

ABSTRACT

Development of the Particle Technology Research Portfolio Online Reporting Tool

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Baylor University is part of the Particle Computed Tomography (pCT) Research Collective which performs research in medical imaging using protons and other particles to quickly and accurately image the human body. Data sharing between the researchers and the ability to process received data and reconstruct images is imperative for continuing in this work. The system previously in place was highly reliant on the users and processing was limited to the few who developed the code base. This document details the design and implementation of the Particle Technology Research Portfolio Online Reporting Tool which allows users to upload data to a common database, search through previously uploaded data sets, and select data sets to be processed on Bayers Kodiak computing cluster. This tool prioritizes the security of medical data and allows for future expansion of the system to the clinics where pCT imaging machines will be installed and utilized.

Development of the Particle Technology Research Portfolio Online Reporting Tool

by

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A Thesis

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TABLE OF CONTENTS

LIST OF FIGURES	vi
ACKNOWLEDGMENTS	viii
DEDICATION	ix
1 Introduction	1
2 Methods	5
2.1 Data Management and Processing System	5
2.1.1 MySQL Database	5
2.1.2 Web Server	7
2.1.3 Server Communications	9
2.2 Evaluating Resulting Images	13
2.2.1 Mask Prep	13
2.2.2 Image Registration	15
2.2.3 Image Comparison	15
2.2.4 How it Works	16
2.2.5 Evaluation Summary	19
3 Results	22
3.1 Web Page Usage	22
3.2 Preprocessing and Reconstructing an Image	30
3.3 Image Quality Comparison	32
3.3.1 CTP404 Sensitom	32

4	Discussion	37
4.1	Future Work	37
4.1.1	Project Refinement and Testing	37
4.1.2	PTRePORT 2.0	38
4.2	Conclusion	38
	APPENDICES	40
	APPENDIX A GitHub Repository	41
	BIBLIOGRAPHY	42

LIST OF FIGURES

2.1	Use Case Diagram	6
2.2	Entity Relationship Diagram	8
2.3	Server Communication Diagram- Data Set Search	10
2.4	Server Communication Diagram- Preprocessing and Reconstruction .	11
2.5	Server Communication Diagram-Data Upload	12
2.6	Original Model Image and its Mask	14
2.7	Matlab's Numbering of the Nine Mask Regions	16
2.8	Selected Blurring Test	17
2.9	Ring Test	17
2.10	Original Additive Test Image	18
2.11	Rotated Image Test	19
2.12	Scaled Image Test	20
2.13	Translated Image Test	21
2.14	Registration Combination Test	21
3.1	Welcome Screen	23
3.2	Sign In	23
3.3	Search Home	23
3.4	Upload Home	24
3.5	Attribute Selection	25
3.6	Verify Upload	25
3.7	Example Search Results	26
3.8	Example Search Results-Expanded	27

3.9	Preprocessing Options	28
3.10	Reconstructing Options	28
3.11	Example Run Results	30
3.12	Example Reconstructed Image of a CTP404 Sensitom Phantom . . .	31
3.13	Diagram of the CTP404 Phantom. Copyright ©2006 The Phantom Laboratory	32
3.14	CTP404 Model Image	33
3.15	CTP404 First Result Image	33
3.16	CTP404 Mask Image	33
3.17	Differences Between Model and Reconstructed	34
3.18	CTP404 Second Result Image	35
3.19	Differences Between Model and Reconstructed	35

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To God be the glory in all things. Romans 11:36

CHAPTER ONE

Introduction

Particle Computed Tomography (pCT) was developed to complement to the already successful proton therapy utilized for targeting specific portions of the body for treatment. Proton therapy is a form of radiation therapy used to target individual cells using a proton beam in the human body. Because protons have a characteristic radiation pattern-a long low dose while traveling followed by a high quick burst of radiation at their destination-they can be used to destroy individual cells. This allows for the destruction of harmful cells while exposing healthy tissue to a much smaller dose of radiation (1). While the currently used X-Ray Computed Tomography (xCT) allows reasonably precise locations for treatment areas, pCT technology allows for imaging on the same scale as the treatment (2). If protons determine the resolution of treatment, the resolution of imaging should also be scaled to protons. Originally proton computed tomography, the particle computed tomography process has been expanded to utilize Helium ions as well. Other particles are currently being tested for effectiveness. By allowing physicians accurate information down to the cell level in the human body, pCT helps ensure that treatment is targeted to only the intended cells.

At its most basic level, the setup for pCT imaging consists of two upstream detector plates, two downstream detector plates, and a range detector (3) (4) (5). Each detector plate is a board printed with horizontal traces on one side and vertical on the other (6). Because the trace the particle passes through can be determined, we can thus determine an x and y location from each detector plate. From two plates, two points are determined, and from two points a line. After passing through the object, the second set of detector plates records the output path and the residual energy

is measured. From this information, the path through the object can be calculated and the composition of the object determined based on the energy loss along the calculated path. After a set of particles is sent through and measured, the system rotates and another set is measured. A series of runs at various angles is collected and this information is used to fully reconstruct an image of the object (7) (8).

An overview of pCT technology and its development can be read in the article Proton Computed Tomography. Eventually it is hoped that pCT imaging can take place as treatment is being performed so that the location of each cell is known in real time (3). While used extensively as an option for cancer treatment, as the technology is developed, there is also the possibility of performing some surgeries using proton therapy inside the human body. For example, the maze surgery used to treat cardiac arrhythmias. In this operation, nerves sending faulty electrical signals to the brain are severed or burned. With proton therapy, this surgery could be performed without having to open up the patient's chest for direct access. Instead, with real time location information for each cell in the body, it is presumably possible to perform this operation using a proton beam in the space between heart beats.

Medical physicists, computer scientists, and others are working to develop pCT imaging at many universities around the world. As such, there is a need for sharing of data between those constructing the development phantoms, those performing the test runs and recording data, those simulating data from models, and those processing the data and reconstructing the data into the final images. The current method for data sharing is for each user to log into Baylor's Kodiak computing cluster under their individual user accounts, load their data into a personal folder, organize the newly uploaded data into a series of subfolders, contact the Baylor system administrator who then moves the newly uploaded files into a general folder where an organizing system designed by another graduate student years ago is implemented. The current system relies on each individual to follow a standard file naming and folder organization

system twenty-five pages in length which is not currently regulated or enforced. It also requires several individuals to be involved in the simple file upload process. Locating files in the system involves navigating through a file system that is sometimes twelve folders deep with any files not following the naming convention often misfiled and therefore difficult to locate. The information about the file run, such as run date, beam type, or phantom imaged is embedded into the folder names so if a file is misplaced, little to no information is known about its origin.

Once these data sets are collected, there are three steps in between the data and the final image (9). First, the correct calibration file must be located (10). The energy loss and other factors in the process are expected to change from week to week and month to month so daily calibration runs are recorded in order to account for those variations. These are compiled into calibration files for the site and adjusted by a medical physicist. The second step is the preprocessing which takes in the calibration files and runs through the data, eliminating data which does not fit within the expected energy levels and locations (11). Within this preprocessing phase, there are a number of parameters that need to be set by the user. The final step the data goes through is reconstruction of the final image (12, 6, 13, 14, 15, 16). Again, there are number of parameters that can be set to alter the final image.

As research is being performed and refinement of the preprocessing and reconstruction code in development (17, 18, 19), it is important that all involved researchers have data sets available and the ability to preprocess and reconstruct files. However, it is also desired that the file names, file locations, and other properties be monitored and validated by an external system. The desired system should also allow for easy upload and download of data from personal computers, allow users to specify run variables and perform preprocessing or reconstruction without having to directly interact with the code base on Kodiak. The design and implementation of this desired system is the subject of this document. Having a system in place that controls data

input, processing, and export, lays the groundwork for the eventual incarnation of the processing system, the clinic computer. After pCT imaging systems are installed in hospitals and clinics, there will be the need to have each clinic able to process their own patient data and view the patient images for diagnostic and treatment purposes. At its current state, the data can be collected, preprocessed, and reconstructed to display the final images in less than five minutes though this processing time is improved upon with each code revision. Having a system available that allows for the data processing without extensive knowledge of the code base or data is the first step in preparing for clinicians to be able to take and view images.

The purpose of this project was to design and implement a single system that allows all members of the research collaborative to upload data sets, process data sets, and receive final results while limiting direct access to files and maintaining data integrity and security. Additionally, some method of evaluating the output images for comparative quality must be established for further research purposes.

CHAPTER TWO

Methods

2.1 Data Management and Processing System

Baylor University is part of a larger particle computed tomography (PCT) group comprised of universities across the United States and in other countries. Each member university has its own focuses within the research with some gathering the data, designing the phantoms, developing the code base for the data processing and reconstruction, and many other tasks. With so many researchers contributing data to the project, it quickly became a significant task to keep track of and share each data set between members for development and processing. The fact that only the few code developers and a few trainees were able to process the data presented another challenge. Comparison of the final images is a valuable evaluation method for updates to calibration methods, phantom designs, or code revisions and without the ability to generate those images, many researchers are reliant on a few peoples to run their data and send individual results. The solution proposed to address these challenges is the data management and processing system described in this document.

The Particle Technology Research Portfolio Online Reporting Tool (PTREPORT) is comprised of a MySQL database and a web server that allows users to search for data sets, connect to Baylor's Kodiak cluster to run the preprocessing and reconstruction software on selected data sets, and upload and download data sets. The following Use Case Diagram in Figure 2.1 specifies the options made available to the user.

2.1.1 MySQL Database

The MySQL database is comprised of eight tables, five of which contain normalized data relating to the data sets, one containing authorized users, and two

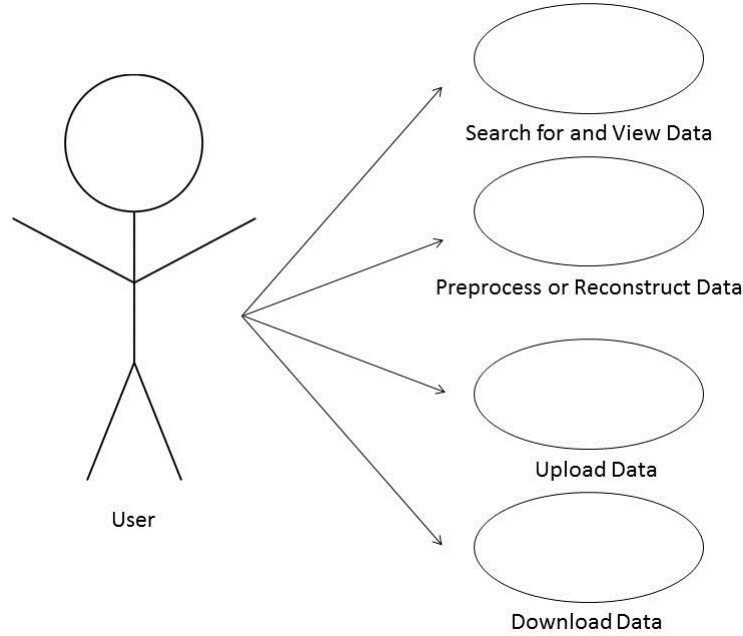


Figure 2.1. Use Case Diagram

containing information about the phantoms and facilities respectively. The authorized user table contains user names for approved users as well as their associated groups. This information is used to control who has access to the site as well as who can process data. Each file uploaded or generated through the system has privileges associated with it regarding the user, the user's group, and the public. Depending on the current user and their associated groups, the authorized user will be able to access and search the system but may be unable to process or download individual files generated or uploaded by another user. While collaboration is the main focus of the system's development, the individual file privileges allow groups to utilize the system's features without exposing all of their data to modification by other groups. The Phantom table contains information related to each of the phantoms currently in use. The table records the official phantom name, the abbreviated name utilized by Kodiak, specifications related to the development, and a model image of the phantom. The Facility table similarly contains information relevant to each of the data

collection locations. In addition to the site name, the table contains the physical address of the location as well as the accelerator type and the beam type. The five data tables are Main, Raw, Preprocessed, Reconstruction, and Images. Each row in the Main table contains a unique, incrementing data set ID number that allows the data files derived to be associated with the information contained in Main. Main contains information applicable to the original data collection such as the facility, the phantom, the data collection date, the beam type, size, energy, the particle utilized etc. Using the unique ID attributed to each row of Main, raw data as well as that that has been preprocessed or reconstructed can be linked to the original data run. The Images table contains the location of images and each row is linked to the reconstruction in which the image was created rather than the original data collection as multiple reconstructions can be created from one data set. Each row in the Raw, Preprocessed, and Reconstruction tables contains information related to that file type alone as well as the name of the file and its location on the Kodiak cluster. This information can easily be read by the web server and used to send instructions to Kodiak on how to and which files to process. The entity relationship diagram in Figure 2.2 summarizes the values associated with each of the tables as well as their relationships to each other.

2.1.2 Web Server

The web server is the brain of PTRePORT. It interacts with the database, performs searches, formats results, allows data set selection, instructs Kodiak to process files, and allows for upload and download of data sets. After entering their username and gaining access to the site, the user is directed to a home search page where search criteria can be entered or the file upload screen can be accessed. The search criteria to be specified all relate to information contained in the Main file so the user is searching for all data associated with a single data run. By entering a date range for the data capture, the phantom used, or the location the data was taken from, in

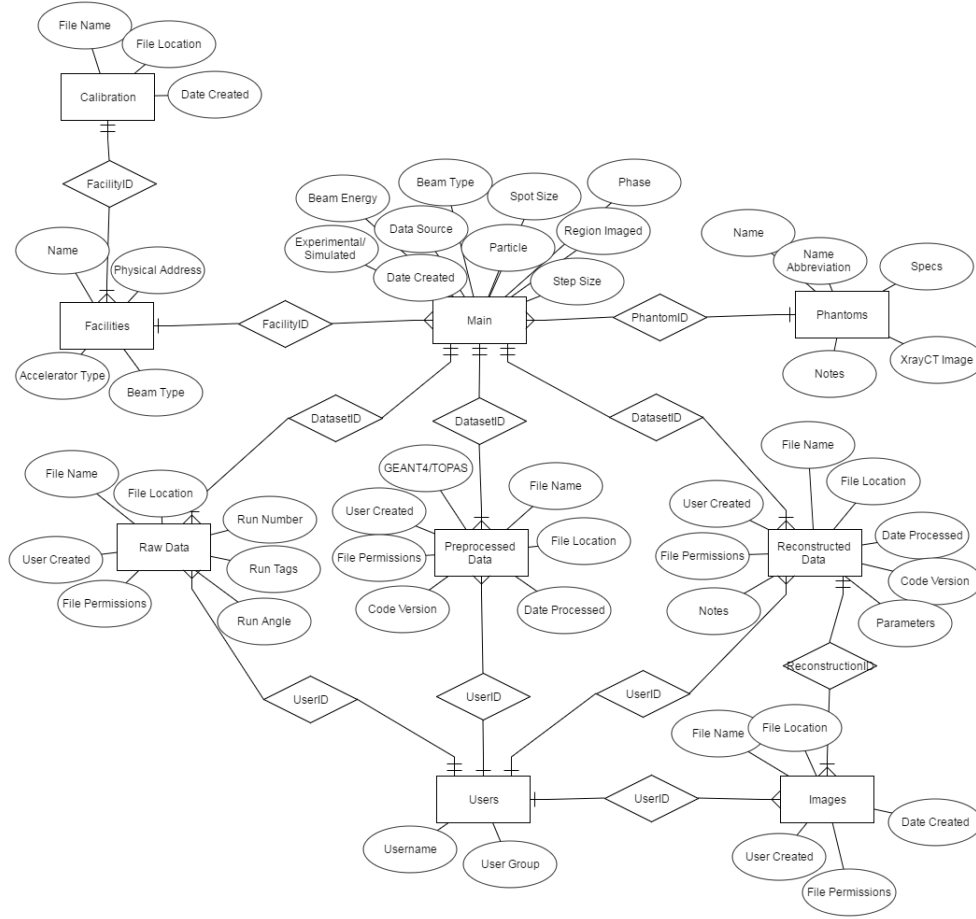


Figure 2.2. Entity Relationship Diagram

addition to other search criteria, the user is able to narrow down their results to only the data collections that interest them. The results are shown as associated blocks with the information about the data collection as a header. Below each header is a table showing the number of Raw, Preprocessed, Reconstructed, and Image files associated with this data collection. Each section can be expanded to view individual files if the user desires. The final layout of this page can be viewed in Figure 3.7 in the next chapter.

From this screen, the user can select a whole folder or a number of individual files to preprocess (for raw files) or reconstruct (for preprocessed files). The user is then instructed to select user permissions and specify the variable values they wish

to use. The web page then sends a command containing the file name, file location, and selected variables to the webserver which establishes a secure shell connection to Kodiak and performs the preprocessing or reconstruction as desired. After the selected data has been processed, the web server gives the user the option to store the generated files in the database or discard them. A significant benefit to the PTRePORT is the automatic capture of data generated by users without relying on each individual to document and share the files they generate. This prevents the loss or isolation of information.

If the upload file branch is selected from the home screen, the individual is led through a series of steps that upload a file and then allow the user to fill in all the associated columns in the database for the new file. Currently, data upload is accomplished through an individual uploading a file to their personal folder on the Kodiak system and waiting for the system administrator to move the files to the publicly available folders. Automation of the upload process and straightforward tracking for newly generated files is a large benefit to the users.

2.1.3 Server Communications

To more fully detail the communication between the user system, the web server, the database, and Kodiak, server communication diagrams have been created. Figure 2.3 illustrates the communication during a data search.

Once the user specifies their desired search criteria, these criteria are read into the the webpage using the personal homepage language (PHP). PHP then creates a search query appropriate to the number and type of search criteria specified and the query is performed at the database level. The database returns an array of matching data sets which are read into a PHP variable in the web server. These results are then formatted into a table and displayed to the user on their system.

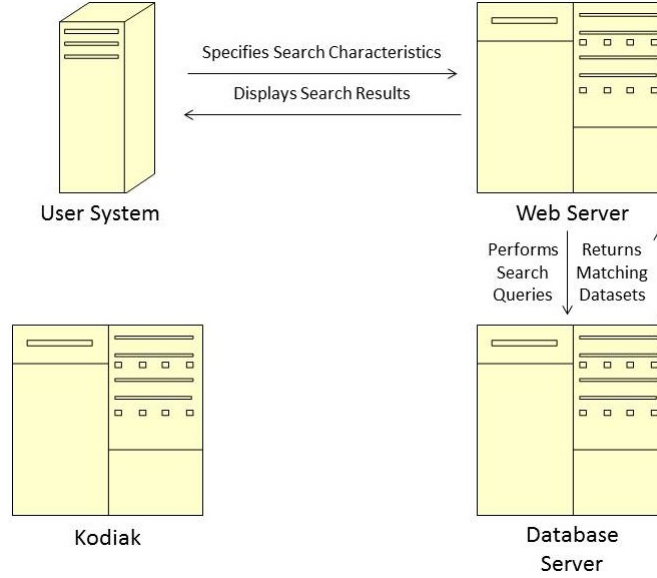


Figure 2.3. Server Communication Diagram- Data Set Search

For preprocessing and reconstruction, communication also takes place with the Kodiak server. This process takes place after the file to be processed has already been searched for and located. Figure 2.4 details this process.

Once a file or files is selected from among those located via the search options, the web server asks the user to specify variable values needed for the preprocessing and reconstruction code and to select the file permissions for the resulting file. While permission enforcement is not currently integrated into the system, PTRéPORT allows users the option to specify file permissions to eventually prevent certain files from being processed or downloaded by other users or groups. Once these values have been specified, PHP constructs the appropriate preprocessing or reconstruction code. Since PHP already knows the input file name and location, the desired output file location, and the processing variables, there is no additional information required from the database. PHP simply sends a command to the web server that immediately creates a secure shell connection to Kodiak and runs the commands the web server specified. These commands consist of the creation of a folder to hold the output

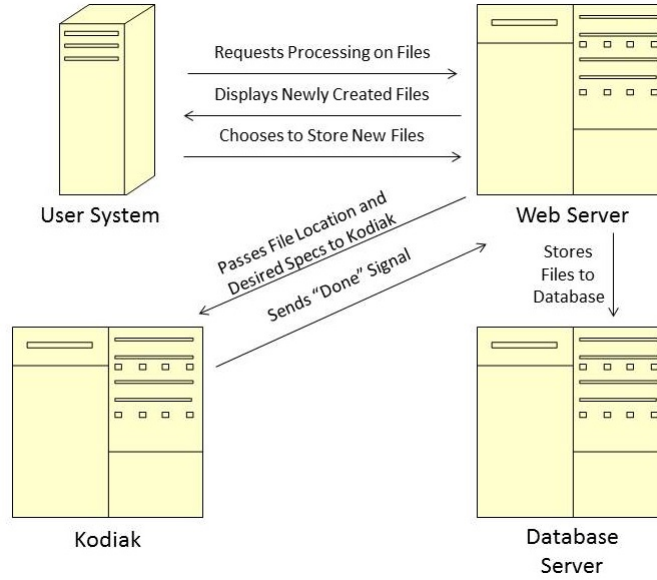


Figure 2.4. Server Communication Diagram- Preprocessing and Reconstruction

files and the running of the preprocessing or reconstruction. Once this command has been sent, the web server displays a message notifying the user that the processing is taking place and waits for a done signal to be returned from Kodiak. Once it receives this signal, it displays an example database entry for one of the newly created files and gives the user the option to store these files. If the user opts to store them, the information is sent to the appropriate database tables and is immediately searchable by any user. If the user opts not to store the files, they still exist in the appropriate results folder on Kodiak but, because they do not appear in the database, cannot be located through the web server's search.

If a user has data not generated by the web server to store in the system, they select the upload tab of the web page. The communication for this scenario is detailed in Figure 2.5

The upload tab offers a typical file upload box as well as a drop down that allows the selection of the data type and a submit button. After submittal, the uploaded file(s) are temporarily stored on the web server. Upon reaching the next

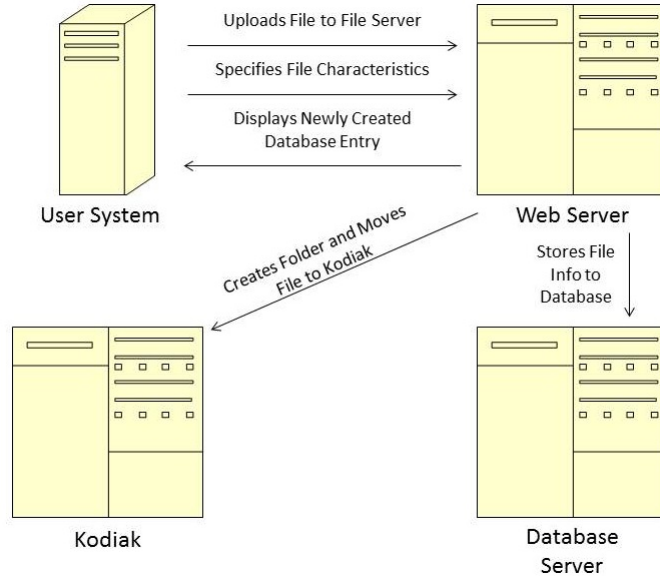


Figure 2.5. Server Communication Diagram-Data Upload

page, the user is presented with a number of drop down menus appropriate to the data type they originally selected that allow them to specify the properties associated with the data they are uploading. This data is the same data that is used by the search: the facility, the particle used, the beam type, and other external variables. The web server then shows the user the created database entry or entries and gives the option to store them or delete them. The user also has the option to return to the property selection page and alter their choices before returning to this page. Once the user opts to store the entry or entries, PHP generates an appropriate file name following the existing convention and sends a command to the web server that, similarly to the file processing, establishes a secure shell connection to Kodiak, creates a folder in the correct location, and moves the uploaded file(s) to their final location. It also connects to the database and stores the filename, new file location, and other file properties in the appropriate tables. If the user opts not to store the file, it remains in the temporary file folder untouched by the search queries, awaiting eventual deletion.

2.2 *Evaluating Resulting Images*

After the web server performs the task of processing and reconstructing data, it is necessary to determine whether the resulting images are of good quality. When comparing methods of preprocessing or reconstructing images from data sets in medical imaging, a large number of images are generated and must be compared. While it is possible to send a human subject to compare image after image by eye, this is overwhelming, subjective, and inefficient. Comparing images pixel by pixel using a computer is possible, but the majority of the image space will be empty and insignificant. As part of this project, a program was created in Matlab by the researcher that takes in a large number of images and compares them each to a model image in specified areas. Areas will be specified using a masking image that marks each region for comparison and the program will return an error vector that contains the magnitude of the difference from the model for each image in each region.

2.2.1 *Mask Prep*

The first step in the image comparison process is the creation and preparation of the masking image. For the example worked through here as part of the development, the model chosen is the modified Shepp-Logan, used in medical imaging applications. The mask was created in a photo processing software and consists of simple shapes of various gray tones surrounding areas of interest. In this example, the smaller shapes were entirely selected as well as the exterior edges of the larger regions. The white pixels are ignored by the system so areas of interest can be selected based on individual research needs. This model image is a good example of one that has a lot of uniform space both inside the phantom and in the background, that in this case, we do not prioritize. Comparing result images with the model in its entirety would consume a significant amount of unnecessary computational power if non-critical portions of an image are not excluded. The model image and its associated mask image are shown in Figure 2.6.



Figure 2.6. Original Model Image and its Mask

After the mask image was created, it was fed to a function called `prepMaski` which takes in the mask as well as an estimate of the number of regions in the mask. The function cycles through the image pixel by pixel ensuring that it is not the white of the background. If not, its value is compared to that of the previous pixel in the row. If the result of their subtraction is less than five values on the standard gray scale, it is assumed that this pixel is not at a shape edge and should be assigned to a region. The value of this pixel is compared to a collection of “region standards” and if it is not within fifteen values on the gray scale of an existing region standard is set as a new region standard. If it is within fifteen values of an existing region standard, the x and y coordinates of this pixel are recorded in the regions matrix corresponding to the region it matched. This is continued until each non-white pixel has been assigned to a region. The function then returns a three dimensional matrix called “regions” that contains the x and y coordinates of the points in each region as well as a “rcount” vector that contains the number of pixels in each region. The example masking image had nine areas of interest so `prepMaski` returned a three dimensional matrix that contained the x and y coordinates of each point in nine two-dimensional matrices. Though this function is relatively slow as a n^2 operation, it only needs to be run once per mask image and the results can be used for comparison with an

unlimited number of result images. This preparation sets up Matlab to perform the comparison of the images.

2.2.2 Image Registration

Because it cannot be guaranteed that a particular result image will be aligned with the model image in terms of rotation, scaling, or translation, image registration is required. Image registration is accomplished for this project using the Matlab image registration toolbox. Depending on the individual image, the registration may need to be run in a different registration “mode”. The registration was tested for result images that were rotated, scaled, translated, and a combination of the three.

2.2.3 Image Comparison

Once the mask preparation and image registration steps have been completed, the program is in possession of the locations of important regions, a model image, and a matched comparison image. With this preparation in place, the actual comparison of images is a relatively simple process. The model image, result image, regions matrix, and count vector are passed to “imcomp” which performs the computation. This function cycles through each region, looping through each point in the selected region. Because the three dimensional region matrix contains the number of points in the largest region, the program first checks to see if both the row and column locations are zero and if not, performs the error computation. For each point, the value of the model image is subtracted from that of the comparison image and the norm of the result taken. The values of these norms are added together for each region and then scaled according to the number of points in the region. This allows the user to, at a glance, see the severity of the error in each region. After the Image Comparison step is completed, we have the desired results.

2.2.4 How it Works

The program returns a vector with a length equal to the number of regions in the mask image, containing the absolute scaled error in each region. This allows location of errors and gives an quantitative evaluation of their severity. By comparing these numbers, it can easily be determined which image is the closest to the model overall or in a specific region. For this example, the resulting errors can be compared to their associated regions as Matlab assigned them. These regions are assigned from top to bottom, left to right and for this example the numbering is shown in Figure 2.7.

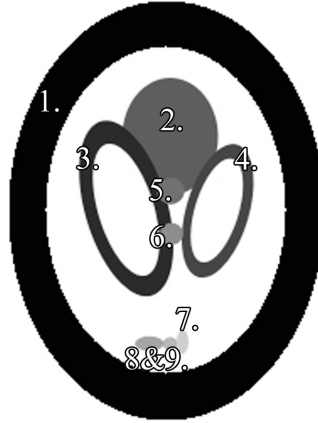


Figure 2.7. Matlab's Numbering of the Nine Mask Regions

A number of test images were created with known errors in order to test the program's functionality. The first test image had a blur applied to the area between regions two and three, the edge of region four, and the entire regions eight and nine. This error is meant to simulate blurring associated with loss of information or over correction of a final image. The resulting image along with a graph of the associated error is detailed in Figure 2.8.

It can be seen from the associated plot that the error values correspond with the regions in which the blurring is taking place. The greatest blur affects region

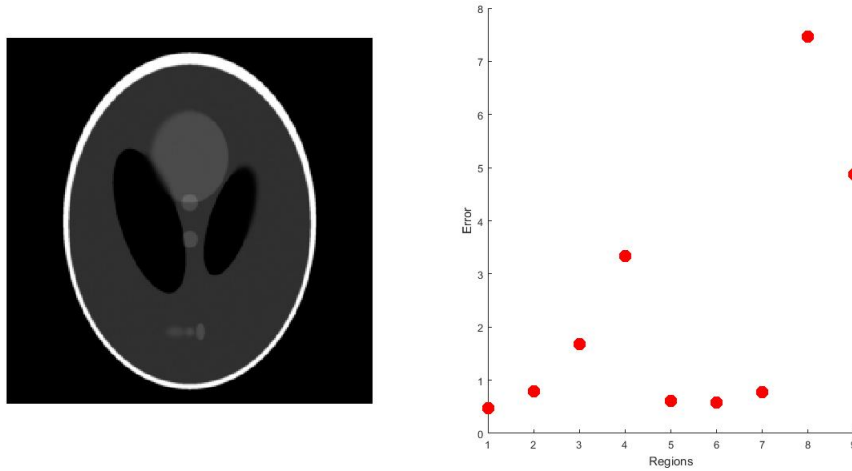


Figure 2.8. Selected Blurring Test

eight which is blurred almost to the point of non-existence. Though region eight is one of the smallest, because the error is normalized to the size of the region, it still appears as the largest overall error.

Another interesting test image was created by adding a ring surrounding region one to simulate the residual artifacts that sometimes appear when performing image reconstruction. The results in Figure 2.9 show that the error affects only region one as expected.

Tests were also run for images containing universal blur, region additives, “dimpling” regions, and removing portions of a region. These test images were created to see how the system responds to common errors associated with too few iterations run, imperfect input parameters, artifacts from the back projection portion of the reconstruction, and missing input data. For each, the program accurately picked out the regions affected and gave a severity value to the imposed error.

Next, an additive resulting image was taken and rotated, translated, and scaled to compare the error with registration to the same resulting image without. The

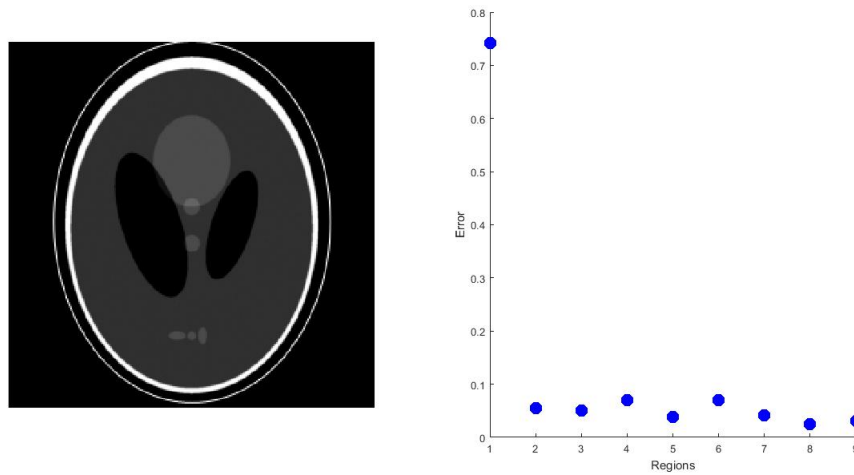


Figure 2.9. Ring Test

original resulting image and its error is compared with the resulting image after various methods of image registration and their errors.

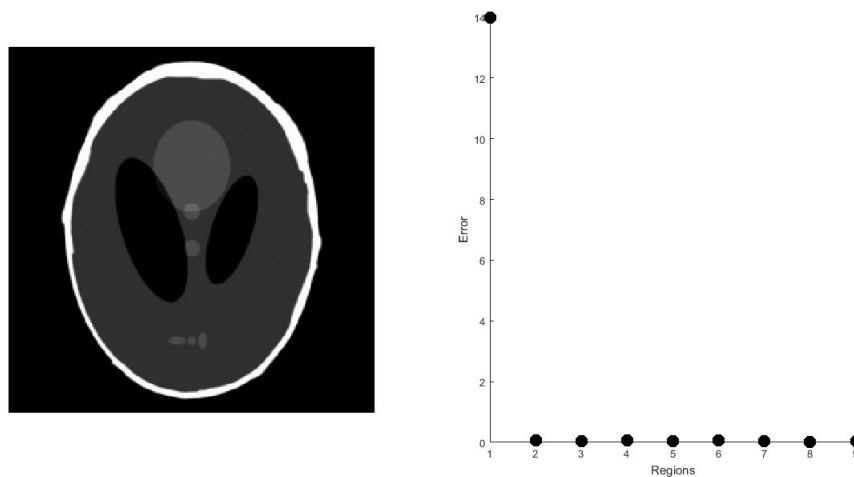


Figure 2.10. Original Additive Test Image

As can be seen from Figure 2.10, the error should be located only in region one. Additional white space has been added to the image in the region one area. This error can be compared with that of the same image after going through an alteration

in rotation angle, scaling, translation, and a combination of the three shown in Figure 2.11, Figure 2.12, Figure 2.13, and Figure 2.14 respectively.

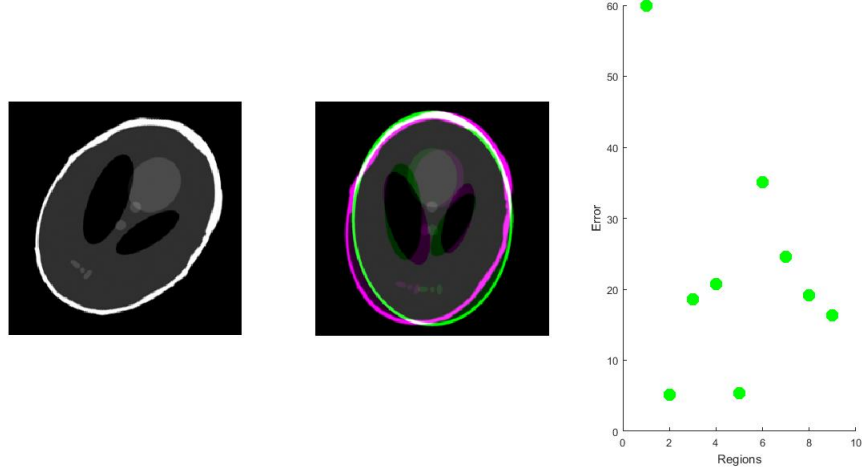


Figure 2.11. Rotated Image Test

Matlab is able to register these images with varying levels of success. While the errors for every region are well above zero, the program does give a much higher error for region one as expected. It can be seen however, that for the smaller regions, the mask no longer overlaps the majority of the desired region in the registered image and thus, the error calculated is larger than merited. Registration of images is the shortcoming of this program but can be much improved over the Matlab generic registration through traditional image processing methods. Additionally, for the purpose of comparing the same image after undergoing preprocessing using a variety of input parameters, the final result images should be similar in terms of rotation angle, scaling, and translation. Thus, the error associated with faulty image registration should be comparable for each result image. These errors can then be easily subtracted from one another to cancel each other out. This leaves only the errors due to the imaging, preprocessing, and reconstruction and still allows for accurate comparison of image quality in each region. It is also possible that, given multiple images, the program

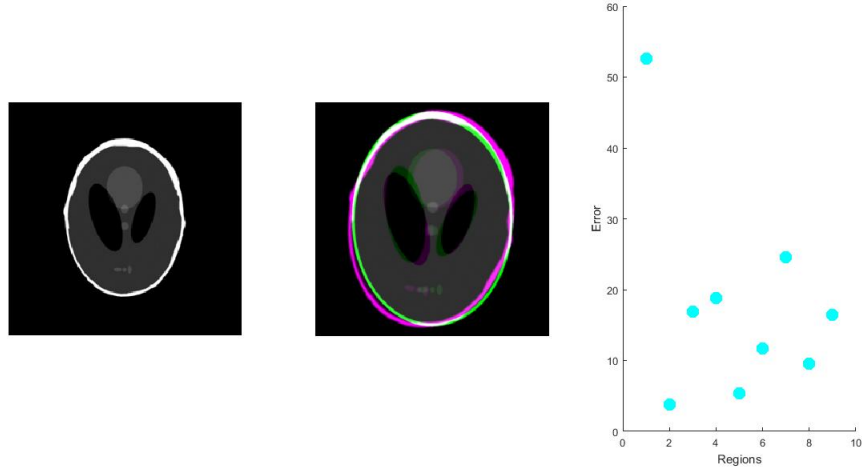


Figure 2.12. Scaled Image Test

could identify the most accurate regions of each in order to create a composite image. This is an area for future expansion of this program.

2.2.5 *Evaluation Summary*

The created Matlab program can compare the quality of images to an original “model” image in selected regions. Though the web server is capable of reconstructing images, a method of evaluating the resulting image quality is required as well. By creating a masking image that highlights and locates areas of importance such as edges or smaller details, the image quality program only compares the necessary areas and records in which area the variance is occurring. This program seeks to alleviate wasteful human and computational power by comparing only the regions that are important. This program allows for the validation of the code the web server is running to preprocess and reconstruct the data from the database into images.

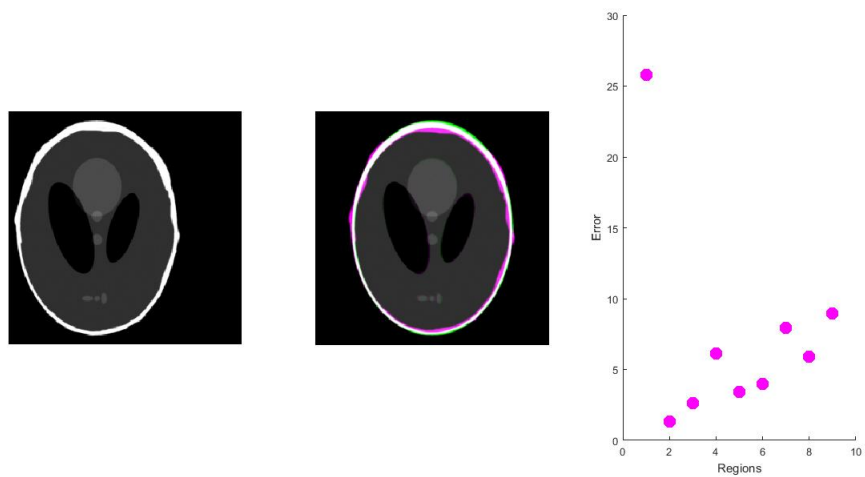


Figure 2.13. Translated Image Test

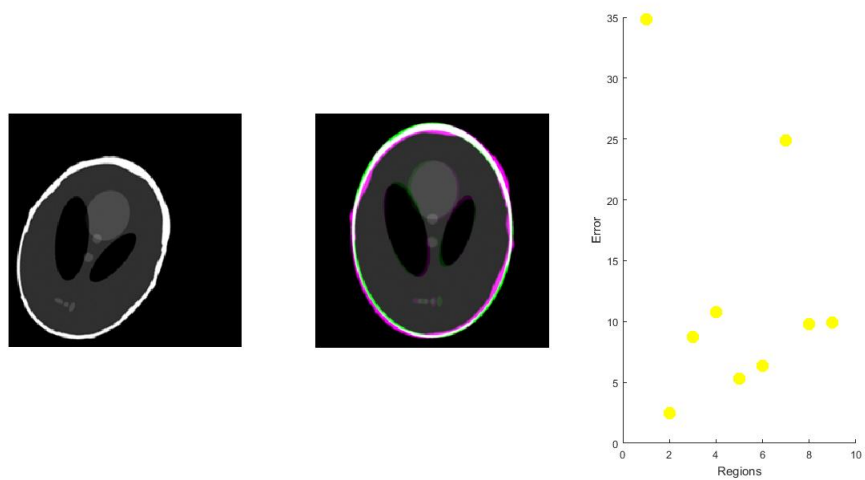


Figure 2.14. Registration Combination Test

CHAPTER THREE

Results

3.1 Web Page Usage

Completion of the PTrEPORT tool and web page allows all members of the Particle Computed Tomography Research Collective to access the previously collected data, add newly collected data sets to the database, and to process the data to arrive at the final result. This system will eliminate many system “bottle necks” in data upload and organization and eliminate the possibility of mislabeling or misstoring data sets. Any user is now able to perform data preprocessing and image reconstruction with their own desired input parameters without relying on one or two individuals to find time to run the code for them. It also ensures that as each member of the collective develops their own portion of the process, they have access to all of the data and images they require.

Upon reaching the web page, the user is greeted with the welcome screen shown in Figure 3.1

After proceeding to the next page as shown in Figure 3.2, the user is asked to provide a preassigned username. The web server checks the database to determine whether the user is authorized, and if so, provides access to the main search page. This user authorization method is not primarily for site security, but rather for determining which user is making changes and processing data. This allows the system to keep more accurate records of changes made to data for future troubleshooting and record keeping. The required user name does have the added benefit of deterring those who stumble across the site in error however, in the future rendition of the PTrEPORT tool, a more thorough user authentication will be performed via Globus’ services as described in the Future work section of this report.

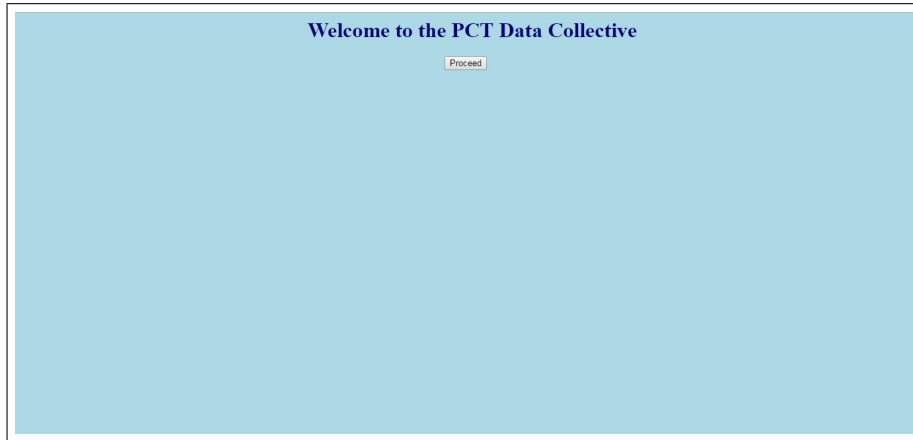


Figure 3.1. Welcome Screen

 A screenshot of a web application's sign-in screen. The background is white. At the top center, the text "Please Sign In" is displayed in a bold, black, serif font. Below this, on the left side, is the text "Please enter your username:" followed by a text input field. Underneath the input field are two buttons: "Submit" and "Reset". A horizontal line separates the sign-in section from the rest of the page.

Figure 3.2. Sign In

 A screenshot of a web application's search criteria screen. The background is white. At the top center, the text "Search Criteria" is displayed in a bold, black, serif font. Below this, on the left side, is the text "Welcome smccarty from BU". To the right of this text is a button labeled "Upload Data". Below the welcome message are several search filters: "Submit" and "Reset" buttons; "Facility: All Facilities" with a dropdown arrow; "Technology: All Technologies" with a dropdown arrow; "Data Source: All Sources" with a dropdown arrow; "Objects: All Objects" with a dropdown arrow; "Data Collection Date Between:" followed by two date input fields in "mm/dd/yyyy" format separated by "And"; "Particle: All Particles" with a dropdown arrow; "Energy: All Energies" with a dropdown arrow; and a "Keywords:" input field with a note "(Keywords must be separated by semicolons ; and must contain no white space)".

Figure 3.3. Search Home

Figure 3.4. Upload Home

Upon coming to the Search home page shown in Figure 3.3, the user is given the option to start performing a search or switch to the upload data page. If the upload data button is selected, the user will be redirected to the screen shown in Figure 3.4. The upload screen allows the user to search through the files on the user’s system and select the file(s) they wish to upload. They are then required to select a data type which will determine the file options presented to the user as well as the destination table in the database. Figure 3.5 shows the options presented to the user after selecting the “Raw Data” option. While there are a significant number of options available to the user, those that are required are shown on the top half of the page and the optional parameters are displayed in the second half. The required attributes to be set include the collection facility, the collection date, whether the data was experimental or simulated, the data phase, the technology utilized, the particle used, and the object imaged. This is the data necessary to properly name, store, and locate the file. The optional parameters provide other information that is useful to interpret data and select the correct parameters for future processing.

After the parameters have been selected and submitted, the web server displays a database entry containing the provided information. An example for a raw data set is shown in Figure 3.6. If any of the parameters are incorrect, the user still has the

Attribute Selection

Please select the attributes associated with the chosen file.

Submit

Reset

Facility: All Facilities

Technology: All Technologies

Phase: All Phases

Data Source: All Sources

Data Collection Date: mm/dd/yyyy

Objects: All Objects

Particle type: Please select an option

Output Data: All Output Data Types

Analysis: All Analysis Types

Step Size: Please select an option

Energy: Please select an option

Region: Please select an option

Spot Size: Please select an option

Beam Type: Please select an option

Run Number: Enter the run

Run Tag: Enter any run

Run Angle: Enter the run

Job Permissions: Please select an option

Group Permissions: Please select an option

Public Permissions: Please select an option

Figure 3.5. Attribute Selection

Upload Verification

Confirm Data Upload

Data Type	Date Created	Data Source	Sim vs Ex	Phantom	Facility	File Name	File Location	Run Number	Run Tag	Run Angle	Step Size	Energy	Region	Spot Size	Beam Type	Particle Type	Phase	User	Group	File Permissions
Raw	20170223	ACT	Experimental	Alignment (Rod) Phantom	Baylor		home\www\uploads	0040	Inf	000	2	200	Inferior		Pencil	Proton	2	accuracy	BU	intervenew-

Figure 3.6. Verify Upload

Search Results											
Expand	Date Created	Data Source	Sim vs Ex	Phantom	Facility	Step Size	Energy	Region	Spot Size	Beam Type	Particle Type/Phase
	2015-05-16			Experimental	Calibration Phantom	0	0	0			2
<input type="checkbox"/> [Preprocess]	Raw	64	<input type="checkbox"/> [Expand]								
<input type="checkbox"/> [Reconstruct]	Preprocessed	4	<input type="checkbox"/> [Expand]								
	Reconstruction	0	<input type="checkbox"/> [Expand]								
	Images		<input type="checkbox"/> [Expand]								
	2014-09-11			Experimental	Calibration Phantom	0	0	0			2
<input type="checkbox"/> [Preprocess]	Raw	37	<input type="checkbox"/> [Expand]								
<input type="checkbox"/> [Reconstruct]	Preprocessed	12	<input type="checkbox"/> [Expand]								
	Reconstruction	0	<input type="checkbox"/> [Expand]								
	Images		<input type="checkbox"/> [Expand]								
	2014-07-20			Experimental	Calibration Phantom	0	0	0			2
<input type="checkbox"/> [Preprocess]	Raw	18	<input type="checkbox"/> [Expand]								
<input type="checkbox"/> [Reconstruct]	Preprocessed	10	<input type="checkbox"/> [Expand]								
	Reconstruction	0	<input type="checkbox"/> [Expand]								
	Images		<input type="checkbox"/> [Expand]								

Figure 3.7. Example Search Results

option to return to the previous pages and change the entered data. Upon selection of the submit button, the data file is moved to its final storage location and the database entry is loaded into the database as shown. The user can return to the home page and immediately search for and process the uploaded data.

Returning to the search home page, the user is presented with a variety of query options. The PTRePORT tool is designed to allow the user to find a group of related data corresponding to a single collection date rather than an individual file although this can be accomplished. Since in the majority of cases, the user will want to reconstruct an entire image rather than a single projection of the image, grouping by data set is the logical choice. Data groups can be located by specifying the desired data collection range, the object imaged, the particle technology utilized, the collection facility, whether data was experimental or simulated and/or the energy level. As expected, these parameters are the same as those required in the upload stage as they are the defining characteristics for a data group as a whole. The user also has the option to enter search keywords such as a file name or type to limit the results. After the parameters are specified, the user is directed to the search results page shown in Figure 3.7.

	Reconstructed	<input type="checkbox"/> Expand									
	Images	<input type="checkbox"/> Expand									
Expand											
Date Created	Data Source	Sim vs Ex	Phantom	Facility	Step Size	Energy	Region	Spot Size	Beam Type	Particle Type	Phase
2014-11-22	Experimental	Calibration	Phantom		0	0		0			2
Preprocess											
Row	File Name	File Location	Run Number	Run Type	Run Angle	User	Group	File Permissions			
<input type="checkbox"/>	Cal10.log	sim-pc-T_data_organized_data_Calibration_Experimental:14-11-22-0007-0012-Input-Cal10.log	220		0	Imported	NONE	rw-rw-r--			
<input type="checkbox"/>	Cal_0008_000.dat	sim-pc-T_data_organized_data_Calibration_Experimental:14-11-22-0007-0012-Input-Cal_0008_000.dat	220		8	Imported	NONE	rw-rw-r--			
<input type="checkbox"/>	Cal12.log	sim-pc-T_data_organized_data_Calibration_Experimental:14-11-22-0007-0012-Input-Cal12.log	220		0	Imported	NONE	rw-rw-r--			
<input type="checkbox"/>	Cal11	sim-pc-T_data_organized_data_Calibration_Experimental:14-11-22-0007-0012-Input-Cal11	220		0	Imported	NONE	rw-rw-r--			
<input type="checkbox"/>	Cal9.log	sim-pc-T_data_organized_data_Calibration_Experimental:14-11-22-0007-0012-Input-Cal9.log	220		0	Imported	NONE	rw-rw-r--			
<input type="checkbox"/>	Cal10	sim-pc-T_data_organized_data_Calibration_Experimental:14-11-22-0007-0012-Input-Cal10	220		0	Imported	NONE	rw-rw-r--			
<input type="checkbox"/>	Cal11.log	sim-pc-T_data_organized_data_Calibration_Experimental:14-11-22-0007-0012-Input-Cal11.log	220		0	Imported	NONE	rw-rw-r--			
<input type="checkbox"/>	Cal_0011_000.dat	sim-pc-T_data_organized_data_Calibration_Experimental:14-11-22-0007-0012-Input-Cal_0011_000.dat	220		11	Imported	NONE	rw-rw-r--			
<input type="checkbox"/>	Cal_0009_000.dat	sim-pc-T_data_organized_data_Calibration_Experimental:14-11-22-0007-0012-Input-Cal_0009_000.dat	220		9	Imported	NONE	rw-rw-r--			
<input type="checkbox"/>	Cal7	sim-pc-T_data_organized_data_Calibration_Experimental:14-11-22-0007-0012-Input-Cal7	220		0	Imported	NONE	rw-rw-r--			
<input type="checkbox"/>	Cal12	sim-pc-T_data_organized_data_Calibration_Experimental:14-11-22-0007-0012-Input-Cal12	220		0	Imported	NONE	rw-rw-r--			
<input type="checkbox"/>	Cal_0010_000.dat	sim-pc-T_data_organized_data_Calibration_Experimental:14-11-22-0007-0012-Input-Cal_0010_000.dat	220		10	Imported	NONE	rw-rw-r--			
<input type="checkbox"/>	Cal7.log	sim-pc-T_data_organized_data_Calibration_Experimental:14-11-22-0007-0012-Input-Cal7.log	220		0	Imported	NONE	rw-rw-r--			
<input type="checkbox"/>	Cal8	sim-pc-T_data_organized_data_Calibration_Experimental:14-11-22-0007-0012-Input-Cal8	220		0	Imported	NONE	rw-rw-r--			
<input type="checkbox"/>	Cal9	sim-pc-T_data_organized_data_Calibration_Experimental:14-11-22-0007-0012-Input-Cal9	220		0	Imported	NONE	rw-rw-r--			
<input type="checkbox"/>	Cal_0007_0000.dat	sim-pc-T_data_organized_data_Calibration_Experimental:14-11-22-0007-0012-Input-Cal_0007_0000.dat	220		7	Imported	NONE	rw-rw-r--			
<input type="checkbox"/>	Cal_0012_000.dat	sim-pc-T_data_organized_data_Calibration_Experimental:14-11-22-0007-0012-Input-Cal_0012_000.dat	220		12	Imported	NONE	rw-rw-r--			
<input type="checkbox"/> Reconstruct											
	Preprocessed	0							<input type="checkbox"/> Expand		
	Reconstruction	0							<input type="checkbox"/> Expand		
	Images								<input type="checkbox"/> Expand		
Expand											
Date Created	Data Source	Sim vs Ex	Phantom	Facility	Step Size	Energy	Region	Spot Size	Beam Type	Particle Type	Phase
2015-02-14	Experimental	Calibration	Phantom		0	0		0			2
Preprocess											
Row	16	<input type="checkbox"/> Expand									

Figure 3.8. Example Search Results-Expanded

Each data group is organized under a header specifying the defining parameters for the data set. Underneath that header are rows for the corresponding raw data, preprocessed data, reconstruction data, and resulting images. In the second column of each row, the number of files in that “folder” are displayed. This allows the user to, at a glance, determine whether specific data has been processed in a certain way. These rows can be expanded to view each individual file of a specific type as shown in Figure 3.8. Once Globus is integrated, the web server will allow the user to select and download specific files to their personal computers for development, viewing, and testing purposes. In this iteration of the PTRePORT tool, after viewing the data, the user has the option to process some or all of a selected file group. The user can either check the box next to a non-expanded folder and process the entire group at once or may select individual files from the expanded folder for processing. Upon submission, the user is taken to the processing screen shown in Figure 3.9 and Figure 3.10. Figure 3.9 shows the options presented to the user upon selecting raw files to preprocess while Figure 3.10 shows the options available for reconstruction of preprocessed files. Regardless of the selection, the user is presented with the available parameters for the appropriate method of processing as well as the desired file permissions for the resulting files.

Process Files

You have chosen to preprocess 2 raw file(s).

Run

Reset

File Permissions for You:

Read Only

File Permissions for Your Group:

Read Only

File Permissions for Everyone Else:

Read Only

The closest Calibration Files Available are the following. Make sure these are acceptable before continuing

Select	Name	Location	Date Created	Facility
<input type="checkbox"/>	Wcalib.txt	ion-pCT_data_calibration_files.p_Facility_20150516-0061	Wcalib.txt	2015-05-16
<input type="checkbox"/>	Wcalib.txt	ion-pCT_data_calibration_files.p_Facility_20150516-0038	Wcalib.txt	2015-05-16
<input type="checkbox"/>	Wcalib.txt	ion-pCT_data_calibration_files.p_Facility_20150516-0062	Wcalib.txt	2015-05-16
<input type="checkbox"/>	TVcon.txt	ion-pCT_data_calibration_files.p_Facility_20150516-0061	TVcon.txt	2015-05-16
<input type="checkbox"/>	TVcon.txt	ion-pCT_data_calibration_files.p_Facility_20150516-0060	TVcon.txt	2015-05-16
<input type="checkbox"/>	Wcalib.txt	ion-pCT_data_calibration_files.p_Facility_20150516-0060	Wcalib.txt	2015-05-16
<input type="checkbox"/>	Wcalib.txt	ion-pCT_data_calibration_files.p_Facility_20150516-0059	Wcalib.txt	2015-05-16
<input type="checkbox"/>	TVcon.txt	ion-pCT_data_calibration_files.p_Facility_20150516-0059	TVcon.txt	2015-05-16

Figure 3.9. Preprocessing Options

Process Files

You have chosen to reconstruct 2 preprocessed file(s).

Run

Reset

Enter a lambda value:

Use runc?

No

File Permissions for You:

Read Only

File Permissions for Your Group:

Read Only

File Permissions for Everyone Else:

Read Only

Figure 3.10. Reconstructing Options

For preprocessing, the user is asked to select the appropriate calibration files. These files are developed by the medical physicists on the project and specify the appropriate calibration parameters for the day the data was collected. The calibration files should ideally have the same collection date and facility as the data to be preprocessed. Both a Wcalib file and a TVcorr file are required for successful preprocessing. The user is also asked to specify the file permissions for the resulting files, allowing them to create files that could be read only for example for other users or groups.

For Reconstruction, the user is asked to specify the desired reconstruction parameters. The reconstruction code allows for over one hundred and fifty parameters to be specified but the web server currently only allows the user to specify the most commonly used. The framework is in place for parameter specification and other parameters can be easily added to the list of options in the future if requested. The file permissions are also requested for the reconstruction files and images that will result.

Regardless of selection, upon submittal of the parameters, the user is brought to the processing results screen shown in Figure 3.11. Once the user arrives at this page, the command is sent to Kodiak to begin the processing of the selected files with the specified attributes. The web page updates to keep the user notified of which files are being processed, displays any errors that result, and finally displays an example of the final product's database entry. This entry contains the parameters associated with the selected files, as well as the new name and location of the result files along with the date of processing. At this point, the data is already created and sorted on Kodiak but has not yet been stored in the database. If the user does not choose to store the file results, the files will still exist but will be unsearchable via the web server. If the results are stored, they will be immediately available for viewing or further processing via the original search menu.

Run Results

Currently preprocessing HeCIRSPHPQ_0042_inf_016.dat.
HeCIRSPHPQ_0042_inf_016.dat was preprocessed successfully.

Data Type	Date Created	Data Source	Sim vs Ex	Phantom	Facility	File Name	Preprocessed Date	File Location	GEANT4/TOPAS	Code Version Used	Step Size	Energy	Region	Type Beam Size Type	Particle Type	Phase	User	Group	File Permissions
Preprocessed	2016-12-03	Experiment		HN15 CIRS Pediatric Head Phantom, Original		ix_0_0.txt	02222017	icu-pCT_data/balium/Preprocessed/0042_inf/02222017/ix_0_0.txt	GEANT4		0	0		0	balium	2	uncertainty	BU	r--r--

Figure 3.11. Example Run Results

This concludes the walk-through of the options available to the user in the current rendition of the tool. Further expansion and development of the tool is detailed in the Future work section of this report.

3.2 Preprocessing and Reconstructing an Image

Using the web server to send the pertinent information to Kodiak and instructing the system as to the input parameters, file locations, and output folders, the web server was able to preprocess and reconstruct various images. Though the code used to perform these tasks was developed by researchers throughout the PCT Research Collaborative, a brief overview of the process will be discussed here as it relates to this project.

The preprocessing code utilized by the PTRePORT tool was finalized by Robert Johnson, a member of the collective working out of the University of California, Santa Cruz. The preprocessing stage of the data reconstruction is responsible for taking the raw data and preparing it for the reconstruction step. The raw data sets contain the locations of the particles passing through the detector plates and the residual energy of each particle. This information is used to perform a number of steps. Information about particles that miss one or more detector plates or experience

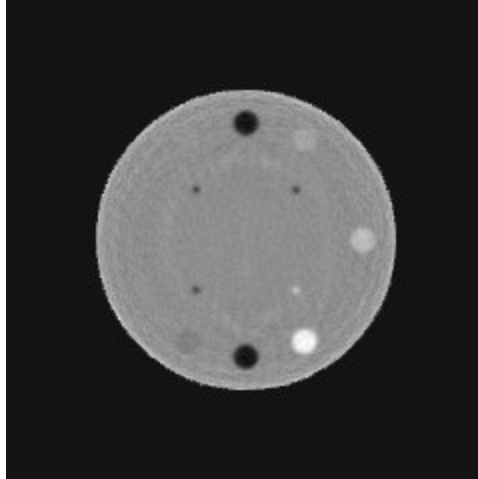


Figure 3.12. Example Reconstructed Image of a CTP404 Sensitom Phantom

a great loss of energy from close interactions with the nuclei of atoms is discarded. The retained paths and final energies of the particles are calculated and the results from each projection is stored in files sorted by run number and the angle the measurement was taken from. These files are then passed to the reconstruction software for the next phase of the process.

Refined by two Baylor students, Blake Schultz and Paniz Karbasi, the reconstruction script used by the system has been in use for a long time and is constantly being optimized and redeveloped by various researchers. The reconstruction code takes in a set of projection files from a single run generated by the preprocessing software and performs a number of steps to reconstruction. The details of these steps are discussed in other documents but in summary, the projection files are sent through a number of processing steps and then a filtered back projection of the image is performed. These processing steps include a calculation of the cord length of each voxel in the path, and a creation of a hull image. The output of the reconstruction code is a number of text image files from each stage of the process which, when converted to image files using ImageJ software, provide the final view of the imaged object. An example of one of these images is shown in Figure 3.12.

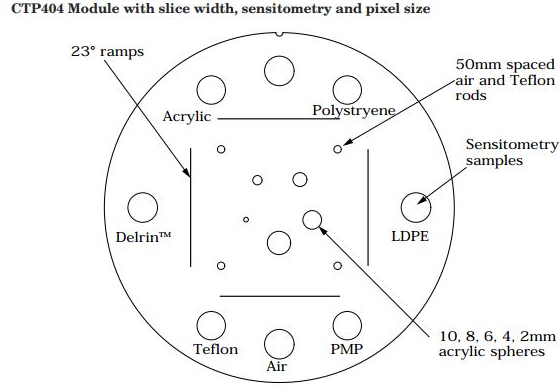


Figure 3.13. Diagram of the CTP404 Phantom. Copyright ©2006 The Phantom Laboratory

3.3 Image Quality Comparison

After completion and connection, the web page was used to preprocess and reconstruct raw data sets into their resulting image. These images were compared against a model image generated using X-rayCT using the “Image Quality Comparison in Selected Regions” software developed for this project. An example of the results is discussed here.

3.3.1 CTP404 Sensitom

The phantom imaged in this experiment is the CTP404 phantom manufactured by The Phantom Laboratory. The manufacturers design of the CTP404 is included as Figure 3.13 (20).

The model image selected for this comparison is a CT image of the CTP404 phantom. The model image is shown in Figure 3.14. The image to be compared comes from slice sixteen of the model after six iterations of the reconstruction software. It can be seen in Figure 3.15. Comparing the images by eye, it can be seen that each imaging method was more successful in rendering portions of the image. The pCT image does not image the leftmost acrylic, Delrin, and teflon inserts well but does render the interior acrylic inserts with more clarity than the CT image. Because CT

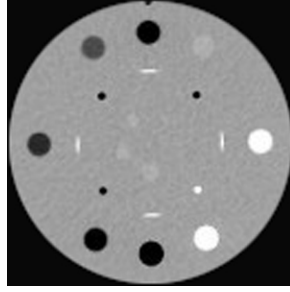


Figure 3.14. CTP404 Model Image

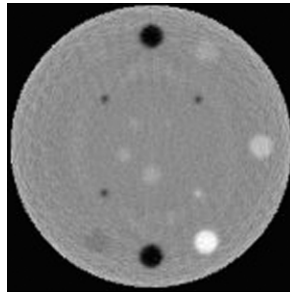


Figure 3.15. CTP404 First Result Image

is not a perfect method of imaging either, the strict difference between the images is not always a negative difference.

A mask image was created for the CTP404 model image as shown in Figure 3.16. The mask image was created to focus on the centers of the inserts as these are the areas of interest. The difference calculated between the model image and the pCT reconstructed image is shown in Figure 3.17.

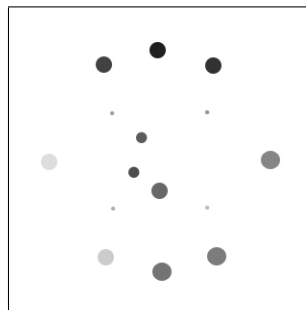


Figure 3.16. CTP404 Mask Image

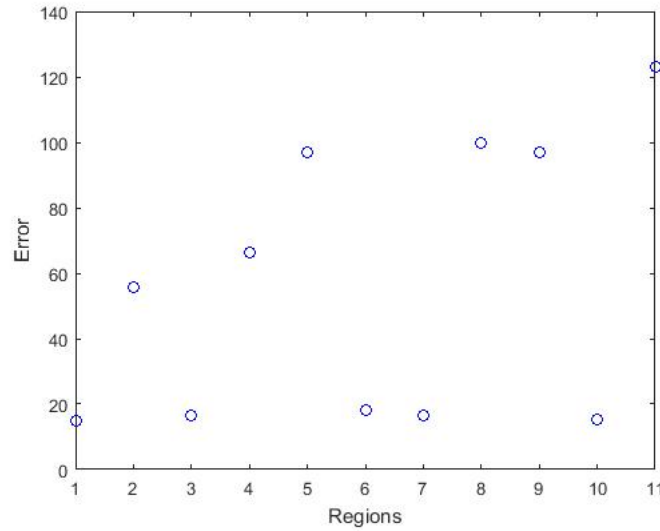


Figure 3.17. Differences Between Model and Reconstructed

It can be seen from the figure that the Image Quality Comparison program found eleven significant regions of interest to compare. The differences in the images can be seen at various levels of severity. While these results identify and locate the differences between the two images, for the singular case this is not the most helpful. For comparison between resultant images, however, it gives a quantitative assessment of comparison value. When the additional resultant image shown in Figure 3.18, from the eighteenth slice after twelve iterations, is run through the software, we can easily compare their similarities to the model. In Figure 3.19 the differences in the first image are shown in blue as before, compared the differences of the second image shown in red.

From the graph of the error, we are, at a glance able to compare the strengths of each image. Each is closer to the model image in selected regions with the largest difference taking place in region five. If researchers are interested in a certain region or material type, all it takes is a quick glance at the error graph to determine which method of reconstruction has produced the better image in a particular region, which is the purpose of this software tool.

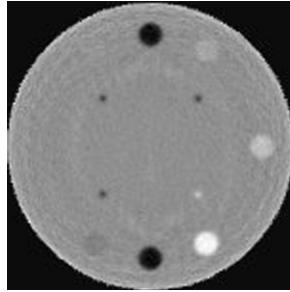


Figure 3.18. CTP404 Second Result Image

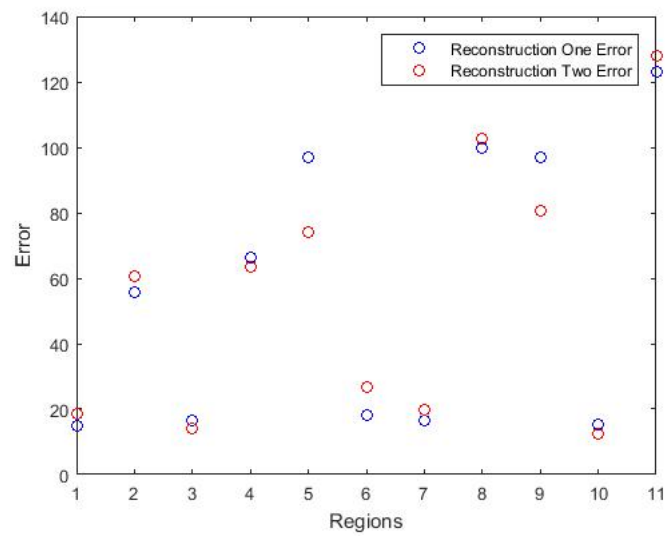


Figure 3.19. Differences Between Model and Reconstructed

As further research to be performed under the UT Southwestern grant, continued investment into optimizing the preprocessing step of the process will be made. There are many parameters that are input into the preprocessing code that dictate which of the particles paths are “good”. By adjusting these parameters, there is a trade off between the quality and quantity of information provided to the system. Research will be conducted on the optimal values for each of these parameters and the output images will be evaluated using this method. By comparing the reconstructed images against a single model image, the result image of highest quality will be easily located.

CHAPTER FOUR

Discussion

4.1 *Future Work*

4.1.1 *Project Refinement and Testing*

As the semester continues, there are a number of refinements to the system that will continue to be implemented. First, the overall appearance and functionality of the website will be improved through Cascading Style Sheets (CSS). CSS will allow the HTML forms and tables to be streamlined and organized in a manner that makes the system more user friendly. It will also take the web page from the stark black and white to a colorful design that is more professional in appearance.

Secondly, further testing of the system will be performed on a larger quantity of data sets with varying phantoms and particles. Although the actual preprocessing and reconstruction code was not altered through this project, further testing will continue to evaluate the effectiveness and accuracy of the system in selecting the correct parameter values and calibration files.

Finally, as discussed earlier, there is the potential for expanding the image quality comparison tool into a program capable of creating the ideal composite image. The program should be expanded to calculate mean error in each pixel and the standard deviation of these errors. By selecting the regions with the smallest differences from the model image from a variety of resulting images, the tool could then create a composite resulting image. This composite image would contain the highest quality portion of each image, returning an image of the highest possible quality from the existing resulting images.

4.1.2 PTRePORT 2.0

At this time, plans are being made for a version 2.0 of the PTRePORT tool to be developed in the coming years. This new version will host a few additions. The first is a integrated authentication system that will allow users to access the site using a more general username and password controlled by an external system. This process may be accomplished through Kodiak although it is more likely that Globus will be used to perform user authentication as well as file sharing. By integrating Globus' features into the web server, the system will allow direct, secure transfer of files from one group to another in addition to the upload system currently in use. A Baylor University Globus subscription has been added to the 2017-2018 Information Technology and Services (ITS) budget and will be integrated next year.

4.2 Conclusion

Though the Particle Computed Tomography research collective has been hard at work developing the process, the code base, and the product configuration, a great deal of time has been invested in managing data through an unreliable system. The system in place before this project consisted of a series of files in a twelve deep folder system that required each user to be familiar with and implement the associated naming and organization conventions. Confusion was common and information was lost through misplaced or mislabeled files. The new tool created through this project, the PTRePORT, seeks to solve those problems so that the research collective can focus on getting their product into the medical field in the next few years. By eliminating the previously required knowledge of the code and the organization system and the need to rely on the one or two individuals who knew how to perform a given step in the process, PTRePORT will permit any researcher to upload, and process the data into the results they need. PTRePORT removes these identified barriers while still allowing researchers the ability to select individual files and input variables. By integrating a database, web server, and communication links to Baylor's computing

cluster, this project was able to enable each user to perform data collection, data sharing, while eliminating data confusion for the Particle Computed Tomography research collective.

APPENDICES

APPENDIX A

GitHub Repository

The code used in the development of the PRePORT tool can be located on github in the PRePORT-codebase repository available at

<https://github.com/pCT-collaboration/PRePORT>

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