An Open-Source C++ Framework for Multithreaded Realtime Multichannel Audio Applications

Matthias Geier[1] Torben Hohn[2] Sascha Spors[1]

[1]Quality and Usability Lab
Telekom Innovation Laboratories
Technische Universität Berlin

[2]Linutronix GmbH

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APF

Audio Processing Framework

- collection of C++ code
- `http://tu-berlin.de/?id=apf`
- open source, GPLv3
- mostly platform-independent
  - tested on Linux and MacOSX
- quite generic
- heavy use of templates
- mostly header-only

APF Components

- `MimoProcessor` → *topic of this talk!*
- biquad & cascade of biquads (IIR filter)
  - several methods for denormal prevention
- (yet another) C++ wrapper for JACK
- iterators
- other tools
- delay line → *coming soon!*
- partitioned convolution (FIR filter) → *coming soon!*

MimoProcessor

Target Applications

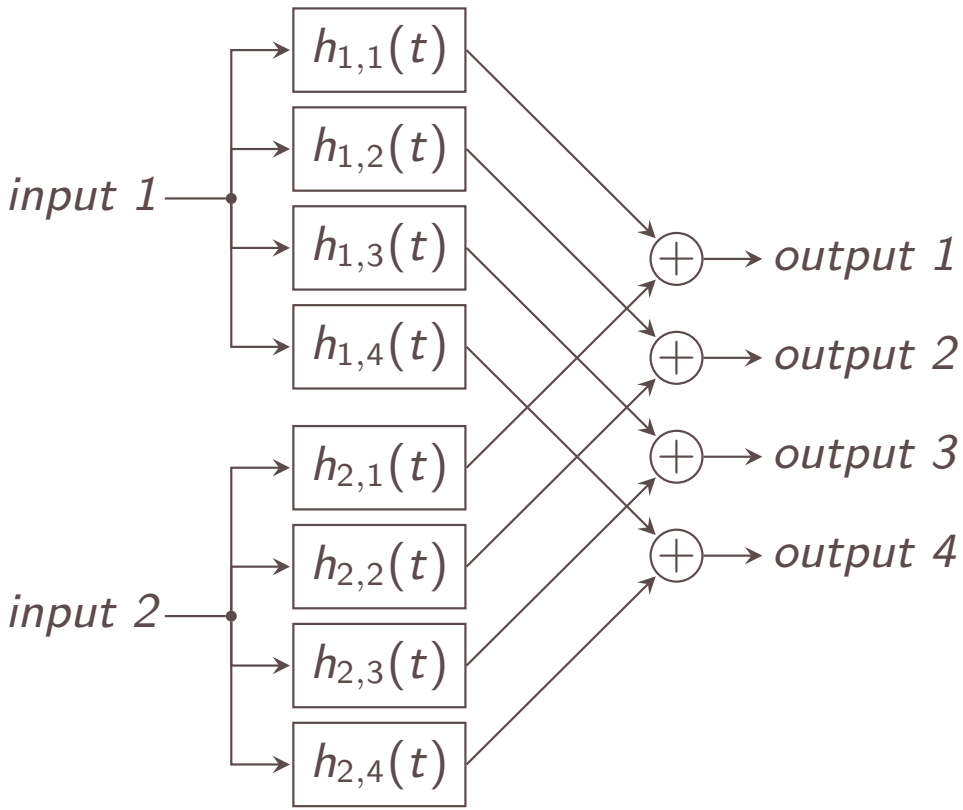
- block-based audio applications
- many inputs/outputs
- both realtime and non-realtime
- interactive applications

example application areas:

- sound field synthesis
- multichannel echo cancelling
- beamforming

MimoProcessor Example Application

Generic MIMO system



MimoProcessor Features

- different audio backends (realtime and non-realtime)
  - *JACK*
  - *Pure Data* (and *Max/MSP*) external using *flext*
  - *MEX*-file for *octave* (and *Matlab*)
  - read/write multichannel audio files
  - *PortAudio* → *coming soon!*
  - . . . and users can provide their own backends!
- "automatic" multithreading
- optional crossfade
- dynamic number of inputs/outputs (if supported by the audio backend)
- safe communication between realtime and non-realtime threads

Realtime & Non-Realtime Threads

- realtime thread:
  - audio callback function
  - limited computation time per audio block
  - blocking functions are forbidden, e.g.
    - allocating/deallocating memory
    - reading/writing files/sockets
    - creating/joining threads
    - waiting for mutexes
    - ...
- non-realtime thread:
  - GUI, network, reading/writing files
  - everything else

MimoProcessor Components

- `LockFreeFifo<Command*>`
  - `push()`, `pop()`
- `CommandQueue`
  - using 2× `LockFreeFifo`
  - `push()`/`wait()`, `process_commands()`
- `Command`
  - abstract base class
  - `execute()`, `cleanup()`
- `RtList<Item*>`
  - using `CommandQueue`
  - `add()`/`rem()`, `begin()`/`end()`/`size()`
- `Item`
  - abstract base class
  - `process()`

MimoProcessor Components

- `MimoProcessor<Derived, policies see below >`
  - `interface_policy`
    - `jack_policy`
    - `pointer_policy`
  - `thread_policy`
    - `posix_thread_policy`
  - `sync_policy`
    - `posix_sync_policy`
  - `xfade_policy`
    - `raised_cosine_policy` (default)
    - `disable_xfade`

Code Example

examples/jack_minimal.cpp

```
#include "apf/mimoprocessor.h"
#include "apf/jack_policy.h"
#include "apf/posix_thread_policy.h"
#include "apf/posix_sync_policy.h"

class MyProcessor : public apf::MimoProcessor<MyProcessor
      , apf::jack_policy, apf::posix_thread_policy, apf::posix_sync_policy>
{
  public:
    typedef MimoProcessorDefaultInput Input;
    class Output;

    MyProcessor();

    void process()
    {
      _process_list(_output_list);
    }

  private:
    rtlist_t _input_list, _output_list;
};
```

```
class MyProcessor::Output : public MimoProcessorOutput
{
  public:
    typedef MimoProcessorOutput::Params Params;

    explicit Output(const Params& p)
      : MimoProcessorOutput(p)
      , _combiner(_parent._input_list, _internal, _parent)
    {}

    virtual void process()
    {
      _combiner.copy(my_predicate());
    }

  private:
    struct my_predicate
    {
      // trivial, all inputs are used
      bool operator()(const Input&) { return true; }
    };

    combine_channels<rtlist_t, Input, InternalOutput> _combiner;
};
```

```
MyProcessor::MyProcessor()
  : MimoProcessorBase()
  , _input_list(_fifo)
  , _output_list(_fifo)
{
  Input::Params ip;
  ip.parent = this;
  _input_list.add(new Input(ip));
  _input_list.add(new Input(ip));

  Output::Params op;
  op.parent = this;
  _output_list.add(new Output(op));

  this->activate();
}

int main()
{
  MyProcessor processor;
  sleep(30);
}
```

Parallel Processing

- `RtList<Item*>`: list of polymorphic base class pointers
- virtual function `Item::process()`
- items within one list are processed in parallel
- fixed number of threads, specified by user
- simple scheduling:
  - each of the N threads gets every N-th item
- one "main audio thread", $N - 1$ "worker threads"
  - communication via semaphores

Crossfade

- block-based processing
- parameter changes only at block boundaries
- artifacts due to discontinuities
- can be reduced by crossfade

- each block is processed twice
  1. with previous parameters, fade out
  2. with current parameters, fade in
- but: only if something actually changes
  - as noticed by `CommandQueue`
- crossfade is optional
  - can be switched off at compile time
    - `MimoProcessor<..., disable_xfade>`

Example

Near-Field-Compensated Higher Order Ambisonics

- implementation of a realtime NFC-HOA renderer
- circular loudspeaker array (2.5D)
- M-th order ($2 \times M + 1$ loudspeakers)
- stages of the algorithm (in `RtLists`):

N	sources/inputs
$N \times (M + 1)$	IIR filters
$M + 1$	objects which add contributions of sources per order

  - multiplication with 2 complex weighting factors
  - resulting in $2 \times M + 1$ values (per audio sample)

block size	IFFTs (of length $2 \times M + 1$)
$2 \times M + 1$	outputs

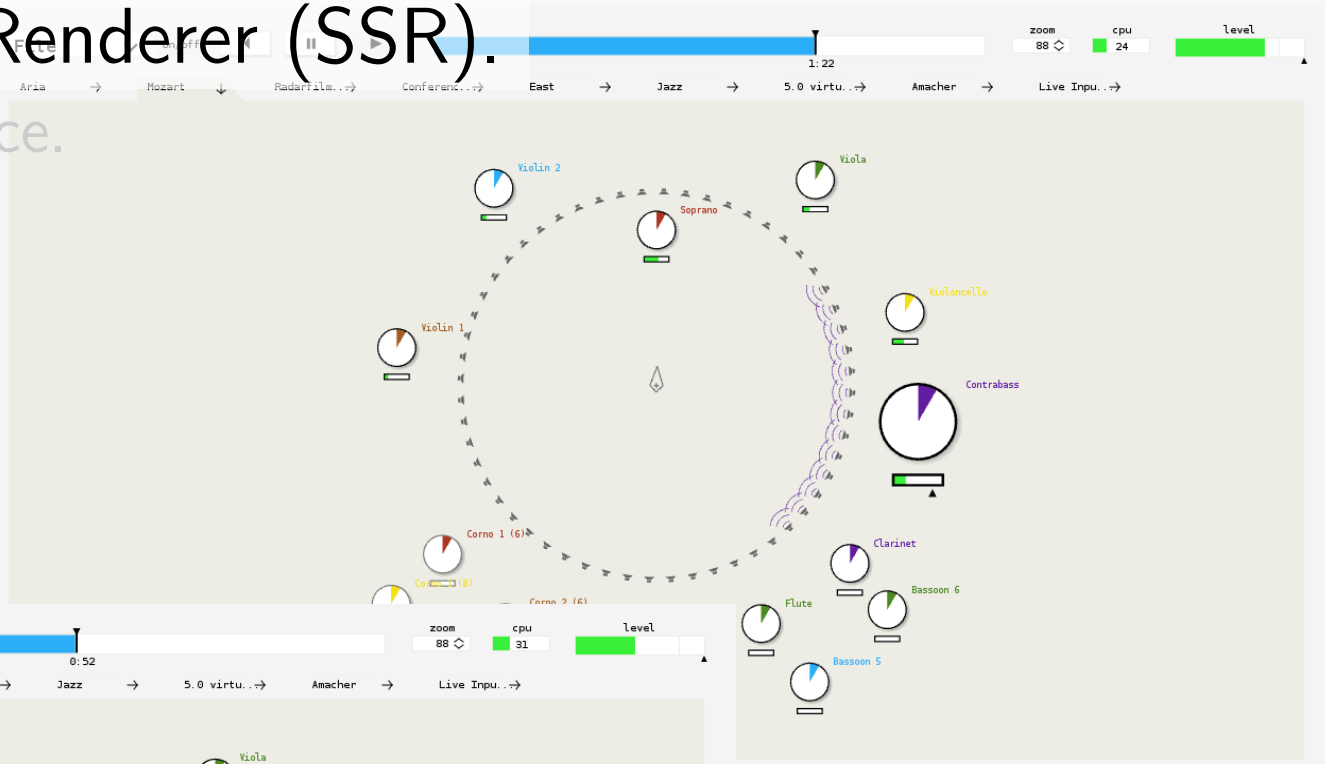
- part of the SSR $\rightarrow$ *coming soon!*
  - What is the SSR? $\rightarrow$ see next page

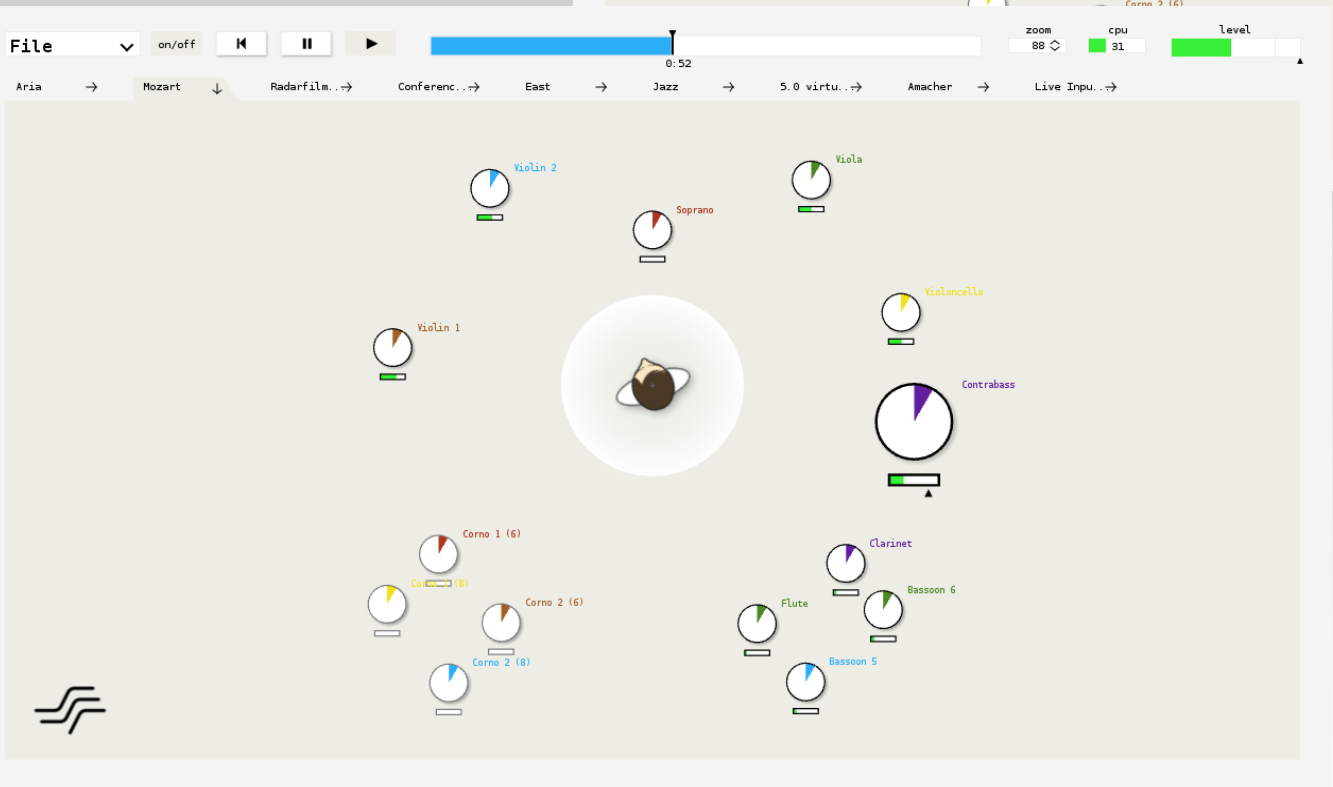
The SoundScape Renderer (SSR)

- software tool for *object-based* realtime spatial audio reproduction
- several different reproduction methods
  - Binaural Renderer
  - Binaural Room Synthesis (BRS)
  - Wave Field Synthesis (WFS)
  - Vector Base Amplitude Panning (VBAP)
  - Ambisonic Amplitude Panning (AAP)
  - Generic Renderer
  - Binaural Playback Renderer (BPB)
  - NFC-HOA Renderer $\rightarrow$ *coming soon!*
- runs on Linux and Mac OSX
- uses the *Jack Audio Connection Kit* (JACK)
- graphical user interface (Qt) and network interface (TCP/IP)
- Free and Open Source Software (GPLv3)
- `http://tu-berlin.de/?ssr`

The SoundScape Renderer (SSR).

Graphical User Interface.





Important Notes

- compile with optimization!
  - e.g. `g++ -O3`
- be aware of cache effects!
  - memory locality
  - false sharing
- look for bottlenecks with a profiler!
  - OProfile, gprof, ...

Conclusion

- goal of `MimoProcessor`: to be ...
  - unobtrusive
  - easy to use
  - re-usable in different contexts
  - easily extensible (e.g. by policy-based design)
- parallelization: simple yet effective
  - trade-off between effort (to use, to implement) and performance
  - significant gain in performance, e.g. for HOA renderer
- unit tests are included
  - using the *CATCH* framework
- well documented
  - *Doxygen* documentation also available at the website

Future Work

- Audio Processing Framework (APF)
  - include delay line and partitioned convolution
  - implement *PortAudio* policy
- SoundScape Renderer (SSR)
  - re-write core using the `MimoProcessor`
  - port all existing renderers
  - include the brand-new NFC-HOA renderer

Thank you very much for your attention!
Questions?

Website: `http://tu-berlin.de/?apf`
Blog: `http://audio.qu.tu-berlin.de`