INFORMATICS FOR HIGH-THROUGHPUT AND DISTRIBUTED ANALYSIS

OF MEDICAL IMAGES

By

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Thesis

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CHAPTER I

INTRODUCTION

Analysis of MR data typically involves interleaving numerous toolsets into a processing workflow. However, these toolsets may not be compatible, may not support all desirable file formats, or may be limited in their ability to interface with multi-processing computing environments or distributed resource management (DRM) systems. These limitations impede the ability of researchers to automatically process large data sets using state-of-the-art, computationally complex algorithms and associated workflows, thus inhibiting both the standardization of these techniques as well as the advancement of our understanding of MR data that will lead to improved processing techniques. The Java Image Science Toolkit (JIST)\textsuperscript{1}, released in 2010, addresses these issues by ensuring interoperability\textsuperscript{2}, generating graphical user interfaces\textsuperscript{1}, providing advanced batch processing tools, and, most importantly, requiring minimal additional programming or computational overhead.

Since its release, we have gained appreciation for the limitations of JIST and of the current state of MR analysis toolsets as a whole. In response, we recognize several opportunities to make JIST a more efficient, interoperable, and intuitive framework for large scale MR analysis. Integrating algorithms from alternate imaging frameworks fosters collaboration and innovation amongst researchers\textsuperscript{2}; generalized grid access and efficient resource requirement prediction realizes large scale batch operations that would otherwise be infeasible. Our implementation of these goals has

\textsuperscript{1} B. Lucas, J. Bogovic, A. Carass et al., "The Java Image Science Toolkit (JIST) for rapid prototyping and publishing of neuroimaging software," Neuroinformatics, 8(1) 5-17 (2010).

\textsuperscript{2} K. Covington, E. S. McCreedy, M. Chen et al., "Interfaces and Integration of Medical Image Analysis Frameworks: Challenges and Opportunities," Biomedical Science and Engineering Conference, Oak Ridge, TN, 1-4 (2010)
significantly improved JIST as a viable tool for large scale image processing. Figure 1 describes the JIST architecture and our contributions.

In this thesis we describe two major extensions to the JIST functionality within Pipeline Layout Tool and the Process Manager. The Pipeline Layout Tool (Figure 2) provides a graphical interface to search for, arrange, and customize the input and output parameters for JIST pipeline modules. The resulting layout can then be loaded into the Process Manager (Figure 3), which allows real-time management of and feedback from JIST jobs, execution of dependent jobs in the correct order, and execution of batch processes in parallel. In our enhancements to the JIST framework, we improve upon JIST’s strengths, and work towards alleviating or eliminating many of limitations in the large scale image processing domain, allowing researchers to focus on large scale analysis and innovation rather than on volatile, low-level software interactions. Chapter II illustrates the challenges and opportunities for grid computing in large-scale MR analysis, describes the limitations of generalized grid interfaces and our solution to this constraint. Chapter III introduces a novel system for distributed estimation of run-time and memory resource constraints for individual jobs in a JIST workflow. Chapter IV describes a proof-of-concept implementation that adapts our grid access to apply it to the Phillips MRI scanner. Chapter V discusses these technologies and addresses avenues of future research.
Figure 1: The JIST architecture and its interactions with our three contributions to the JIST workflow.
Figure 1: The Pipeline Layout Tool. Algorithms from the menu can be dragged and dropped into the layout. Input and output parameters for each selected algorithm are populated here.

Figure 2: The JIST Process Manager. A dependency tree tracks which processes are ready to be executed. Processes that are ready are executed when they are next in queue, and when there are fewer jobs running than the maximum number of jobs if specified by the user.
CHAPTER II

CUSTOMIZABLE CLUSTER PROCESS CONTROL

Process pipelines created in the JIST Layout Tool often represent hundreds or thousands of individual jobs, each of which may take several hours to compute. While the Process Manager eliminates user overhead during execution by automatically scheduling processes in batch, it is often inappropriate to execute these computation-intensive processes locally. When first released, the JIST Process Manager relied on the Distributed Resource Management Application API (DRMAA)\(^3\) for task scheduling and resource assignment through the Process Manager, allowing complex processes to be executed through supercomputing resources when available. This feature significantly increases computation throughput by allowing more processes to execute simultaneously, and removes the resource burden from the experimenter’s machine which may be far less powerful than a processor on a supercomputer. However, while the Java DRMAA package is designed to handle Java bindings to grid process controllers, it assumes that the accessed grid architectures are relatively homogeneous. In the last several years modern DRM implementations have emerged, including the Oracle Grid Engine and the Torque Resource Manager, each prioritizing a highly customizable interface. Configuring DRMAA to manage execution of JIST processes on any users’ implementation of these DRMs is a daunting task that has proved unsuccessful. In the absence of a generalizable DRMAA implementation, grid processing has been limited to individual job execution through command line modules which require user knowledge of complicated Java classpaths. This solution does not support

batch operations, nor does it support those algorithms not classified by JIST as “Processing Algorithms,” which includes algorithms derived from other frameworks (see Section I), limiting both the scale and scope of processing operations.

Individual JIST users process data in radically different environments; even those who access supercomputing resources through the same DRM may encounter different configurations of that DRM which require different access parameters. However, these users do not require extensive network connections or access to multiple schedulers; instead they need to connect to a single grid computing interface, and are not required to have an extensive knowledge of grid access protocols. To facilitate a user base that may use different DRM configurations but have minimal knowledge about the specifics of their supercomputing resources, we require a light-weight, user-friendly protocol, that is abstract so that most grid configurations are accessible, but does not come preloaded with many different configurations that the user must choose from. These requirements are not facilitated by existing middleware – most of these interfaces bind only to a subset of common DRM implementations, or bind to many systems but require extensive user-side setup and significant user resources to maintain. For instance, the highly successful Globus Toolkit may provide the functionality required for JIST, but it also is capable of supplying data about operating system, hardware, and network load among many other features. The overhead of maintaining a JIST interface to Globus\textsuperscript{4} or another toolkit, as well as the added installation of a comprehensive solution, is beyond the scope of JIST’s grid access requirements.

As an alternative to a DRMAA implementation, and in lieu of a sufficient alternative middleware, we have designed a new cluster process controller that provides abstract access to

grid computing resources from JIST. Our implementation assumes (1) the user is executing JIST on a processor with access to a cluster and (2) this cluster can execute “qsub” and “qdel” commands. Typically users who have access to cluster resources are given disk space to read and write data to on a cluster executable processor. The former assumption requires the user to install JIST in this cluster-executable location, which may not be the default for the user, but eliminates the need for complex ssh logic. We have determined that this tradeoff significantly simplifies initial client-side system setup, and allows for more generalizable and maintainable grid access overall. More importantly, this assumption also improves data security, which is a primary concern when transporting medical imaging data. Portable Batch Script (PBS), a POSIX-compliant suite of commands, is supported by several popular meta schedulers and is compatible with “qsub” and “qdel” commands. Due to wide support for PBS, we believe the latter assumption affords a maintainable solution to grid process control without sacrificing portability.

Implementation and Applications

In order to generalize PBS job submissions, we have introduced a PBS template file (Figure 4) which is initialized with a PBS file that submits JIST jobs to the grid to be executed.

```bash
#!/bin/bash
#PBS -M covingkj@gmail.com
#PBS -m bae
#PBS -l nodes=1:ppn=1:x86
#PBS -l walltime=%WALLTIME%
#PBS -l mem=%MEMORY%MB
#PBS -o %OUTPUTLOC%%report.out
#PBS -e %OUTPUTLOC%%report.err
#PBS -j oe

xvfb-run -f %OUTPUTLOC%%xvfb-run -e %OUTPUTLOC%%null -a --server-args="-screen 0 1600x1280x24 -ac -extension GLX" %COMMAND% 
```

Figure 4: Template file which executes JIST jobs on the Vanderbilt ACCRE grid.
As visualized by Table 1, this template allows the user to specify grid-specific parameters, as well as additional commands specific to the user, while special variables (see Table 1) distinguished by “%%” characters are dynamically instantiated by JIST’s Process Manager for each process, providing seamless integration with the user’s PBS configuration. These variables represent known parameters that may depend on the experiment and process to be run.

<table>
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<tr>
<th>Variable</th>
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<tr>
<td>EMAIL</td>
<td>The email address that the grid should send notifications to.</td>
</tr>
<tr>
<td>MEMORY</td>
<td>The estimated memory requirements for the process.</td>
</tr>
<tr>
<td>WALLTIME</td>
<td>The estimated wall time requirements for the process.</td>
</tr>
<tr>
<td>OUTPUTLOC</td>
<td>The output location for process results.</td>
</tr>
<tr>
<td>COMMAND</td>
<td>The Java call specified by the JIST classpath and process command.</td>
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When a process begins, the Process Manager reads the template file specified by the user in the Layout Preferences Panel (Figure 5). JIST then creates a pbs file in the output directory for the process, replacing all variables with the correct values. Finally it submits the job specified by the new pbs file to the available cluster via the “qsub” command. If the user clicks the Stop or Stop All commands in the Process Manager, JIST submits a request to cancel the job via the “qdel” command.

Figure 5: The Layout Preference Panel. The user can specify the output location, heap and wall time estimates in lieu of Hypervisor prediction, as well as grid engine and hypervisor parameters (see Chapter III).
Often a user will need to track the progress of a job during execution, or determine why a job has failed. This can be done both through JIST and through log files found in the process’s output directory. Should the user wish to track the job’s status directly from the grid engine, the Job ID provided by the grid can be accessed through the JIST command line output, or via a text file in the process’s output directory. This Job ID can then be used to request information from the grid interface directly. The user can also track output and error data through the Process Manager interface, or through the log files in the process’s output directory. For example, the PBS file created by the template file in Figure 4 would log this data to the report.out and report.err files respectively. Access to this data both inside and outside JIST simplifies the debugging of template files and complicated workflows, as well as the diagnosis of potential grid interface issues.

Our PBS-based process control system has proven immediately useful to researchers, allowing large scale batch operations through JIST where previously only those workflows that could feasibly be executed locally were possible. This system also permits advanced quality control measures for JIST and JIST-supported algorithms by facilitating the efficient execution of batch unit tests on the ACCRE cluster. Finally, it provides an opportunity for us to enhance JIST’s resource scheduling and allocation mechanisms, which we describe in the following section.
CHAPTER III

CENTRALIZED PROCESS SUPERVISOR

Many of the DRM implementations considered in Section II require an estimate of the resource requirements (memory and wall time) that a process will consume. Users creating a grid engine work flow must make an estimate, which might be incorrect, or which may not be accurate for all jobs in the workflow. This inaccuracy can greatly impact efficiency when submitting to a grid engine scheduler; overestimating resource requirements could place an individual process lower in the cluster queue, while underestimating them loses time when the job has to be resubmitted. In large process trees both of these options could significantly increase the runtime of the tree as a whole.

In addition to cluster process controller described in Chapter II we have implemented a centralized process supervisor, called the Hypervisor, which provides memory and wall time estimates for each process individually with minimal user interaction. In the following sections, we describe the existing technologies that compose this service, the implementation and methods used to build the service and calculate accurate estimates, and provide an analysis of the convergence of the estimator on several workflows with several confidence thresholds.

Existing Technologies

An Apache Axis 2 webservice facilitates communication between JIST and the database server. Axis2 allows development of both client- and server-side code in Java, using Plain Old Java Objects (POJOs) which are converted automatically to Web Service Definition Language
(WSDL) messages⁵. These features allows rapid integration into JIST’s Java codebase and ensures future interoperability by placing client-side code directly into JIST.

A MySQL database stores usage statistics on a secure Ubuntu 64-bit virtual machine. MySQL is accessible from our server code through the java.sql library⁶, and is scalable to handle a reasonable estimate of our required throughput⁷.

VirtualBox⁸ houses our Ubuntu 64-bit virtual machine. This machine is secured by opening only the port required by Axis2 for communication.

Implementation

Message passing

Client-side code exists in several places throughout the JIST source code, allowing new execution contexts to request resource estimates, and finishing contexts to update the database with the inputs and resource usage of the completed process. Both types of messages are only sent if the user enables resource estimation and provides the IP address of the Axis2 server (Figure 5).

The Axis2 server-code receives these client messages and executes the appropriate routine. These routines call a MySQL database whose location is specified in the preferences of the Axis2 server-side implementation. An update request simply returns a Boolean value to the client confirming that the update was successful. An estimation request returns time and memory

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estimates as an integer array of size two. The client extracts these values and formats them to be compatible with the current JIST implementation.

Data Storage

The MySQL database creates a table for each algorithm it encounters named with the MD5 hash of the algorithm’s name. Estimation requests simply hash the algorithm name and request the data under this pseudonym. This ensures that table names will not exceed the 64-character limit imposed by MySQL.

Within an algorithm table, each column represents either an input or a resource requirement. Since the number of inputs varies based on the algorithm, while the number of resource requirement outputs provided by JIST is not, each column that represents an input is named as “inputX”, where X is a number, while resource requirement variables have specific names. The total number of inputs and outputs is limited by MySQL to 4096, and cannot exceed 65,535 bytes of storage. These constraints have not been found to limit the number of inputs logged for JIST algorithms.

Each row of the table represents a specific instance of the algorithm’s execution, and stores each of the execution’s inputs, and the observed resource requirements.

This storage scheme allows past executions to be rapidly compared with a proposed execution via the server’s resource estimation routine.
Resource Estimation

Run-time and memory usage predictions are still an active area of research, which in a general case can be inaccurate and error-prone. In light of the current literature, several different techniques for estimating run-time resource requirements were tested:

- Mean resource usage
- Exponential smoothing
- K-Nearest Neighbors

Mean Resource Usage and Exponential Smoothing

The mean of resource usage in previous runs of the same module as well exponential smoothing\(^9\) of this data were implemented, in the hope that a computationally simple solution would suffice for our performance requirements. Exponential smoothing is meant to overcome the disadvantages of taking a simple average, or of taking the longest observed time: while the simple average is less likely to greatly overestimate, taking the longest observed time greatly decreases the chances that a job will fail because the resource requirements were underestimated. This technique was chosen based on the assumption that users will tend to execute a module many times within shorter bursts, and these users will likely be processing somewhat homogeneous data sets. Thus, weighting the most recent data (theirs) strongly was assumed to be a better method than weighting previous jobs from different users or on different data sets. Taking a weighted average based on recent events is meant to overestimate less than taking the longest observed time while protecting more jobs from failure.

Unfortunately, this assumption provided only slight performance gains over the mean and random guess methods. Furthermore, contrary to our initial belief that recent data could serve as

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an indicator for resource requirements in the near future, our exponential smoothing method proved unable to learn over time and converge towards satisfactory performance.

K-Nearest Neighbors

Beyond these simple techniques JIST has a distinct advantage over many systems discussed in the literature regarding run-time predictions\textsuperscript{9,10,11}. The inputs to a JIST module are defined by the module-writer such that JIST knows the number of inputs as well as their individual labels and the data types. When a process is about to be scheduled by the Process Manager, the label, data-type and value of the inputs of the module that the process will execute are easily accessible. After execution, the inputs are still accessible in addition to information about the resources that the process required to run. Because the inputs and outputs for a given process are well-defined, and each process that executes the same module has the same number of inputs with the same labels and data-types, it is much simpler to aggregate usage statistics and to interpret those statistics before a process is scheduled than it is for many other systems. We have combined this key advantage with a K-Nearest Neighbors (KNN) implementation to derive the relationship between a process’s inputs and its resource requirements.


Methods

Definition of Estimation Success

For a resource estimation technique to be considered successful in our usage case, it must be able to perform moderately well with few training samples, and it must converge over the term of a typical JIST processing workflow. A user who engages the estimation module and sees failures or unusually long queue times will not be willing to continue using it; on the other hand it is reasonable to suggest that the estimator should be more accurate over time, and since a user may not process a similar workflow the next time they engage the module, some convergence should be evident during the lifetime of the particular workflow.

The initial accuracy of an estimator could be analyzed simply by considering the percentage of jobs that completed successfully. However, quantifying convergence towards a successful estimation, and an estimator’s success compared to an algorithm that is similarly accurate upon initialization, is more complex. If the resource requirements for a process are overestimated, the process may wait longer in queue before it can be executed. If underestimated, the process may be terminated by the scheduler before it can finish, and will have to be run again with a higher estimate of the resource requirements.

To provide a numerical comparison of different estimation techniques, we have constructed a unique cost function that penalizes both overestimation and underestimation, where the loss for a particular estimate is modeled as a function of the estimate. While it would be more precise to model overestimation as the time spent in queue with due to the actual estimate, versus how long it would have spent in queue given the true resource requirements, the latter cannot be determined accurately. For each resource requirement, wall time and memory, we model
overestimating the resource requirements of a process as the difference between what is estimated and what the true resource usage is,

\[ L(\theta) = \theta - t \]  

(1)

where \( \theta \) is the estimate and \( t \) is the true resource requirement. Both of these values are known after execution. Underestimating the resource requirements of a process is more complicated. The grid engine will allow the process to execute until the estimated resource consumption, \( \theta \), is reached, at which time the process will be terminated. In the case of an underestimated process, the Hypervisor does not attempt to re-estimate the resource requirements, because it will not necessarily have more reliable information about the process on a second pass. It is up to the user to determine the resource estimation for subsequent attempts to execute the process. Thus the loss function is represented by the resources used by the process before it is terminated on the first execution and the loss incurred by whatever function the user creates for estimating resource requirements successive executions, or:

\[ L(\theta) = \theta + L(f(\theta)) \]  

(2)

where \( f(\theta) \) is a user-defined function. Since this function depends on the user, we simplify the loss function for estimation in our analysis:

\[ L(\theta) = \theta \]  

(3)

Equations (1) and (3) model our belief that a user will prefer a slightly longer queue time to having to rerun processes, so that the goal for the estimation algorithm is to approximate the resource requirements as closely as possible without underestimating.
KNN Implementation

The inputs to our KNN implementation are the inputs of the module to be run, and whose outputs are the expected execution time and memory consumption of the module given those inputs. Since image data must be obscured to ensure subject privacy, only the dimensions of image inputs are sent to the Hypervisor. We assume that images that vary greatly in size may also have different resource requirements when processing them. While comparing the images themselves could provide more information on how the algorithm performs, we do not consider our assumption to be a major loss in data. A general distance metric for any two images would need to consider the algorithm that is being run – different JIST algorithms, and different image inputs within algorithms, may need different distance metrics. While this would increase overhead when increasing the library of JIST algorithms, simply comparing the image dimensions does not. We have made similar assumptions about configuration files, matrices, and non-numeric options – for these inputs we only compare whether or not they are identical. For numerical inputs, we use a Euclidean distance metric. These assumptions decrease complexity and improve maintainability, while still allowing the Hypervisor to report adequate estimations.

The ideal number of neighbors to choose may vary greatly from algorithm to algorithm; the number of training samples, the number of inputs to the algorithm and how much those inputs vary in user experiments cannot be reasonably determined \textit{a priori}. Thus in order to maintain flexibility in our implementation, we have chosen to take the $\sqrt{n}$ nearest neighbors which we assume will retrieve a sufficient coverage of a neighborhood without overfitting. Estimation is suppressed until there are at least ten training samples for a particular algorithm.

Finally, we have determined that for different workflows and experiments the user may require a different level of confidence that an algorithm will succeed based on the resulting
resource estimates. To provide this flexibility, we have added a threshold to the Layout Preferences Panel (Figure 5). For threshold values greater than or equal to one, the Hypervisor returns

\[ f(\bar{x}) = \max(x) \times \alpha \]  

(4)

for each resource requirement, where \(x\) is the array of the resource requirement for each neighbor, and \(\alpha\) is the user-selected threshold. For threshold values less than one, equidistant neighbors form finite Gaussian curves, which are then weighted by their inverse distance and summed with all other curves. The returned resource estimate represents the point on the resulting curve at which \(\alpha \times 100\) percent of the chosen set of neighbors would have succeeded.

**Typical Workflows for Analysis of Estimation Modules**

In order to cover a range of common experiments that would benefit from resource estimation, we tested two different workflows. The first (Figure 6) simply creates a mask over many images that have the same dimensions and thus appear to be identical to our estimator. This provides a homogenous process tree with several hundred instances to train the estimators on (Figure 6a), demonstrating the ability of our estimator to converge quickly to an estimation that succeeds for processes that will require similar resources. The second (Figure 6b) registers a large set of images to itself. Those processes that register an image to itself will take significantly less time and memory than others of its class, without providing the estimator with a clear numeric reason for this fluctuation. This workflow tests the ability of our estimator to manage a large number of inputs, which unlike the first workflow will vary for each process, as well as its performance under extreme fluctuations in resource requirements that will not have an obvious numerical difference associated with it.
Figure 6a: Layout for the Create Mask algorithm.

Figure 6b: Layout that registers a specified dataset to itself.
Results and Discussion

In order to test both the convergence of the Hypervisor on multiple workflows and the proper threshold for different types of processes, the Create Mask and Registration layouts were tested with a threshold of 1.2, 1.0, and 0.8. Since we found that the resource consumption of the processes is deterministic, experiments were only processed once per threshold.

The Flirt and Vabra, and the Transform and Deform Volume algorithms within the Registration Layout were found to have similar properties; as such our analysis focuses only on the Vabra and Deform Volume processes within this layout. The first ten processes for each algorithm were executed independently of the others, to ensure that the jobs would have sufficient training data to receive estimations. After the first ten processes, the “Simultaneous Processes” value in the Layout Preferences Panel was set to 10 for the Create Mask Layout, and to 30 for the Registration Layout, to maintain the number of sets of processes allowed to converge to a reasonable estimation given that there are three times as many processes in the Registration Layout. The estimator converged rapidly however, so only the first 300 processes in the Registration Layout are analyzed here. Table 2 presents the results of these experiments, omitting the 0.8 threshold for Vabra and Deform Volume because processes were failing the majority of the time.

These results demonstrate two important messages: 1. with a well-chosen threshold, our implementation provides highly stable results with only a few training samples; 2. this threshold varies depending on the process type and the user’s preference for safety vs. lowered queue times. 1. Given at least ten training samples, a threshold of 1.2 allowed most processes to succeed. Note that since the major varying input for each of these process types is the image input, the neighborhood is relatively simple. While more complicated experiments might require
more training data, or a higher threshold, most workflows will not vary all of the parameters that
they are given. Because of this tendency, our observations are relevant to most JIST users. 2.
Workflows that require more resources, and those whose varying parameters more heavily in
impact resource usage, require a higher threshold for optimal results. For homogeneous
processes like those in the Create Mask Layout, a threshold of 1.0 results is dramatically lower
loss than those above or below 1.0. For more heterogeneous workflows, a higher threshold such
as 1.2 is more appropriate. A threshold below 1.0 does not perform as well, and may be most
useful in situations where it is less important that a process succeeds, and more important that is
start at a better position in the grid engine queue.

TABLE II
HYPERVERISOR EXPERIMENTAL RESULTS

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<th>Average Wall Time Loss (ms)</th>
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CHAPTER IV

HIGH-THROUGHPUT BUNDLED RESOURCE IMAGING SYSTEM

Picture Archiving and Communication Systems (PACS) enables systematic and verifiable tracking, access, visualization, and data providence for medical imaging data throughout the healthcare information management system from acquisition to interpretation, especially for three- and higher- dimensional imaging techniques, such as magnetic resonance imaging\textsuperscript{12}. These pervasive informatics platforms serve as ideal targets in which to integrate and evaluate new analyses and techniques for eventual inclusion in patient care\textsuperscript{13}. Advanced integration of PACS system throughout the entire chain of care is an active area of informatics research and engineering development\textsuperscript{14}.

A variety of imaging frameworks have emerged to fit the needs of research groups both in terms of functionality and visualization capabilities\textsuperscript{1,15,16,17}, while a multitude of specialized image analysis techniques remain largely in the hands of their creators and collaborators. Integrating these techniques, and bridging the gap between these emerging image analysis technologies and those technologies ready for clinical research and patient trials, is a

\textsuperscript{13} T. Yoshinobu, K. Abe, Y. Sasaki \textit{et al.}, “Data Management Solution for Large-Volume Computed Tomography in an Existing Picture Archiving and Communication System (PACS),” J Digit Imaging, (2009).
monumental effort\textsuperscript{18,19,20,21}. Here, we explore a set of technologies which could allow for earlier feedback of clinical collaborators on emerging technologies and facilitate collaborations between imaging researchers, who typically develop methods using custom software platforms, and clinical researchers, who typically prefer established visualization and analysis approaches afforded by PACS-centric systems.

Custom image post-processing in the clinical as well as the research medical imaging setting is often limited by the separation of the processing from the image acquisition hardware platform that connects to the institution’s PACS. The separation decreases the chances that the post-processed images will ever be entered into the PACS and creates an obstacle for routine usage and acceptance of the available post-processing algorithms. For example, novel image reconstruction techniques often require substantive changes to the software pipeline within the image reconstruction environment. PACS systems are typically not configured to provide seamless acceptable, transmission, and access the raw data (prior to reconstruction), so it is often not possible to use a PACS system to archive the requisite non-imaging data and meta-data necessary for reconstruction. Hence, an alternative data processing workflow must be constructed, which can involve error-prone human-machine interaction (e.g., numerous clicks). Finally, the alternative workflow must be configured as a DICOM send node and must retain institution specific accession syntax (which requires additional meta-data and programming) and must be authorized to transmit data to the central PACS server (which may conflict with institutional security policies).

To address this problem, we developed a high-throughput bundled resource imaging system (HUBRIS) for integrated medical imaging analysis which directly interfaces with the scanner and injects custom image analysis results into the PACS pipeline at the point of acquisition. HUBRIS extends the Philips Research Imaging Development Environment (PRIDE, Philips Healthcare, Best, The Netherlands). Using HUBRIS, three distinct systems (the image acquisition equipment, image post-processing algorithm workflow server and algorithm execution server) seamlessly communicate to provide advanced image post-processing directly from the medical imaging equipment. The images generated by this framework can be sent to the institution’s PACS in the same manner as other acquired images.

Methods

In this proof-of-concept case, the medical imaging equipment is a magnetic resonance imaging scanner (Philips Healthcare, Best, The Netherlands) running release 2.6.3.4 software or newer. The scanner is equipped with the inline PRIDE functionality that allows any user-defined executable or script to be invoked automatically upon the completion of an image acquisition. The automatically called process is passed a unique identifier that enables the process to extract the associated image volume from the scanner’s database. Additional parameters can be passed using the inline PRIDE process invocation. Upon completion of operation, the invoked inline PRIDE process can write resulting images to a pre-defined folder location. Images found in that location will be read automatically by the scanner’s software and imported into the scanner’s database to enable the new images to be easily sent to the PACS. Typically, inline PRIDE processes run on the scanner console computer and are restricted in memory and CPU usage. Furthermore, the available post-processing library and tools are limited to those that have been
compiled and provided for the scanner console computer’s operating system (Windows XP embedded 64-bit).

To increase the power and flexibility of the image post-processing workflow available directly from the scanner, we have integrated the Java Image Science Toolkit (JIST)$^1$ server with the scanner’s inline PRIDE capability to provide access to a large library of algorithms using JIST’s open application program interface (API)$^2$. JIST is an open-source, platform-independent framework to rapidly develop image analysis tools and distribute them to the scientific community. JIST provides a high level of interoperability, advanced batch processing tools, and requires minimal additional programming or computational overhead. Finally, to address the demands for memory and processing power by many of the algorithms, the JIST server is able to sends jobs to a supercomputer grid.

In this case, the processing power is provided by Vanderbilt’s Advanced Computing Center for Research and Education (ACCRE, $\text{http://www.accre.vanderbilt.edu/}$). ACCRE is an education/research grid High Performance Computing facility with a theoretical peak performance of 20 TeraFLOPS using approximately 3,000 interlinked x86-based core processors running 64-bit Linux. Compute nodes all have a disk drive and dual copper gigabit Ethernet ports, but hardware visualization capabilities are disabled. Resource management, scheduling of jobs, and usage tracking are handled by an integrated scheduling system by Moab/Torque.

Results

Figure 7 illustrates the data flow in the HUBRIS system. Running the “Start Hubris” tool in Inline PRIDE opens StartHubris.xml. These tools are defined with a simple, human readable eXtensible Markup Language (XML) definition file as shown in Figure 8. This file configures
PRIDE to call StartHubris.bat, which first calls the PRIDE-Leacher tool to pull the image data (or raw data) from the internal PRIDE database and copy it into the “tempinputseries” folder. While access to raw data is not a natural part of the in-line PRIDE feature, the unique identifier passed to the inline PRIDE invocation is enough information to query the scanner’s database and to extract raw data associated with a given MR imaging series. As long as the called script is able to go all the way from raw data to XML/REC image results, the inline PRIDE tool accepts the results even if the XMLRECleacher program is never used. However, in the cases where raw data is saved and there are some scanner produced images, those XML/REC files are a convenient template for stuffing in the new reconstruction results. Different configuration files with different default arguments can be configured to automatically run for differing modalities. While the scanner’s inline PRIDE feature is limited to serial execution, and as such inline PRIDE jobs cannot run simultaneously, multiple images and raw data acquisitions can be simultaneously processed by sending these to the “Stage Hubris” script.

Figure 7: HUBRIS dataflow diagram. The image acquisition device (left) automatically triggers a processing script with each scan event of a specific type. This script communicates with a JIST server (center) through a standard WSDL connection. In JIST stages the data and manages job submission to a parallel computing facility using the Sun Grid Engine (right).
Figure 8: Inline PRIDE interface configuration. Standard XML scripts define process events and allow for default parameters to be configured.

Figure 9: The JIST WSDL server provides XML encapsulation of algorithm discovery, self-documentation, algorithm submission, and response.

A (WSDL) Axis 2 server provides access to the JIST image processing server routines (Figure 9), and facilitates data transfer via client- and server-side Java methods that use Plain Old Java Objects (POJOs). The Axis2 server automatically converts these POJOs to WSDL XML, which clients use to access server data, and which the server stores on the Internet to be accessed by clients.
Once the data are extracted, a Java class HubrisClient, with WSDL support via Axis 2
libraries, is initialized and loads the data from the tempinputseries folder. HubrisClient is
designed to either automatically pass a predefined script along with the tempinputseries data to
the server, or in the absence of a script or server location information to load a graphical user
interface (GUI).

The GUI simplifies debugging and configuration of the client-server architecture. The
GUI allows the user to specify the IP address and port number for the Axis 2 server. Once
HubrisClient has successfully contacted the server, it uses Axis 2 WSDL messages to call Jist's
discover() method from a Java class HubrisServer, which is called by the Axis 2 server.
HubrisServer collects the results from discover(), and builds a list of available algorithms along
with their inputs and requirements. This list is returned to HubrisClient, which populates the GUI
with the possible algorithms (Figure 10a). Note that HUBRIS/JIST infrastructure detects any
custom modules installed on the server and exposes these functionalities to the client — even if
the client does not know a priori that such modules exist.

When the user clicks on a desired algorithm, a new window is created which lists all
available input arguments, notes which arguments are required, and allows the user to set the
desired input arguments (Figure 10b). The user can then choose to run the algorithm with the
appropriate input arguments, or generate the corresponding script for use in automatic run
configurations.
Figure 10. Client-side Hubris GUI. Server configuration and a clickable listing of algorithms available for processing on the server are made available to the user (left). Arguments to individual algorithm are customized by the user and then either submitted for processing or the corresponding script is saved for future use (right).

If the user elects to run the algorithm as defined, HubrisClient uses Axis 2 generated WSDL messages to call the RunAlgorithm method in the HubrisServer class on the server, to send the image data, and to provide any other necessary data as arguments as illustrated in Figure 11. RunAlgorithm parses the arguments and sends the request and all necessary data to JIST's run() method on the cluster, which calls the specified algorithm and returns the output to RunAlgorithm. The server sends the output back to HubrisClient, which writes the output data in an appropriate place. Finally PRIDEXMLRECleacher removes the original image data from tempinputseries to prevent a buildup of data on the server. For grid processing, HUBRIS invokes executables through the X virtual framebuffer (Xvfb, David P. Wiggins, The Open Group, Inc.) framework so that a software X session is available for algorithms which require access to visual
Figure 11: Inline PRIDE interface on the Philips MRI scanner (top) communicates with a JIST server running on a different computer (bottom) to send, processes, and retrieve imaging data.
elements (e.g., font handles or rendering libraries) even if the elements are not displayed on screen.

Image arithmetic is a simple example of HUBRIS functionality. In order to add two reconstructed images from the MRI console, the user sends the first image to a temporary location via StageHubris. The user can then send the second image via StartHubris, either by sending the image with a predefined HUBRIS script that sends the two images to the server and requests that the two images be added, or by running StartHubris with no commands. The latter will cause the HUBRIS GUI to be initialized, at which point the user can select the ImageArithmetic algorithm, leave the operation argument at its default (add), and input the locations of the images in the “inFirst” and “inSecond” arguments respectively. Finally the user selects “Run Algorithm,” at which point the image data and arguments are sent to the server, the server performs the operation, and the output data is returned to the tempoutputseries folder, which the user can then access. Figure 12 demonstrates an example of the potential use of HUBRIS for testing a novel off-line image reconstruction method for diffusion-weighted (DW) sensitivity encoding (SENSE) MR images. It compares fractional anisotropy (FA) map acquired using conventional single-shot (ssh) (Figure 12a) and new multi-shot (msh) EPI (Figure 12b) technique. Usually the evaluation of a new imaging method has been limited to specific users and systems due to relatively large volume of raw data and/or intensive user interactions and computations required for off-line image reconstruction. However, the use of HUBRIS system could provide more convenient environment for imaging scientists and clinicians by incorporating any conventional and emerging technologies within existing PACS system.
Figure 12. Example potential application of HUBRIS for the reconstruction of improved diffusion tensor imaging (DTI) fractional anisotropy (FA) maps using a multi-shot acquisition. The presented color maps from single-shot (a) and multi-shot (b) echo-planar imaging (EPI) data show multi-shot EPI exhibits reduced blurring and geometric distortions. The generation of the improved images requires a custom reconstruction algorithm that can be accessed by HUBRIS.
CHAPTER V

CONCLUSIONS AND FUTURE WORK

Given layouts that represent workflows that we might expect a user to process through JIST, the Hypervisor converges so rapidly to its estimate that we can rely on it for resource estimations after as little as ten samples processes. This is due to two key advantages that the JIST processing pipeline has compared to other systems that require resource estimates. 1. The inputs to an algorithm are known \textit{a priori}, and their types are fixed to predetermined JIST classes such as 3D integer points, matrices, configuration files, and image inputs. These input constraints are ideal for a nearest neighbor model. 2. In many user-designed layouts, only one or two out of as many as several dozen inputs will vary throughout an experiment. As a result, the dimensionality of the neighborhood for the experiment may remain low, and be populated quickly by processes that executed within the layout, yielding more accurate results early in the experiment. The addition of a user-selected confidence threshold provides flexibility between efficient queue times and safe resource predictions. While this threshold varies depending on the type of layout to be processed, a sufficient threshold can be determined by considering the properties discussed in our results.

While the results of this estimation technique are highly successful, it does not consider all variables that could influence resource consumption. Our current model aggregates all usage statistics for a given algorithm independent of the user who submitted it, which grid to which it was submitted to or if it was executed locally, and the hardware that executed the process.
Furthermore, the assumptions taken by our distance metric may not be ideal. All of these considerations are promising areas of improvement for our estimator.

In addition to cluster control and resource estimation within JIST, we have presented an advanced proof-of-concept workflow to enable seamless medical image post-processing invoked from a clinical magnetic resonance imaging scanner. The generated images can then easily be transferred to the institution’s PACS like any other typically acquired medical image. The system integrates three distinct systems: (1) the medical imaging acquisition hardware, (2) a JIST server to provide access to advanced open-source post-processing algorithms, and (3) a high-powered supercomputer to execute the requested algorithms. While obstacles still exist that prevent its release, the current implementation promises significant advances in the MRI processing workflow if deployed.
## Appendix A

### Create Mask Results, Threshold 1.2

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## APPENDIX B

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DEFORM VOLUME RESULTS, THRESHOLD 1.0

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