X-TRACT: software for simulation and reconstruction of X-ray phase-contrast CT

CSIRO Materials Science and Engineering
13 November 2008
Contents of the talk

1. X-ray phase-contrast imaging: theory and examples
2. In-line phase retrieval
3. Phase-contrast CT
4. X-TRACT architecture and main modules
5. Multi-threading, multi-processing and GPUs
6. GPU speed test results
7. TS-Imaging.net

Acknowledgements
In-line X-ray imaging. Direct problem

X-rays: Sample ----> Image(s)

\[ 1 - \delta(r, \lambda) - i\beta(r, \lambda) = n(r, \lambda) \rightarrow I(r_\perp, R_n, \lambda) \]
Phase and absorption contrast in in-line imaging

Phase contrast
(sharp black/white stripes near the edges)

Absorption contrast
(darker and lighter areas)
In-line X-ray imaging. Inverse problem

3D distributions $\beta(r)$ and $\delta(r)$; $\text{Cu}(r)$, $\text{Si}(r)$, $\text{Al}(r)$

**Elemental analysis**

**Methods:**
- **Tomography**
- **Backpropagation**
- **Deconvolution**
- **Phase retrieval**
Phase retrieval in in-line imaging

Intensity vs. Position

Thickness vs. Distance

Phase retrieval in in-line imaging

CSIRO. X-TRACT: software for phase-contast CT
X-ray phase-contrast computed tomography

Phase retrieval

Backpropagation

CT reconstruction
X-ray micro-tomography in the laboratory

• Tomographic data is a series of images acquired while rotating the sample.

• We combine images using phase-contrast cone-beam algorithm to produce 3D reconstruction of object

Microwire composites from Stuart Bateman’s group (CMSE)
Main interest is in distribution of microwires within polymer
Sample at left around 400 microns across
Data collected and processed by Dachao Gao (CMSE)
Our CT reconstruction software (X-TRACT)

- Windows MDI application
- ISO C++ numeric code
- GUI uses MFC
- Multi-threaded
- Multi-processing via CWS
- GPU enabling is in progress
- Implements: phase retrieval FBP algorithm FDK algorithm etc.
X-TRACT: software for quantitative X-ray imaging

The software requires a computer running Windows XP (32-bit or 64-bit) or Windows Server 2003 with at least 512 MB of RAM, x86 CPU (Intel or AMD) at 1.5 GHz or faster, and 100 MB or more of hard disk space. X-TRACT software includes the following facilities for X-ray image simulation, analysis and processing.

1. PreProc (image pre-processing) module: implements typical operations for step-wise and batch preprocessing of images (dark current correction, flat field correction, CCD defective pixel replacement, image drift correction, etc.) and also includes simple phase retrieval in a batch mode. (Used in CT!)

2. CoProc (image co-processing) module: implements simple automated search functions for simultaneous matching of magnification and drift or rotation and drift for pairs of images with an option of choosing a "region of interest" to be used in image matching.
X-TRACT: software for quantitative X-ray imaging

3. Phase retrieval module: implements >20 algorithms for phase and/or amplitude extraction from in-line X-ray images (e.g. Transport of Intensity based algorithms, Born and Rytov based Fourier optics type methods and Gerchberg-Saxton-Fienup type algorithms, combinations of the above).

4. Convolution, deconvolution and correlation module for image filtering, super-resolution, estimating X-ray source size and spatial resolution, etc. (includes regularized Wiener deconvolution, Richardson-Lucy deconvolution, iterative Taylor (local) deconvolution, etc.)

5. "Image calculator" module: implements >50 major operations (e.g. for summation, division, rotation, padding, interpolation, etc, of images, Fast Fourier Transform, evaluation of Kirchhoff integrals, simulation of Poisson and Gaussian noise, spatial filtering, etc.). All operations can be performed on a single image file or batches of files applying a single operation or a multi-command script to each image.
X-TRACT: software for quantitative X-ray imaging

6. CT. Sinogram calculation; several variants of parallel-beam FBP and cone-beam FDK reconstruction algorithms; simulation of CT projections with optional free-space propagation, arbitrary incident X-ray spectrum and the ability to handle arbitrary sample composition in 3D, etc.

7. ABI (analyser-based phase retrieval). Simulation of ABI images with arbitrary analyser crystal reflections (including asymmetric reflections). Multiple methods of amplitude/phase reconstruction from experimental ABI images (geometric optics, weak object, linear transfer function, iterative methods, etc).

8. OMNI optics. Simulation of multiple phase-contrast imaging modalities (Zernike, Schlieren, dark field, DIC-Nomarsky, in-line imaging, interferometry, etc) with multiple adjustable parameters.
Web-based image processing services for computed tomography and other applications

**FRONT END**
- **User PC** (GUI front ends, local graphics, local computing)
- **Data Acquisition facility** (XuM, synchrotron beamline, etc.)
- **Data Visualization facility** (presentation: 3D, movies, etc.)

**BACK END**
- **Web Server** (user account DB, security configuration, payments, software updates)
- **Compute Cluster** (remote high-performance computing)
- **File Server** (high bandwidth file I/O via fast network)

**Rich-client application (X-TRACT Type 4)**

Requests → **Web Server**

Responses ← **Web Server**

Control ← **Compute Cluster**

Control → **File Server**

Raw data → **File Server**

Processed data ← **File Server**

Cluster: CWS infrastructure, MS CCS, GUI-less worker applications (X-TRACT Type 5)
Internet front-end infrastructure (STI)

STI library provides the following functionality to Windows desktop applications.

(1) Provides fine-grain control over the download and use of STI-enabled applications on remote user PCs (including immediate disabling if necessary);

(2) Enables secure time-limited trials of fully-functioned Windows desktop applications by remote users (users need to have a live Internet connection).

(3) Can collect and store information about the usage of the downloaded applications (only anonymous statistic information is currently collected).

(4) Provides automatic optional and compulsory updates of downloaded applications.

STI infrastructure can be used to “Web-enable” almost any Windows desktop application! No components other than standard Windows OS need to be present on the user PC.
“Master” and “slave” modules are implemented as a single C++ library. A “stub” is implemented as an ASP.NET application written in C# (uses SOAP for communications).

In the case of X-TRACT, “master” and “slaves” are (almost) the same application compiled & launched in different modes: as an MDI Windows application or as a GUI-less command-line application, respectively.

“Master” runs on a user PC. It not only launches and controls “slave” applications on a remote cluster, but also provides feature-rich standard Windows interface to the user, allows to view images and retains the ability to optionally perform calculations locally on the user PC in a multi-threaded regime.

“Slaves” are always single-threaded, as the “threading”, as well as queuing, is controlled by the MS Compute Cluster Server in a generic fashion.

CWS infrastructure can be used to “cluster-enable” any suitable Windows application! It provides a remote cluster back-end functionality for the whole system. No knowledge of the cluster OS is required from the user.
In order to perform calculations on a remote Windows cluster, rather than locally, it is only necessary to check this box!
CSIRO. X-TRACT: software for phase-contast CT

TBI compute cluster used for Web-based image processing services

- 1 x Gigabit switch
- New CPU/GPU node
- 3 x dual quad-core Xeon CPU nodes
  - 24 CPU cores
  - 26 x 250 GB hard drives
  - 144 GB of RAM
- 1 x KVM switch
- 3 x UPS
- 1 x Web server
- 1 x Web server
New CSIRO CSS compute cluster

- Heterogeneous CPU / GPU cluster capable of running multiple OS (Linux and Windows)
- Approx. 640 Xeon CPU cores
- Approx. 160 Nvidia 10-series GPUs (40 Tesla S1070 HPC modules)
- 20 Gb Infiniband connections between nodes
- Up to 32 Tflops combined processing power
- Approx. 80 TB high-performance local storage

X-TRACT will be able to utilize the combined CPU+GPU computing power of the new cluster.
### Characteristics of some GPUs

<table>
<thead>
<tr>
<th></th>
<th>GeForce GTX 260</th>
<th>GeForce GTX 280</th>
<th>Tesla C870</th>
<th>Tesla C1060</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Processor Cores</strong></td>
<td>192</td>
<td>240</td>
<td>128</td>
<td>240</td>
</tr>
<tr>
<td><strong>Processor Clock</strong></td>
<td>1.242 GHz</td>
<td>1.296 GHz</td>
<td>1.35 GHz</td>
<td>1.296 GHz</td>
</tr>
<tr>
<td><strong>Memory</strong></td>
<td>896MB GDDR3</td>
<td>1GB GDDR3</td>
<td>1.5GB GDDR3</td>
<td>4GB GDDR3</td>
</tr>
<tr>
<td><strong>Interface</strong></td>
<td>448-bit</td>
<td>512-bit</td>
<td>384-bit</td>
<td>512-bit</td>
</tr>
<tr>
<td><strong>Memory Clock</strong></td>
<td>999 MHz</td>
<td>1107 MHz</td>
<td>800 MHz</td>
<td>800 MHz</td>
</tr>
<tr>
<td><strong>Memory Bandwidth</strong></td>
<td>111.9 GB/s</td>
<td>141.7 GB/s</td>
<td>76.8 GB/s</td>
<td>102 GB/s</td>
</tr>
<tr>
<td><strong>Bus Support</strong></td>
<td>PCI-E 2.0 x16</td>
<td>PCI-E 2.0 x16</td>
<td>PCI-E 1.0 x16</td>
<td>PCI-E 2.0 x16</td>
</tr>
<tr>
<td><strong>Max. Power</strong></td>
<td>182 W</td>
<td>236 W</td>
<td>171 W</td>
<td>200 W</td>
</tr>
<tr>
<td><strong>Compute Capability</strong></td>
<td>1.3</td>
<td>1.3</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>Price</strong></td>
<td>350-400 AUD</td>
<td>550-600 AUD</td>
<td>~1,400 AUD</td>
<td>~1,700 USD</td>
</tr>
</tbody>
</table>
### GeForce GTX260 performance for simulation of CT projections

#### Total projection time

<table>
<thead>
<tr>
<th></th>
<th>CPU(1)</th>
<th>CPU(1) +GPU</th>
<th>Speed-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>512&lt;sup&gt;3&lt;/sup&gt; -&gt; 180x512&lt;sup&gt;2&lt;/sup&gt;</td>
<td>374.4” = 6’14.4”</td>
<td>13.8”</td>
<td>27.1x</td>
</tr>
<tr>
<td>1024&lt;sup&gt;3&lt;/sup&gt; -&gt; 360x1024&lt;sup&gt;2&lt;/sup&gt;</td>
<td>7,217.6” = 2h17.6”</td>
<td>131.2” = 2’11.2”</td>
<td>55.0x</td>
</tr>
</tbody>
</table>
GeForce GTX260 performance for FBP reconstruction

## Total CT reconstruction time

<table>
<thead>
<tr>
<th>Resolution</th>
<th>CPU(1) Fastest (NN)</th>
<th>CPU(1) +GPU</th>
<th>Speed-up (BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>180x512^2</td>
<td>1'13.1”</td>
<td>44.1”</td>
<td>1.65x (8.1x)</td>
</tr>
<tr>
<td>-&gt; 512^3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>360x1024^2</td>
<td>14’51.6”</td>
<td>4’38.4”</td>
<td>3.2x (9.8x)</td>
</tr>
<tr>
<td>-&gt; 1024^3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720x2048^2</td>
<td>3h36’51”</td>
<td>43’</td>
<td>5.0x (14.4x)</td>
</tr>
<tr>
<td>-&gt; 2048^3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
GeForce GTX260, performance for FBP reconstruction

Parallel-beam, 2048x720 -> 2048x2048

- CPU(1): 4.98x
- CPU(1)+GPU: 3.81x
- CPU(3)+GPU: 13.93x
This website offers access to web-enabled image and data processing and analysis tools. All services are arranged in two groups:

**SIMPLE SERVICES**

Simple services are provided free of charge directly on this website and do not require subscription (or user registration). They can be accessed through the menu or [here](#).

**SUBSCRIPTION SERVICES**

Subscription services are provided as downloadable Windows applications and are available to registered clients only. Some applications may be available free of charge while others will require payment.

To access subscription services, please fill out the [sign-up form](#) to submit a request to open an account. If your request is approved, you will usually be given a period of free trial access to your application of interest (this will vary depending on the application). Upon the expiry of the trial period, you may be able to purchase continued access. For some applications, unlimited access may be provided free of charge to approved clients.

Subscription services use [Software Toll Infrastructure (STI)](#) for maintaining real-time connection between the downloaded subscription software and user accounts on the server.

Subscription services currently offer the following applications:

**X-TRACT**

An image analysis and processing application with functionality targeting researchers working in imaging science and technology fields, especially in optical, electron and X-ray microscopy and astrocytology. [More information](#).

**HCA-VISION**

A standalone automated cell morphological image analysis application that can perform nucleic acid analysis, cell scoring, co-culture analysis and sub-cellular analysis. [More information](#).

**DCM (DATA CONSTRAINED MORPHOLOGY)**

A program that computes the complete microstructure of a volume of material, based on X-Ray tomography data and optionally, one or more chemical composition sections. [More information](#).
Welcome, Tim Gureyev!

Account balance: 14810 points

APPLICATION SUBSCRIPTIONS
You currently have time-based subscriptions for the following application(s).

<table>
<thead>
<tr>
<th>Application</th>
<th>Expiry Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-TRACT</td>
<td>22-Jul-2013 (AEST)</td>
</tr>
<tr>
<td>Data Constrained Morphology</td>
<td>11-Jun-2009 (AEST)</td>
</tr>
<tr>
<td>HCA-Vision</td>
<td>11-Jun-2009 (AEST)</td>
</tr>
<tr>
<td>X-TRACT CWS</td>
<td>06-Jun-2013 (AEST)</td>
</tr>
</tbody>
</table>

APPLICATION DOWNLOADS
The following TS-Imaging applications available for you to download:

- X-TRACT
- HCA-Vision
- Data Constrained Morphology
- X-TRACT CWS

INFORMATION
- X-TRACT Web Help
- Latest X-TRACT release notes
Acknowledgements

• X-TRACT development is carried out in CSIRO MSE as part of the Computational and Simulation Sciences Platform and Medical Imaging theme

• X-TRACT contains some IP of XRT Limited, the company which also commercializes X-TRACT (www.xrt.com.au)

• X-TRACT contains algorithms developed by Dr.D.Paganin and Dr.G.Myers of Monash Uni School of Physics

• X-TRACT contains modules developed by Mr.D.Ternovski (Trident Software Pty Ltd) and Mr.M.Hughes (Computing Design Pty Ltd)