INSIGHT: A New R&D Program in Medical Image Data Processing from the Visible Human Project

Terry S. Yoo and Michael J. Ackerman
National Library of Medicine
National Institutes of Health
Bethesda, MD 20894 USA

Abstract. The National Library of Medicine, in partnership with the National Institute for Dental and Craniofacial Research, the National Eye Institute, the National Science Foundation, the National Institute for Deafness and Other Communication Disorders, and the National Cancer Institute, has founded a software consortium to support the creation of a public resource in high-dimension data processing tools. The initial emphasis of this effort is to provide public software tools in 3D segmentation and deformable and rigid registration, capable of analyzing the head-and-neck anatomy of the Visible Human Project data. The eventual goal is for the consortium to provide the cornerstone of a self-sustaining software community in 3D, 4D and higher dimensional data analysis. The consortium is committed to open-source code, public software including open interfaces supporting connections to a broad range of visualization and graphic user interface platforms.

1. Introduction

The creation of computer models of anatomy is an essential step in most medical simulation and visualization. However, the tools by which we register, segment, classify, and validate our anatomical models are often hampered by a lack of common research guidelines. Moreover, in the absence of accurately segmented data to serve as ground truth, validation of segmentation and registration algorithms often becomes a study in the comparison and contrasts of new methods against more established approaches. The results of such studies leave open questions regarding implementation details and parameter selection.

To surmount these problems, the National Library of Medicine (NLM), with its partner institutes: the National Institute of Dental and Craniofacial Research (NIDCR), the National Eye Institute (NEI), the National Institute of Deafness and Other Communication Disorders (NIDCD), the National Science Foundation (NSF), and the National Cancer

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Institute (NCI) are sponsoring a program to develop an application programmer interface (API) and first implementation of a segmentation and registration toolkit.

The goal of this initiative is to create a self-sustaining code development effort to support image analysis research in segmentation, classification, and deformable registration of medical images. Ultimately, we hope that this will be a public software resource that will serve as a foundation for future medical image understanding research. The intent is to amplify the investment being made through the Visible Human Project and future programs for medical image analysis by reducing the reinvention of basic algorithms. We are also hoping to empower young researchers and small research laboratories with the kernel of an image analysis system in the public domain. An objective of NLM and partner Institutes is to support development that will form prototypes for advanced applications based on the VHP data sets.

The evolving design of the toolkit includes future expansion to parallel implementations and large memory requirements. The software is being engineered to accommodate change by periodic and incremental modifications. These modifications are likely to be refinements to the existing methods and algorithms. Modifications may also involve the inclusion of new techniques as additional modules as advances in computer vision research and additional research funding become available.

A Research Consortium including partners in academia and in industry has been formed to carry this work forward. The prime contractors are: General Electric Corporate R&D, Kitware, Inc., MathSoft, Inc., the University of North Carolina at Chapel Hill, the University of Pennsylvania (the VAST Lab and the Department of Radiology), and the University of Tennessee. Subcontracts from the prime contractors have been extended to: Harvard Brigham and Women's Hospital, U. Penn's GRASP Lab, the University of Pittsburgh, and Columbia University. The prime contractors and their subcontractors comprise the software research consortium. A software architecture, an algorithm validation methodology, and performance metrics are being formalized. Further details of the architecture and the design philosophy of the software tools consortium will be presented at MMVR2000.

2. Background and History

The Visible Human Project was initially formed to collect data from human subjects to serve as a guidebook and baseline dataset in modern anatomy research and education. Data from two subjects, one male and one female, were collected through a variety of methods including the standard radiological techniques of X-ray CT studies, magnetic resonance imaging, and plain film radiographs. In addition to these conventional clinical studies, the subjects were frozen and sectioned at 1 mm (male subject) and 1/3 mm (female subject) intervals. The exposed surfaces were photographed with 35 mm and 70 mm film and digitized with an electronic camera. The resulting data has entered into wide-spread use in education, as well as in medical visualization and simulation research [1].

Despite the unprecedented detail in the Visible Human Project information and its demonstrated utility in conveying information about gross anatomy, deficiencies in the data compromise its use in the focussed teaching of specific areas of human anatomy. In February 1998, a workshop sponsored jointly by NLM and NIDCD explored the growing needs of the research and education community for more powerful digital tools and higher

resolution models of human anatomy. An initial mission for higher resolution data was expanded to include an in-depth analysis of the existing data, focussing on the anatomy of the head and neck. The meeting also recommended the pursuit of advanced image analysis software tools to accommodate future higher resolution data [2]. Many of these findings were confirmed through individual meetings at the Second Visible Human Conference, held at NIH in Bethesda, MD in October 1998. The demand for more powerful segmentation and registration tools was made clear during panel discussions and other exchanges during the conference [3].

The NLM and its partner institutes and agencies have begun a three prong effort within the Visible Human Project to address these new concerns. The first initiative will be the creation of a new, online, digital, head-and-neck atlas. This effort will exercise the male dataset from the Visible Human Project at its existing resolution. The project will demonstrate the utility of the existing data, providing a platform for new work in education and medical research. It should also serve to expose the flaws of the volume image arising from data collection artifact, indistinguishable tissue types from low contrast in the color and radiological data (suggesting the future use of staining procedures and wide-spectrum data collection), and morphological aberrations from the cryogenic procedure. The limits of the current resolution of the data should also become apparent. In a competitive, peer-reviewed bid process, NLM commissioned the VHP Head and Neck Atlas in a 24 month effort to the University of Colorado Health Sciences Center beginning in September 1999.

A second initiative in advanced data collection will be launched this fiscal year. Issues to be covered through this program include a reduction of data collection artifacts, suppression of morphological changes in subject anatomy during fixation, and staining and wide-spectrum methods for increasing tissue contrast. Other aspects of data collection may be explored as this effort evolves.

The third initiative is the software research program described here. A competitive, peer-reviewed request for proposals was issued in March 1999, and several contract proposals were collected at the end of May. Following the technical and business reviews, contracts were issued to six groups in September and October of 1999.

3. Design Principles

During the planning phases of this project, we solicited guidance to help structure the initiative. In particular, we have tried to learn from previous attempts in radiation treatment tools programs, computational geometry software repositories, and other efforts in unifying research in image understanding. A contract mechanism, rather than a grants program, was chosen to ensure the delivery of software and to help enforce quality control standards across multiple developers. In addition, we incorporated other advice into the framework of our research program and began our pursuit of our new software base with several guiding principles.

- A Commitment to Open Source
- Toolkits as a Software Engineering Philosophy
- Compactness
- Versatility
- Support
- Validation
- 3D

3.1. A Commitment to Open Source

NLM has taken the strong position that an essential vehicle for communicating software ideas is open access to source code. We recognize that many research communities become vested in a software system or product, often reducing the flexibility of software and sometimes the mobility of their personnel. Moreover, if new software is built on proprietary software foundations, the resulting new ideas are often difficult to port to other environments. A public toolkit is envisioned to encourage portable software ideas; open source is required to promote non-proprietary portable implementations as a means of communicating advanced ideas in medical image analysis.

Open source software is also considered an asset in computer science research and education. One of the most effective means of learning complex programming techniques is to read the program itself. Access to source code also encourages researchers to build upon the existing software base, making incremental refinements to the existing methods while reducing redundant work in basic programming of established methods. Thus open source software can assist small research groups which lack the means of supporting a large software infrastructure. Finally, since much computer science research is evaluated by comparing the precision, robustness, and efficiency of multiple programs, public software resources provide shared implementations that can be used as benchmarks; if that software is source-code accessible, differences in programming techniques can be normalized and more effective comparisons can be made. By committing this project to a policy of open source software, NLM will provide all future software accompanied with the written source files as part of the tool kit.

3.2. Toolkits as a Software Engineering Philosophy

Public software projects have failed through insufficient structure in their basic architectures. Others have been short lived in part because they were too closely tied to a particular system, user community, applications environment or hardware platform. NLM has chosen the concept of software toolkit, rather than software library or monolithic system, as the defining principle for its software development initiative. In this context, a *toolkit* is distinguished from a system as having an applications programmer interface (API) rather than a user interface. More than a library of system calls and routines, a toolkit has a unified software architecture that lends structure to the flow of data and process control mechanisms required to execute complex computations. To be effective and widely acceptable, a toolkit should be compact, self-sufficient (not requiring many other links to other software packages), and have a consistent API.

The promotion of this development effort as a toolkit distinguishes it from most previous sponsored programs: this project is not simply a software repository or library, nor will it result in a single programming environment or application system. All programs included in this effort will have a common, unified architecture, will adhere to particular coding standards and conventions within the consortium, and will comply with common style sheets that have been approved by the consortium members. If multiple software objects require similar functions or capabilities, those common elements will be built into base classes shared by the entire toolkit. The resulting toolkit should be modular, link-able to other code, and easily incorporated into other programming structures.

3.3. Compactness

Compactness is a corollary to the toolkit concept. We are not promoting a system, nor will this software be tied to a system. We are distinctly not developing plug-ins for a larger user interface or application. The resulting software should not have multiple dependencies requiring another software package unless a substantial fraction of the function of that library is required for a large common fraction of the toolkit. Under those circumstances, requiring the separate package will reduce the need for re-implementation of the necessary methods. The basic tenets of this program mandate that any required supplementary software package itself have a policy of open source and public distribution. Furthermore, the NLM project software should be easily installed. Compactness may even be extended to sub-modules, perhaps requiring only those modules required for the current task. Thus the eventual user would not need to link and load the complete toolkit, but only the required subsets of the tools as needed.

3.4. Versatility

The deliverables for this suite of contracts do not include user interface development, nor do they include visualization products. These programmatic decisions were not undertaken lightly and have their roots in project focus and funding realities. However, the absence of user interface and visualization support reinforces a principle of versatility for the toolkit. By not providing a focus for user interface development, each team is encouraged to connect the toolkit to its own research environment, providing a *de facto* testbed for the API. Systems such as the Vesalius project viewers (Columbia), 3Dviewnix (U. Penn. Radiology), and the Visualization Toolkit (vtk) (Kitware) have all already been promoted as visualization environments. Beyond these individual connections to the API, the consortium is actively considering the wrapping of toolkit functions in TCL and Java, facilitating access to the new tools from a variety of other systems.

NLM adheres to a policy of portable code. Both Unix and Windows based environments will be supported. The incorporation of other platforms is still being considered.

3.5. Support

The Project officers recognized early that other similar programs have failed for lack of computer and user support. Although the toolkit may eventually be sustained by an active user community, project officers emphasized early support and careful design of a software suite that *can* be supported. We accepted proposals that had strong components in systems architecture and systems integration. The technical evaluation team considered experience in supporting large collaborative software development programs a strong asset. Formal engineering practices such as bug lists, enforced accountability for bug fixes, regression testing, etc. were adopted early in the framework of this program. User training, courseware, tutorials, textbooks, and continuing software maintenance were encouraged as part of the software development initiative. Continuing maintenance and support awaits future funding, pending the success of the initiative, but NLM considers the support of the software a necessary element in the long-term success of this project.

3.6. Validation

Verification of segmentation and registration algorithms has grown throughout the project definition process to become a significant element of the program. Initial focus on software quality control has now been accompanied by an exploration of clinical effectiveness of computer vision methods. See Section 4. below.

3.7. 3D.

A pervasive and insidious exaggeration in visualization and image analysis research is that methods are easily generalized from 2 to 3 dimensions. The NLM is emphasizing the development and distribution of 3D segmentation and registration methods through this initiative. We recognize that 2D and 2½ D methods have been developed and are available as products as well as freeware. The growth of the size of medical datasets is making these methods untenable. When medical volume data is represented as a stack of 1,000 slices, visiting each slice or even every 10^{th} slice in a routine segmentation pass is unrealistic. In addition, registration of multiple medical datasets is inherently a 3D problem. Any incorporation and distribution of 2D methods in the segmentation and registration toolkit will be incidental in pursuit of 3D (and higher dimensional) methods for image processing.

4. Evaluation, Verification, and Validation

We wish to distinguish the software engineering principles of software verification (regression testing, style compliance, documentation integrity, and quality control) from the concept of validation of clinical effectiveness of any developed method. An exhaustive and elaborate infrastructure for the software control process is being constructed to support the diverse computer programming collaboration among the consortium members. Regression tests and documentation will be required from each contractor before any software deliverable is considered complete.

Beyond the testing of software to assure developers that given an input dataset, an answer can be generated and repeated, the usefulness of the answer also deserves scrutiny. We choose to evaluate software based on three criteria: precision (repeatability), accuracy (agreement with ground truth), and efficiency (computational complexity as well as the requirements for user input). Different methods will necessarily be useful for different imaging tasks. A separate design subcommittee of the consortium is charged with the mission to develop metrics to evaluate segmentation and registration methods along each of these axes, across a variety of applications. In addition, the metrics should be constructed so that meaningful comparisons can be made between programs, given the same user input and the same input volume.

5. Target Audience for the Toolkit

This project has by necessity not focussed on the end-user, but rather on the applications developer that supports the broader community. Nevertheless, the eventual end-user appears throughout all of the design decisions made so far. As validation metrics are proposed, architectural decisions are debated, and the need for parallel and distributed

computing components are questioned, the needs of the end user are constantly appraised. Beyond the software itself, the validation metrics may be one of the most important products of this research effort. Our design decisions have been intended to support the broadest possible audience possible given the initial premise that the software must be suitable for analyzing multispectral / multivalued medical volume image data represented by the Visible Human Project data.

The segmentation and registration software, like the Visible Human Project data, will be owned and distributed by the NLM. The software, including the source code, will be available on a no-cost basis.

6. Closing Remarks

As of this writing, the consortium has held its initial organizational meeting. Initial design decisions indicate a preference for an object-oriented, data flow architecture based on C++. A meeting of an Algorithm and Architecture Subcommittee of the full consortium is planned for January 2000 to continue the design discussion. The consortium is currently investigating how to support Java, TCL and other links through an open API. A Validation Subcommittee meeting is planned for March 2000, and the meeting of the full group will be reconvened in June 2000 to confirm the goals and rules developed by the subcommittees and commit the consortium to a common effort. Public distribution of most of the software is not expected until late in year 2002.

The NLM wishes to avoid any costly errors of previous publicly supported software development efforts. We are actively soliciting input toward guiding this development program to a successful culmination of software engineering talent and image processing expertise. The target is a powerful adjunct to the Visible Human Project data, a public software resource of image processing tools for exploring the data, for extracting visual and quantitative information, and for forwarding the selected information of interest to other software systems for analysis and display. Ultimately, we hope to found a common public forum where the software research community can exchange new ideas in image understanding by making current and future algorithms and methods available as source code. Our most ambitious hope is that this effort will gain wide acceptance, and the fledgling community will become self-sustaining: with users voluntarily contributing new ideas, algorithms, and methods, fixing bugs, and continuing the discourse on 3D, 4D, and higher dimensional data analysis. We hope to aid this future collaborative exchange by defining some common software engineering principles and creating a common software foundation.

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