CTSim 3.5 User Manual

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Ian Kay, Ph.D.
Special thanks to Dr. Kay for contributing portions to this manual. Dr. Kay has assisted the development of `CTSim` with the addition of helical scanning, bug reports, and paches.

Gabor T. Herman, Ph.D.
Dr. Herman's publications on computed tomography inspired the initial version `CTSim` in 1983. Dr. Herman has graciously permitted use of his copyrighted head phantom for use in `CTSim`.

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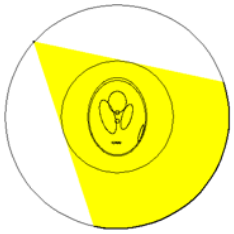

Computed tomography is a technique for estimating the interior of an object from measurements of radiation collected around the object. This radiation can be either projected through or emitted from the object. `CTSim` simulates the process of projecting X-rays through a phantom object. `CTSim` can then reconstruct the interior of the object from those projections. `CTSim` integrates numerous visualization and analytic tools.

This manual begins with an introduction into the concepts of `CTSim`. Next, the graphical, command-line, and web shells are presented. Finally, the installation of `CTSim` is discussed.

I hope that you enjoy `CTSim`!

2. Concepts

2.1 Conceptual Overview

The operation of `CTSim` begins with the phantom object. A phantom object consists of geometric elements. A scanner is specified and the collection of x-ray data, or projections, is simulated. This projection data can be reconstructed using various user-controlled algorithms producing an image of the phantom object. These reconstructions can be visually and statistically compared to the original phantom object.

In order to use `CTSim` effectively, some knowledge of how `CTSim` works and the approach taken is required. `CTSim` deals with a variety of object, but the two primary objects that we need to be concerned with are the *phantom* and the *scanner*.

2.2 Phantoms

`CTSim` uses geometrical objects to describe the object being scanned. A phantom is composed of one or more phantom elements. These elements are simple geometric shapes, specifically, rectangles, triangles, ellipses, sectors and segments. With these elements, the standard phantoms used in the CT literature can be constructed. In fact, `CTSim` provides a shortcut to load the published phantoms of Herman[2] and Shepp-Logan[3]. `CTSim` also reads text files of user-defined phantoms.

The types of phantom elements and their definitions are taken with permission from G.T. Herman's publication[2].

2.2.1 Phantom File

Each line in the text file describes an element of the phantom. Each line contains seven entries, in the following form:

```
element-type cx cy dx dy r a
```

The first entry defines the type of the element, either `rectangle`, `ellipse`, `triangle`, `sector`, or `segment`.

For all phantom elements, `r` is the rotation applied to the object in degrees counterclockwise and `a` is the X-ray attenuation coefficient of the object. Where objects overlap, the attenuations of the overlapped objects are summed.

As opposed to the `r` and `a` fields, the `cx`, `cy`, `dx` and `dy` fields have different meanings depending on the element type.

2.2.2 Phantom Elements

ELLIPSE

Ellipses use `dx` and `dy` to define the semi-major and semi-minor axis lengths with the center of the ellipse at `(cx,cy)`. Of note, the commonly used phantom described by Shepp and Logan[3] uses only ellipses.

RECTANGLE

Rectangles use `(cx,cy)` to define the position of the center of the rectangle with respect to the origin. `dx` and `dy` are the half-width and half-height of the rectangle.

TRIANGLE

Triangles are drawn with the center of the base at `(cx,cy)` and a base half-width of `dx` and a height of `dy`. Rotations are then applied about the center of the base.

SEGMENT

Segments are complex. They are the portion of an circle between a chord and the perimeter of the circle. `dy` sets the radius of the circle. Segments start with the center of the chord located at `(0,0)` and the chord horizontal. The half-width of the chord is set by `dx`. The portion of an circle lying below the chord is then added. The imaginary center of this circle is located at `(0,-dy)`. The segment is then rotated by `r` and then translated by `(cx,cy)`.

SECTOR

Sectors are the like a "pie slice" from a circle. The radius of the circle is set by `dy`. Sectors are defined similarly to segments. In this case, though, a chord is not drawn. Instead, the lines are drawn from the origin of the circle `(0,-dy)` to the points `(-dx,0)` and `(dx,0)`. The perimeter of the circle is then drawn between those two points and lies below the x-axis. The sector is then rotated and translated the same as a segment.

2.2.3 Phantom Size

The overall dimensions of the phantom are increased by 1% above the specified sizes to avoid clipping due to round-off errors from sampling the polygons of the phantom elements. So, if the phantom is defined as a rectangle of size 0.1 by 0.1, the phantom size is 0.101 in each direction.

2.3 Scanner

Understanding the scanning geometry is the most complicated aspect of using `CTSim`. For real-world CT simulators, this is actually quite simple. The geometry is fixed by the manufacturer during the construction of the scanner and can not be changed. `CTSim`, being a very flexible simulator, gives tremendous options in setting up the geometry for a scan.

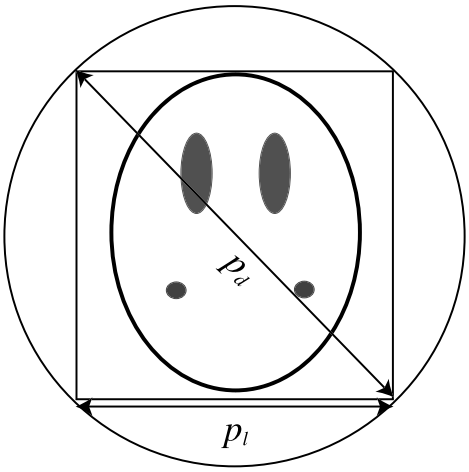

Figure 2.1: Phantom Geometry

2.3.1 Dimensions

The geometry for a scan starts with the size of the phantom being scanned. This is because `CTSim` allows for statistical comparisons between the original phantom image and it's reconstructions. Since CT scanners scan a circular area, the first important variable is the diameter of the circle surround the phantom, the *phantom diameter*. Remember, as mentioned above, the phantom dimensions are padded by 1%.

The other important geometry variables for scanning phantoms are the *view diameter*, *scan diameter*, *focal length*, and *center-detector length*. These variables are input into `CTSim` in terms of ratios rather than absolute values.

Phantom Diameter

The phantom diameter is automatically calculated by `CTSim` from the phantom definition. The maximum of the phantom length and height is used to define the square that completely surrounds the phantom. Let p_l be the width and height of this square. The diameter of this boundary box, p_d, is given by the Pythagorean theorem and is

$$p_d = p_l\sqrt{2} \tag{2.1}$$

CT scanners collect projections around a circle rather than a square. The diameter of this circle is the diameter of the boundary square p_d. These relationships are diagrammed in figure 2.1.

View Diameter

The *view diameter* is the area that is being processed during scanning of phantoms as well as during rasterization of phantoms. By default, the *view diameter* is set equal to the *phantom diameter*. It may be useful, especially for experimental reasons, to process an area larger (and maybe even smaller) than the phantom. Thus, during rasterization or during

projections, `CTSim` will ask for a *view ratio*, v_r. The *view diameter* is then calculated as

$$v_d = p_d v_r \tag{2.2}$$

By using a v_r less than 1, `CTSim` will allow for a *view diameter* less than *phantom diameter*. This will lead to significant artifacts. Physically, this would be impossible and is analogous to inserting an object into the CT scanner that is larger than the scanner itself!

Scan Diameter

By default, the entire *view diameter* is scanned. For experimental purposes, it may be desirable to scan an area either larger or smaller than the *view diameter*. Thus, the concept of *scan ratio*, s_r, arises. The scan diameter, s_d, is the diameter over which x-rays are collected and is defined as

$$s_d = v_d s_r \tag{2.3}$$

By default and for all ordinary scanning, the *scan ratio* is to `1`. If the *scan ratio* is less than `1`, you can expect significant artifacts.

Focal Length

The *focal length*, f, is the distance of the X-ray source to the center of the phantom. The focal length is set as a ratio, f_r, of the view radius. Focal length is calculated as

$$f = (v_d/2) f_r \tag{2.4}$$

For parallel geometry scanning, the focal length doesn't matter. However, for divergent geometry scanning (equilinear and equiangular), the *focal length ratio* should be set at `2` or more to avoid artifacts. Moreover, a value of less than `1` is physically impossible and it analagous to having the x-ray source inside of the *view diameter*.

Center-Detector Length

The *center-detector length*, c, is the distance from the center of the phantom to the center of the detector array. The center-detector length is set as a ratio, c_r, of the view radius. The center-detector length is calculated as

$$f = (v_d/2) c_r \tag{2.5}$$

For parallel geometry scanning, the center-detector length doesn't matter. A value of less than `1` is physically impossible and it analagous to having the detector array inside of the *view diameter*.

2.3.2 Parallel Geometry

The simplest geometry, parallel, was used in first generation scanners. As mentioned above, the focal length is not used in this simple geometry. The detector array is set to be the

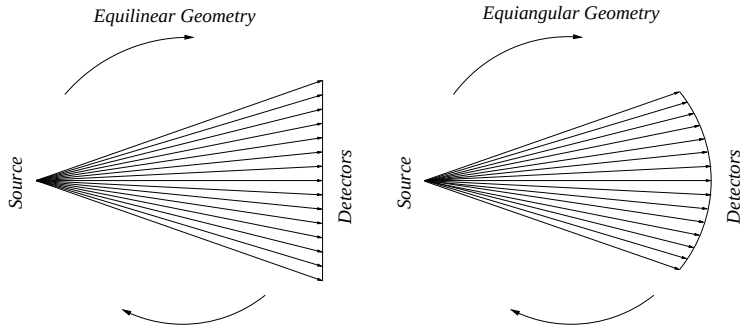

Figure 2.2: Equilinear and equiangular geometries.

same size as the *scan diameter*. For optimal scanning in this geometry, the *scan diameter* should be equal to the *phantom diameter*. This is accomplished by using the default values of `1` for the *view ratio* and the *scan ratio*. If values of less than `1` are used for these two variables, significant distortions will occur.

2.3.3 Divergent Geometries

For both equilinear (second generation) and equiangular (third, fourth, and fifth generation) geometries, the x-ray beams diverge from a single source to a detector array. In the equilinear mode, a single source produces a fan beam which is read by a linear array of detectors. If the detectors occupy an arc of a circle, then the geometry is equiangular. These configurations are shown in figure 2.2.

Fan Beam Angle

For these divergent beam geometries, the *fan beam angle* needs to be calculated. For real-world CT scanners, this is fixed at the time of manufacture. `CTSim`, however, calculates the *fan beam angle*, α, from the *scan diameter* and the *focal length* as

$$\alpha = 2\sin^{-1}((s_d/2)/f) \tag{2.6}$$

This is illustrated in figure 2.3.

Empiric testing with `CTSim` shows that for very large *fan beam angles*, greater than approximately 120°, there are significant artifacts. The primary way to manage the *fan beam angle* is by varying the *focal length* since the *scan diameter* is usually fixed at the size of the phantom.

To illustrate, the *scan diameter* can be defined as

$$s_d = s_r v_r p_d \tag{2.7}$$

Further, the *focal length* can be defined as

$$f = f_r(v_r p_d/2) \tag{2.8}$$

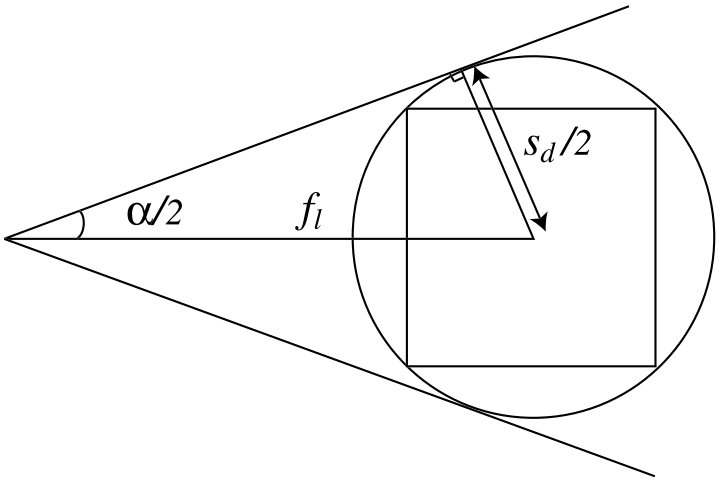

Figure 2.3: Calculation of α

Substituting these equations into equation 2.6, We have,

$$\begin{aligned} \alpha &= 2 \sin^{-1} \frac{s_r v_r p_d/2}{f_r v_r (p_d/2)} \\ &= 2 \sin^{-1}(s_r/f_r) \end{aligned} \tag{2.9}$$

Since in normal scanning $s_r = 1$, α depends only upon the *focal length ratio* in normal scanning.

Detector Array Size

In general, you do not need to be concerned with the detector array size – it is automatically calculated by `CTSim`. For the particularly interested, this section explains how the detector array size is calculated.

For parallel geometry, the detector length is simply the scan diameter.

For divergent beam geometries, the size of the detector array also depends upon the *focal length*: increasing the *focal length* decreases the size of the detector array.

For equiangular geometry, the detectors are equally spaced around a arc covering an angular distance of α as viewed from the source. When viewed from the center of the scanning, the angular distance is

$$\pi + \alpha - 2 \cos^{-1}\left(\frac{s_d/2}{c}\right)$$

The dotted circle in figure 2.4 indicates the positions of the detectors in this case.

For equilinear geometry, the detectors are equally spaced along a straight line. The detector length depends upon α and the *focal length*. This length, d_l, is calculated as

$$d_l = 2\,(f + c)\tan(\alpha/2) \tag{2.10}$$

This geometry is shown in figure 2.5.

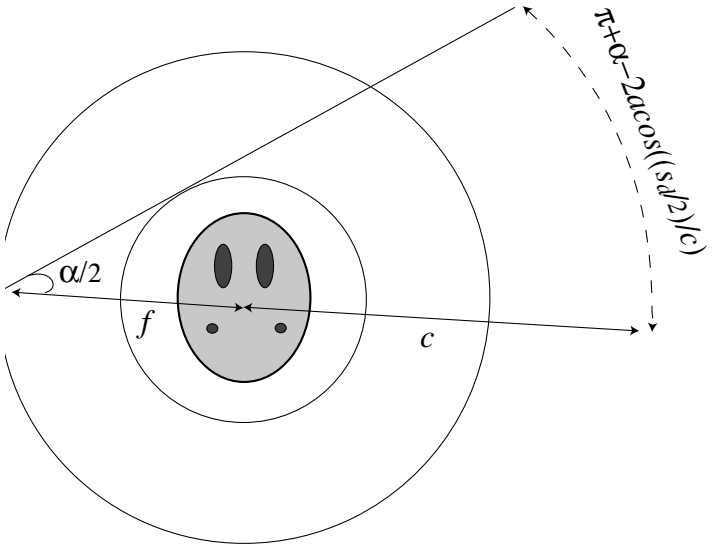

Figure 2.4: Equiangular geometry

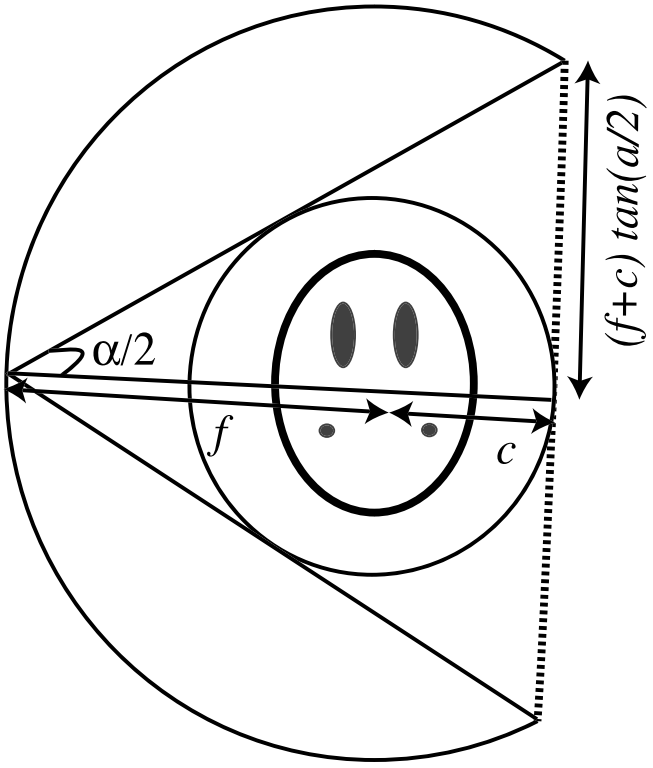

Figure 2.5: Equilinear geometry

2.4 Reconstruction

2.4.1 Direct Inverse Fourier

This method is not currently implemented in `CTSim`; however, it is planned for a future release. This method does not give results as accurate as filtered backprojection. This is due primarily to interpolation occurring in the frequency domain rather than the spatial domain.

2.4.2 Filtered Backprojection

The technique is comprised of two sequential steps: filtering projections followed by backprojecting the filtered projections. Though these two steps are sequential, each view position can be processed independently.

Parallel Computer Processing

Since each view can be processed independently, filtered backprojection is amendable to parallel processing. Indeed, this has been used in commercial scanners to speed reconstruction. This parallelism is exploited both in the `CTSim` graphical shell and in the *LAM* (section 4.2) version of `CTSimText`. `CTSim` can distribute it's workload amongst multiple processors working in parallel.

The graphical shell will automatically take advantage of multiple CPU's when running on a *Symmetric Multiprocessing* computer. Dual-CPU computers are commonly available which provide a near doubling in reconstruction speeds. `CTSim`, though, has no limits on the number of CPU's that can be used in parallel. The *LAM* version of `CTSimText` is designed to work in a cluster of computers. This has been testing with a cluster of 16 computers in a Beowulf-class ($http://www.beowulf.org$) cluster with excellent results.

Filter projections

The first step in filtered backprojection reconstructions is the filtering of each projection. The projections for a each view have their frequency data multipled by a filter of $|w|$. `CTSim` permits four different ways to accomplish this filtering.

Two of the methods use convolution of the projection data with the inverse Fourier transform of $|w|$. The other two methods perform an Fourier transform of the projection data and multiply that by the $|w|$ filter and then perform an inverse fourier transform.

Though multiplying by $|w|$ gives the sharpest reconstructions, in practice, superior results are obtained by reducing the higher frequencies. This is performed by mutiplying the $|w|$ filter by another filter that attenuates the higher frequencies. `CTSim` has multiple filters for this purpose.

Backprojection of filtered projections

Backprojection is the process of "smearing" the filtered projections over the reconstructing image. Various levels of interpolation can be specified.

2.5 Image Comparison

Images can be compared statistically. Three measurements can be calculated by `CTSim`. They are taken from the standard measurements used by Herman[2]. They are:

- d The normalized root mean squared distance measure.
- r The normalized mean absolute distance measure.
- e The worst case distance measure over a 2×2 pixel area.

These measurements are defined in equations 2.11 through 2.15. In these equations, p denotes the phantom image, r denotes the reconstruction image, and $\bar{p}$ denotes the average pixel value of p. Each of the images have a size of $m \times n$. In equation 2.13 $[n/2]$ and $[m/2]$ denote the largest integers less than $n/2$ and $m/2$, respectively.

$$d = \sqrt{\frac{\sum_{i=1}^{n}\sum_{j=1}^{m}(p_{i,j} - r_{i,j})^2}{\sum_{i=1}^{n}\sum_{j=1}^{m}(p_{i,j} - \bar{p})^2}} \tag{2.11}$$

$$r = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m}|p_{i,j} - r_{i,j}|}{\sum_{i=1}^{n}\sum_{j=1}^{m}|p_{i,j}|} \tag{2.12}$$

$$e = \max_{\substack{1 \le k \le [n/2] \\ 1 \le l \le [m/2]}} (|P_{k,l} - R_{k,l}|) \tag{2.13}$$

where

$$P_{k,l} = \tfrac{1}{4}(p_{2k,2l} + p_{2k+1,2l} + p_{2k,2l+l} + p_{2k+1,2l+1}) \tag{2.14}$$

$$R_{k,l} = \tfrac{1}{4}(r_{2k,2l} + r_{2k+1,2l} + r_{2k,2l+1} + r_{2k+1,2l+1}) \tag{2.15}$$

3. The Graphical User Interface

`CTSim` is the graphical shell for the CTSim project. This shell uses the wxWindows (*http* : *//www.wxwindows.org*) library for cross-platform compatibility. The graphical shell is compatible with Microsoft Windows, GTK (*http* : *//www.gtk.org*), and Motif (*http* : *//www.openmotif.org*) graphical environments.

3.1 Starting CTSim

Usage

```
ctsim [files to open...]
```

You can invoke `CTSim` by itself on the command line, or include any number of files that you want `CTSim` to automatically open. `CTSim` can open projection files, image files, phantom files, and plot files.

On Microsoft Windows platforms, the simplest way to invoke `CTSim` is via the *Start* menu under the *Programs* sub-menu.

3.2 Quick Start

The fastest way to put `CTSim` through it's basic operation is:

1. `File - Create Phantom...`
   This creates a window with the geometric phantom. Choose the `Herman` head phantom.
2. `Process - Rasterize...`
   This creates an image file of the phantom by converting it from a geometric definition into a rasterized image. You may use the defaults shown in the dialog box.
3. `View - Auto...`
   Use this command on the new rasterized image window. This will optimize the intensity scale for viewing the soft-tissue details of the phantom. Select the `median` center and a standard deviation factor of `0.1`.
4. `Process - Projections...`
   Use this command on the geometric phantom window. This simulates the collection of x-ray data. You may use the defaults shown in the dialog box. Additionally, you may wish to turn on `Trace - Projections` to watch to x-ray data being simulated.

5. `Reconstruction - Filtered Backprojection...`
   Use this command on the projection window. This will reconstruct an image from the projections. Once again, you may use the defaults shown in the dialog box.
6. `View - Auto...`
   Use this command on the new reconstructed image window. This will optimize the intensity scale for viewing the soft-tissue details of the reconstruction. Select the `median` center and a standard deviation factor of `0.1`.
7. `Analyze - Compare Images...`
   Use this command on the rasterized phantom image window. This will bring up a dialog box asking for the comparison image. Select the reconstruction image that you just made and also select the "Make difference image" check box. You'll then see the image distance measurements and also a new window with the difference between the rasterized phantom and the reconstruction.
8. **That's it!** You have just performed the basic operations with `CTSim`. By varying the parameters of the rasterization, projection, and reconstructions you perform endless computed tomography experiments. `CTSim` also has many other visualization and analysis features that you learn more about by reading the manual.

3.3 File Types

3.3.1 Phantom

Besides loading phantom files from the disk, the Herman[2] and Shepp-Logan[3] phantoms are built-in to `CTSim`. Phantom files can be read from and written to the disk. Phantom files are stored in a simple ASCII format. A text editor is required to create and edit these files.

3.3.2 Image

Image files contain 2-dimensional arrays that store 4-byte floating point values. Images files can be either real or complex-valued. Typically, all images are real-valued except for images that have been processed by Fourier transforms. As you might expect, complex-valued images are twice the size of real-valued images since both a real and imaginary component need to be stored. When complex-valued images are viewed on the screen, only the real component is displayed.

Images files can store any number of text labels. `CTSim` uses these labels for recording history information regarding the creation and modifications of images.

3.3.3 Projection

Projection files are created from phantom files via the projection process. Numerous options are available for the creation of the these files. The files are stored in a binary format with cross-platform compatibility on little and big-endian architectures.

3.3.4 Plot

Plot files are created by `CTSim` during analysis of image files. They can be read from and written to the disk. They are stored as ASCII files for easy cross-platform support and editing.

3.4 Global Menu Commands

These global commands are present on the menus of all windows.

3.4.1 File - Create Phantom

This command displays a dialog box showing the phantoms that are pre-programmed into `CTSim`. After selecting one of these phantoms, the new window with that phantom will be generated. The pre-programmed phantoms are:

Herman	The Herman head phantom[2]
Shepp-Logan	The head phantom of Shepp & Logan[3]
Unit pulse	A phantom that has a value of `1` for the center of the phantom and `0` everywhere else.

3.4.2 File - Create Filter

This command displays a dialog box showing the pre-programmed filters of `CTSim`. This command will create a 2-dimensional image of the selected filter. The center of the filter is at the center of the image.

These filters can be created in their natural frequency domain or in their inverse spatial domain.

Filter Selects the filter to generate. The available filters are:

- $|w|$ Bandlimit
- $|w|$ Hamming
- $|w|$ Hanning
- $|w|$ Cosine
- $|w|$ Sinc
- Shepp
- Bandlimit
- Sinc
- Hamming
- Hanning
- Cosine
- Triangle

Domain Selects either the `Frequency` or `Spatial` domain. The filters have the frequency domain as their natural domain. The spatial domain is obtained either analytically or performing an inverse Fourier transformation.

X Size Number of columns in the output image.

Y Size Number of rows in the output image.

Hamming Parameter This parameter adjusts the smoothing of the Hamming filter and can range from `0` to `1`. At a setting of `1`, the Hamming filter is the same as the bandlimit filter. At a setting of `0.54`, the Hamming filter is the same as the Hanning window.

Bandwidth Sets the bandwidth of the filter.

Axis (input) Scale Sets the scale for the filter input. By default, the input to the filter is the distance in pixels from the center of the image. By changing this value, one can set a scale the input to the filter. For example, if the output image is `101` by `101` pixels and thus the center of the image is at `(50,50)`, then a pixel lying at point `100,50` would be 50 units from the center of the filter. By applying an `Axis scale` of `0.1`, then that point would be scaled to 5 units from the center of the filter.

Filter (output) Scale Multiplies the output of the filter by this amount. By default, the filter has a maximum value of `1`.

3.4.3 File - Import

This command allows the importing of non-`CTSim` file formats into `CTSim`. `PPM` and `PNG` formats will be read into an imagefile window. Color images will be converted to grayscale. If a `DICOM` library was linked in with your version of `CTSim`, then you can also import `DICOM` projection files and image files.

3.4.4 File - Preferences

This command displays a dialog box that allows users to control the behavior of `CTSim`. These options are saved across `CTSim` sessions. Under Microsoft Windows environments, they are stored in the registry. On UNIX and Linux environments, they are stored in the user's home directory with the filename of `.ctsim`.

Advanced options This option is initially turned off in new installations. These advanced options are not required for normal simulations. When `Advanced Options` is set, `CTSim` will display more options during scanning of phantoms and the reconstruction of projections.

Ask before closing new documents This option is initially turned on in new installations. With this option set, `CTSim` will ask before closing documents that have been modified or never saved on disk. By turning off this option, `CTSim` will never ask if you want to save a file – you'll be responsible for saving any files that you create.

Verbose logging This option is initially turned off in new installations. With this option set, `CTSim` will log more events than usual. There extra events are not important for viewing with typical operation of `CTSim`.

Show startup tips This option is initially turned on in new installations. With this option set, `CTSim` will display helpful tips when `CTSim` is started.

Run background tasks This option is initially turned off in new installations. With this option set, `CTSim` execute lengthy calculations in the background. A background window will appear when processes are running in the background and will disappear when no background processes are executing. This background window shows the status and progress of all background processes. **NOTE:** Due to limitations of `wxWindows`, this function is only supported on Microsoft Windows.

3.4.5 File - Open

This command opens a file section dialog box. Of special consideration is the `File Type` combo box on the bottom of the dialog. You need to set the this combo box to the type of file that you wish to open.

3.4.6 File - Save

This command saves the contents of the active window. If the window hasn't been named, a dialog box will open asking for the file name to use.

3.4.7 File - Close

As one would expect, this closes the active window. If the contents of the window have not been saved and the *Advanced Preferences* option `Ask before closing new documents` is turned on, then you will be prompted if decide if you want to save the contents of the window prior to closing.

3.4.8 File - Save As

Allows the saving of the contents of the active window to any file name.

3.4.9 Help - Contents

This command displays the online help.

3.4.10 Help - Tips

This command displays a dialog with tips on using `CTSim`.

3.4.11 Help - Quick Start

This command displays a recommend approach to helping new users learn to use `CTSim`.

3.4.12 Help - About

This command shows the version number and operating environment of `CTSim`.

3.5 Phantom Menus

3.5.1 Properties

Displays the properties of a phantom which includes:

- Overall dimensions of a phantom
- A list of all component phantom elements

3.5.2 Process - Rasterize

This creates an image file from a phantom. Technically, it converts the phantom from a vector (infinite resolution) object into a 2-dimension array of floating-point pixels. The parameters to set are:

X size	Number of columns in image file
Y size	Number of rows in image file
Samples per pixel	Numbers of samples taken per pixel in both the x and y directions. For example, if the `Samples per pixel` is set to `3`, then for every pixel in the image file 9 samples (3×3) are averaged.

3.5.3 Process - Projections

This command creates a projection file from a phantom. The options available when collecting projections are:

Geometry	Sets the scanner geometry. The available geometries are: • `Parallel` • `Equiangular` • `Equilinear`
Number of detectors	Sets the number of detectors in the detector array.
Number of views	Sets the number of views to collect.
Samples per detector	Sets the number of samples collected for each detector.
View Ratio	Sets the field of view as a ratio of the diameter of the phantom. For normal scanning, use a value of `1.0`.
Scan Ratio	Sets the length of scanning as a ratio of the view diameter. For normal scanning, use a value of `1.0`.
Focal length ratio	Sets the distance between the radiation source and the center of the phantom as a ratio of the radius of the phantom. For parallel geometries, a value of `1.0` is optimal. For other geometries, this should be at least `2.0` to avoid artifacts.

Advanced Options

These options are visible only if *Advanced Options* has been selected in the `File - Preferences` dialog. These parameters default to optimal settings and don't need to be adjusted except

by expert users.

Rotation Angle Sets the rotation amount as a fraction of a circle. For parallel geometries use a rotation angle of `0.5` and for equilinear and equiangular geometries use a rotation angle of `1`. Using any other rotation angle will lead to artifacts.

3.6 Image Menus

3.6.1 File - Properties

Properties of image files include:

- Whether the image is real or complex-valued.
- Numeric statistics (minimum, maximum, mean, median, mode, and standard deviation).
- History labels (text descriptions of the processing for this image).

3.6.2 File - Export

This command allows for exporting image files to a standard graphics file format. This is helpful when you want to take an image and import it into another application. The current *intensity scale* is used when exporting the file. The supported graphic formats are:

PNG Portable Network Graphics format. This uses 8-bits or 256 shades of gray.

PNG-16 This is a 16-bit version of PNG which allows for 65536 shades of gray.

PGM Portable Graymap format. This is a common format used on UNIX systems.

PGM ASCII ASCII version of PGM.

3.6.3 View

Intensity Scale

These commands are used change the intensity scale for viewing the image. These commands do not change the image data. When the minimum value is set, then the color pure black is assigned to that image value. Similarly, when the maximum value is set, the the color pure white is assigned to that image value.

Changing the intensity scale is useful when examining different image features. In clinical medicine, the intensity scale is often changed to examine bone (high value) versus soft-tissue (medium value) features.

Set

This command displays a dialog box that sets the lower and upper values to display.

Auto

This command displays a dialog box that allows `CTSim` to automatically make an intensity scale. The parameters that `CTSim` needs to make this automatic scale are:

Center This sets the center of the intensity scale. Currently, `CTSim` allows you to use either the mean, mode, or median of the image as the center of the intensity scale.

Width This sets the half-width of the intensity scale. The half-width is specified as a multiple of the standard deviation.

As an example, if `median` is selected as the center and `0.5` is selected as the width, the the minimum value will be $median - 0.5 \times standardDeviation$ and the maximum value will be $median + 0.5 \times standardDeviation$.

Full

This command resets the intensity scale to the full scale of the image.

3.6.4 Image

These commands create a new image based upon the current image, and for some commands, also upon a comparison image.

Add, Subtract, Multiply, Divide

These are simple arithmetic operations. `CTSim` will display a dialog box showing all of the currently opened image files that are the same size as the active image. After the selection of a compatible image, `CTSim` will perform the arithmetic operation on the two images and make a new result image.

Image Size

This command will generate a new image based on the current image. The new image can be scaled to any size. A dialog appears asking for the size of the new image. Bilinear

interpolation is used when calculating the new image.

3-D Conversion

This command generates a 3-dimensional view of the current phantom. This view can be rotated in three dimensions. The left and right arrow control the z-axis rotation and the up and down arrows control the x-axis rotation. The y-axis rotation is controlled by the `T` and `Y` keys. Other options are presented on the `View` menu and include:

- Surface plot versus wireframe plot.
- Smooth shading versus flat shading.
- Lighting on or off.
- Color scale on or off.

3.6.5 Filter

These commands filter and modify the image

Arithmetic

These commands operate on the image on a pixel-by-pixel basis. The commands support both real and complex-valued images. The available arithmetic commards are:

Invert	Negate pixel values.
Log	Take natural logrithm of pixel values.
Exp	Take natural exponent of pixel values.
Square	Take square of pixel values.
Square root	Take square root of pixel values.

Frequency Based

These commands perform Fourier and inverse Fourier transformations of images. By default, the transformations will automatically convert images between Fourier to natural orders as expected. For example, `2-D FFT` will transform the points into natural order after the Fourier transform. Similarly the inverse, `2-D IFFT`, will reorder the points from natural order to Fourier order before applying the inverse Fourier transformation.

As you would expect, images that undergo frequency filtering will be complex-valued after than filtering. Only the real component is shown by `CTSim`. However, `CTSim` does have options for converting a complex-valued image into a real-valued image via the `Magnitude` and `Phase` filtering commands.

The available frequency-based filtering commards are:

- 2-D FFT
- 2-D IFFT
- FFT Rows
- IFFT Rows
- FFT Columns
- IFFT Columns
- 2-D Fourier
- 2-D Inverse Fourier
- Shuffle Fourier to Natural Order
- Shuffle Natural to Fourier Order
- Magnitude
- Phase

3.6.6 Analyze - Plot

The commands plot rows and columns of images. There are commands that perform FFT transformations prior to plotting. To select the row or column to plot, click the left mouse button over the desired cursor point.

The available plot commands are:

- Plot Row
- Plot Column
- Plot Histogram
- Plot FFT Row
- Plot FFT Col

3.6.7 Analyze - Compare

This command performs statistical comparisons between two images. An option also exists for generating a difference image from the two input images.

The three distance measures reported are:

d The normalized root mean squared distance measure.

r The normalized mean absolute distance measure.

e The worst case distance measure over a 2×2 pixel area.

There are also commands for comparison plotting of rows and columns from two images. This is quite helpful when comparing a phantom to a reconstruction. As with plotting of rows and columns, click the left mouse button over the desired cursor point to choose which row and column to plot.

3.7 Projection Menus

3.7.1 File - Properties

The displayed properties include:

- Number of detectors in the projections.
- Number of views.
- The parameters used when generating the projections from the phantom.

3.7.2 Process - Convert Rectangular

The commands takes the projection data and creates an image file using the projection data.

3.7.3 Process - Convert Polar

This command creates an image file with the polar conversion of the projection data. The parameters to set are:

X Size	Number of columns in output image.
Y Ssize	Number of rows in output image.
Interpolation	Selects the interpolation method. Currently, the `bilinear` option provides the highest quality interpolation.

3.7.4 Convert - Convert FFT Polar

The parameters for this option are the same as the *Convert Polar Dialog*. For this command, though, the projections are Fourier transformed prior to conversion to polar image.

3.7.5 Convert - Interpolate to Parallel

This command filters divergent projection data (equiangular or equilinear) and interpolates (or rebins) to estimate the projection data if the projections had been collected with parallel geometry.

3.7.6 Analyze - Plot Histogram

Plots a histogram of projection data attenuations.

3.7.7 Analyze - Plot T-Theta Sampling

Plots a 2-dimensional scattergram showing the `T` and `Theta` values for each data point in the projection data. This is especially instructive when scanning with divergent geometries and the scan ratio is close to `1`.

Theta Range

This dialog box allows the constraint of Theta values for the T-Theta Sampling scattergram.

3.7.8 Reconstruct - Filtered Backprojection

This command displays a dialog to set the parameters for reconstructing an image from projections using the filtered backprojection technique. The parameters available are:

Filter Selects the filter to apply to each projection. To properly reconstruct an image, this filter should consist of the the absolute value of distance from zero frequency optionally multiplied by a smoothing filter. The optimal filters to use are:

- `abs_bandlimit`
- `abs_hamming`
- `abs_hanning`
- `abs_cosine`

Hamming parameter Sets the alpha level for Hamming window. This parameter adjusts the smoothing of the Hamming filter and can range from `0` to `1`. At a setting of `1`, the Hamming filter is the same as the bandlimit filter. At a setting of `0.54`, the Hamming filter is the same as the Hanning window.

Filter Method Selects the filtering method. For large numbers of detectors, the FFT-based filters are preferred whereas for smaller numbers of detectors `convolution` can be faster. When *Advanced Options* have been turned off, this menu only shows the two basic choices: `convolution` and `FFT`. However, when *Advanced Options* have been turned on, additional selections are available as discussed in the next section.

Interpolation Interpolation technique during backprojection. `cubic` has optimal quality when the data is smooth. Smooth data is obtained by taking many projections and/or using a smoothing filter. In the absence of smooth data, `linear` gives better results and is also many times faster than cubic interpolation.

- `nearest` - No interpolation, selects nearest point.
- `linear` - Uses fast straight line interpolation.
- `cubic` - Uses cubic interpolating polynomial.

Advanced Options

These options are visible only if *Advanced Options* has been selected in the `File - Preferences`

dialog. These parameters default to optimal settings and don't need to be adjusted except by expert users.

Filter Method Selects the filtering method. The general comments about this parameter given the previous section still apply. With *Advanced Options* on, the full set of filter methods are available:

- `convolution`
- `fourier` - Uses simple Fourier transform.
- `fourier-table` - Optimizes Fourier transform by precalculating trigometric functions.
- `fftw` - Uses complex-valued Fourier transform with the *fftw* library.
- `rfftw` - Uses optimized real/half-complex Fourier transform.

Backprojection Selects the backprojection technique. A setting of `idiff` is optimal.

- `trig` - Use trigometric functions at each image point.
- `table` - Use precalculated trigometric tables.
- `diff` - Use difference method to iterate within image.
- `idiff` - Use integer iteration techique.

Filter Generation Selects the filter generation. With convolution, `direct` is the proper method to select. With any of the frequency methods, `inverse-fourier` is the best method.

- `direct`
- `inverse-fourier`

Zeropad Zeropad factor when using frequency-based filtering. A setting of `1` is optimal whereas a setting of `0` disables zero padding. Settings greater than `1` perform larger amounts of zero padding but without any significant benefit.

ROI These four settings control the *region of interest* for the reconstruction. The default values match the dimensions of the entire phantom. By constraining the ROI to be a smaller square, the reconstruction will be magnified.

3.7.9 Reconstruct - Filtered Backprojection (Rebin to Parallel)

The command reconstructs the projection data via filtered backprojection as described above. As opposed to the above command, this command also rebins divergent projection data to parallel prior to reconstruction. This greatly speeds reconstruction of divergent geometry projections.

3.8 Plot Menus

3.8.1 File - Properties

The displayed properties include:

- the number of curves in the plot and the number of points per curve.
- the EZPlot commands used to format the plot are displayed.
- history labels from the originating image(s) and the plot function.

3.8.2 View Menu

These commands set the scaling for the y-axis. They are analogous to the options used for setting the intensity scale for images.

Set

This command sets the upper and lower limits for the y-axis.

Auto

This command automatically sets the upper and lower limits for the y-axis. Please refer to the image file *View - Auto* (section 3.6.3) documentation for the details.

Full

The command resets the upper and lower limits of the y-axis to the minimum and maximum values of the curves.

4. The Command Line Interface

`CTSimText` is the master shell for all of the command-line tools. The command-line tools can perform most of the functions of the graphical shell. These command-line tools are especially appropriate for use on systems without graphical capability or for batch processing, shell scripting, and parallel processing.

4.1 Starting ctsimtext

`CTSimText` can be invoked via three different methods.

1. `CTSimText` can executed without any parameters. In that case, `CTSimText` offers a command-line to enter the function-names and their parameters. The output of the command is displayed. Further commands may be given to `CTSimText`. The shell is exited by the `quit` command. `CTSimText` uses the readline (*http* : *//www.gnu.org*) library on UNIX and Linux platforms to provide command history processing.
2. `CTSimText` can also be called to execute a single command. This is especially useful for batch files containing multiple `CTSimText` commands. This is invoked by calling `ctsimtext function-name parameters...`.
3. Using operating systems that support soft or hard linking of files (such as UNIX and Linux), the executable file `CTSimText` can be linked to the function names. This is automatically done by the installation program and the `rpm` manager. Thus, to use `CTSimText` with the function name `pjrec`, the below command can be executed:
   ```
   pjrec parameters...
   ```
   as a shortcut to the equivalent command
   ```
   ctsimtext pjrec parameters...
   ```

4.2 Parallel Processing

`CTSimText` can distribute it's processing over a cluster. Specifically, `CTSimText` supports the LAM (*http* : *//www.mpi.nd.edu/lam*) version of the MPI environment. On platforms with LAM installed, a parallel version of `CTSimText` is created. The name of this program is `ctsimtext-lam`. The functions that take advantage of the parallel processing are:

- `phm2if`
- `phm2pj`
- `pjrec`

This parallel processing version has been tested with excellent results on a 16-CPU Beowulf ($http://www.beowulf.org$) cluster.

4.3 if1

Performs math functions on a single image. The commands works with both real and complex-valued images.

Usage

```
if1 input-filename output-filename [options...]
```

Options

`--invert`	Negate pixel values.
`--log`	Take natural logrithm of pixel values.
`--exp`	Take natural exponent of pixel values.
`--sqr`	Take square of pixel values.
`--sqrt`	Take square root of pixel values.

4.4 if2

Performs math functions on a two images. The command works with both real and complex-valued images.

Usage

```
if2 input-filename1 input-filename2 output-filename [options...]
```

Options

`--add`	Add the two images.
`--sub`	Subtract the two images.
`--multiply`	Multiply the two images.
`--divide`	Divide the two images.
`--comp`	Statistically compare the two images. The standard *three distance measurements* (section 2.5) are reported.
`--column-plot n`	Plot the values of a particular column. The plot file is saved to disk.
`--row-plot n`	Plot the values of a particular row. The plot file is saved to disk.

4.5 ifexport

Export an image file to a standard graphics file.

Usage

```
ifexport input-filename output-filename [options...]
```

Options

`--format`

- `png` - Portable network graphics format. This is the default output format.
- `png16` - 16-bit PNG format.
- `pgm` - Portable graymap format, binary format.
- `pgmasc` - ASCII PGM format.

`--center` Set center of intensity window.

- `median`
- `mode`
- `mean`

`--auto` Set half-width of intensity window as a multiple of the standard deviation.

- `full`
- `std0.1`
- `std0.5`
- `std1`
- `std2`
- `std3`

`--scale` Set size of output image. A value of `1` is default and creates an output image the same size as the input image. A value of `2` will double the size of the output image.

`--min` Set the minimum intensity value.

`--max` Set the maximum intensity value.

4.6 ifinfo

Displays information about an image file. By default, history labels and image statistics are displayed.

Usage

```
ifinfo input-filename [options...]
```

Options

`--no-labels` Suppress history labels.

`--no-stats` Suppress image statistics.

4.7 phm2pj

Simulates collection of X-rays data (projections) around a phantom object.

Usage

```
phm2pj projection-filename number-detectors number-views [options...]
```

Options

`--phantom` Select a standard phantom.

- `herman`
- `shepp-logan`
- `unit-pulse`

`--phmfile` Reads a user-created phantom file.

`--geometry` Sets the scanner geometry. Valid values are:

- `parallel`
- `equiangular`
- `equilinear`

`--nray` Number of samples per each detector

`--rotangle` The rotation angle as a fraction of a circle. For parallel geometries use a rotation angle of `0.5` and for equilinear and equiangular geometries use a rotation angle of `1`. The default is to use to appropriate rotation angle based on the geometry.

`--view-ratio` Sets the field of view as a ratio of the diameter of the phantom. For normal scanning, the default value of `1.0` is optimal.

`--scan-ratio` Sets the length of scanning as a ratio of the view diameter. For normal scanning, the default value of `1.0` is optimal.

`--focal-length` Sets the distance between the radiation source and the center of the object as a ratio of the radius of the object. For parallel geometries, a value of `1.0` is optimal. For other geometries, this should be at least `2.0` to avoid artifacts. The default value is `2`.

4.8 phm2if

Generates a raster image file based on a phantom.

Usage

```
phm2if phantom-filename image-filename x-image-size y-image-size [options...]
```

Options

`--nsamples`	Number of samples in x and y directions per pixel
`--view-ratio`	Sets the view ratio. For normal scanning, the default value of `1.0` is optimal.

4.9 pj2if

Convert a projection file into an image file where each row of the image file contains the projection data from a single view.

Usage

```
pj2if projection-filename image-filename [options...]
```

Options

`--dump`	Print all projection data to the console.

4.10 pjinfo

Displays information about a projection file.

Usage

```
pjinfo projection-filename [options...]
```

Options

`--binaryheader`	Dump the binary header to the standard output. This option is only used when manually creating a composite projection file from several different projection files.
`--binaryview`	Dump binary view data to the standard output. This option is only used when manually creating a composite projection file from several different projection files.
`--startview`	Sets starting view to display. Default is `0`.
`--endview`	Sets ending view to display. Default is the last view.
`--dump`	Print all projection data to the console.

4.11 pjrec

Reconstructs the interior of an object from a projection file.

Usage

```
pjrec projection-filename image-filename image-cols image-rows [options...]
```

Options

Parameter	Options
`--filter`	Selects which filter to apply to each projection. To properly reconstruct an image, this filter should consist of the the absolute value of distance from zero frequency optionally multiplied by a smoothing filter. The optimal filters to use are: • `abs_bandlimit` • `abs_cosine` • `abs_hamming` • `abs_hanning`
`--filter-parameter`	Sets the alpha level for Hamming window. This parameter adjusts the smoothing of the Hamming filter and can range from `0` to `1`. At a setting of `1`, the Hamming filter is the same as the bandlimit filter. At a setting of `0.54`, the Hamming filter is the same as the Hanning window.
`--filter-method`	Selects the filtering method. For large numbers of detectors, `rfftw` is optimal. For smaller numbers of detectors, `convolution` might be a bit faster. • `convolution` • `fourier` - Uses simple Fourier transform. • `fourier-table` - Optimizes Fourier transform by precalculating trigometric functions. • `fftw` - Uses complex-valued Fourier transform with the *fftw* library. • `rfftw` - Uses optimized real/half-complex Fourier transform.

`--filter-generation` Selects the filter generation. With convolution, `direct` is the proper method to select. With any of the frequency methods, `inverse-fourier` is the best method.

- `direct`
- `inverse-fourier`

`--interpolation` Interpolation technique during backprojection. `cubic` has optimal quality when the data is smooth. Smooth data is obtained by taking many projections and/or using a smoothing filter. In the absence of smooth data, `linear` gives better results and is many times faster than cubic interpolation.

- `nearest` - No interpolation, selects nearest point.
- `linear` - Uses fast straight line interpolation.
- `cubic` - Uses cubic interpolating polynomial.

`--backprojection` Selects the backprojection technique. A setting of `idiff` is optimal.

- `trig` - Use trigometric functions at each image point.
- `table` - Use precalculated trigometric tables.
- `diff` - Use difference method to iterate within image.
- `idiff` - Use integer iteration technique.

`--zeropad` Zeropad factor. A setting of `1` is optimal whereas a zeropad of `0` performs no zero padding. Settings greater than `1` perform additional zero padding, but without any significant output difference.

5. The Web Interface

5.1 Overview

`CTSim` can also be executed via a web browser. The Perl program `ctsim.cgi` takes projections of a standard phantom object, performs reconstruction, and then compares the rasterized phantom object with the reconstruction. The comparison is performed both visually by an image subtraction as well as by statistical analysis.

The `ctsim.cgi` program is invoked from the HTML file `simulate.html`.

5.2 Requirements

- Apache ($http://www.apache.org$) or other CGI-compatible web server
- Perl (version 4.0 or higher)
- A client web browser than can display PNG files. Most current web browsers support PNG.
- A knowledgable system administrator.

5.3 Installation

Installation is rather automatic on Linux and UNIX systems. The `configure` script needs to be given options that specify the directory for web pages and for CGI programs.

6. Installation

6.1 Download

The latest version of CTSim, both as executable programs and source code, can be downloaded from the official CTSim web site ($http://www.ctsim.org$). Additionally, these files are also available from the CTSim FTP site ($ftp://ftp.ctsim.org$).

6.2 Installing Windows Binary

Download the Windows executable file. Simply execute this program to begin the installation program. CTSim will then be accessible from the Start Menu under the Programs submenu.

CTSim is compatible with Windows 98, Windows Me, Windows NT 4.0, and Windows 2000. Due to use of the OpenGL and htmlhelp libraries, CTSim is not compatible with the stock Windows 95 system.

6.3 Installing Linux RPM

Download the CTSim RPM file, then use the rpm manager program as follows:

```
rpm -Uvh ctsim-*.rpm
```

CTSim and CTSimText will then be installed in the /usr/local/bin directory. The online help file, ctsim.hhp, will be installed in directory /usr/local/man.

6.4 Build From Sources

Refer to the INSTALL file included in the source distribution for instructions.

6.4.1 Optional Libraries

These libraries are optional and not required to build CTSim from source code. However, they add functionality to CTSim and there inclusion is recommended.

- **wxWindows 2.3**
  Used for the platform-independent graphical interface. The graphical version of CTSim requires this library.

Web site ($http://www.wxwindows.org$)

- **FFTW3**
  Used for fast Fourier transformations of projections and images. Without this library `CTSim` will use slower, traditional Fourier transformations.
  Web site ($http://www.fftw.org$)

- **libpng**
  Used for PNG file export.
  Web site ($http://www.libpng.org/pub/png/libpng.html$)

- **zlib**
  Used for PNG file export.
  Web site ($http://www.info-zip.org/pub/infozip/zlib/zlib_docs.html$)

- **readline**
  Used for `CTSimText` interactive shell.
  Web site ($http://www.gnu.org$)

- **dmalloc**
  Used for debugging memory allocation.
  Web site ($http://www.dmalloc.com$)

- **ctn**
  DICOM library used to support import/export of DICOM files Web site ($http://www.erl.wustl.edu/DICOM/ctn.html$)

A. Algorithms

`CTSim` uses a number of interesting algorithms. This appendix details some of the techniques that `CTSim` uses.

A.1 Phantom Processing

Key Concepts

`Geometric transformations`
`Matrix algebra`

Phantom objects are processed in two different ways: rasterization and projections. `CTSim` uses optimized techniques to perform those procedures.

The primary tool used to optimize these processes is *Geometric transformations*. For every primitive *phantom element* (section 2.2.2) , a standardized configuration is defined. This standard configuration is used to speed the process of collecting projections.

In general, to transform an object into the standard configuration, the following sequence of transformations occur. When this sequence is performed, the coordinates are termed the *normalized phantom element* coordinates.

- Scaling by the inverse of its size, that is usually scaling by `(1/dx,1/dy)`.
- Translating the object to the origin, that is usually translation by `(-cx,-cy)`.
- Rotating the object by `-r`.

These steps can by combined into a single matrix multiplication which involves only 4 multiplications and 6 additions to transform both `x` and `y` coordinates. This matrix is precalculated and stored when the phantom is created. Similarly, the inverse of the matrix is precalculated and store to perform the inverse of this transformation.

As an example of this technique, consider the problem of finding the length of an arbitrary line that may intersect an arbitary ellipse. Define the endpoints of the line by `(x1,y1)` and `(x2,y2)`.

1. First, transform the coordinates into the normalized phantom element coordinates. At this point, the ellipse will have been transformed into a unit circle centered at `(0,0)`.

2. Translate the coordinates by `(-x1,-y2)`. The line now has the endpoint centered at the origin. The ellipse will now have its center at `(-x1,-y1)`.
3. Rotate the coordinates by the negative of angle of the line with respect to the x-axis.

At this point the line will now lie along the positive x-axis with one end at `(0,0)`. The circle will be rotated around the origin as well. At this point, it is fairly trivial to calculate the length of the intersection of the line with the unit circle. For example, if the `y` coordinate for the center of the circle is greater than `1` or less than `-1`, then we know that the unit circle doesn't intersect the line at all and stop further processing. Otherwise, the endpoints of the intersection of the line with the unit circle is a simple calculation.

Those new, intersected endpoints are then inverse transformed by reverse of the above transformation sequence. After the inverse translation, the transformed endpoints will be the endpoints of the line that intersect the actual ellipse prior to any transformations.

Though this sequence of events is somewhat complex, it is quite fast since the multiple transformations can be combined into a single matrix multiplication. Further, this technique is amendable to rapidly calculating the intersection of a line with any of the phantom elements that `CTSim` supports.

A.2 Background Processing

Key Concepts

```
Multithreading
Critical sections
Message passing
Re-entrant code
```

The `CTSim` graphical shell can optionally perform background processing. `CTSim` uses threads as tools to achieve this functionality. Using multiple threads, termed *multithreading*, allows `CTSim` to:

- Execute a lengthy calculation in the background while the graphical shell remains available for use.
- Automatically take advantage of multiple central processing units (CPU's) in a symmetric multiprocessing (SMP) computer.

When background processing option is turned on or when `CTSim` is running on a SMP computer, and `CTSim` is directed to perform reconstruction, rasterization, or projections, `CTSim` will spawn a *Background Supervisor* thread. This supervisor thread then creates a *Supervisor Event Handler* (supervisor). The supervisor communicates with the rest of graphical user interface of `CTSim` by using message passing to avoid issues with re-entrant code.

The supervisor registers itself via message passing with the *Background Manager* which will display the execution progress in a pop-up window. The supervisor also registers itself with

the document being processed. This is done so that if the document is closed, the document can send a message to the supervisor directing the supervisor to cancel the calculation.

After registering with `CTSim` components, the supervisor creates *Worker Threads*. These worker threads are the processes that actually perform the calculations. By default, `CTSim` will create one worker thread for every CPU in the system. As the workers complete unit blocks, they notify the supervisor. The supervisor then sends progress messages to background manager which displays a gauge of the progress.

As the worker threads directly call the supervisor, it is crucial to lock the class data structures with *Critical Sections*. Critical sections lock areas of code and prevent more than one thread to access a section of code at a time. This is used when maintaining the tables of worker threads in the supervisor.

After the workers have completed their tasks, they notify the supervisor. When all the workers have finished, the supervisor kills the worker threads. The supervisor then collates the work units from the workers and sends a message to `CTSim` to create a new window to display the finished work.

The supervisor then deregisters itself via messages with the background manager and the document. The background manager removes the progress gauge from its display and resizes its window. Finally, the background supervisor exits and background supervisor thread terminates.

This functionality has been compartmentalized into inheritable C++ classes `BackgroundSupervisor`, `BackgroundWorkerThread`, and `BackgroundProcessingDocument`. These classes serve as base classes for the reconstruction, rasterization, and projection multithreading classes.

A.2.1 Advantages

This structure may seem more complex than is necessary, but it has several advantages:

- Since the background threads do not directly call objects in the graphical user interface thread, problems with re-entrant code in the graphical interface are eliminated.
- A supervisor can parallel process with any number of worker threads to take advantage of potentially large numbers of CPU's in SMP computers.
- Allows for continued user-interaction with `CTSim` while lengthy calculations are performed in the background.

A.2.2 Disadvantages

The above advantages are not free of cost. The disadvantages include:

- Increased memory usage.
  The workers threads allocate memory to store their intermediate results. When the worker threads finish, the supervisor allocates memory for the final result and collates the results for the workers. This collation results in a doubling of the memory

requirements. Of course, after collation the supervisor releases the memory used by the workers.

- Slower execution on single CPU systems.
  Creating multiple threads, sending progress messages to the background manager, and collation of results for worker threads adds overhead compared to simply calculating the result directly in the foreground. On single CPU systems this results in slower processing compared to foreground processing. On dual-CPU and greater SMP systems, though, the advantage of using multiple CPU's in parallel exceeds the overhead of background processing.

B. Simple Graphics Package

Simple Graphics Package was created in 1980 by Kevin Rosenberg and is modelled after the hypothetical graphics library described by Foley and van Dam[1]. It is designed to be platform-independent.

B.1 Transformation Sequence

Master coordinate (MC) level
↓
Apply *Current transformation matrix*
↓
World coordinate (WC) level
↓
Clipping against Window
↓
Convert to Normalized device coordinates (NDC)
↓
Clipping against Viewport
↓
Convert to Physical device coordinates (PDC)

B.2 Functions

B.2.1 Master coordinate functions

`setWindow(xmin,ymin,xmax,ymax)`	Set window for world coordinates
`moveAbs(x,y)`	Move graphics cursor to absolute position
`moveRel(dx,dy)`	Move graphics cursor relative to current position
`pointAbs(x,y)`	Draw point at current position
`pointRel(dx,dy)`	Draw point relative to current position
`lineAbs(x,y)`	Draw line from current position to absolute position
`lineRel(dx,dy)`	Draw line from current position to position relative to current position
`markerAbs(x,y)`	Draw marker at current position
`markerRel(dx,dy)`	Draw marker relative to current position
`polylineAbs(x[],y[],n)`	Draw a series of lines to absolute position
`polylineRel(dx[],dy[],n)`	Draw series of lines relative to current position
`drawString(str)`	Draw text string at current positon
`drawCircle(r)`	Draw circle at current positon
`drawArc(r,start,stop)`	Draw arc with center at current positon
`drawRect(xmin,ymin,xmax,ymax)`	Draw rectangle

B.2.2 Normalized coordinate functions

`Viewport(xmin,ymin,xmax,ymax)`	Viewport for window in NDC
`stylus(x,y,beam)`	Draw a line from current position if beam = 1, otherwise move stylus to new position
`markerNDC(xndc,yndc)`	Draw marker at NDC position

B.2.3 Master coordinate to World coordinate transformations

These transformation functions operate on the *Current transformation matrix* (CTM).

`clearCTM()`	Sets the CTM to an identity matrix
`preTranslate(x,y)`	Apply translation to CTM
`postTranslate(x,y)`	Apply translation to CTM
`preScale(x,y)`	Apply scale to CTM
`postScale(x,y)`	Apply scale to CTM
`preRotate(angle)`	Apply rotation to CTM
`postRotate(angle)`	Apply rotation to CTM
`preShear(x,y)`	Apply shear to CTM
`postShear(x,y)`	Apply shear to CTM

B.2.4 Coordinate transformation functions

`transformMCtoNDC(&x,&y)`	Convert from master coordinates to NDC
`transformNDCtoMC(&x,&y)`	Convert from NDC to master coordinates

B.2.5 State functions

`eraseWindow()`	Clears the screen
`setColor(color)`	Set current pen color
`setLinestyle(style)`	Set current pen style
`setLinewidth(width)`	Set current pen width
`setTextColor(foreground, background)`	Set text colors
`setMarker(type,color)`	Set marker attibutes
`setRasterOp(rasterOp)`	Set raster operator

B.3 Coordinate Mapping

B.3.1 Dimensions

Window (World Coordinates): $X_{wmin}, X_{wmax}, Y_{wmin}, Y_{wmax}$
Viewport (Normalized Device Coordinates): $X_{vmin}, X_{vmax}, Y_{vmin}, Y_{vmax}$
Physical (Physicial Device Coordinates): X_{pmax}, Y_{pmax}

B.3.2 Formulas

To convert from Master coordinates to World coordinates:

Apply *current transformation matrix*

To convert from WC to NDC:

$$X_{ndc} = X_{vmin} + (X_{vmax} - X_{vmin})(X_{wc} - X_{wmin})/(X_{wmax} - X_{wmin}) \tag{B.1}$$

$$Y_{ndc} = Y_{vmin} + (Y_{vmax} - Y_{vmin})(Y_{wc} - Y_{wmin})/(Y_{wmax} - Y_{wmin}) \tag{B.2}$$

To convert from NDC to PDC:

$$X_{pdc} = X_{ndc} X_{pmax} \tag{B.3}$$

$$Y_{pdc} = X_{ndc} Y_{pmax} \tag{B.4}$$

Bibliography

[1] J.D. Foley and A. van Dam. *Fundamentals of Interactive Computer Graphics*. Addison-Wesley, 1982.

[2] G.T. Herman. *Image Reconstruction from Projections: The Fundamentals of Computerized Tomography*. Academic Press, New York, 1980, 1980.

[3] L. Shepp and B. Logan. The fourier reconstruction of a head section. *IEEE Transactions in Nuclear Science*, NS-21(6):21–43, 1974.

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