Aeolus
A church organ in your PC

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Overview

- Targets
- What is an organ?
- Organ sound
- Requirements
- Short demo
- Choice of algorithm
- Synthesis editor
- Program architecture
- Audio processing
- Demo

Karl Schuke organ at St. Stephani, Helmstedt, Germany
Photo by Matthias Nagorni
A story....

Trinity Church, Wall Street, New York

- September 2001: the organ is destroyed by the corrosive dust of the twin towers.
- Summer 2003: A new instrument is installed. It features:
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  - ?
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  - 14 high-end personal computers running Linux,*
  - 74 separately amplified audio channels, and as many speakers,
  - 33 hours of stored samples, taking 5 man-years of recording and preparation.

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My ambitions for Aeolus ar more modest. . .

- *Not* a 'perfect' imitation or replacement for a real organ.
- A *musical* instrument, that can be enjoyed by musicians.
- Give the user access to all parameters, to
  - modify and adapt the program to his/her own needs,
  - or even define a completey new instrument.
- Have a framework for future research and development.
What is an organ?

- "A musical instrument producing sound by blowing air through pipes, and played via a keyboard.”

- History goes back to Greek and Roman times.

- Disappeared from Western Europe at the end of the Roman Empire, preserved by and re-imported to Europe from the Byzantine culture.

- Oldest existing instruments are from the 15th century.

- A long and complicated history, linked to music history, religion and politics.

- Some important periods:
  - Baroque period in Gemany: Buxtehude, Pachelbel, Bach.
  - Second half of 20th century: the authenticity movement.

There is an enormous diversity in organ types, sizes, and sounds.
Some organ jargon

**Stop** : a set of pipes, one (or more) for each note, all having the same type of sound.

- Each stop can be separately switched on or off.
- Stop names are traditional or refer to other instruments.
- There are *thousands* of different stops.
- Pitch is indicated by the length in feet of the largest pipe:
  - 8 : nominal pitch.
  - 16, 32 : one or two octaves lower.
  - 4, 2, 1 : one, two or three octaves higher.
  - $2\frac{2}{3}$ : one octave plus a fifth higher ($F \times 3$).
  - $1\frac{3}{5}$ : two octaves plus a third higher ($F \times 5$).

**Division** : a set of stops controlled by the same keyboard.

- Each division is a ’mini’ organ, and also has its own character.

**Organ** : an instrument consisting of one or more (1...6) divisions.

- The church of the Palácio National in Mafra, Portugal, has six large organs...
Stops 1

Labial or flue stops

- No moving parts - vibrating air column
- Pitch determined by pipe length
- Pipe also acts as a filter
- Relatively soft sound
Reed stops

- Sound produced by vibrating metal spring
- Pipe mainly acts as a filter
- All sorts of weird pipe shapes
- Very bright sound
• The sound of a single pipe starts with an 'attack' phase, normally less than 0.5 seconds.
  – Each harmonic has its own attack profile.
  – Some harmonics 'overshoot' the steady state level.
  – Others only build up after a delay.

• The attack is followed by a 'steady state' phase, showing only minimal variation over time, caused by air turbulence and complex interactions with other parts.

• Many pipes also produce *chiff* - filtered noise.
  – Noise can be quite prominent during the attack.
  – There is no simple relation between the harmonic and noise spectra.
  – Noise spectrum is typical for a lattice (waveguide) filter.
Organ sound 2

Typical labial pipe spectrum

(Recording by Reiner Janke).
• The spectrum of a stop changes significantly over the range of five octaves. Notes that are close together are similar but never identical.

• Some stop combinations blend together, in others each stop remains a separate sound. This depends on the spectra, and on psycho-acoustics. Sounds are separated by
  – small differences in frequency or delay,
  – different attack profiles,
  – different direction or apparent distance.

Human hearing is very apt at picking up these hints.

• Even for a small organ, the sound is modified by reflections in the cabinet. For larger organs these can have significant delays.

• Every real organ is designed for a particular environment. A large organ needs the acoustics of a large space such as a church in order to sound good.

• The sound of a real organ is defined by the *voicing* process: each individual pipe is adjusted to arrive at a balanced sound.
Organ sound 4 : Tuning

• **Pitch**: frequency of $a_1 : 400\ldots480$ Hz.

• **Temperament**: relative tuning of the 12 notes of an octave. This poses a fundamental problem - it is impossible to get all the intervals right.
  
  – 12 musical fifths are equal to 7 octaves, but
    $(3/2)^{12}$ is not exactly equal to $2^7$.
  
  – 3 musical thirds are equal to 1 octave, but
    $(5/4)^3$ is not exactly equal to 2.

• Every temperament is a compromise.
  
  – Optimise for a few keys only (meantone temperaments - modal music).
  
  – Allow all keys, but keep different character (circulating temperaments - baroque music)
    
  – Distribute the errors evenly (equal temperament - romantic music)

• **Temperament has significant influence on the 'character' of stops that have a prominent $3^{rd}$ or $5^{th}$ harmonic.**
Requirements

- Generators flexible enough to allow for all types of stops.
- Correct modelling of the complex attack phase of a pipe sound.
- All parameters that define a stop are a function of the note number.
- Programmable variations in delay time, frequency, spectrum, attack profile...
- Flexibility in tuning and temperament.
- Correct emulation of the acoustic environment.
- One to four divisions, up to 32 stops per division.
- The end user must be allowed to define the instrument.
- As much parameters as possible should be accessible.
- The program should run on a medium performance PC.
First demo

- General features.
- A guided tour.
- A short musical example.
Choice of algorithm 1

- Recorded samples
  - Realism and quality
  - Lots of work in recording and preparation
  - Also picks up reverb : less flexible
  - Copyright issues

- Additive synthesis
  - Very flexible
  - Intuitive mapping between parameter set and sound
  - Parameter sets can be obtained by analysis
  - Lots of parameters
Choice of algorithm 2

- **Waveguide filters**
  - Close to physical reality
  - Requires specialist knowledge and tools

- **Physical modelling**
  - High quality results
  - Complex
  - Requires specialist knowledge and tools

- **Subtractive and FM synthesis**
  - No systematic approach - results are found more or less by accident.
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Additive synthesis was chosen for the first release.
Choice of algorithm 3

- Up to a few hundreds of pipes can sound at the same time.
  - Wavetables are the only solution.
  - Separation of generation and rendering.
  - Allows re-use of rendering engine.

- Wavetables need to be recalculated if pitch, temperament or sample frequency are modified.

- Each wavetable consist of an attack part, and a loop.

- Loop length is determined by required frequency accuracy:
  - Maximum absolute error < 0.1 Hz.
  - Maximum relative error < 0.1 %.
  - Find integers $n, k$ so that $n/k \sim f/F_{samp}$
  - Continued fraction algorithm provides short average loop length.
  - Wavetable length is dominated by attack phase.

- Wavetables can not be used easily to generate noise.
  - Separate solution required - not yet implemented.
Aeolus structure

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• At least three parameters are a function of both note number $n$ and harmonic number $h$:
  – harmonic level,
  – attack time,
  – attack type.

• With 61 notes and 64 harmonics, this gives 11712 values for a single stop.

• First reduction:
  – Define only every $6^{th}$ note, and interpolate.
  – Requires fourth parameter: random variation of level.
  – Still requires up to $4 \times 11 \times 64 = 2816$ values

• Second reduction:
  – Not all 11 notes need to be defined if not necessary.
  – Manageable solution, but requires dedicated GUI.
• Other parameters are function of note number only, and defined at up to 11 points, with interpolation:
  – volume,
  – systematic detune,
  – random detune.

• Remaining parameters are:
  – pipe length (pitch),
  – stop name,
  – filename,
  – comments and copyright.

• Parameters for each stop are stored in separate files.

• Set of stops for each division and some options are defined in a configuration text file.
Additive synthesis parameters 3

Attack phase profiles.
• Only the audio thread runs in real-time mode.

• Relation between audio thread and main thread is MCV.

• Some shared memory for efficient implementation.
Audio processing - Ambisonics

- Surround sound technology developed more than 20 years ago by UK mathematician Michael Gerzon.
  - Originally developed for military applications (SONAR).
  - Aims at accurate sound field reproduction rather than ‘surround effects’.
  - The only solution for high quality 2-D or 3-D surround sound.

- First order Ambisonics B-format consist of four signals:
  - A mono signal $W$,
  - Three difference signals, one for each axis of 3-D space, $X, Y, Z$.
  - $X, Y, Z$ correspond to the gradient of the sound field, and hence to the perceived direction of the sound.

- B-format is used internally in Aeolus and is also one of the output options.
Audio processing - Top level

Top level audio processing
Audio processing - Division

Audio processing for one division
Audio processing - Division

Audio processing for one division - implementation

- Per-pipe delay lines replaced by shared circular buffers.
- Audio data never moves, the pointers do.
- Process fragment size is always 64 samples.
The future - things to do

- Clean up the code
- Manual and documentation
- Adding ‘chiff’ generators
- More detailed control over attack phase
- Improved reverb, maybe via BruteFIR
- Add auralised headphone output
- New stops and instruments (e.g. French Romantic)
- Other synthesis algorithms
I wish to thank the following people for their contributions:

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Martin Kares

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Matthias Nagorni

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Reiner Janke

The ALSA and JACK teams
The parameter editor.

Question time.

More music.