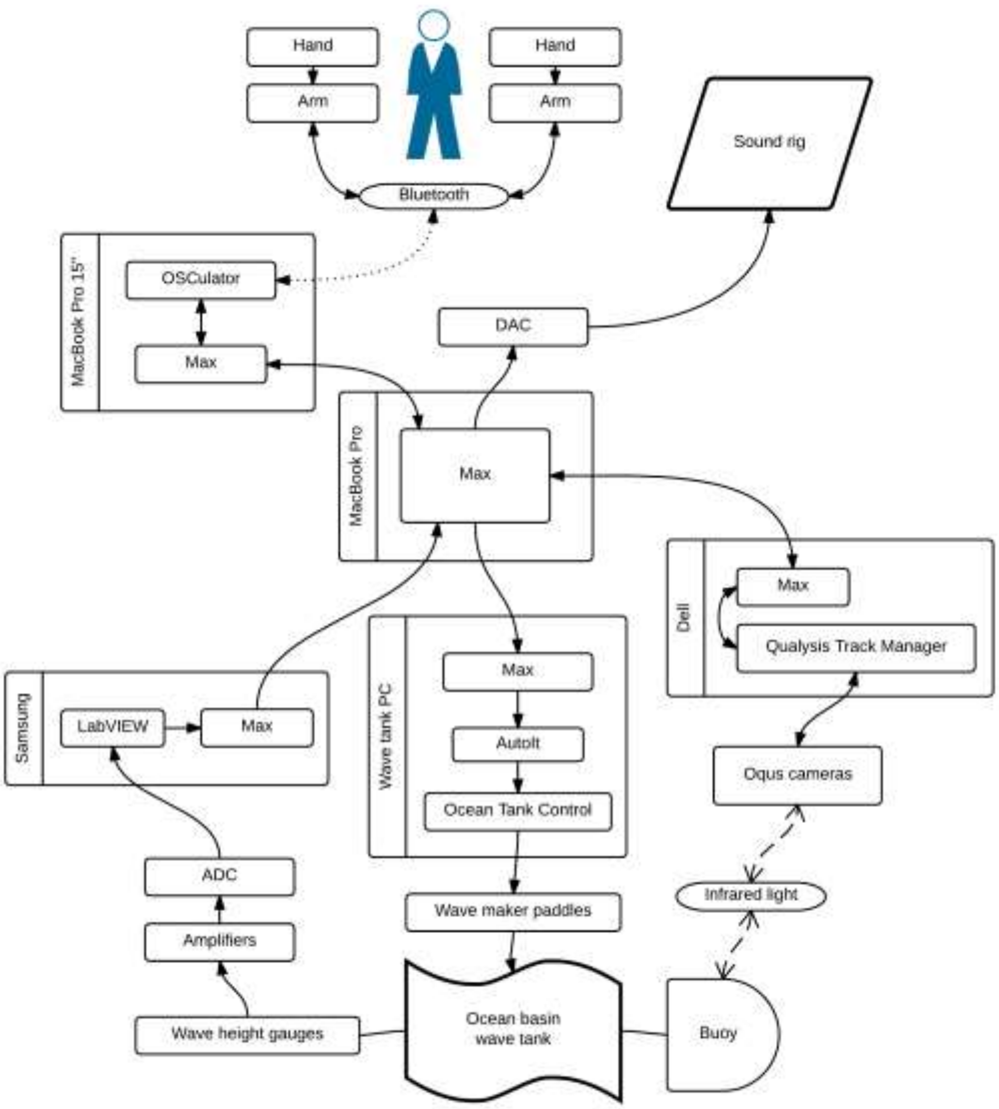

Fig. 2. Sound-Wave instrument system network overview showing hardware and software for wave and sound control.

Two Wiimotes are worn by the demonstrator who straps one to each forearm; the infra-red sensor of each Wiimote is pointed toward the hand, and the flat of the Wiimote – on which the home, A, and other buttons (not used in this system) are found – is held against the arm. Each Wiimote is held securely in place so that it will stay aligned to the forearm on which it is mounted, and the vibration feature of the Wiimote is used to provide the demonstrator with haptic feedback about certain operations. Each Wiimote then has a Nunchuk attachment connected. Holding a Nunchuk in each hand provides two sets of inertial sensor (pitch, roll, yaw) data, as well as data from four finger buttons and two thumb joystick controls; inertial sensor (pitch) data from the Wiimotes is used to measure the position of each arm. That data is transmitted by the Wiimotes, via BlueTooth, to the OSCulator software that runs on a computer (labelled 'MacBook Pro 15') concealed at the side of the gantry.

Making waves

The actual wave patterns which could be trigged in the demonstration (listed in Table 1) were synthesised in another piece of EDL software by the second author with the assistance of the COAST team, during the development of the work.

Table 1. Wave types available during demonstration

Wave Type	Level
Sine	Small
Sine	Large
Sine	Over-driven
Focused	Point
Focused	Line
Quilt	Small
Quilt	Large
Spectral Sea State	Large

Fig. 3. Over-driven Sine wave during demonstration; the demonstrator can be seen in spotlight on the bridge-like gantry, and the buoy in the water below.

The simplest type of wave is the Sine in which all of the paddles move in unison at a constant frequency in order to produce evenly spaced peaks and troughs in the water; the wave-height is determined by the amplitude of that movement. If the paddle speed and amplitude are increased sufficiently then the waves begin to break on themselves, creating a noisy white water effect, as in the Over-driven Sine wave seen in Figure 3. Sine waves can be produced at an angle so that they travel diagonally across the water. The additive-synthesis of two such waves, given equal and opposite angles, will create a interference pattern which we call a Quilt wave (after its checkered pattern of peaks and troughs); this is shown in Figure 4.

Fig. 4. Quilt wave (small) during demonstration; the wave paddles in motion can be seen in lower left of the image.

Focused waves are more complex: they require the paddles to perform a sequence of movements that will produce a number of different wave-fronts at specific frequencies and amplitudes. Higher-frequency movements are followed by lower-frequencies of greater amplitude. Because lower-frequency waves travel faster in water than higher-frequency waves do, the numerous waves made by the paddles will converge, and their energies combine, to create a single wave that breaks at a predetermined location. Focused waves were programmed to break at where the buoy is anchored in the ocean basin. Figure 5 shows the build-up of the Line

Focused wave that will break in front of the gantry. The Point Focused wave is similarly formed, over a period of several seconds, by a series of semi-circular ripples targeting the location of the buoy.

Fig. 5. Showing the buoy with its four reflective markers for motion tracking.

Wave pattern selection is achieved by pre-defined sequences of gestures using finger, hand and arm movements. The system must be in its wave-mode to select wave patterns. Other modes available are the synth-, buoy- and pad-modes, which are described below. The method of switching between these modes, always via the system's default safe-mode, is shown in Figure 6.

The arm location definitions for selecting waves were incorporated into arm movements that were designed to minimize the possibility of gesture detection error, while still giving the demonstration audience a sense of the type of wave coming. After selection, there is a delay of a few seconds as the wave generation process involves stopping the previous wave, loading in a new wave program and starting up the paddles. Another element of practicality was that the wave paddles were noisy when moving. To some extent this could be disregarded because we found that the overall audiovisual impression of the interactive sonification was so strong that people were unconcerned about the paddle noise. It can be noted that for the demonstrator, the sound of the paddles beginning to move, or discontinuing, is a helpful eyes-free confirmation that the system is operating as directed. It also helps to direct the attention of the audience, who have been watching the demonstrator, onto the tank and waves. Another way to think about the sound of the paddles was to consider the mechanical noises as an integral part of the demonstration when viewed as a musical performance: the audible rhythm of the paddles in motion can be heard as setting tempo for the rise-and-fall changes that will manifest, some seconds later, in the sonification of the wave gauge data. That aural connection is particularly evident for the Sine type waves, but is present in each case.

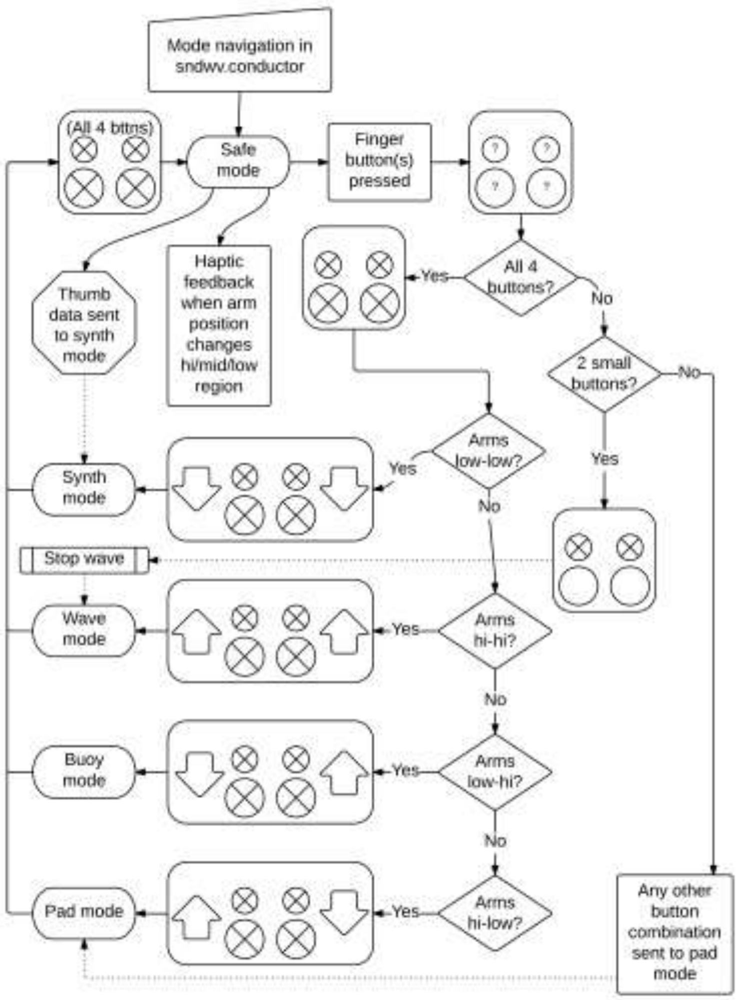

Fig. 6. Mode navigation in the control system of the demonstrator arm positions and finger triggers.

Wave Sonification.

A number of approaches were considered for the interactive wave sonification. They were judged against four primary considerations: (i) the ability of the audience to see a relationship between the wave behaviour and the sound, (ii) sufficient controllability of the sound to make it significantly interactive, (iii) the technical feasibility, and (iv) the ability to construct an audio-visual demonstration of sufficient length and interest.

One idea was to relate data from specific areas of the wave tank to discrete audio channels in order to create a spatial-sound sonfication in the building. The acoustics of the mostly concrete space and the planned distribution of audience, however, were not thought conducive to such an approach. Furthermore, the water waves themselves provided a significant spatial distribution of sound as they travelled around the wave tank. The sonification was thus monophonic with loudspeakers (provided and managed by a third party) being distributed to provide general coverage for audience on the ground floor and mezzanine levels. Another idea that was not seriously considered from the beginning was to linearly map the frequency of the waves in the water to a frequency of sound. This would only be audible with the faster waves, and the average listener would be unable to sense the mapping between the frequency of sound and the wave. Since a common mapping was desired for all frequencies of wave (so as to simplify the correlation for the audience), it was decided that the instantaneous wave height and direction were preferable for parameter mapping.

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In terms of what to map wave height to, pitch was again considered. However this would lead to quite an unintuitive demonstration as listeners normally expect pitch to be more controlled. The system would essentially be perceived as a form of variable vibrato, i.e., frequency modulation, which is not a particularly attractive sonification when done at metronomic accuracy. Loudness and timbre were also examined. It was clear that having significant changes in timbre, would be more audible than loudness (bearing in mind the sound of the waves and the wave paddles could be quite loud). To create a loudness variation sufficient to be perceivable over the other noises would lead to issues of dynamic range, and perhaps even perceptions of silence between loudness peaks (i.e. a form of audio gating rather than variable tremolo, i.e., amplitude modulation). This decision to use timbre as the basic form of sonification was the foundation of the whole system, which was designed as described below.

Two types of sensor are used in the sonification for wave motion measurement in the ocean basin: wave gauges and motion tracking of a floating buoy. Wave gauge sensors work by measuring the resistance of the water between the two parallel wires of the probe which is proportional to the height of the wave front passing them at a particular time. Two wave gauge probes were placed on the sides of the tank, at diagonals, and another two were placed diagonally opposite on the sides of the gantry. Spacing of the probes ensured that the peaks of the waves would reach them at different times. The other sensor type comprises a motion capture system and a buoy, employing similar techniques to those used in films for the motion capture of actors, and in sports science research. The buoy in our system is held by a bungee cord that is hooked to the floor of the wave tank, so it cannot move too far, but will be set in motion by the waves. On top of the buoy are a number of small reflective marker spheres which are arranged at different heights to be recognisable by the system as points on a 3D model (visible in Figure 5). An array of Oqus infrared digital cameras, fixed at different elevations and on either side of the wave tank building, visually track the light reflected by the marker spheres. From these multiple points of view, a six degrees-of-freedom (6DOF) data set is calculated in real-time. The buoy tracking data gives a finer sense of what is happening in the tank than a wave gauge, which solely captures height at a point, but the richness of the 6DOF tracking data presents its own challenges for creating meaningful mappings to audio parameters.

The data routing of the buoy tracking is as follows: the Oqus cameras are

LAN connected to the Qualisys Track Manager (QTM) software on the computer marked ‘Dell’ on the diagram. QTM supports real-time OSC output for the 6DOF data. An adaption of a Max patch provided by Qualisys bridges connection of that data to the central computer (labelled ‘MacBook Pro’). Rather than use the 6DOF data as continuous control parameters, it was decided to use relative changes in the 3D position of the buoy to trigger percussive sounds. Many people have an association between bell sounds and buoy movement as some navigational sea buoys have bells installed. A bell-like instrument was made for the buoy (actually based on our own glockenspiel samples, played at 0.25 speed). This created a stronger link between the buoy being struck by a wave, and a sound being made. Two thresholds of delta-movement on the X-axis will trigger a sample, the pitch of which is determined by the Y-axis position of the buoy at the time. The pitches available are consonant with other musical elements in the demonstration (such as the pad sound, which will be discussed later). A third motion threshold on the X-axis, set to to greater value, triggers a sound whose pitch is linked to the Z-axis. The more intensely the buoy is moved by waves, the more frequent the bell-like sounds will be. The demonstrator has control of the output gain of this buoy linked instrument which defaults to a muted level; this further enables stages of the demonstration to be controlled as sections of a music performance.

The second strategy was based on pitch selection within the current chord for the pad (sustained background sound), with its four voices correlating to the four wave probes. This was envisioned as a sonification of the more general wave-tank state, rather than the behavior of specific waves and patterns. It was not designed so that the audience would directly perceive the notes being selected in relation to tank state, but so that when the wave tank was in a more rapid high amplitude state, the more frequent change of pitches would contribute to a more dynamic sound over-all. The use of chordal notes, as opposed to scaled or continuous pitch selections, was so that the more dynamic tank states seemed impressive rather than chaotic. Excess dissonance would have contributed to a sense of chaos. In effect, the mapping of wave height data for the pad instrument creates a variable arpeggio in the sonification.

Interactive Sonification.

Aside from the sample-based bell-sound synthesiser already mentioned, there are two other key synthesis elements. One has already been referred to as the synth, and the other as the pad. The synth is based on four oscillators with each being modulated by one of the wave-height gauges. Two of the oscillators are assigned to be controlled by the left arm and hand, and the other pair is controlled by the right, effectively giving the demonstrator control of two synth voices when the Sound-

Wave conductor system in in synth-mode. The octave of each voice is set using the finger buttons of the associated hand (Nunchuk). Pitch within the octave is set based on how high or low the arm is (actually angle of the forearm using the 'pitch' data from the Wiimote). Pitch can either be set to any integer frequency within the current octave from A at the lowest angle up the A above, or – by twisting the wrist (using the 'roll' data from the Nunchuk) – the pitch can be mode quantized to pitches of C Major. The loudness is set using the thumb by pushing or pulling the Nunchuk joystick. The height of waves passing the four wave gauges modulates a phase-distortion parameter of each oscillator. This combination of controls allows the demonstrator to articulate simple melodies, apparently by moving his hands in the air. This was shown to the audience, ahead of starting waves in the tank, to emphasise the controllability inherent in the demonstration. Another possibility, used in Sound-Wave, is to simply lock the synth at a single note by entering safe mode of the system, and leave it running underneath other activity. This was found to be quite effective when water waves were modulating the filtering.

The third sound-making element of the instrument provides the pad-type sound which comprises four voices that are again mapped to the four wave gauges such that a passing wave-front will modulate the timbre of each voice. In this case timbre is affected is used to sonify motion in the water by proportionally adjusting the gains of low-pass, high-pass, and band-pass filters on the audio signal within the voice. Each voice sounds at a pitch selected from within a chord chosen by the demonstrator. The pad has four chords of differing inversions that are switched between by using the Nunchuk finger buttons, and a thumb is used to control loudness. If the water in the wave tank were at rest, then the pad would sound with four pitches (the three notes of a chord plus the octave over its root) at a uniform timbre; a solitary wave-front traversing the tank would first be detected by the wave gauge mapped to the first voice of the pad, the timbre of that voice would change accordingly, and if the hight of the wave is sufficient to exceed a data threshold then the pitch of that voice would also change to a different note of the chord. Different notes in the chords are thus selected in an arpeggio-like way based on the wave height data.

Video documentation.

Demonstration Structure.

The demonstration was structured into two main wave sets, shown in Table 2. The first set was designed to introduce basic waves and to allow the audience to perceive the relationship between the wave movements and the sounds they created. It also began with a simple set of pitch slides done without any waves, triggered by moving the Wii controllers through the air. This showed the audience how the demonstrator had control through arm gestures, and focused the audience on the arms – which would be the core of control during the rest of the demonstration.

The second wave set was designed as a climatic build-up, with the largest waves, and finishing with the Over-driven Sine wave. The pad sounds were utilized here to add futher layers to the sonification. The demonstration structure is shown in Table 2. A video recording of key moments in the demonstration is available online here:

http://www.youtube.com/watch?v=72F-EjaM74M&list=PLICvGmV1_RRJpfgVBiyJ_IerTiyXT6udy

Table 2. Wave types available during demonstration

Wave Set	**Approx. Length**	**Wave**
1	01:30	Focused (Line)
	01:00	Sine (Small)
	00:30	Quilt (Small)
2	01:55	Focused (Point)
	00:40	Sine (Large)

	00:35	Quilt (Large)
	03:45	Sine (Over-driven)

Results and Conclusions.

The final result was an interactive sonification system which was useable dynamically – i.e. based on a demonstration plan which could be adjusted into new configurations. However the interactive system was quite consistent and led to quite a repeatable demonstration, as apparent in the relationship between the practice sessions and the final public demonstration. A key reason for this was the actual control configuration. The initial controller sketches by the first author were re-designed, extended and made practical by the second author. One limitation of using such a large wave tank facility, to which access is time-limited, was that the more subtle pitch manipulations were left to the movements of the Wii controller rather than being driven by data from the wave tank. The Sound-Wave demonstrator and LAN-based instrument system comprise a unique combination of scientific research technologies and computer sound techniques, all controlled by human gesture in the context of interactive sonification for demonstration purpose.

The system worked successfully during the demonstration with no crashing or unexpected behavior. A number of responses were provided by those watching the public demonstration. Examples are given below:

"An excellent event yesterday both the formalities and the demonstrations of the facilities. I have to admit to being a little dubious when I heard about the musical entertainment but my suspicions were unfounded and it proved to be an enlightening experience." (Marine professional).

"Definite Wow factor new Marine Building. Extraordinary musical, computer generated sound and wave performance" (Local politician)

"[the demonstrator] waves his arms and a storm of jumbled, breaking waves is accompanied by a tempest of electronic music. An-other gesture and…he restores calm, so that the hundreds of spectators gathered round the ocean wave tank might be able to see their reflections. So sophisticated is the control of the tank's 24 paddles that [the demonstrator] was able to generate a tiny wave that sprang out of an otherwise flat surface, tossing a metre-wide buoy into the air and leaving the audience open-mouthed." (Journalist).

When preparing this paper, one of the Coastal Scientists we showed it to included in their response the following useful evaluation:

"It was a real 'world first' for wave tank openings and is still being talked about amongst the marine renewable energy community."

There have been a number of pieces of research which sonify waves (Bašić 2005)(Richards and Gonzalez 1986)(Telegraph 2004)(Sturm 2002)(Sturm 2005)(Bednarz, Bokuniewicz and Vallier 2011), some of which have a level of interactivity (Erlach, Evans and Wilson 2011). However as far as we are aware this is the first time a wave tank has been used in the mode of interactive sonification. Although the wave making aspect of the system is slow to react, the demonstrator has complete control of it. So the order in which waves and modes were triggered in the public demonstration was but one possible demonstration configuration. In this way it is seen to fulfil the needs of being a re-useable interactive system, albeit a site-specific one. It is also interesting because of its large scale, which made for a novel, and according to audience feedback – enjoyable – audiovisual experience for the audience. The multi-sensory experience of the large waves in combination with the correlated electronic sound in the large, mostly concrete space, is difficult to capture in video or audio recordings of the demonstration.

In terms of evaluation, there is not necessarily an equivalent system to compare this to. However one possible approach is to use the evaluation approach proposed in (Hermann and Hunt 2005) which lists 3 high priority questions for interactive sonification systems. How does a user's performance compare to a visual only solution? How does a user's performance compare to a non-interactive solution? How rapidly is the solution achieved?

Firstly question 1: given the feedback of those present at the demonstration, it would appear that the sonification was preferable to the visual-only solution. Comments above like 'it was enlightening' by previously skeptical observers, and 'definite Wow factor' were typical of the feedback received – which clearly saw the sonic element as key to the impact of the wave demonstration. We asked the wave tank business manager, who has given a number of non-sonified demonstrations since the sonified demonstration, how the two approaches compared. Specifically we asked if any of the normal demonstrations have had the same impact as the sonified Sound-Wave system:

"We have now done quite a few demos but not on the same scale, and impact largely depends on the audience. Sound-Wave was fantastic for what we in the COAST Lab and Marine Building were trying to achieve at the time; that is a launch event for the building and its facilities with 'wow' factor. However, for certain groups of more knowledgeable individuals it is necessary to demonstrate more sophisticated aspects of the Basin's performance, eg. wave device developers who have tested at many other labs. Overall, no, Sound-Wave had the most impact."

However we feel that there is scope to create a more flexible system, where the waves can control pitch and timbre in more complex ways. As has been mentioned, in the current system the more subtle pitch control was achieved by sonifying arm gestures directly.

As for question 2: the people seeing this demonstration had to be convinced that the wave tank was re-useable by them in multiple scenarios – i.e. controllable by them. By creating a wireless network which made the control clearly visible and sonified both wave behavior and (at times) arm gestures – we kept the whole issue of control foremost in their minds – as exemplified in the journalist's comment above. However, we feel that it would be helpful if the system was quicker to train on and use, as then audience members could have tried it out themselves. In reality it required the user to strap multiple controllers to their arms, and learn certain patterns and button presses over time.

As for question 3, the question of rapidity can be viewed from two perspectives: the length of the demonstration and the rapidity of response of the interactive system. The demonstration made a large impact on around 200 people in less than 15 minutes of their time. As has been mentioned – the system response (in terms of wave triggering) was not instantaneous. However it was rapid enough for the audience to see a correlation between the arm movements, and the waves which emerged after a delay. In an ideal system, rather than having to stop one wave and then trigger a new one, it would be preferable that one wave pattern on the paddles could be morphed into a new one without resetting the paddles. This is because it takes three to four seconds to reset the paddles.

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