Imaging Tools for the Visible Human

A Report to the Board of Scientific Counselors

May 13, 1999

Investigator:
Terry S. Yoo, Ph.D.
Office of High Performance Computing and Communications
Lister Hill National Center for Biomedical Communications

1 Abstract

The proposed project in image processing is a broad effort within the Lister Hill National Center for Biomedical Communications and the National Library of Medicine in the field of medical information processing. Non-print collections are some of the fastest growing areas in information archives. New methods for navigating, indexing, and understanding image information have become a critical need in the information sciences. Set within the context of the Visible Human Project, this proposed research program will improve existing strengths within NLM through the acquisition, development, and integration of image analysis tools. It will also augment current activities with related research in image processing theory. Finally, it will further the project mission through the study of image acquisition ideas, providing feedback for future data collection efforts.

2 Background

In 1989, the NLM Board of Regents empowered an ad hoc panel of experts to recommend the position that NLM should take in the rapidly evolving field of electronic imagery. In August of 1991, the University of Colorado School of Medicine was awarded a contract resulting in the acquisition of the NLM Visible Human Male and Female (VHP) data sets. NLM then made the data sets available under a no-cost license agreement over the Internet. The VHP male data set contains 1,971 digital axial anatomical images obtained at 1.0-mm intervals (15 Gbytes), and the VHP female data set contains 5,189 digital images obtained at 0.33-mm intervals (39 Gbytes). The optical data is supplemented by a complete series of clinical radiographic data including multiple MRI studies as well as X-ray CT images [Spitzer 96]. Since the introduction of the data sets and initial licensed use by over 1000 Worldwide participants, two VHP Conferences have been hosted by the NLM. These Conferences have highlighted the importance of sponsoring development of applications of the Visible Human project.

While the data from the Visible Human Project may be some of the most widely distributed and studied anatomical data, there have been several impediments to creating advances in the visualization of human anatomy. Efforts to use the combined information of the CT, MRI, and the optical macrotome sectioned data have been hampered by the difficulties in the registration of the multiple 3D datasets. In addition, computational methods that are capable of identifying objects from the synthesis of multiple types of data are still in the early stages of their development.

What is needed are new methods for computer assisted multimodal registration and segmentation or object identification. Registration and segmentation are inseparable issues, since the initial identification of the objects is the first step in aligning multiple datasets. What is not clear is how to handle the complex deformations required to align arbitrary datasets. Even the seemingly simple problem of aligning two datasets of the same patient acquired from different technologies, or even the same imaging modality at different times can be very complex. Differences in the growth of the pathological condition under study, changes between preoperative conditions versus postoperative analysis, or even radiological examination on a patient with a full stomach as opposed to an empty stomach can lead to large non-rigid deformations of the anatomical structures. Although the registration of rigid objects through affine transformations is a well studied problem, deformable registration and segmentation are still active areas of research [Bajcsy 89, Cohen 92, Szeleski 94].

Finally, advanced diagnoses based on the multimodal data will require new thinking about the presentation of multiple datasets. A common alignment will enable the synthesis of multiple values; however, the presentation of multi-valued data is not a well-defined problem. Even the relatively simple task of using and displaying color data is not obvious. Current methods for rendering the data from the Visible Human Project yield images that appear cartoon-like, with color distorting and not enhancing the exquisite anatomical information embedded within the data. New methods should be developed to take advantage of the deep structures that will be made available by the accurate alignment of the multiple data types of X-ray CT, MRI, and color optical sections.

3 Project Objectives

I propose to conduct research in the following areas:

1. Multiscale Image Statistics for Segmentation
2. Differential Geometry for Data Registration
3. Visualization of Multivalued Data
4. Data Acquisition

The four research areas, when studied collectively, are part of the same cycle. Figure 1 shows how these parts interact. An initial segmentation is required for an initial registration. If the combined information of the initial alignment of registered multiple sources of image data generate superior segmentation, that information can be used to refine the registration. Ultimately improvements in segmentation generates the potential for better registration. Subsequently, this enables better visualization. Improvements in the visualization of multivalued medical data are expected to drive new standards and better image acquisition technologies. Finally, increased resolution and new modalities such as functional/physiological information will require advances in registration, segmentation and display.

This project will focus on using the existing radiological data from the Visible Human Project to study the problems of multimodal segmentation and deformable registration. Advances are also expected in the use of color data applied to the rendering and visualization of the same data. In the later stages of this project, the resulting advances should suggest ideas for standard protocols for additional image acquisition techniques. Indeed, the demand for other datasets to validate the results of this research will necessitate the collection of other multimodal data to demonstrate the effectiveness of the new techniques in registration and segmentation.

4 Project Significance

The current datasets are only single artifacts similar to specimens in a museum. As such they cannot represent the breadth of variation in human anatomy. Meaningful comparisons and successful leveraging of the data depends on extending its life beyond anatomy and instruction to clinical applications. Clinical applications will require meaningful correspondences between patient data and the archetypes represented by the data from the Visible Human Project.

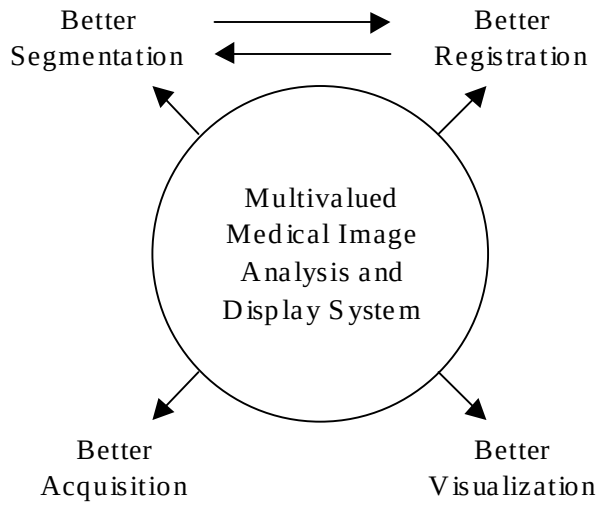


Figure 1. The elements of multivalued medical image display.

Ultimately, advances in computational methods for object identification and alignment would enable advances in visualization of clinical data of current patients. Anatomical atlases based on the data from the Visible Human Project could provide deep insights into patient conditions. The problems of aligning data between patients are even more difficult than within patient comparisons, yet the use of atlases to aid diagnoses requires quantitative comparisons rather than subjective information.

5 Methods and Procedures

I believe that a deep understanding for object shape will arise from a greater understanding of how the human mind perceives solid geometry. I choose as my model, the human visual system. This is not to say that I shall study psychology or neurology. Rather, I shall use as a model for object definition the human visual system, with its layers of increasing complexity from low level vision to higher more specialized cognitive function. I set aside the pattern matching methods of the connectionist schools of neural networks as being insufficiently rich to support the broad mission of object recognition. I will, however, borrow techniques from them from time to time.

This is a departure from the more common basic computational approaches where edge detecting filters and contrast enhancement algorithms are the goal. Object recognition implies several complex stages including object definition (sometimes called segmentation) and labeling (also called classification). These stages should include the multiple complex relationships between objects including the semantic relationships of function, connectivity, and form (e.g., the leg bone IS connected to the hip bone; however, the ball-and-socket joint is also part of the relationship).

5.1 Multiscale Image Statistics for Segmentation

My current research has been in developing *multiscale image statistics*, a new model for low level vision. This model has been developed as one of the scale-space approaches to low level vision. Specifically, I have been working to understand how an image understanding model can employ a

variety of resolutions governed by a regular tempered distribution, suggested by the Gaussian function as a regularizing sampling kernel. This approach precludes other approaches such as the coarse-to-fine pyramid analysis systems and wavelet based methods. Koenderink suggested applying a Gaussian filter at multiple apertures as a method for generating a rich higher dimensional space for analyzing structure. This mechanism has been suggested as a vehicle for emulating the overlapping visual fields of a retinal vision system [Koenderink 87]. Scale space methods are supported by an extensive mathematical structure [Lindeberg 92, Eberly 94]. Unlike related methods based on the scale-space derivative models of Florack and ter Haar Romeny, [ter Haar Romeny 91, Florack 94] my research incorporates local statistics of image intensities [Yoo 96].

Consider the input image of Figure 2. If the object is analyzed across the entire image, a histogram can be generated for all of the image intensities. Some conclusions can be generated regarding the

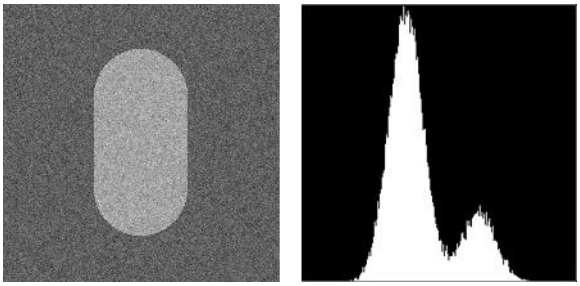


Figure 2. Test figure with global histogram. Left: Test figure is 256×256 with a background pixel intensity of 0 and a foreground value of 64. Additive uncorrelated noise has variance of 256. Right: the global histogram shows the asymmetric bimodal distribution of pixel intensities.

structure of the image, but the conclusions are limited since only global information is available.

However, if distributions of local neighborhoods within the image are considered, more specific conclusions can be drawn, and conjectures can be made that accurately describe the geometry of the image. Consider the same image with histograms extracted not from the whole image, but from individual regions. Figure 3 shows five histograms of five local regions from the image. When the local region is taken from only the foreground or only from the background intensities, a simple distribution with a single mode arises. When the local neighborhood is evenly balanced between object and background, a symmetric bimodal distribution is generated. Finally, when the number of foreground and background pixels is not evenly balanced, a skewed distribution results, with the skew favoring the pixel values that appear in greater number.

As the sample neighborhood smoothly varies its location, certain patterns arise. For example, a local region with a balanced bimodal distribution of intensities suggests a boundary between two regions. As the location of the local sampling region is perturbed, nearby locations with balanced bimodal intensity distributions are exposed. Following the set of all connected loci where this condition is met will extrude a perimeter where boundariness can be evaluated. Moreover, the histograms themselves suggest a means of determining the strength of that boundary, even relative to the noise in the image. The separation between the two modes can be captured and evaluated relative to the spread or dispersion of intensity values about the modes.

While the combined set of local histograms can be illuminating, it is both inconvenient and unwieldy

to generate and analyze a local histogram for each pixel in the image. A more compact description of the distribution of local image intensities is desired. One means of describing any distribution of samples is through the generation of its central moments, a series of descriptive statistics of the sample set. In the case of image analysis, *multiscale image statistics* not only capture the local intensity distribution, they can also be calculated directly from the image without the intermediate

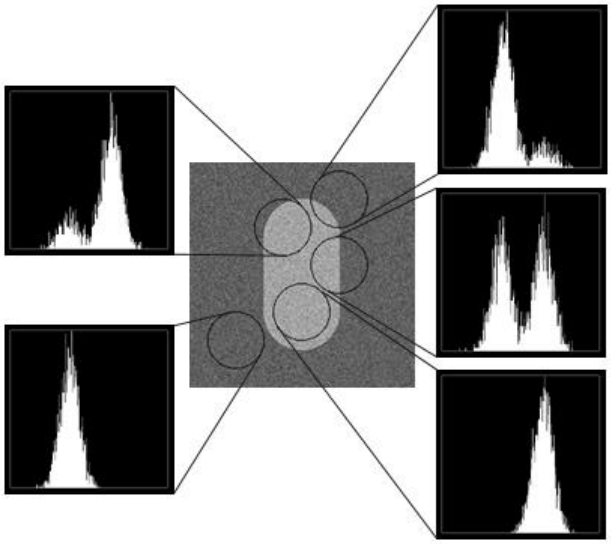


Figure 3. Test figure with local histograms. Histograms of pixel intensities shown for the local regions depicted by the gray circles. Note the changing symmetry of the local histograms depending on the overlap of the neighborhood, the figure, and the background.

step of first generating local histograms.

Consider the one-dimensional image in Figure 4.

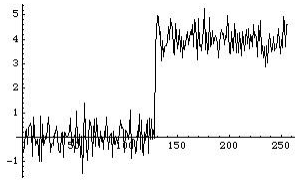


Figure 4. An example input Signal $\overline{I}(x)$ - a noisy 1D step.

Local means, variances, skews, and kurtoses can be computed for local neighborhoods within this input image. These statistics can combine to capture the histogram or probability densities of the local area of the image. Moreover, the size or aperture of the sampling kernel can be varied to create a multiscale representation of local image statistics.

Figure 5 shows the multiscale mean operator applied at four different scales. Figure 6 shows the multiscale variance operator applied at four different scales. Note that the maximum of the variance function localizes about the discontinuity and remains in the same location as scale changes. This behavior is similar to the gradient magnitude operator. Both are invariant with respect to rotation and translation, and both have similar responses to a given input stimulus.

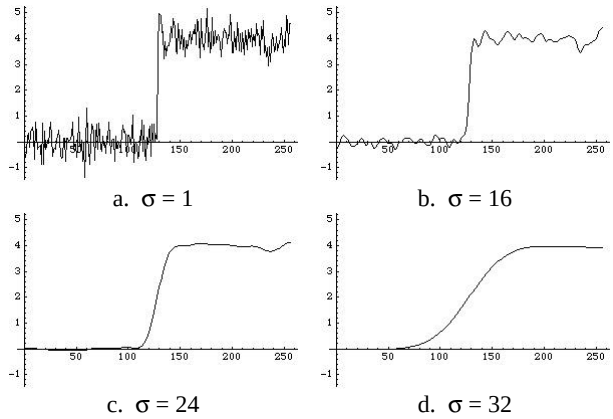


Figure 5. 1D multiscale mean operator $\mu_{\bar{I}}(x|\sigma)$ for the input function shown in Fig. 3. Four different apertures are applied (a. σ = 1, b. σ = 16, c. σ = 24, d. σ = 32).

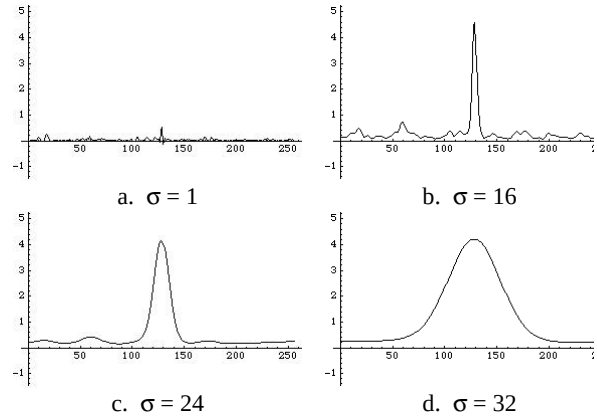


Figure 6. $\mu^{(2)}_{\bar{I}}(x \mid \sigma)$, 1D multiscale variance operator for the function in Fig. 3. Four different apertures are applied. (a. σ = 1, b. σ = 16, c. σ = 24, d. σ = 32).

Figures 7 and 8 show the multiscale responses of the 3rd and 4th order central moments of the function from Figure 4 respectively. The 3rd order central moment (reflecting skew) has a zero crossing at the locus of the discontinuity that persists through changes in scale. Similarly, the 4th order moment has a local minimum at the discontinuity which also persists through scale.

Figure 9 shows a noisy computer generated image of a teardrop shape. In the examples presented here, the term signal to noise ratio (SNR) will refer to the difference of the foreground intensity and the background intensity divided by the standard deviation of the additive spatially uncorrelated noise. The measured SNR per pixel within that image has been set to 4:1 on a raster resolution of 128 x 128 pixels.

The images of Figure 10 are four local statistical measurements made of the teardrop using an aperture whose spatial aperture is 3 pixels wide. Figure 10a shows the local mean values. Figure 10b shows the measured local variances. Figures 10c and 10d show the local third and fourth moments respectively.

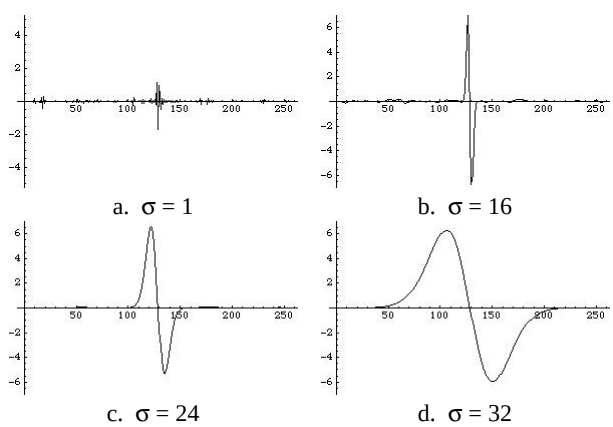


Figure 7. $\mu^{(3)}_{\bar{I}}(x \mid \sigma)$ 1D multiscale 3rd order central moment operator with four apertures for the function in Fig. 3. (a. σ = 1, b. σ = 16, c. σ = 24, d. σ = 32).

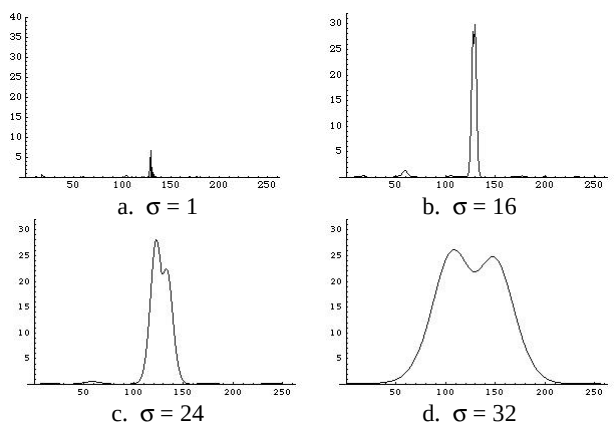


Figure 8. $\mu^{(4)}_{\bar{I}}(x \mid \sigma)$, 4th order central moment operator applied to the function from Fig. 3. (a. σ = 1, b. σ = 16, c. σ = 24,d. σ = 32).

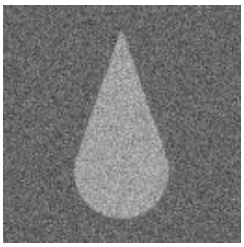
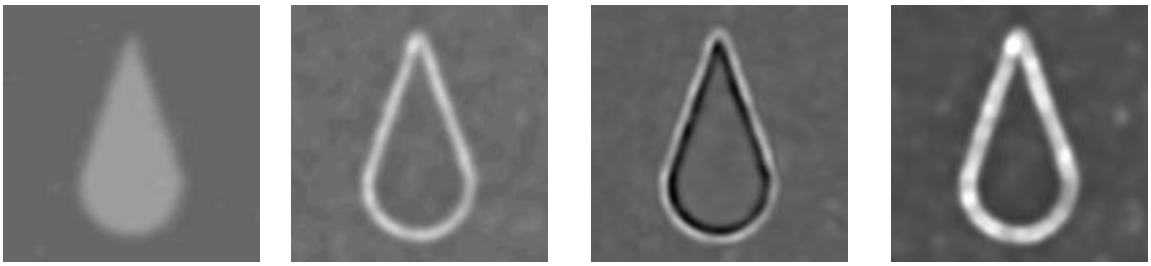


Figure 9. A 128 × 128 pixel Teardrop (SNR 4:1).

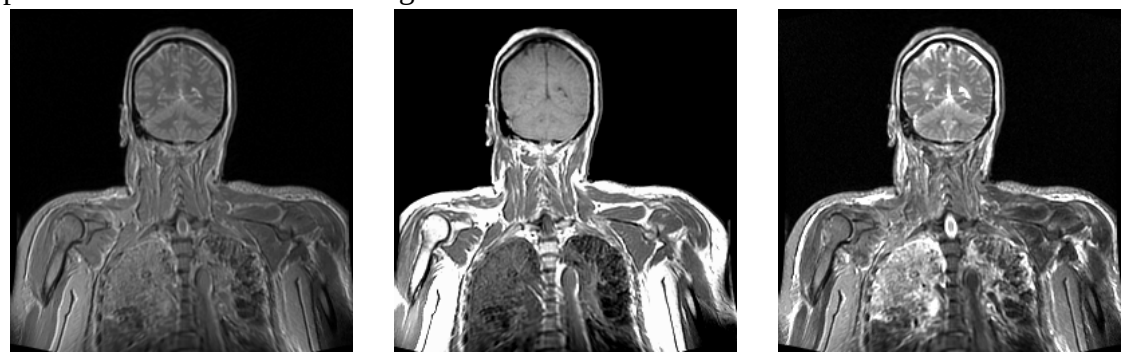
Figure 10 demonstrates aspects of multiscale statistical representations that are significant with respect to image processing tasks. The mean image is the input processed with a Gaussian filter. The variance image reflects edge strength and is analogous to the squared multiscale gradient magnitude of intensity. The third order local moment measurement has a locus of zero crossings along the boundary of the teardrop shape. This behavior is similar to the response of the Laplacian of the Gaussian on the same image.



a. k = 1 b. k = 2 c. k = 3 d. k = 4

Figure 10. Local statistical measures (k = order) of the teardrop from Fig. 9 (a: local means, b: local variance, c and d: local moments of the 3rd and 4th order).

Currently, this research has been applied to scalar valued medical data. One of the first goals of the proposed research project is to extend the use of these multiscale statistics to images with multiple values. Of particular interest are multi-echo MRI studies where the data are acquired simultaneously, so dataset alignment is not a problem. When such data are considered, additional statistics such as covariance, co-skew, and co-kurtosis must be accommodated. Figure 11 is an example of multivalued data showing one slice of a multi-echo MRI dataset.



a. Proton Density b. T1 weighted c. T2 weighted

Figure 11. One MRI slice of the Visible Human Project female data, acquired with different pulse sequences. The T2 weighted image has the best contrast for displaying fluid. The T1 weighted image has good bone definition. The Proton Density image has the best overall anatomy. The combined information should yield superior segmentation and visualization.

Multivalued data represent a rich source of information that is often overlooked in medical image analysis. Synthesis of the multiple channels of information is often left to the human observer. Among those applications that do employ multiple channels of data, segmentation based on the global histograms and gain field equalization to meet those demands are often the approach. If analytical segmentation techniques that use multiecho MRI data continue to develop, I believe that multiscale analysis based on image statistics will become an increasingly important method.

5.2 Differential Geometry for Data Registration

Alignment and registration of multiple datasets is required before the combined information from the different data types can be synthesized. One approach to the registration of multiple datasets is to embed known fiducial markers within the data at the time of acquisition to aid in data alignment. However, this approach does not account for minor deformations of geometry (changes in positions of limbs, modifications of the viscera from the process of digestion, etc.). What is desired is a means of registration that uses the shape and structure of the objects within the data to aid in its alignment.

I propose to study the geometry of images. In particular, I suggest that application of differential geometric methods to the intensity level sets of the 3D data will yield valuable information that will enable better registration of 3D data. Cohen and Ayache take the related approach of attempting to find extrema of level set curvature for use as landmarks within 3D data [Cohen 92]. Their approach requires the precise localization of loci of principal curvature. I propose to map regions of similar geometric properties, rather than the boundaries or extrema of geometric regions. I propose that the segregation of broad areas that have common geometry is one approach to understanding shape and an important element in advancing object definition and 3D data registration. I propose to extend earlier approaches based on manifold surfaces to the broader concept of level set curvature embedded within 3D data.

One side effect of this research is that it is much easier to begin the development of such methods on known objects, often abstract or at least measurable and quantifiable objects. A brief study of implicit surfaces will be required to begin developing these methods. Implicit surfaces are the boundaries of objects defined by mathematical equations. Such clean abstractions make for simpler quantification of the results.

Another source of quantifiable results would be in the analysis of well-defined objects. In the computer graphics field, several known datasets are used extensively for comparisons. While the visible human data can be used as such a standard, the volume and extent of internal structures is not always apparent, nor does everyone agree to their boundaries. This research may include the collection of data from simple objects upon which to experiment.

5.3 Visualization of Multivalued Data

One part of this research program will address the challenges in the display of complex medical data. Radiological data was inherently two dimensional and displayed solely on film until the advent of tomographic modalities. Computer assisted data acquisition is commonplace; however the computer assisted display of 3D medical data is not accepted widely in health care. Moreover, complex multivalued or vector-valued data are difficult to render. I will approach three issues in my research.

Illumination and Rendering: Color Spaces and Texture

The Visible Human Project data presents a new form of data that requires new rendering methods. The color channels generated as part of the visible human data are useful for the supplementing of the visualizations with texture information. However, they are also important in segmentation, identification, and the rendering of the anatomical structures. Moreover, indiscriminate application of color information will lead to non-realistic images.

Improved rendering of the data from the Visible Human Project will require better understanding of the reflectance models associated with the frozen section data. In particular, I believe that the color models used in volume rendering of the data are improperly applied. Most rendering methods either use the data as texture information, or at least they apply the information as the Red, Green, Blue (RGB) parameterization directly from the data. I propose to explore the uses of alternate color spaces, specifically Hue, Saturation, and Lightness (HSV) and the CIE LAB normalized reflectance color models as the basis for new algorithms in volume rendering.

Visualization Algorithms: Memory Management

Considering the density of the data, it may be necessary to consider alternate algorithms for visualizing the Visible Human Project data. The sheer size of the anatomical dataset requires us to rethink the computer science aspects of navigating large spaces. Methods for memory management, image compression, and rendering from compressed data will become topics for research.

Rendering Technology: Immersive Display

There are many emerging technologies in the areas of immersive rendering and display. I anticipate that new methods for presenting medical data will be developed using these technologies for the purposes of clinical simulation and the representation of complex data. In particular, the new devices that track the position of the head and hand of the user to allow a changing perspective of the image may be used to generate more compelling views of the data. These devices are widely used in virtual reality systems. Head and hand tracking combined with head mounted and projection screen display can create immersive environments where the presentation of information is not limited to 2D planes. In such systems, 2D views of 3D data can be supplemented with visual cues such as stereo viewing and head motion parallax to enrich the perceptions of spatial relationships of objects within the data. As part of this research program, I plan to explore the use of tracking and alternate display systems to demonstrate surgical simulation and other applications that use the Visible Human Project data.

Force feedback or haptic rendering is another concept that I expect to have an important impact of the visualization of complex data. Surgeons, diagnosticians, and other experts often rely on tactile feedback to convey the characteristics of objects. These characteristics often include elasticity and firmness. While, relatively inexpensive user interfaces capable of providing some haptic feedback are now available, there remain many unanswered questions on the presentation and representation of tactile information. I propose to include a study of the translation of multivalued 3D information to such characteristics as sponginess or resilience as part long term goal of this project

5.4 Data Acquisition

As this research develops, additional sources of data will be required. Tracking the advances in medical scanner technology and the concurrent improvements in resolution and information content will be necessary to maintain active and interesting research. For example, high resolution clinical X-ray CT machines with the capability of generating images with a 1K x 1K matrix are now becoming available. As part of this research, I anticipate the collection of some datasets collected using standard imaging protocols. The image acquisition protocol best suited for diagnosis by a human observer is not always the best data collection method for computer analysis. Three phases of this type of research are expected.

- The collection of several datasets from several different modalities using a series of standard protocols. This effort is mostly a research exercise in developing standards in data collection to optimize computer data analysis.

- The development of methods and the collection of new cryosection data with a variety of light sources and detectors, augmenting the visible light spectrum currently available. Like multiecho MRI data, multispectral optical analysis should yield new insights. More research in optical data collection methods will be required.

6 Evaluation

The different areas of this program are at different stages of their development. Evaluation criteria for the separate parts of the research program are divided into appropriate validation approaches. Each area of research is to be executed in phases. A hypothesis or proposed approach will be adopted and milestones or interim goals that validate the research approach will be chosen. Attainment of the milestone or goal will signal the start of a new phase of the research. The collection of milestones will be a measure of overall progress.

6.1 Evaluation Plan: Multiscale Image Statistics for Rendering

This research area is nearing the completion of its theoretical development on single valued images, and new phases will begin soon. Much of the work to date has been applied to known computer generated images and mathematical functions. The ability of multiscale image statistics to capture local image geometry has been theoretically demonstrated. Multiple journal articles are currently either in preparation or have been submitted for publication.

1. While the statistical models can be built from local image information, directional information is currently theoretical. A robust and computationally efficient mechanism for computing directional multiscale statistics will be required to proceed with validation steps.

2. The hypothesis is that directional multiscale statistics are useful in segmentation of medical data acquired from clinical imaging scanners. To test this proposition, after completing the development of new software for computing local directional statistics, these methods will be applied to (a) synthetic computer generated images with known properties, (b) simple physical objects scanned with medical scanners, and (c) clinical medical data including the data from the

Visible Human Project. This serial progression is necessary to permit a logical series of validating experiments. The segmentation of medical information is often a subjective task. By confirming quantitative values such as volume and surface area of known mathematically generated objects and simple physical artifacts, the validity of these methods can be supported when they are applied to clinical images.

3. Concurrently, the theory for local statistics will be expanded to include multivalued data. After some theoretical foundations for local directional covariance, co-skew, and co-kurtosis are establish, a similar progression of implementation and staged validation will be used to test the proposition that multivalued image statistics can generate a segmentation superior to one generated from single valued statistics alone.

6.2 Evaluation Plan: Differential Geometry for Data Registration

This research area will be marked by a progression of research and development stages. Unlike the previous topic, a considerable amount of initial development is expected. The following is a preliminary sketch of the milestones for this research area.

1. The first task is to create a development environment for the generation of implicit surfaces. This will serve as a workbench for the creation of multiple synthetic objects with known properties. This is especially important to be able to validate the quantitative measurement of surface properties such as local curvature.

2. Once synthetic objects can be easily created, discrete gray-valued datasets will be generated to simulate clinical data. Discrete numerical approximations of quantitative measurements will be compared to the analytical measurements made of the mathematical functions that underlie the implicit surfaces. This will provide a lower error bound for geometric measurements of clinical data since the synthetic data will be free of noise from the scanner.

3. Rigid alignment of synthetic objects with similar shapes will be tested, and an error metric based on a least-squares measurement will be generated. By generating rudimentary rigid registration methods on known simple shapes, a baseline can be set to compare the efficacy and accuracy of more advanced registration methods.

4. Segmentation of surface regions of synthetic objects will be performed. These surface segments will segregate the surface into patches with similar geometric properties (concave, convex, hyperbolic, etc.). Here, too, the segmentation of numerical data can be compared with the results from the analytical models and exact error measurements can be generated.

5. To test the robustness of these methods, the generation of surfaces and segmentation of surface regions will be applied to data created by taking scans of simple easily measured physical objects with a medical scanner. The research methods can therefore be compared to the results from implicit models and their accuracy evaluated.

6. The next step is the application of these methods to clinical data. Surface modeling and geometric segmentation will be applied to medical data, including data from the Visible Human Project. Successful completion of the previous milestones will help support the validity of the

results from this stage.

7. At this point, new research in deformable registration techniques based on the alignment of geometric regions can begin. A baseline for rigid registration will have been established, and the error bounds on the geometric measurements will have been documented. One approach to deformable registration that I am currently considering is the use of active surfaces through reaction-diffusion equations to match and align surfaces. Another approach is the use of finite element models based on space filling lattices to model deformations and the warping of solid objects. Consideration of the appropriate approach is still ongoing; however, other foundation work is beginning soon.

6.3 Evaluation Plan: Visualization of Multivalued Data

There are three topics in my research plan in the area of Visualization. However, at the current time, I have begun the scientific evaluation of only one of them. However, I believe that they are each related, and will therefore develop simultaneously. On the topics of illumination and rendering, my hypothesis is that color renderings of the Visible Human Project data do not employ sufficiently realistic reflectance functions in the representation of human features. The current reconstructions are far from being realistic. The following section is a sketch of the test of this conjecture and a means for generating comparison images.

1. I propose the construction of a new volume rendering system that incorporates a light transport model that can be modified to accept different models for reflectance functions for different substances. In particular, I will focus on the use of color spaces and the choice of color parameterizations as part of this development. After completion of the rendering system, I will generate several test views of the Visible Human Project data.

2. The next step in this research will be the construction of new models for the reflectance functions of various surfaces in the Visible Human Project data. As an initial surface, I propose to model the reflectance and light transport functions of skin. This can be accomplished by studying the information that is generated by surface scanning systems such as Cyberware scanners. Once the reflectance models are created, they should be integrated into the rendering system, and new views of the Visible Human Project data generated for comparison with the original images. Subjective evaluation by expert observers will be used to evaluate the success of the effort.

The other topics of memory management for navigating large spaces and modeling tactile characteristics will follow a similar course of implementation, modeling, and comparison. The volume rendering system generated in milestone 1 above will serve as infrastructure for both the haptic rendering research and the exploration into new algorithms for information management in large data spaces.

6.4 Evaluation Plan: Data Acquisition

In several stages of these individual projects, data of simple physical objects or artifacts will be required as test data. Some metrics such as object volume can be easily measured and used to check for errors in the acquisition procedures. Imaging modalities such as X-ray CT have artifacts in

volume measurement arising from filtering effects of bone and other dense substances in the body. Magnetic Resonance Imaging often has nonlinearities of the imaging field arising from variations in the induced magnetic field. The imaging parameters of each of the scans of the test objects will be recorded, and as the data are processed, variations in the test metrics will be noted. As new data is acquired, feedback from the earlier computer based analysis will be used to adjust the imaging parameters and improve the quality of the data from the perspective of computer-assisted image analysis. Progress of this part of the research will be shown as test metrics such as object volume show fewer discrepancies between the calculated values and measurements of the physical objects. The ultimate goal of this progression will be the generation of standard imaging parameters that create clinical data optimized for computer analysis.

7 Project Plan

7.1 Extension of current research

It is my desire to complete publication and to extend work performed as part of my dissertation research. The thrust of that work was in multiscale image statistics. This work is mostly theoretical, will serve as a precursor to segmentation, following the process of registration. The first two papers are currently in submission. A third applied-statistics paper is expected to be ready by July of 1999.

7.2 Short Range Targets (1 year projection)

As part of an intramural research initiative, I will begin exploring new ground in differential geometry and image illumination. In the coming months, I will broaden my research to include related topics including registration, illumination and rendering, mesh refinement, and medical image segmentation.

It is not possible for a single individual to pursue all of these topics. However, it will be necessary for me to understand new work in each of these areas to keep pace with the research community. Therefore, I will be seeking colleagues and collaborators to work on new ideas in each of these areas. Some of my colleagues are in the local Baltimore/D.C. Area, and I will them and others at their research organizations. It is my intent to work with outside institutions mainly in the areas of mesh refinement and decimation as well as rendering.

I do not wish to create conflicts among those institutions that might wish to apply for funding from the NLM in the areas of segmentation and registration, so the scope of my collaborations will be limited to problems of medical visualization. The segmentation and registration elements of this research will likely be performed solely within NIH organizations.

Differential Geometry

In addition to a background of statistical image processing and scale space geometry, I am bringing some new ideas from differential geometry to the fields of registration and decimation/mesh-refinement. Since traditional researchers in these areas are mostly practitioners of computer graphics, the programs to accomplish mesh refinement and registration are often applied to polygonal data or extracted contours. Most medical data, including the Visible Human, is very rich.

It contains volumetric relations that should be included in any algorithm used to perform these tasks.

As I work to complete the current phase of my research in multiscale image statistics, I shall begin the construction of a workbench in differential geometry. The initial basis for this program will be the visualization of the geometry of implicit surfaces (blobby surfaces or metaballs). This area is currently an important area in computer graphics; however, I see it only as one avenue toward understanding more complex volumes. It is my intent to work on the generation and simplification of polygonal meshes of simple surfaces generated by implicit models. Beyond mesh refinement of surfaces embedded in volumes, I hope to explore the modification of meshes based on the principles described on 2D contours by Sander and Zucker [Sander 92] through reaction-diffusion equations.

Illumination and Rendering: Color Spaces and Texture

Recent discussions have revealed a gap between the interest in using the color Visible Human data and our ability to manipulate the information appropriately. Detailed knowledge of color spaces is often not appropriately applied to the problem, leading to unusual rendering of the color data. During the fall of 1999, I plan to begin an exploration of rendering directly from color RGB images.

The thrust of this research will be in the transformation from RGB space to a more appropriate color space. RGB color space cannot be treated as a geometric vector, so normal measurements of the magnitude and tensor derivatives of the color data are not meaningful. There are color spaces where the representative values are more linear, and local differences between two adjacent colored pixels can be measured with some degree of confidence.

The overall goal of this research grows from an appreciation that texture and illumination are separate processes in rendering. Color photographic data is often used to generate textures. However, the images in the photograph have their own illumination parameters. One can consider an image textured by a photograph to have been illuminated twice: once for the acquisition of the image and once in the texturing from the image.

Learning to separate color texturing from global illumination is the challenge presented by this idea.

7.3 Mid-range Target: An Image Research Laboratory (3 year projection)

A three year goal for my program will be the establishment of an image research laboratory. The purpose of the lab will be three-fold. One purpose for the lab will be to serve as a repository and dissemination center for Visible Human related segmentation, registration, and other image analysis methods either developed at NIH or through extramural research contracts. A second purpose for the lab will be as an application demonstration center for our research partners. The third purpose for the lab will be to serve as a focus for image acquisition protocol development.

Segmentation and Registration Toolkits

It is my hope to create or assemble a segmentation and registration toolkit. Such a resource should work on the Visible Human data and all of the multiresolution, hierarchical data structures to follow. It should also be extensible to be applicable to a variety of medical data.

The NLM's imaging laboratory could serve as a coordinator and developer of this work. Some arbiter will be required to integrate the diverse ideas expected to be generated by the next round of the Visible Human project. That work should be supported by a research and development lab, staffed with skilled practitioners of visualization and medical image processing.

Application Demonstration Center

As the work of the NLM continues to evolve, I anticipate that more than database access points and Web sites will be required to support the growing mission pioneered by the Visible Human project. A laboratory, not office space nor a training lab, is required for this purpose. For those parts of the public sector that are performing non-proprietary research, new ideas would be encouraged to be brought to the NLM and demonstrated here.

As part of its function, the imaging research laboratory could serve as a focal point for application development in Visible Human research. In particular, research in advanced display systems will require laboratory space as immersive display technologies continue to be assimilated into medical research. Experimental space is required to develop and present applications and simulations that demonstrate tracked viewing displays and haptic/tactile feedback.

In addition, this lab will encourage a hands-on approach to managing the expected contracts in segmentation and registration envisioned for the next round of Visible Human research. It will also allow us to respond more quickly to take advantage of opportunities for visiting research associates when they are available.

Image Acquisition Protocol Development

As we consider new data, NLM will need to generate standards for image acquisition protocols for the visible human project. Even if limited specimens are acquired for the foreseeable future, issues of image resolution, dynamic range, contrast, and quality should be investigated before licensing arbitrary protocols for image acquisition. While there is some value in being able to handle a broad range of imaging parameters, the variation in image quality often hampers progress. We should examine the possibility of devoting some effort toward standard radiological protocols for acquiring new image data.

This implies that the laboratory will provide guidance and feedback on the acquisition of new specimens and datasets. In particular, the protocols used for computer assisted analysis of medical images are not always the protocols used to create the data with the greatest visual contrast for human based diagnosis. Our interest should be in providing the most useful data to the research community or at least standards by which those data can be most easily acquired, compared, and quantified.

Finally, the question of what data to pursue remains open. An in-house research and development effort should be able to contribute guidance on a new dataset. Should we collect another specimen? Or will a library of CT/MRI data representing the variation of the human condition be a greater research challenge?

7.4 Directions for Long Range Plans (beyond 3 years)

Long range projections include the establishment and management of new leveraged projects for advancing medical imaging: segmentation and registration. This effort should be able to project new work beyond the limited sample represented by the two specimens currently in the dataset. This can be accomplished in a variety of ways, many of which should be pursued. Research in deformable models should be encouraged to allow comparisons between the existing data and arbitrary patient data. Libraries of new data should be licensed or contracted, including in-vivo images, developmental information, and functional physiological images. Being able to correlate information between datasets (e.g., correlating structures between the visible human specimens and newly acquired data) will provide visual semantic handles on a broad range of problems in indexing and anatomical/physiological analysis.

8 Project Resources

The proposed project can be advanced with relatively modest resources. The initial elements necessary to begin this project are currently in place. Additional resources will be necessary as the research program grows. This section describes what program pieces are currently available as well as the anticipated future needs for the project.

8.1 Personnel

This project requires contributions from research personnel with expertise in advanced computer graphics, image processing, and data acquisition techniques. The principal investigator, Dr. Yoo, has a background in medical image processing and in interactive computer graphics. In addition, he served as a professor and research director in the Department of Radiology at the University of Mississippi Medical Center.

Also within NLM, there are experts in medical visualization, anatomy, and information processing. Activity on this project is expected to encourage collaboration among these groups. Other research input will come from collaborations with institutions outside of NLM. The Visible Human Project has enjoyed high visibility and has encouraged interaction among the medical image research community. This project plan is also being developed to encourage a dialogue with researchers in the medical image processing field with the hope of advancing particular areas of research outlined here while also archiving methods and tools for broad use in anatomical and physiological research.

As the project continues to develop, the need for additional in-house research personnel is anticipated. The current recommendation is that funds be designated to establish limited or visiting positions here at the NLM for work on medical image processing research. Postdoctoral fellows or visiting faculty would be encouraged to come and contribute to the research effort for a limited time. As with any academic research program, the long term mission and direction of the program cannot be guaranteed far into the future. The recommendation for visiting positions and/or fellowship positions would allow us to retain the services of research personnel of the highest caliber while maintaining maximum flexibility in human resource management.

8.2 Data

The extensive data from the Visible Human Project will serve as the initial data for this research. Indeed, the available data from that source alone will provide sufficient work for many phases of this research. However, in order to draw general conclusions, any algorithms, methods, or applications must be verified on other data as well. Moreover, while clinical diagnosis by humans is often drawn from subjective assessments of medical images, one goal computer image analysis is to assist the clinical evaluation by providing quantitative measurements.

Additional data will be collected during the course of this research. The predominant source of data will be from clinical scanners. Some data will be acquired of phantom objects, usually common objects from which exact measurements (length, volume, surface area, etc.) can be measured. Other data will be patient data that is released for use with this project. As the research project matures, feedback from the visualization research and the image analysis effort will begin suggesting parameter adjustments and new methods for data acquisition, leading to new efforts in data collection.

8.3 Laboratory and Hardware Requirements:

The Learning Center for Interactive Technologies (TLC) has provided space for this research. An appropriate location for the proposed image processing laboratory and the application demonstration center have been supplied within the TLC.

A high-end workstation with hardware accelerated computer graphics has also been procured for this project. The Visible Human Project continues to require large amounts of computing capability as well as high quality, interactive image generation, analysis, and display support. The project will push back frontiers in image analysis, data handling/manipulation, and visualization. These issues indicate that a research program in this area requires an extensible, powerful computing system capable of advanced graphics and display. To meet these requirements, we purchased a dual processor Onyx2 with Infinite Reality Graphics from Silicon Graphics Incorporated (SGI).

While a machine with high-end graphics capabilities will be required to meet the demonstration and computing demands for new research in the visible human project, most programming can be performed on smaller, less costly equipment. The expected growth of intramural research on the image analysis and application efforts on the Visible Human Project will encourage visiting researchers to spend some time in the HPCC office. A development workstation has been identified among the available machines in the TLC. An SGI Inidgo2 with Maximum Impact Graphics is already in the TLC. It could serve as a software development workstation for visiting faculty or research fellows resident at NLM. While it is a slightly older product line from SGI, it can run the latest release of their operating system and would be compatible with the software development expected for the proposed research. Future growth may require the procurement of an additional software development machine. Those needs can be judged at a later time.

9 Summary

It is my intent to develop a research program in the areas of registration, segmentation, and

visualization. This program is intended to complement and support new activity in the Visible Human project.

As part of the HPCC office and the Visible Human Project, I also see it as my place help to evaluate and plan the next step forward. The research community has made it clear that segmentation and registration are some of the hard problems presently before them. The Visible Human data presents some unique challenges and hard problems from which future research will grow. My individual efforts in this problem domain and my continued efforts to publish should keep me in communication with the researchers involved in this area.

I will begin new research in the areas of color image analysis, differential geometry, and the application of these ideas to volume image analysis, rendering, and visualization. Some of the work in developing these ideas will be of interest to the computer science community in their own right, and I will endeavor to publish the tools and their ideas as appropriate. I plan to work toward applying the theory of color spaces, differential geometry, and multiscale image analysis toward solving deep problems in issues related to the Visible Human project.

10 References

Bajcsy, R. and S. Kovacic. Multiresolution elastic matching. Computer Vision, Graphics and Image Processing, 46:1{21, 1989.

Cohen, Isaac, Laurent Cohen, and Nicholas Ayache. Using deformable surfaces to segment 3d images and infer differential structures. CVGIP : Image understanding '92, September 1992.

Eberly, D. 1994. A differential geometric approach to anisotropic diffusion. in *Geometry-Driven Diffusion in Computer Vision*, ed. B.M. ter Haar Romeny, 371-392. Dordrecht, the Netherlands: Kluwer.

Florack, L.M.J., B.M. ter Haar Romeny, J.J. Koenderink, and M.A. Viergever. 1994. General intensity transformations and differential invariants. *J. of Math. Imaging and Vis.* 4: 171-187.

Koenderink, J.J., and A.J. van Doorn. 1987. Representation of local geometry in the visual system. *Biol. Cybern.*, 55:367-375.

Lindeberg, T. 1994. *Scale Space Theory in Computer Vision*. Dordrecht, the Netherlands: Kluwer.

Sander, Peter T. and Steven W. Zucker. Singularities of principal direction fields from 3-d images. IEEE Trans. on Pattern Analysis and Machine Intelligence, 14(3):309{317, March 1992.

Spitzer, V., M. J. Ackerman, A. L. Scherzinger, and D. Whitlock. The Visible Human Male: A Technical Report, Journal of the American Medical Informatics Association, 3: 118-130, 1996.

Szeliski, Richard and Stephane Lavallee. Matching 3-d anatomical surfaces with non-rigid volumetric deformations. In Proceedings of the IEEE Workshop on Biomedical Images Analysis (WBIA'94), Seattle, Washington, June 1994. Also in AAAI 1994 Spring Symposium Series. Application of Computer Vision in Medical Image Processing, Stanford University,

ter Haar Romeny, B.M. and L.M.J. Florack. 1991. A multiscale geometric approach to human vision. in *Perception of Visual Information*, ed. B. Hendee and P. N. T. Wells, 73-114. Berlin: Springer-Verlag.

Yoo, Terry S. 1996. Image Geometry Through Multiscale Statistics. Ph.D. Dissertation. The University of North Carolina at Chapel Hill.

CURRICULUM VITAE

Name: Terry S. Yoo

Position Title: Computer Scientist

Education and Training:

Institution	Degree	Year	Field of Study
Harvard University	A.B.	1985	Biology
Univ. of North Carolina at Chapel Hill	M.S.	1990	Computer Science
Univ. of North Carolina at Chapel Hill	Ph.D.	1996	Computer Science

Research and Professional Experience:

1998 - Present **Computer Scientist**
Lister Hill National Center for Biomedical Communications
National Library of Medicine, National Institutes of Health, Bethesda, MD

1995 – 1998 **Assistant Professor of Radiology**
University of Mississippi Medical Center, Jackson, MS

Research Assistant Professor of Engineering (joint appointment)
University of Mississippi, Oxford, MS

1991 – 1993 **Senior Research Associate**
1993 – 1995 **Research Assistant**
1990 – 1991 Department of Computer Science
University of North Carolina at Chapel Hill, Chapel Hill, NC

1987 – 1990 **Member Technical Staff**
Microelectronics Center of North Carolina Research Triangle Park, NC

1986 – 1987 **Information Systems Designer**
AT&T Technologies, Burlington, NC

1985 – 1986 **Scientist**
BBN Laboratories, Incorporated, Cambridge, MA

Selected Publications:

Dissertation

Terry S. Yoo. 1996. Image Geometry Through Multiscale Statistics. Ph.D. Dissertation. The University of North Carolina at Chapel Hill.

Refereed

Terry S. Yoo and David T. Chen. 1994. Interactive 3D Medical Visualization: A Parallel Approach to Surface Rendering. In *Computer Applications to Assist Radiology,* (Proceedings of S/CAR '94, Symposium for Computer Assisted Radiology). John M. Boehme, Alan H. Rowberg, and Neil T. Wolfman, *eds*. 100-105. Carlsbad, CA: Symposia Foundation.

Terry S. Yoo and James M. Coggins. 1993. Using Statistical Pattern Recognition Techniques to Control Variable Conductance Diffusion. In *Information Processing in Medical Imaging* (Lecture Notes in Computer Science 687), Harrison H. Barrett and Arthur F. Gmitro, *eds.* 495-471. Berlin: Springer-Verlag.

Terry S. Yoo, Ulrich Neumann, Henry Fuchs, Stephen M. Pizer, Tim Cullip, John Rhoades, and Ross Whitaker. July 1992. Direct Visualization of Volume Data. *IEEE Computer Graphics and Applications* 12(4):63-71.

supersedes

Terry S. Yoo, Ulrich Neumann, Henry Fuchs, Stephen M. Pizer, Tim Cullip, John Rhoades, and Ross Whitaker. 1991. Achieving Direct Volume Visualization with Interactive Semantic Region Selection. In *Proceedings of IEEE Visualization '91*. Gregory Nielson and Larry Rosenblum, *eds*. 58-65. Los Alamitos, CA: IEEE Computer Society Press.

Helen E. Harrison, Stephen P. Schaefer, and Terry S. Yoo. 1988. Rtools: Tools for Software Management in a Distributed Computing Environment. In *Proceedings of USENIX '88* . 85-94. Berkeley, CA: Usenix Association.

Unrefereed

Terry S. Yoo. 1994. Statistics and Scale in Variable Conductance Diffusion. In *Proceedings of Computer Vision in Medicine* (AAAI Spring Symposium Series, Stanford University, Palo Alto, CA). AAAI Technical Report SS-94-05. 186-190.

Technical Reports

T. Marc Olano and Terry S. Yoo. 1993. Precision Normals: Beyond Phong. Technical Report TR93-021, Department of Computer Science, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina. 1-4.

Terry S. Yoo and T. Marc Olano. 1993. Instant Hole: Windows onto Reality. Technical Report TR93-027, Department of Computer Science, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina. 1-13.

Other Publications

Terry S. Yoo *ed.* 1998. *3D Visualization in Medicine,* Tutorial Notes for SIGGRAPH 98. 300 pp.

Henry Fuchs and Terry S. Yoo *eds.* 1993. *Three-dimensional Visualization Using Medical Data,* Tutorial Notes for SIGGRAPH 93. 200 pp.

Elliot Herman and Terry S. Yoo. January 1993. Photo, *Agricultural Research* 41(1): Cover.

Terry S. Yoo. 1992. Statistics and VCD. Poster, Visualization in Biomedical Computing (VBC '92), Chapel Hill, NC.

Suresh Balu, James C. Chung, Brad Crittenden, and Terry S. Yoo. 1991. Radiation Treatment Planning with a Head Mounted Display. Interactive Demonstration of a VR System (SIGGRAPH '91, Las Vegas, NV). Abstract in *Proceedings of Tomorrow's Realities* (refereed forum), 13.

Terry S. Yoo, Ulrich Neumann, Henry Fuchs, Stephen M. Pizer, Tim Cullip, John Rhoades, and Ross Whitaker. 1991. Methods for Direct Visualization of 3D Medical Data. Poster, Information Processing in Medical Imaging (IPMI '91), Wye College, Kent, UK.