An Extensible Parallel Computing Framework for Ultra-Fast X-Ray Imaging

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Institute for Data Processing and Electronics

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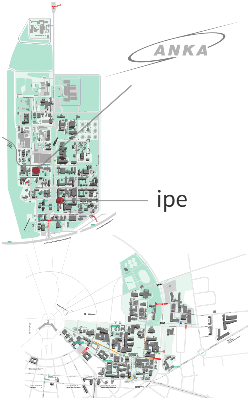
Hardware

- Development (FPGA, ASIC)
- Manufacturing (circuit production, bonding)
- Characterization and long-term tests

Software

- Experiment control and data acquisition
- Analysis of acquired data
- Large scale data storage



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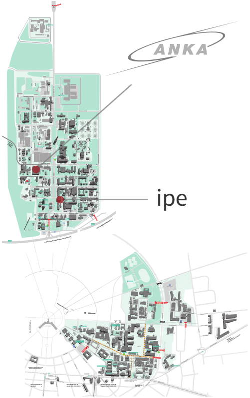


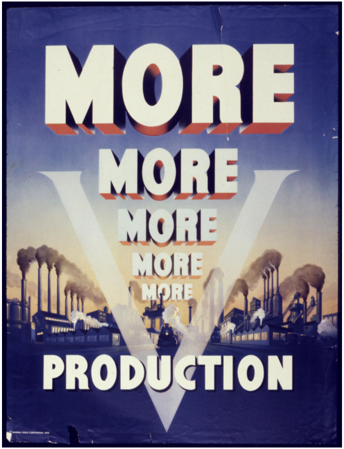
Data analysis for synchrotron μCT

Demanding requirements

- Compute-intensive reconstruction
- Variety of pre- and post-processing steps
- Fast and direct feedback

More data

- Better sensors
- Higher throughput
- Time-resolved scans



Data analysis for synchrotron μCT

Demanding requirements

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More data

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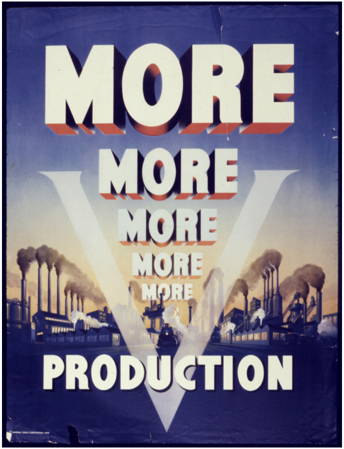
- Higher throughput
- Time-resolved scans

Existing tools can hardly satisfy the demands!



Fast image processing on GPUs

ufo framework

- Streamed data processing using heterogeneous compute resources
- Pipelined and parallelized on multiple levels
- Suited for high-volume image processing (e.g. tomography)

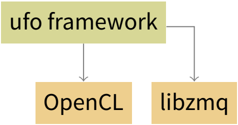
This talk

- Framework does *not* provide any functionality on its own
- Domain-specific tools and applications have to be developed
- This will be a quick tour what is possible and how it is done

Recap

- Core framework written in C and OpenCL
- Large suite of pre-defined filters for high-throughput image processing
- User specifies workflow, framework takes care of the rest
- Open source (LGPL) and hosted at GitHub `github.com/ufo-kit`

Components



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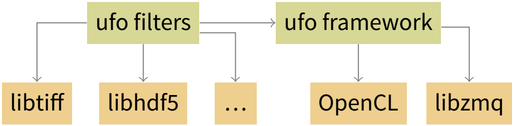

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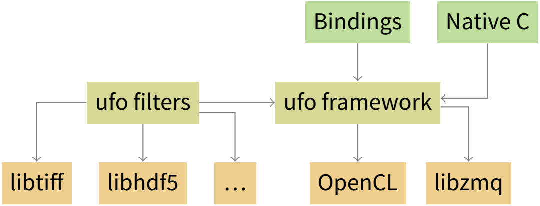
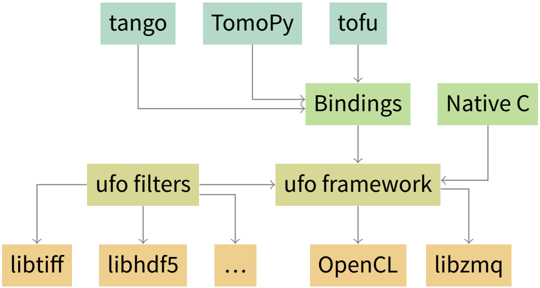

Bindings
Native C
ufo filters
ufo framework
libtiff
libhdf5
...
OpenCL
libzmq

Components



tango
TomoPy
tofu
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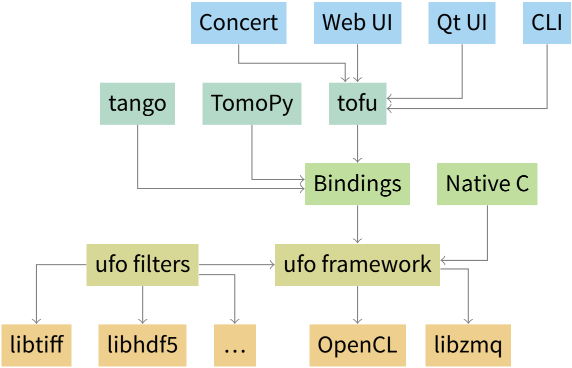

Concert
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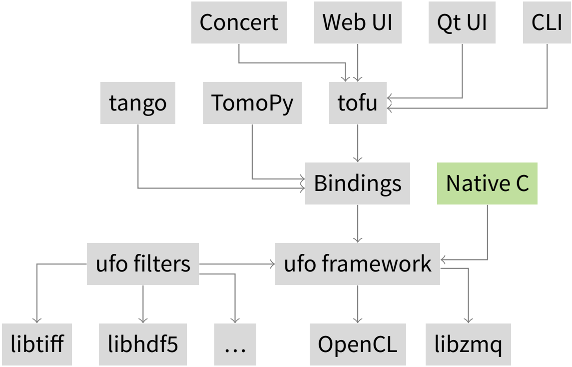
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Builtin tools

Written in native C

- Tools written directly in C
- General purpose: `ufo-launch` and `ufo-runjson`
- (Domain-specific: laminographic reconstructor)

Builtin tools

Written in native C

- Tools written directly in C
- General purpose: `ufo-launch` and `ufo-runjson`
- (Domain-specific: laminographic reconstructor)

Launching linear pipelines

- Used for basic one-off jobs and specified on the command line
- Tasks separated by exclamation marks
- Parameterized with key-value property assignments

Launch examples

Read and write data

```
ufo-launch read path=folder/sino*.tif !
    write filename=multi.tif
```

Launch examples

Read and write data

```
ufo-launch read path=multi.tif !
    write filename=folder/single-%05i.tif
```

Launch examples

Read and write data

```
ufo-launch read path=folder/sino*.tif !
    write filename=output.h5:/raw
```

Launch examples

Downscale input data

```
ufo-launch read path=folder/sino*.tif !
    rescale factor=0.5 !
    write filename=output.h5:/raw
```

Launch examples

Apply OpenCL expressions

```
ufo-launch read path=folder/sino*.tif !
    rescale factor=0.5 !
    calculate expression="log(v)" !
    write filename=output.h5:/raw
```

Launch examples

Remove vertical stripes

```
ufo-launch read path=folder/sino*.tif !
    rescale factor=0.5 !
    calculate expression="log(v)" !
    fft dimensions=2 ! filter-stripes ! ifft dimensions=2 !
    write filename=output.h5:/raw
```

Launch examples

Compute filtered backprojection

```
ufo-launch read path=folder/sino*.tif !
    rescale factor=0.5 !
    calculate expression="log(v)" !
    fft dimensions=2 ! filter-stripes ! ifft dimensions=2 !
    fft ! filter ! ifft ! backproject !
    write filename=output.h5:/entry/data/data
```

JSON representation

- `ufo-launch` can only execute linear pipelines
- Complex relationships must be expressed programmatically or with a data structure
- We use a simple JSON format to serialize the data structure
- This structure can then be run via

```
$ ufo-runjson dataflow.json
```

JSON example

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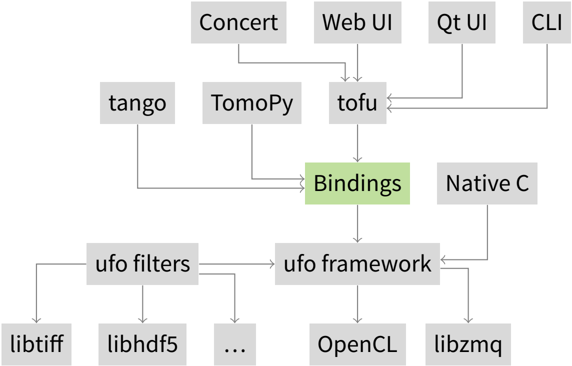
```
{
  "nodes": [
    {"plugin": "read", "name": "read",
     "properties": {"path": "folder/sino*.tif"}},
    {"plugin": "rescale", "name": "rescale",
     "properties": {"factor": 0.5}},
    {"plugin": "write", "name": "write",
     "properties": {"filename": "output.h5:/raw"}}
  ],
  "edges": [
    {"from": "read", "to": "rescale", "input": 0},
    {"from": "rescale", "to": "write", "input": 0}
  ]
}
```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Language bindings

- JSON is a good format to freeze a data flow
- Further customization requires writing C code or bind to a scripting language
- Introspection mechanism allows for third-party language support
- Including JavaScript, Python, Ruby, Lua, Go, Haskell …

Language bindings

- JSON is a good format to freeze a data flow
- Further customization requires writing C code or bind to a scripting language
- Introspection mechanism allows for third-party language support
- Including JavaScript, Python, Ruby, Lua, Go, Haskell …
- However, our primary target for now is Python

Binding interface

```python
# "ufo-runjson" in five lines

import sys
from gi.repository import Ufo

pm = Ufo.PluginManager()
g = Ufo.TaskGraph.read_from_file(pm, sys.argv[1])

sched = Ufo.Scheduler()
sched.run(g)
```

Binding interface

```python
from gi.repository import Ufo

pm = Ufo.PluginManager()
read = pm.get_task('read')
rescale = pm.get_task('rescale')
write = pm.get_task('write')

read.set_properties(path='folder/sino*.tif')
rescale.set_properties(factor=0.5)
write.set_properties(filename='output.h5:/raw')

g = Ufo.TaskGraph()
g.connect_nodes(read, rescale)
g.connect_nodes(rescale, write)

sched = Ufo.Scheduler()
sched.run(g)
```

Improved Python integration

Global Interpreter Lock

- GIL would block Python interpreter during computation
- GIL is released during execution and insertion of data

Interfacing with NumPy

- C module converts between ufo and NumPy
- Alternatively data pointers can be re-used

High-level abstractions

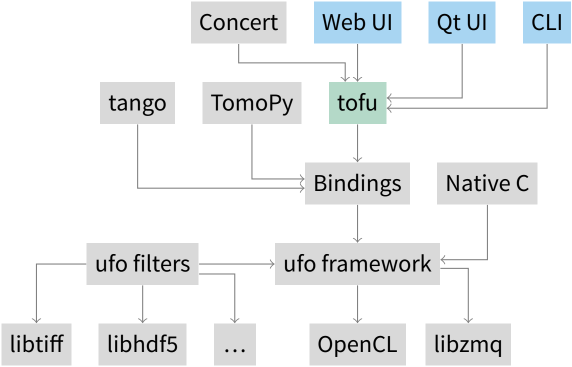
- `ufo` module wraps filters during import
- More magic but cleaner instantation and setup

High-level Python

```python
from ufo import Read, Write, Rescale

read = Read(path='folder/sino*.tif')
rescale = Rescale(factor=0.5)
write = Write(filename='output.h5:/raw')

# wait for execution to finish
write(rescale(read())).run().wait()
```

High-level Python

```python
from ufo import Read, Rescale

read = Read(path='folder/sino*.tif')
rescale = Rescale(factor=0.5)

# use result immediately
for image in rescale(read()):
    print(np.mean(image))
```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TOFU reconstruction toolkit

Idea

- Move reconstruction-related code to single Python module
- Simplifies setup and execution of reconstruction pipelines using ufo
- Visualization widgets based on PyQtGraph

Focus

- Tomographic reconstruction with FBP, DFI and SART
- Laminographic reconstruction with FBP
- Manual and automatic axis alignment

Command line interface

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- Offline reconstruction for power users
- Parameters are stored in a configuration

```
$ ufo-reconstruct init
$ vi reco.conf
$ ufo-reconstruct tomo
```

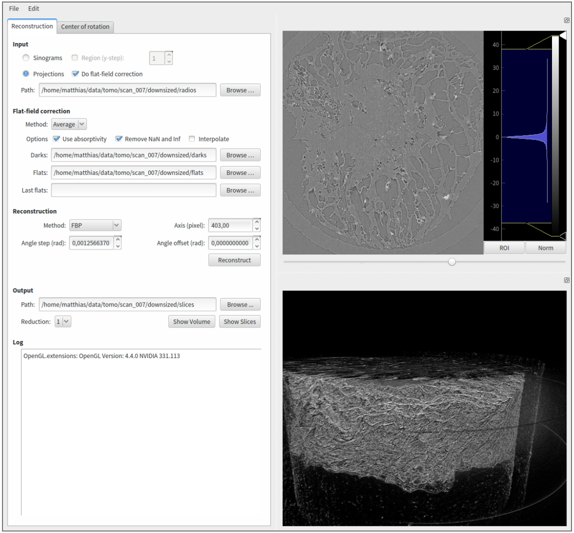
- …which can be overriden with command line arguments

```
$ ufo-reconstruct run --axis=234.5
```

Qt GUI

- Offline reconstruction for regular users
- Shares configuration with command line version
- Uses PyQt and PyQtGraph widgets for visualization

Qt GUI


File
Edit
Reconstruction
Center of rotation
Input
Sinograms
Region (y-step):
Projections
Do flat-field correction
Path: /home/matthias/data/tomo/scan_007/downsized/radios
Browse ...
Flat-field correction
Method: Average
Options
Use absorptivity
Remove NaN and Inf
Interpolate
Darks: /home/matthias/data/tomo/scan_007/downsized/darks
Flats: /home/matthias/data/tomo/scan_007/downsized/flats
Last flats:
Reconstruction
Method: FBP
Axis (pixel): 403,00
Angle step (rad): 0,0012566370
Angle offset (rad): 0,0000000000
Reconstruct
Output
Path: /home/matthias/data/tomo/scan_007/downsized/slices
Reduction: 1
Show Volume
Show Slices
Log
OpenGL.extensions: OpenGL Version: 4.4.0 NVIDIA 331.113
ROI
Norm

Qt GUI

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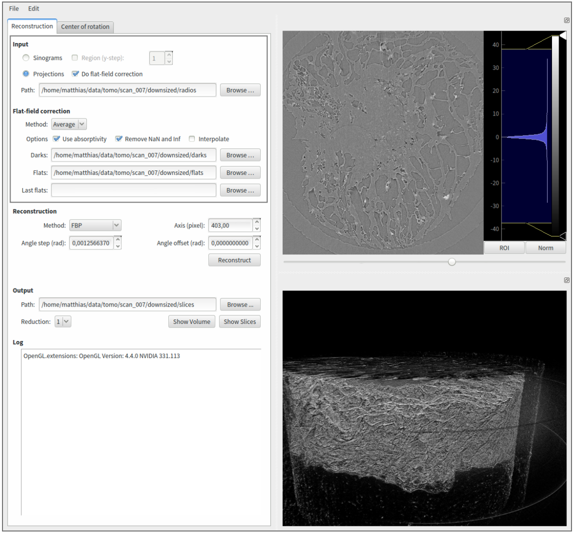
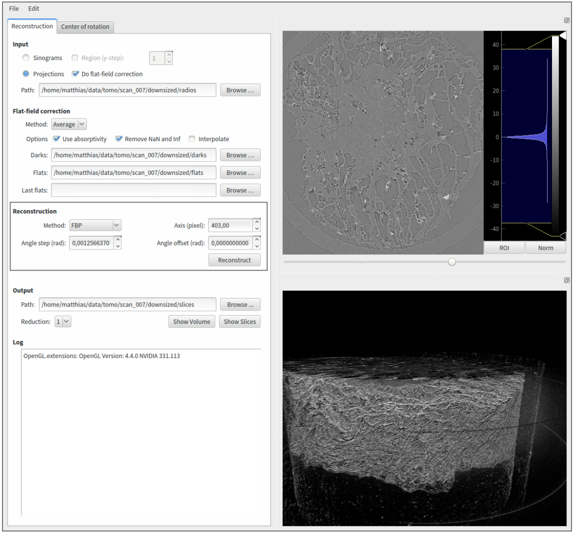
Input



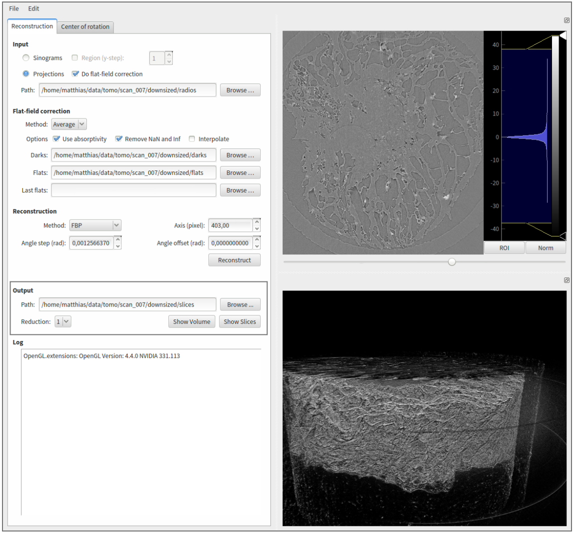
Qt GUI

Parameters



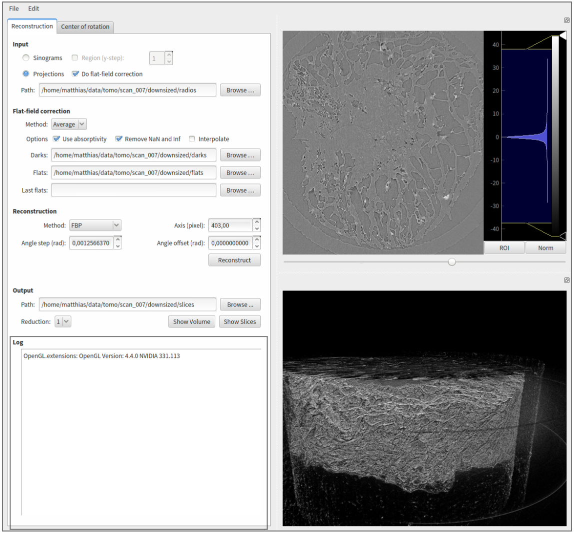
Qt GUI

Output



Qt GUI

Log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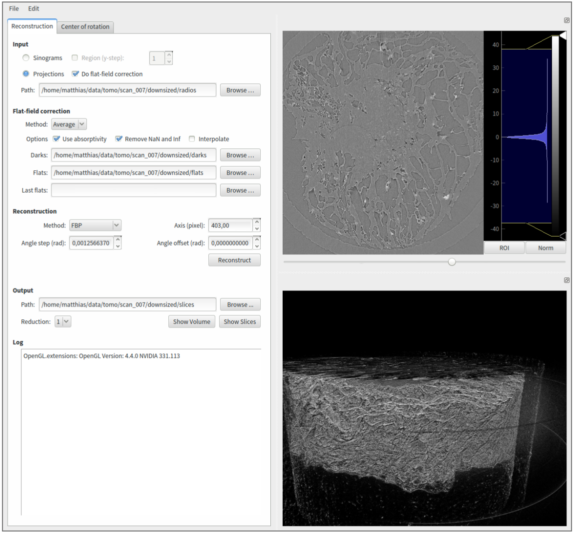
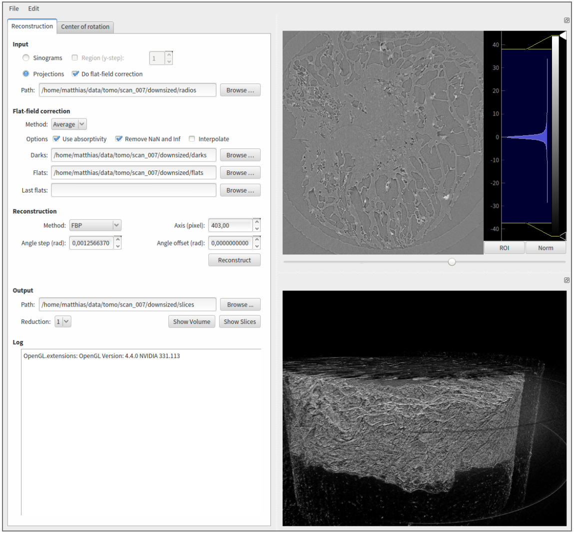


Slices

Qt GUI

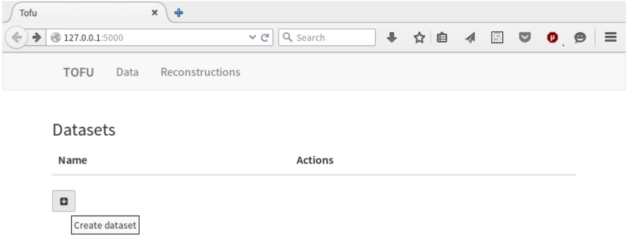


Volume

Web UI

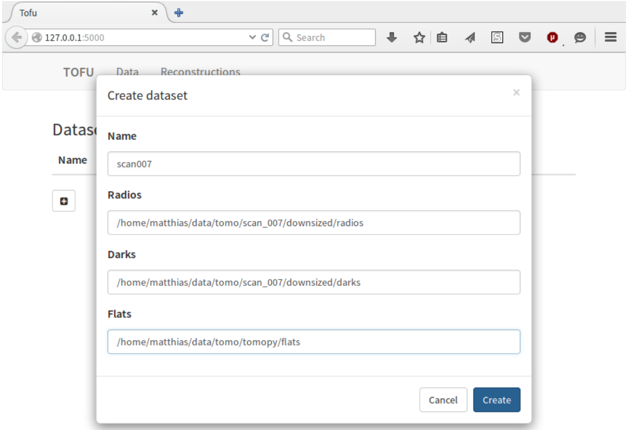
- Offline reconstruction for regular users
- Simplifies deployment and maintenance
- Uses Flask backend, Bootstrap frontend and WebGL for basic visualization

Web UI prototype



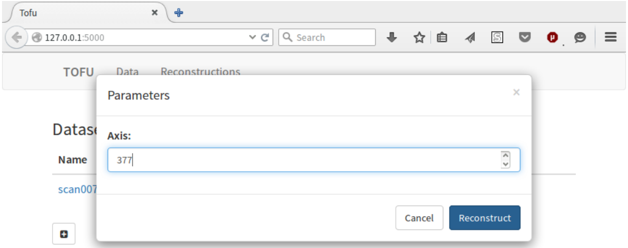
Create dataset from experiment data

Web UI prototype



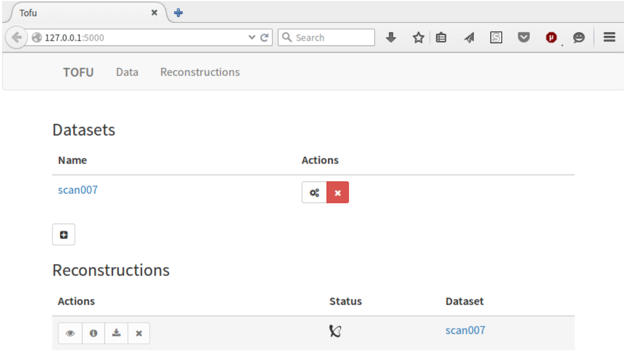
…by specifying paths for now.

Web UI prototype



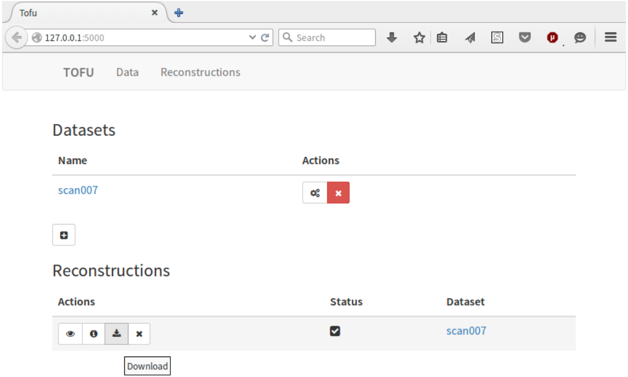
Start a reconstruction

Web UI prototype



and wait for reconstruction to finish.

Web UI prototype



Download result

Web UI prototype

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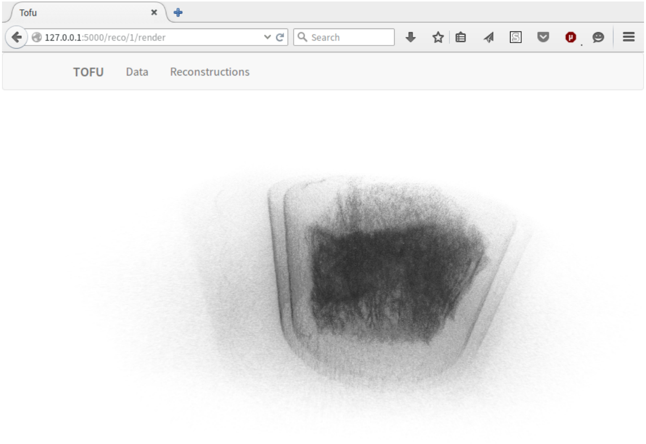
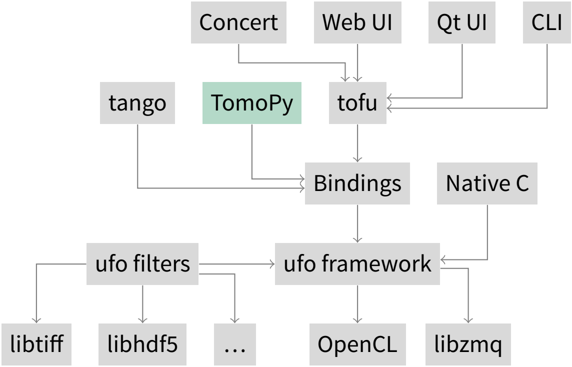


...or visualize it.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TomoPy

Versatile reconstruction platform

- TomoPy is APS' Python reconstruction toolkit
- A custom `ufo` Python module hooks into TomoPy

Benefits

- We can re-use existing I/O and pre-processing code
- TomoPy's reconstruction speed can be improved

TomoPy Standard Demo

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```python
import tomopy

data, white, dark, theta = tomopy.xtomo_reader('demo/data.h5')

d = tomopy.xtomo_dataset()
d.dataset(data, white, dark, theta)
d.normalize()
d.correct_drift()
d.phase_retrieval()
d.correct_drift()
d.center = 661.5
d.gridrec()

tomopy.xtomo_writer(d.data_recon, 'tmp/test_', axis=0)
```

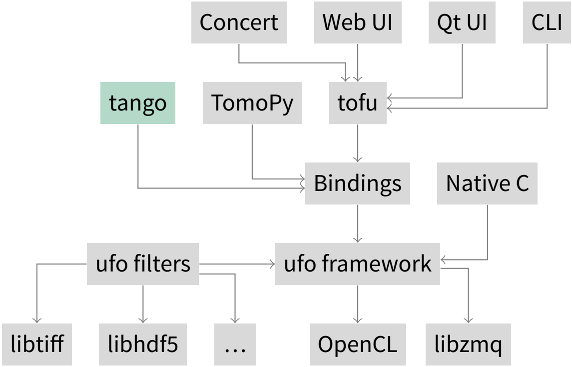
TomoPy + UFO

```
import tomopy
import ufo.tomopy   # <<<< new

data, white, dark, theta = tomopy.xtomo_reader('demo/data.h5')

d = tomopy.xtomo_dataset()
d.dataset(data, white, dark, theta)
d.normalize()
d.correct_drift()
d.phase_retrieval()
d.correct_drift()
d.center = 661.5
d.ufo_fbp()          # <<<< changed

tomopy.xtomo_writer(d.data_recon, 'tmp/test_', axis=0)
```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TANGO integration

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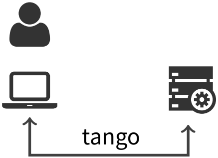
- tango is the European synchrotron *de facto* control system
- It provides "device" servers to access hardware devices or software services
- Using tango's Python interface we can provide remote computing within the existing control system infrastructure

TANGO
Connecting things together

Approach

Protocol

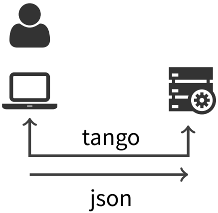
- Server listens for compute requests



Approach

Protocol

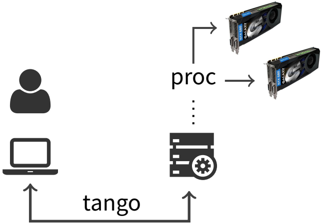
- Server listens for compute requests
- Client sets the `json` attribute and calls the `Run` or `RunContinuous` command



Approach

Protocol

- Server listens for compute requests
- Client sets the `json` attribute and calls the `Run` or `RunContinuous` command
- The server spawns a new compute process identified by a process id



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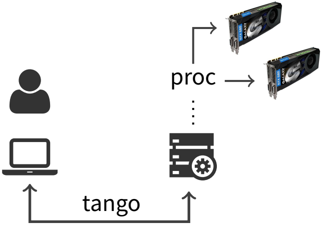

Execution models

1. Single-run processes ("fire and forget")
2. Continuous processes (update description and re-run)

Single-run processes

Interface

```python
process = PyTango.DeviceProxy('hzgctkit/process/1')
process.json = "{ ... }"

pid = process.Run()
print(process.Running(pid))   # still running?
print(process.jobs)           # list of active jobs, e.g. [7041]

process.Wait(pid)
print(process.ExitCode(pid))  # return code of job
```

Single-run processes

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Interface

```
process = PyTango.DeviceProxy('hzgctkit/process/1')
process.json = "{ ... }"

pid = process.Run()
print(process.Running(pid))   # still running?
print(process.jobs)           # list of active jobs, e.g. [7041]

process.Wait(pid)
print(process.ExitCode(pid))  # return code of job
```

Remarks

- Simple to use and understand
- No extended use of resources

Continuous processes

Interface

```
pid = process.RunContinuous()
process.Continue(pid)       # trigger execution
process.json = "{ ... }"    # update description
process.Continue(pid)
process.Stop(pid)           # terminate process
```

Continuous processes

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Interface

```
pid = process.RunContinuous()
process.Continue(pid)       # trigger execution
process.json = "{ ... }"    # update description
process.Continue(pid)
process.Stop(pid)           # terminate process
```

Remarks

- Enables continuous exploration
- Resources are allocated as long as process is running
- Forgetting to call `Stop` leaks resources

Outlook

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Status

- The ufo framework provides various integration points
- All presented tools are open sourced and free for anyone to use

Ongoing

- Use tofu for the TomoPy integration
- Batch reconstruction within astor
- Finish web GUI and merge with the astor data portal