ON WAVE FIELD SYNTHESIS AND ELECTRO-ACOUSTIC MUSIC - STATE OF THE ART 2007

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ABSTRACT

Wave Field Synthesis is a spatialisation technique, which in recent years has reached a state of usability for live performance in concerts. This paper gives an overview of the technology available, several works created so far on these systems, and discusses aesthetic perspectives of the technology.

1. INTRODUCTION

Wave Field Synthesis (WFS) is a method for sound spatialisation. As opposed to most multichannel systems, it has no sweet spot, but instead a large listening area, making the technology attractive for concert situations.

The main principle of WFS is illustrated in figure 1. A wave field can be synthesized by a superposition of wave fields caused by a lot of small secondary sources, provided the right delays and amplitude factors are calculated for each source signal for each secondary source.

In recent years the technology has become through the increase in CPU power of commercially available computer technology, as well as multichannel sound cards. Additionally, software has become available to make the technology usable. Still, the technology does require such an amount of hardware, that makes it relatively expensive to use, and thus there are not many systems available to actually do WFS. Nonetheless, more and more institutes are showing an interest in the technology, and investing in WFS systems.

Since a few years, composers and engineers have been able to explore possibilities of WFS, as well as its limitations, and gradually it becomes apparent what the strengths of the technology are.

2. AVAILABLE SYSTEMS AND TOOLS

2.1. TU Berlin

In 2006/2007, the TU Berlin launched a project to equip one of the lecture halls with a large WFS system [1, 2], of in total 840 loudspeaker channels, both for sound reinforcement during the regular lectures, as well as to have a large scale WFS system for both scientific and artistic research purposes. Additionally, a second, smaller system will be set up in the next year, in one of the studios of the TU.

The system is controlled by the open source software sWONDER, which has been redesigned for this purpose [3]. The software can be controlled via OpenSoundControl (OSC) [4], and there have been several tools created to use the system, ranging from LADSPA [5] and VST [6] plugins, to a 3D graphical interface.

2.2. The Game of Life

In 2006, a mobile Wave Field Synthesis system [7] was realised for the Dutch foundation The Game of Life. It consists of a loudspeaker array (designed by Raviv Ganchrow) of 192 SEAS coaxial 2-way loudspeakers, 12 active subwoofers (Hypex) (see figure 2), driven by two G5 computers running software written in SuperCollider [8] by Wouter Snoei and Jan Trutzschler. The system was premiered at November Music 2006¹ in Gent (BE) and Den Bosch (NL). Composers Barbara Ellison, Yannis Kyriakides and Wouter Snoei created pieces for this system. Further projects utilising this system are being planned, such as the interdisciplinary project Sternenrest about science, art and contemplation [9].

The user interface for this system has been created in SuperCollider on MacOSX, and provides many useful graph-

¹http://www.novembermusic.net
ical tools both for composition and live control (see for example figure 3).

The Institute for Sonology is in close cooperation with the Game of Life foundation and one of the topics of the “sound and space” course is wave field synthesis.

2.3. Casa del Suono

In the Casa del Suono in Parma, Italy, two systems are installed that utilise Wave Field Synthesis. One is a listening room, equipped with WFS, the second is a sound chandelier, the lampadario, used to focus sound sources.

For the inauguration of the exhibit, Martino Traversa created a composition titled NGC 353, from the name of a spiral galaxy located 8 millions lightyears from Earth. The composition is a sort of “sonic sculpture”, dancing around and above the head of the listener, who gets the feeling of being able to touch the sounds.

2.4. Commercial systems

To date there are two companies that market complete WFS systems, sonicEmotion and IOSONO, including hardware and software to do WFS.

The Fraunhofer Institute for Digital Media and IOSONO have installed larger systems at the Lindenkino in Ilmenau, in Bregenz and in Bavaria Filmstadt. IOSONO provides software for rendering and control of the sources, and have worked together with the company LAWO, to integrate their software interface with a mixing desk.

sonicEmotion have organised several presentations in collaboration with the Musikforum in Stuttgart, as well as realised several artistic works in collaboration with IRCAM and Centre Pompidou in Paris, such as for the DADA exhibition and the Samuel Beckett exhibition. The software of sonicEmotion is controllable via OSC, and they created an interface to IRCAM’s spatialisateur, as well as a plugin for the Pyramix multitrack software.

Other companies are starting to market Wave Field Synthesis as well.

2.5. Further research systems

Several research institutes have invested in WFS systems, these institutes include the sound control group of the TU Delft, IRCAM, the Institute for Telecommunications and Multimedia Applications (iTEAM) of the Technical University of Valencia in Spain, Fraunhofer Institute for Digital Media, Institut für Rundfunktechnik (IRT), Centre Pompidou, Samuel Beckett exhibition, March 14 2007 - June 25 2007. http://www.ircam.fr/equipes/salles/WFS_WEBSITE/Index_wfs_site.htm

Figure 2: Prototype WFS speakers for the Game of Life system (April 2006). Photo by Raviv Ganchrow

Figure 3: The path editor of the WFS software by Wouter Snoei.
the University of Erlangen\textsuperscript{13}, Fachhochschule Düsseldorf\textsuperscript{14}, the T-Labs of the Deutsche Telekom\textsuperscript{15}, Digitale Medien of the Furtwangen University\textsuperscript{16} and McGill University, Montréal, Canada\textsuperscript{17}. Most of these institutes are interested in collaborations with artists, though this is not the primary focus for all of them, e.g. the University of Erlangen presented on the Hörkunstfestival 2005 in Erlangen, Germany, several works\textsuperscript{18} of various composers.

From the author’s experiences with users of the sWONDER-software, there must be at least a dozen or so other small WFS systems, both set up by artists and by researchers in small companies. For example, the sound designer, developer, composer and instrumentalist Alex McMahon installed the Supermono system (a wavefield radiator for live music performance) in the gallery for Stasis, his spectral composition for string quartet and electronics\textsuperscript{19} for a performance in September 2006.

### 2.6. Compatibility

With all these different systems, the question arises whether compositions are transferable to other systems. This is still a problem that needs to be solved, and currently efforts are being undertaken to agree upon a common file format to store the composition data.

Though there are existing standards, such as MPEG4\textsuperscript{12}, which include spatial audio coding, these standards do not cover all rendering possibilities that WFS is capable of; also the use of compressed audio is not desirable for electro-acoustic music. Furthermore, it is not an free standard, which makes implementation in open source software difficult. Another existing format is XML-3DAudio\textsuperscript{13}, which could serve as a basis for a common format.

The format should (for each virtual source) contain information on position, type (plane wave, point source, directional source, 3D object) and room effects for each moment within the composition. Additionally, it is of interest to be able to store scenes: i.e. fixed constellations of virtual sources. Also details of the speaker array need to be stored.

There are still a number of questions to solve to make a compatible format: as the software implementation details differ between systems, and it is unclear what effects these have on the audible result, e.g. some systems include Doppler effects within the source movement, or have this as an option, whereas other systems do not; another example is the multichannel equalisation for the flat panel loudspeakers\textsuperscript{14, 15}. Also, not all implementation details are well documented, or the documentation is not open.

Furthermore, it is still questionable how well compositions made for small systems (and thus usually also a smaller space) scale up to large systems, and vice versa. It is unlikely that there will be a straightforward way of scaling compositions: a composer may have audio material on different tracks that are related to each other (together forming a sound object), which if they are scaled up like they were single tracks may loose their common sound impression. When working with a larger system, it may make sense to have more separate sound sources\textsuperscript{20}, as more sound sources will be distinguishable by the listener, whereas when downscaling, several tracks could be combined.

Compatibility with other spatialisation technologies is also an issue. Each spatialisation technology has its own advantages and limitations, and it depends on the techniques used with the technology, whether or not the same effects can be reached with another technology. Within these limits, it is possible to achieve compatibility with ambisonic and binaural formats. This compatibility has as an advantage that composers can prepare their work on such systems, before having access to the actual WFS system. On the other hand: both in ambisonics and binaural techniques, it is possible to add the vertical dimension, which up to now, has not been implemented yet for WFS (see also subsection 6.3), mostly due to technical and financial reasons.

### 3. Compositions

In previous papers\textsuperscript{16} several compositions were described for a small frontal array of speakers, which were presented at the Club Transmediale Festival in Berlin and at the Electrofringe Festival in Newcastle, Australia, in 2003. With the creation of the large WFS system at the TU Berlin, we have invited several more composers to compose pieces: Hans Tuschku, Christian Calon, Victor Lazzarini, André Bartetzki and Shintaro Imai. Some of these pieces were created for the Linux Audio Conference 2007 (March 2007), others for the opening of the hall and the Lange Nacht der Wissenschaften\textsuperscript{21} on the 9th of June, 2007.

#### 3.1. Rituale - Hans Tuschku

The 15 minute piece “Rituale” (2004) processes human voices and instrumental sounds from various cultures to a sound ritual. It is a continuation of the work on “Rojo” and “object-obstacle”, which were both also concerned with the theme of rituals. The composition uses extensively the possibility to place sound sources close to the listeners, i.e. inside the listening room.

“Rituale” was originally (in 2004) created for the IOSONO Wave Field Synthesis system in the Ilmenauer Linden-
3.2. Streams - Victor Lazzarini

In the piece Streams, sounds of recognisable sources are split apart in space and timbre; so space is tied in with spectromorphology. The piece starts with entries of the four woodwind instruments in different sides of the room, then their spectra are split in two and glide the components in opposite directions as they move apart in space. Eventually they meet together 180 degrees of where they start, fusing into their original spectra. In other sections of the piece, the instruments’ spectra are split in four and then move around the room, spinning etc.

Though WFS was seen as the most suitable diffusion environment for realising this type of idea, the principle is independent of technology and the composer has also prepared an ambisonics version of the piece. However, as Victor Lazzarini notes, “some diffusion technologies will convey the ideas better and more precisely than others...”. He also noted that the Doppler effect (which was gained automatically by the delayline based implementation) gave an extra element to the piece.

4. INSTALLATIONS

As the wave field created with WFS is stable in the sense that sources stay where they are when walking around as a listener, this is an interesting technology for use in sound installations. Within a sound installation the listener is usually not bound to one listening position, as with seated concerts. Thus, the listener can become an active participant in the installation, by moving around within the sound field, and thus gaining several perspectives on the piece.

Note, this difference of perspective on the sound field, based on the listener’s position, is also an important issue for concert situations. It has been argued that with WFS there is no sweet spot, but rather a large listening area. However, it is not true that everyone will have the same listening experience, instead it is comparable to having different seats during a concert of an orchestra, where similarly the impression of the acoustic event depends on where one is seated in the concert.

4.1. Edwin van der Heide’s sound installations

Edwin van der Heide has created several sound installations which use the principle of sound holography, by recording a sound field with an array of microphones and reproducing it via a similar loudspeaker array, such as "A World Beyond the Loudspeaker (1998): an installation with 40 channel wave field recording and wave field synthesis", which utilises a planar array of speakers. In

22 as opposed to spatialisation with stereophonic techniques where the localisation of a source tends to move along with you, until it collapses onto the speaker.

23 http://www.evdh.net

Figure 4: The loudspeaker array of the sound installations A World Beyond the Loudspeaker (1998) and Impuls #6 (2000) by Edwin van der Heide

"Wavescape (2001): underwater wave field recording with acoustic wave field synthesis", he uses a linear array of hydrophones, which record the underwater sound, which is then played back via much closer spaced speakers on the waterside; the ratio between the speaker distance and the hydrophone distance correspond to the ratio of the sound velocity in air and in water. In these two works, there was a one-to-one relationship between the microphone recordings and the loudspeaker reproduction.

Impuls #6 (2000) was created for the same plane of 40 loudspeakers as A World Beyond the Loudspeaker, but here the necessary delays and amplitude factors for the (virtual) sound sources and reflections were calculated with a MAX/MSP [17] patch.

4.2. L’Amiral cherche une maison à louer (2005) - Gilles Grand

For the Dada exhibition in Centre Pompidou from October 5th, 2005, till January 9th, 2006, Gilles Grand created a sound installation utilizing the Wave Field Synthesis system of sonicEmotion, in cooperation with IRCAM [18]. The sound installation was based on the poem (Simultangedicht) of Tzara, Huelsenbeck and Janco from 1916, and aimed to create a new interpretation of this poem which was cited simultaneously by three actors in three languages, German, English and French. The installation was presented as a completely white room; the 56 speakers used were flat panel speakers which invisible for the audience. The three virtual actors would move around through the space. In the realisation also the option of using directional sources was used, so one could hear

24 http://ouir.free.fr
a difference depending on in which direction the virtual actor was turned.

4.3. Hallenfelder (2006) - Kirsten Reese

The sound installation Hallenfelder was created for the Donaueschinger Musiktage and used recorded sounds as its basic material. The recordings were made in nine halls in Donaueschingen, used as concert halls during the Musiktage, but which normally host other activities, such as sports, Carneval parties, flea markets, exams, or cinema. On the one hand the basic room noise, caused by ventilation and heating and other noises which penetrate and resonate in the empty hall, was recorded, and on the other hand specific events taking place in the halls. Certain sounds were also recorded with a mono microphone to get just the direct sound in the recording. The wave field synthesis reproduction was done with a frontal linear array of 20 loudspeakers with a distance of 35 cm (spanning 7m.).

The main challenge during the production of this sound installation was to create a spatial impression of the rooms with the recordings made, though the aim was not so much to create a completely natural reproduction of the room sounds, but in a way accentuate it. The four channels of the recordings were positioned as point sources within the room, in an approach similar to virtual panning spots [19], i.e. the points were used as virtual loudspeakers between which the sound is panned, or in this case they correspond directly to the microphone positions and thus reflect the spatiality in the recording. For different scenes the actual locations of the point sources were different and transitions from one scene to another were achieved by moving the point sources to their new location during a certain time span. For some isolated events, where there were recordings of the direct sound available, a moving point source was used to move the sound through the space; partly these were sounds that you expect to move, such as a basketball and footsteps, but this was also used for sounds that normally do not move, such as the sound of someone jumping on a trampoline and the opening of a snack package. This effect was used sparsely, but effective.

The result was very good: due to the wave field synthesis, a very spatial feeling was achieved, and during scenes where there was a lot of activity, the impression was very realistic: one could really imagine the people making the sounds in the sport hall, without having the feeling that the sound was coming from the loudspeakers. Despite the relatively large distance between the speakers, there were no perceptually disturbing aliasing effects (see also section 5).

4.4. Realtime use

It should be noted that most of the examples above were precomposed. However, with the current tools available it is possible to change the positions of sound sources in real time, and thus make this dependent of a realtime process in an installation. This was done for example in the installation Scratch (2004) by the author, which has been described in [16].

In this case, latency of the system may be a concern, though depending on the actual hardware setup, latency can be minimized: the WFS processing of the TU Berlin system introduces a latency of 256 samples, i.e. 5.8 ms at 44.1 kHz. This is without the latency introduced by the sound traveling from its virtual position to the listener. In the case of focused sources, there needs to be a predelay, which needs to be configured beforehand.

If sound is recorded, processed and send back over the system, feedback may become a problem, as not all traditional methods to prevent feedback may be applied, due to the large amount of speaker channels involved.

5. WHY AND WHY NOT?

Wave Field Synthesis offers new possibilities for electroacoustic music, in that it allows more accurate control over movement of sound sources, enables other types of movement than those often seen with circular octaphonic setups, such as movements which use depth and movements through the listening space, and provides an interesting possibility for contrasts between the effect point sources and of plane waves: a source with a fixed position versus a source which moves along when the listener walks through the sound field. Additionally, it is possible to work with virtual room reflections, even with room dimensions changing over time.

The clarity of localisation that can be achieved with WFS can also be regarded as a weakness or a challenge for the composer, as Wouter Snoei notes in an email exchange with the author:

“In regular (non-WFS) spatialisation sometimes the fact that it’s not that good benefits the sound. It creates a kind of tension where your ears try to figure out what’s
happening but never really find out. The spatial position of sounds thus stays unclear, as if a kind of cloak is around it. Obviously partially hidden things can sometimes be much more exciting than the whole thing uncovered. In WFS all spatial positions are always crystal-clear, which can be a bit dull sometimes. It would be nice if one could have the clarity or quality of spatialisation as an extra parameter, and of course having that on a per-sound basis would be a really interesting addition to the power of WFS."

At the same time, electro-acoustic music is by its nature more likely to run into the limitations of Wave Field Synthesis, mainly the problem of spatial aliasing [20]. Due to the distance between the loudspeakers, sounds with a wavelength smaller than this distance, cannot be reproduced accurately by WFS, as spatial aliasing occurs. The aliasing frequency \( f_{al} \) can be calculated from the speaker distance \( \Delta x \) as follows:

\[
f_{al} \leq \frac{c}{\Delta x(1 + |\sin\alpha|)}
\]

where \( \alpha \) is the angle of incidence on the speakers of the wave.\(^{26} \) While in the reproduction of natural sound sources, which tend to have a spectrum with a considerable amount of energy in the lower part of the spectrum, electronic sounds can (and often do) have any imaginable spectrum and so the problem of aliasing will be more prominent.

An important distinction to other applications of WFS is that in electro-acoustic music one does not necessarily want to create an sonic impression that has a natural equivalent, i.e. there is an interest to create sonic events, which would not be possible in a natural environment, and only be possible within a synthesized virtual environment, thus creating a new psycho-acoustic challenge for the listener. An example is to create several virtual sound sources, each in another virtual room.

Another aspect which must be taken into account is the influence of the listening room on the result; this is of course also a problem with other loudspeaker spatialisation technologies. Generally it is recommended to use a dry room for WFS reproduction. On the other hand, recent research has shown that the interaction with the actual listening room is that the room will add reflections to the sound, but that these will be the reflections from the virtual source position. This will be further described below in subsection 6.1.

5.1. Recording techniques

Recording techniques for Wave Field Synthesis can be distinguished based on the effect that is aimed at recording:

1. a single sound, which will later be spatialised,
2. the acoustics of a space, which will later be used to add these acoustics to virtual sound sources,
3. a real environment, which will be reproduced as is, i.e. there will be no further adaptation of the spatialisation in the production.

For the first, it is important that the source signal is as dry as possible, so the recording should only contain the direct sound. The source can then be reproduced as a point source with WFS. There are also methods to record the directivity pattern of a sound source [21].

To record the acoustics of a space microphone arrays need to be used. There are several techniques to process the measurements for use on any WFS configuration, for example a plane wave decomposition [22]. Theoretically, such measurements would need to be made for each source position that the virtual source will take within the room, however in practice we can measure the responses for fewer source positions, as we do not hear small differences in reflection patterns [23]. The results of these measurements and processing can then be used to add virtual room reflections to virtual sources.

Recording a real environment for reproduction by WFS is of interest for compositions based on field recordings. Here also microphone arrays will be needed to record the spatial properties of the environment, and the same post processing techniques can be used. However, whereas microphone array measurements for room impulse responses are usually made by moving the microphone after each measurement, for recording a real environment an array is needed where all channels are recorded simultaneously [24, 25].

6. CURRENT DEVELOPMENTS

Apart from technical improvements in speaker arrays (e.g. [26]), flat panel speaker technology, and room compensation, several developments with WFS research focus on expanding the possibilities of WFS, which will be briefly described in this section.

6.1. Source characteristics

Current research topics for WFS are the reproduction of source characteristics.

Corteel [27] (IRCAM) describes how directional source characteristics can be reproduced and used both for creating direct sound with directive characteristics [28], as well as a tool to influence the reverberant field in the listening room [29], by using a directive source to emit more energy to the walls of the room, and thus creating more lateral energy in the listening area.

At the TU Berlin, work is done on the auralisation of 3D objects [30]. Using a source model of a 3D object, the WFS speaker response can be calculated. For this several aspects are taken into account, such as the contribution of elevated source points [31] and diffraction around the object itself [32].

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\(^{26}\) for a speaker distance of 10cm this amounts to 1.7 kHz in the worst case, 3.4 kHz in the best case, for a speaker distance of 15 cm. to 1.1 kHz and 2.2 kHz respectively
6.2. Room characteristics

Measured room impulse responses can be further analysed and processed to allow for artistic control over the reflection patterns of the virtual room. Tools for this are being developed by Melchior [33, 34].

6.3. The vertical dimension

The vertical dimension has up to now not really been implemented for WFS, due to several practical considerations:

- In theory one needs a plane of loudspeakers to do this, which has a problem that even more hardware and processing power is needed.
- A plane of speakers renders itself impractical for combination with theatre and/or film, as the stage or screen would be blocked by the speakers.
- The human hearing is less sensitive to vertical positioning of sound sources. Moreover, the perception of vertical position is based on spectral filtering of the sound. Due to spatial aliasing with WFS, this may be more difficult to achieve.

Currently, research is being done at the TU Delft on adding at least a little bit of vertical information to the wave field, by adding loudspeaker arrays at the ceiling. This way, ceiling reflections may be added to the wave field.

7. CONCLUSIONS

Since the first public concert with electronic music composed for Wave Field Synthesis in February 2003, several compositions and sound installations have been created and presented to the public. There are now a number of Wave Field Synthesis systems available, not only in research laboratories, but also in performance spaces, or even mobile systems. There are also a variety of tools available, both as plugins for other programs, as well as separate programs for spatial control, furthermore several implementations feature the possibility for OSC control to enable integration with other compositional and live electronics tools. Compatibility between different WFS systems is still a topic of discussion.

In current research further control over source and room characteristics are being developed.

Providing tools and opportunities for composers and other sound artists to explore both the possibilities and limitations of WFS will be worthwhile as they will in the end be the ones to provide content for this technology and this may determine the economical succes of a technology like WFS.

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9. REFERENCES


