10:24:11 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 02/14/92

Active

Project #: C-50-605 Cost share #: C-50-313 Rev #: 5
Center # : 10/22-1-F6825-0A1 Center shr #: 10/22-1-F6825-0A1 OCA file #:
Work type : RES
Contract#: EID-8920774 Mod #: ADM REV Document : GRANT
Prime #: Contract entity: GTRC

Subprojects ? : N CFDA: 47.041
Main project #: PE #: N/A

Project unit: GVU Unit code: 02.010.314
Project director(s):
HODGES L COMPUTING (404)894-8787
LAWTON D T COMPUTING

Sponsor/division names: NATL SCIENCE FOUNDATION / GENERAL
Sponsor/division codes: 107 / 000

Award period: 890915 to 930228 (performance) 930531 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	89,400.00
Funded	0.00	89,400.00
Cost sharing amount		4,063.00

Does subcontracting plan apply ?: N

Title: BENEFITS OF THREE DIMENSIONAL DATA IN CHARACTERIZING ULTRASOUND IMAGES

PROJECT ADMINISTRATION DATA

OCA contact: Mildred S. Heyser 894-4820

Sponsor technical contact

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NATIONAL SCIENCE FOUNDATION
ENGINEERING INFRASTRUCTURE DEVELOPMT
1800 G STREET, NW
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Sponsor issuing office

NICK NAYAK
(202)357-9602

NATIONAL SCIENCE FOUNDATION
DIVISION OF GRANTS AND CONTRACTS
1800 G STREET, NW
WASHINGTON, DC 20550

Security class (U,C,S,TS) : U
Defense priority rating : N/A
Equipment title vests with: Sponsor GIT X

ONR resident rep. is ACO (Y/N): N
NSF supplemental sheet

Administrative comments -
TO CORRECT COST-SHARING NO. PER PROFS FROM SANDI CHESTNUT DATED 2/14/92.

SR 426

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 03/10/93

Project No. C-50-605 Center No. 10/22-1-F6825-0A1

Project Director HODGES L School/Lab GVU

Sponsor NATL SCIENCE FOUNDATION/GENERAL

Contract/Grant No. EID-8920774 Contract Entity GTRC

Prime Contract No.

Title BENEFITS OF THREE DIMENSIONAL DATA IN CHARACTERIZING ULTRASOUND IMAGES

Effective Completion Date 930228 (Performance) 930531 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	
Final Report of Inventions and/or Subcontracts	N	
Government Property Inventory & Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

CommentsLETTER OF CREDIT APPLIES. EFFECTIVE DATE 9-15-89.
CONTRACT VALUE $89,400.

Subproject Under Main Project No.

Continues Project No.

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other HARRY VANN-FMD	Y
FRED CAIN-OOD	Y

Georgia Tech

Georgia Institute of Technology
School of Information and Computer Science
Atlanta, Georgia 30332-0280
404•894•3152
Fax: 404•853•9378

To: Wilbur L. Meier, Jr., Ph.D.
Director, Office For Engineering
Infrastructure Development
National Science Foundation
1800 G. Street N.W.
Washington, D.C. 20550

From: Larry F. Hodges, Ph.D.
Assistant Professor

Date: June 8, 1990

Re: Second Year Funding for Creativity Award of Mr. Yves Jean

This is the progress report and budget for next year's funding for the project originally titled: "Benefits of Three-Dimensional Data in Characterizing Ultrasound Images." Please note that although the Creativity Award was made in 1988, funding did not begin until fall 1989. A copy of Dr. Butcher's letter approving this change is attached.

Mr. Jean has successfully met his goals for the first year of this project. He has written prototype software tools to display and process medical images and established contacts with Emory University Hospital in Atlanta as a source of medical image data. He has also taken the hospital's technical course *Introduction to Magnetic Resonance Imaging*. At Georgia Tech he has completed the course work crucial to the success of the research work.

For the second year the objectives and scope of Mr Jean's work will continue in medical image understanding. Emory University Hospital is an integral part of this effort. The institution is providing data and access to medical professionals. In the original proposal the use of Magnetic Resonance (MR) images was considered if availability was not an issue. Because of the support we are receiving from Emory University Hospital, we have been able to concentrate Mr. Jean's research on display and processing of MR images. Using MR technology alleviates some of the problems documented in the original proposal. Unlike Ultrasound, three dimensional data is intrinsic in MR. Therefore the construction of a mechanism to acquire 3-D data in Ultrasound is unnecessary. Unlike Ultrasound slices that must be processed to remove the effects of blurring due to probe motion, the absence of a mechanical system in obtaining MR images eliminates the need for deblurring. Also, MR data is more promising in detecting tissue abnormalities.

The plan of using three dimensional medical image data (multiple slices) will be continued and augmented with the graphical display and manipulation of the data. The tissue characterization effort will be reduced to allow greater stress on the "...determination of tissue boundary properties and 3-D tissue structures." The shift in emphasis is due to the selection of the heart as the organ of interest. The medical abnormalities to be studied are those related to heart tissue, structure, and function. Specifically, MR image slices of the heart will be used to generate a 3-D model. This model can then be manipulated by a cardiologist graphically. Any plane can then be defined to slice into the 3-D model and produce a 2-D image. Consistent with the original proposal, the second year's work will use the physician as part of the analysis system: "Because 3-D data is available, a 3-D color-coded image could be displayed for the operator to manipulate. This combination of machine computation and human intelligence has the potential of uncovering new UTC techniques." The use of the acronym UTC is no longer appropriate and is a discontinued reference to this work. MR Tissue and Function Characterization is more descriptive. Finally, the goal in the original proposal of creating "...a viable clinical tool for diagnosing tissue abnormalities...nurses and even technicians would be able to detect warning signs and even correctly diagnose medical problems without a doctor's assistance" is still the driving force of Yves' research.

We would like to request that Dr. Daryl Lawton be added to the contract as a Co-Principal Investigator. Dr. Lawton is an expert in vision systems and has been very helpful in defining the focus of Mr. Jean's research. We feel that his participation will be crucial to the success of this project.

Yves Jean has made satisfactory progress, both in academic work and in achieving the Creativity Award objectives. Enclosed with this letter is our budget for the coming year.

Lynn Boyd
Authorized Institutional Representative

Georgia Tech

Larry F. Hodges, Ph.D.
College of Computing

Georgia Institute of Technology
Atlanta, Georgia 30332-0280
404-894-8787 larry@cc.gatech.edu

To: Wilbur L. Meier, Jr., Ph.D.
Director, Office For Engineering
Infrastructure Development
National Science Foundation
1800 G. Street N.W.
Washington, D.C. 20550

From: Larry F. Hodges, Ph.D.
Assistant Professor

Date: June 13, 1990

Re: Third Year Funding for Creativity Award of Mr. Yves Jean

This letter reports on Yves Jean's progress during the second year of research on MR Tissue and Function Characterization (originally titled Ultrasound Tissue Characterization) and outlines our plans for the third year. Yves has made satisfactory progress in his academic work as well as in achieving grant objectives. The goals outlined in the second year report have been successfully achieved. That report indicated that "the medical abnormalities to be studied are those related to heart tissue, structure, and function" and that "the plan of using three dimensional medical image data (multiple slices) will be continued and augmented with the graphical display and manipulation of the data."

The graphical display and manipulation of MR images of the heart have been implemented. This accomplishment includes:

1) Creating a graphical model of the 3D image data.

2) Image processing to detect the contours of the heart structure.
3) Virtual devices as manipulators of the graphical data.
4) Animation of the model.
5) Stereoscopic display of the model.
6) Physician's input and guidance.

A video tape of this work is available on request.

The results of Yves' work so far enables a cardiologist to manipulate a patient's heart scan images graphically while they are animated. This creates a tool and medium for physicians and researchers to communicate knowledge and ideas related to analyzing cardiac MR images.

For the third year Yves will implement quantitative algorithms to analyze the heart tissue. The data will be similar to the current MRI data but will be augmented with a "tagging" feature. The data is provided by Emory University Hospital with medical expertise from Dr. Roderic Pettigrew, PhD MD. The tagging feature provides a means for tracking tissue motion over the cardiac cycle. These images will be processed to extract the motion information and then analyzed using techniques from the following areas:

1) Computer Vision :

Motion and shape analysis from images have been studied extensively by researchers in Robotics, Image Processing , and Computer Graphics and Animation. Yves has taken courses in these areas and has collected published works related to our cardiac MRI motion problem. Specifically, work by David Marr, Dana Ballard and other motion in Computer Vision researchers.

2) Finite Element Analysis :

Finite Element Analysis (FEA) of linear elastic models is a mature research area. Non-linear models pose a computational intractability problem. Yves has interested Georgia Tech Computational Mechanics researchers to apply FEA techniques to the processed tagging data, using the GTSTRUDL package. Yves plans to support a student in this area for one quarter to help in all aspects of applying this FEA package to the processed tagging data. Specifically, designing a linear elastic model of the heart tissue and after analyzing the results designing a non-linear model. The non-linear model may not be implemented depending on the computational complexity of the model but the goal is to learn as much about heart tissue modeling. One unintended benefit of this work is that a platform would have been developed which would allow physicians to perform quantitative analysis of the effect of cardiac treatment drugs. The FEA method will render the position and intensity of stress points in a patients heart. No other technique currently exists for generating such treatment feed back.

The two areas above will serve as a rich base of methodologies for quantitative analysis of the cardiac MRI data. The quantitative analysis goals are aggressive and may not be completed in one year but the benefits are worthy of the effort.

The work completed this year will be an indispensable tool for integrating the quantitative analysis results with the original cardiac MR images. The combination of the two would be a great aid in characterizing abnormalities of heart tissue, structure, and function.

(SEE INSTRUCTIONS ON REVERSE BEFORE COMPLETING)

9-15-91 to 9-14-92

SUMMARY PROPOSAL BUDGET

APPENDIX IV

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (MONTHS) Proposed	Granted
AWARD NO.		

ORGANIZATION

Georgia Tech Research Corporation

PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR

Larry F. Hodges, Assistant Professor and Co-Research Advisor
Daryl T. Lawton, Associate Professor and Co-Research Advisor

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	NSF FUNDED PERSON-MOS. CAL.	ACAD	SUMR	FUNDS REQUESTED BY PROPOSER	FUNDS GRANTED BY NSF (IF DIFFERENT)
1. Larry F. Hodges, Asst. Prof. and Co-Research Advisor	–	–	–	$ --	$
2. Daryl T. Lawton, Assoc. Prof. and Co-Research Advisor	–	–	–	--	
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. ( ) TOTAL SENIOR PERSONNEL (1-6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POST DOCTORAL ASSOCIATES					
2. ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (2) GRADUATE STUDENTS (1 for 1/3 time for 3 months at 866.66/mo. and 1				20,908	
4. ( ) UNDERGRADUATE STUDENTS for 1/2 time at the full-time rate of 36,616)					
5. ( ) SECRETARIAL-CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)					
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $1,000:)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				3,092	
2. FOREIGN					
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 2. TRAVEL 3. SUBSISTENCE 4. OTHER					
TOTAL PARTICIPANT COSTS					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES					
2. PUBLICATION COSTS/PAGE CHARGES					
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES				3,000	
5. SUBCONTRACTS					
6. OTHER					
TOTAL OTHER DIRECT COSTS					
H. TOTAL DIRECT COSTS (A THROUGH G)				27,000	
I. INDIRECT COSTS (SPECIFY)					
TOTAL INDIRECT COSTS Administrative Allowances				3,000	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				30,000	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPM 252 AND 253)				4,854 *	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 30,000	$

PI/PD TYPED NAME & SIGNATURE*	DATE	FOR NSF USE ONLY		
	6/24/91	INDIRECT COST RATE VERIFICATION		
INST. REP. TYPED NAME & SIGNATURE* David B. Bridges	DATE 6/27/91	Date Checked	Date of Rate Sheet	Initials - DGC Program

NSF Form 1030 (1-87) *Supersedes All Previous Editions*

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPM 233)

* As indicated, these monies were not deducted from I

NSF Grant Conditions (Article 17, GC-1, and Article 9, FDP-11) require submission of a Final Project Report (NSF Form 98A) to the NSF program officer no later than 90 days alter the expiration of the award. Final Project Reports for expired awards must be received before new awards can be made (NSF Grants Policy Manual Section 677).

Below, or on a separate page attached to this form, provide a summary of the completed projects and technical information. Be sure to include your name and award number on each separate page. See below for more instructions.

PART II - SUMMARY OF COMPLETED PROJECT (for public use)

The summary (about 200 words) must be self-contained and intelligible to a scientifically literate reader. Without restating the project title, it should begin with a topic sentence stating the project's major thesis. The summary should include, if pertinent to the project being described, the following items:

The primary objectives and scope of the project
The techniques or approaches used only to the degree necessary for comprehension
The findings and implications stated as concisely and informatively as possible

See attached.

PART III - TECHNICAL INFORMATION (for program management use)

List references to publications resulting from this award and briefly describe primary data, samples, physical collections, inventions, software, etc. created or gathered in the course of the research and, if appropriate, how they are being made available to the research community. Provide the NSF Invention Disclosure number for any invention.

I certify to the best of my knowledge (1) the statements herein (excluding scientific hypotheses and scientific opinion) are true and complete, and (2) the text and graphics in this report as well as any accompanying publications or other documents, unless otherwise indicated, are the original work of the signatories or of individuals working under their supervision. I understand that willfully making a false statement or concealing a material fact in this report or any other communication submitted to NSF is a criminal offense (U.S. Code, Title 18, Section 1001).

	3-1-93
Principal Investigator/Project Director Signature	Date

IMPORTANT:
MAILING INSTRUCTIONS
Return this *entire* packet plus all attachments in the envelope attached to the back of this form. Please copy the information from Part I, Block I to the *Attention block* on the envelope.

NSF Form 98A (Rev. 8/92)

PART IV – FINAL PROJECT REPORT – SUMMARY DATA ON PROJECT PERSONNEL

(To be submitted to cognizant Program Officer upon completion of project)

The data requested below are important for the development of a statistical profile on the personnel supported by Federal grants. The information on this part is solicited in resonse to Public Law 99-383 and 42 USC 1885C. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. You should submit a single copy of this part with each final project report. However, submission of the requested information is not mandatory and is not a precondition of future award(s). Check the "Decline to Provide Information" box below if you do not wish to provide the nformation.

Please enter the numbers of individuals supported under this grant.
Do not enter information for individuals working less than 40 hours in any calendar year.

	Senior Staff		Post-Doctorals		Graduate Students		Under-Graduates		Other Participants[1]	
	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.
A. Total, U.S. Citizens	1				1					
B. Total, Permanent Residents										
U.S. Citizens or Permanent Residents[2]:										
American Indian or Alaskan Native										
Asian...........................										
Black, Not of Hispanic Origin.........					1					
Hispanic.......................										
Pacific Islander..................										
White, Not of Hispanic Origin....... ...	1									
C. Total, Other Non-U.S. Citizens										
Specify Country 1.										
2.										
3.										
D. Total, All participants (A + B + C)	1				1					
Disabled[3]										

☐ Decline to Provide Information: Check box if you do not wish to provide this information (you are still required to return this page along with Parts I-III).

[1] Category includes, for example, college and precollege teachers, conference and workshop participants.

[2] Use the category that best describes the ethnic/racial status fo all U.S. Citizens and Non-citizens with Permanent Residency. *(If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)*

[3] A person having a physical or mental impairment that substantially limits one or more major life activities; who has a record of such impairment; or who is regarded as having such impairment. *(Disabled individuals also should be counted under the appropriate ethnic/racial group unless they are classified as "Other Non-U.S. Citizens.")*

AMERICAN INDIAN OR ALASKAN NATIVE: A person having origins in any of the original peoples of North America and who maintains cultural identification through tribal affiliation or community recognition.

ASIAN: A person having origins in any of the original peoples of East Asia, Southeast Asia or the Indian subcontinent. This area includes, for example, China, India, Indonesia, Japan, Korea and Vietnam.

BLACK, NOT OF HISPANIC ORIGIN: A person having origins in any of the black racial groups of Africa.

HISPANIC: A person of Mexican, Puerto Rican, Cuban, Central or South American or other Spanish culture or origin, regardless of race.

PACIFIC ISLANDER: A person having origins in any of the orignal peoples of Hawaii; the U.S. Pacific territories of Guam, American Samoa, and the Northern Marinas; the U.S. Trust Territory of Palau; the islands of Micronesia and Melanesia; or the Philippines.

WHITE, NOT OF HISPANIC ORIGIN: A person having origins in any of the original peoples of Europe, North Africa, or the Middle East.

PROJECT SUMMARY

The advent of medical scanning technologies such as Computer Tomography (CT) and Magnetic Resonance Imaging (MRI) provides clinicians with volumetric image data capturing physiologic and anatomic information. Currently, these images are either transferred to film or displayed on a monitor for viewing by a physician. When the tissue of interest encompasses a volume the number of tomographic images produced makes a concise integrated display difficult. Computer graphics and medical imaging researchers have addressed this problem by combining their respective backgrounds to develop specialized volume visualization techniques. We outline an approach to visualizing and manipulating volume data, in particular, four-dimensional cardiac MRI data sets. Motivated by the need to animate and interact with volume data we have created a volume rendering model that preserves and renders the volume data, displaying the surfaces and volumes of interest while maintaining the original grayscale and contrast. The model provides an effective solution to visualization problems involving interactivity and data integrity.

Final Report

For

Creativity in Engineering Award for Mr. Yves Jean
MR Tissue and Function Characterization
(originally titled Ultrasound Tissue Characterization)

To

Director, Office For Engineering Infrastructure Development
National Science Foundation
1800 G. Street N.W.
Washington, D.C. 20550

From

PI: Larry F. Hodges, Ph.D.
Assistant Professor
College of Computing
Georgia Institute of Technology
Atlanta, GA 30332-0280
Ph: (404) 894-8787
e-mail: hodges@cc.gatech.edu

February 28, 1993

FINAL REPORT

FOR

CREATIVITY IN ENGINEERING AWARD FOR MR. YVES JEAN
MR TISSUE AND FUNCTION CHARACTERIZATION
(ORIGINALLY TITLED ULTRASOUND TISSUE CHARACTERIZATION)

PROGRESS OF MR. JEAN IN THE GRADUATE PROGRAM

Mr. Jean entered the graduate program in the College of Computing (then the School of Information & Computer Science) in the fall of 1989. He completed his M.S. degree at the end of the Fall quarter, 1991 and was admitted into the Ph.D. program. He is currently making satisfactory progress toward completing his Ph.D. degree with an anticipated graduation date in the Spring of 1995. At the end of his three years of NSF funding from the Creativity in Engineering award, Mr. Jean was awarded a fellowship from Intel Corporation that is currently supporting his continued research.

DISSEMINATION OF PROJECT RESULTS

The following presentations and publications have resulted from this project:

"Stereoscopic Computer Graphics," Hewlett-Packard Computer Graphics Symposium, Fort Collins, CO. June19, 1991. (This was a joint talk Dr. Hodges. Jean discussed the use of stereo for display of MRI data.)

Jean, Y., Hodges, L.F., and Pettigrew, R. A method for interactive manipulation and animation of volumetric data. *Proceedings of Visualization in Biomedical Computing '92* (1992), 453-461. A preliminary version of this paper is available from the Graphics, Visualization and Usability Center at Georgia Tech as Technical Report GIT-GVU-91-32.

"Real-time Interactive Graphical Models of 3D Datasets," Presented at the Intel Foundation Second Annual Graduate Fellowship Forum. Intel Santa Clara Campus, January 21 - 23, 1993.

OVERVIEW OF RESEARCH ACCOMPLISHMENTS

1. INTRODUCTION

The advent of medical scanning technologies such as Computer Tomography (CT) and Magnetic Resonance Imaging (MRI) provides clinicians with volumetric image data capturing physiologic and anatomic information. Currently, these images are either transferred to film or displayed on a monitor for viewing by a physician. When the tissue of interest encompasses a volume the number of tomographic images produced makes a concise integrated display difficult. Computer graphics and medical imaging researchers have addressed this problem by combining their respective backgrounds to develop specialized volume visualization techniques. In this paper we outline an approach to visualizing and manipulating volume data, in particular, four-dimensional cardiac MRI data sets. Motivated by the need to animate and interact with volume data we have created a volume rendering model that preserves and renders the volume data, displaying the surfaces and volumes of interest while maintaining the original grayscale and contrast. The model provides an effective solution to visualization problems involving interactivity and data integrity.

1.1 Previous work

Most previous volume rendering techniques can be classified as either surface or volume methods.[1,2] Surface techniques fit a geometric model to the volume data and render the model. Volume methods attempt to generate more faithful reproductions of the volume by simulating some form of chromatic light ray transformation through the data. The two techniques have different advantages and disadvantages. In general, surface modelling creates a smaller rendering load for the graphics pipeline, potentially leaving residual graphics rendering power for interactivity and animation, but at the risk of introducing artifacts and suppressing salient information.[3] In addition, surface-based techniques require that the surface of interest be detectable and mappable to the geometric model. Volume rendering algorithms model the data as opacities or densities by using ray casting techniques to simulate the spectral transformation of the ray through the volume.[4,5] While volume techniques are more powerful, they are also computationally expensive.

Interestingly, some of the volume techniques are similar to surface techniques in that they incorporate some type of surface extraction component. Levoy detects surfaces and composes the total color from evenly spaced samples along a ray through the volume.[5] Other researchers have produced similar as well as more robust work.[6] Drebin uses a material mixture model to classify voxels of multiple substance composition.[7] More sophisticated models and fitting techniques have been developed. They use more complex geometric models and/or constraints to dynamically deform the model to fit the surface data .[8]

There are three general categories of attributes that we wish to represent in medical image visualization: anatomical, physiological, and temporal. Anatomical information refers to the gross structures of the human body. Physiological attributes are represented by the actual grayscale texture data. In clinical settings such texture is the basis of diagnostic medicine. Texture captures both macro and micro features in the data. The extent of a texture can represent the size of a tissue region (macro) while the spectral quality captures the state (micro). Temporal attributes record the time-varying conditions of the data. Such attributes capture the change of various features over time, but more interestingly, capture the change of structure and texture over time (a requirement when analyzing 4D cardiac MRI data).

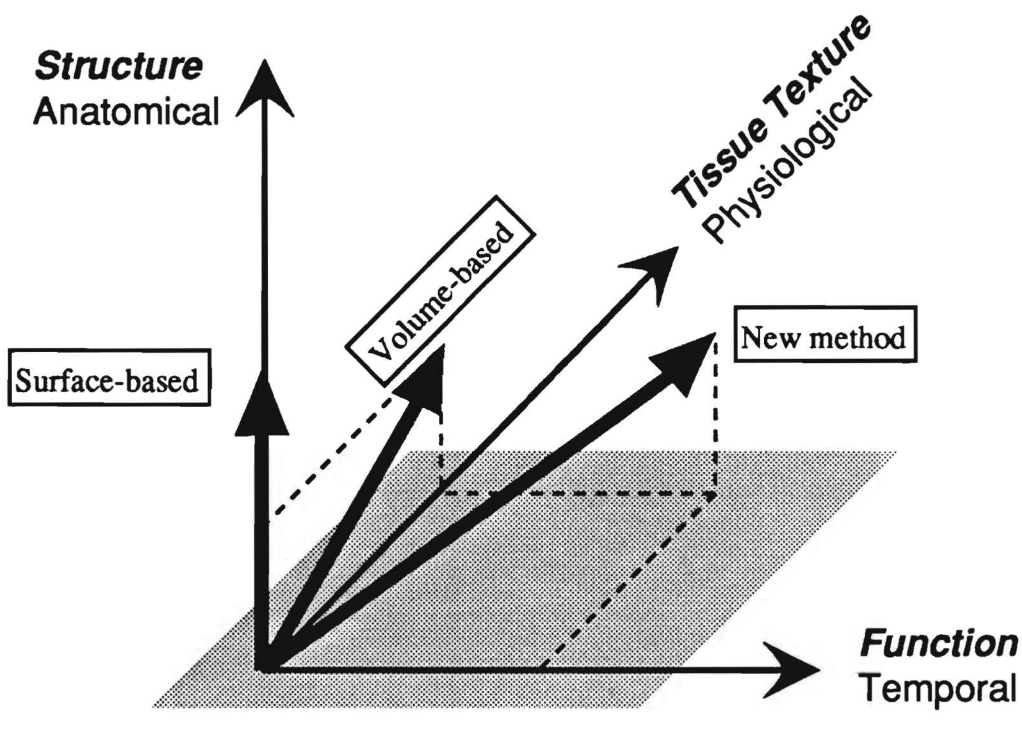


Fig. 1. Medical Data Volume Rendering Space. Superimposed are vectors representing the feature space character of volume and surface-based techniques and our new rendering method.

Fig. 1 illustrates current modelling approaches with respect to their temporal, physiological, and anatomical characteristics. Surface-based techniques and the geometric models they render capture the anatomical structures in medical volume data. Since volume techniques also use surface information, they can become functionally equivalent to surface-based ones with the difference being the absence of a geometric model. A good example of this is the Marching Cubes algorithm.[6] Therefore, it would be inaccurate to restrict their domain to tissue texture, although representation of physiological data is the dominant characteristic of volume techniques. Unlike surface-based techniques, volume techniques may represent both anatomical and physiological attributes.

Neither current surface nor volume rendering techniques are adequate for real-time interactive manipulation of volumetric data and the reproduction of it's intrinsic structural, textural, and temporal characteristics.

2. MATERIALS

Our model is rendered on a Silicon Graphics Iris 120 GTX graphics workstation. In addition to traditional flat screen images, we also provide stereoscopic images to aid visualization of the 3-D relationships of the slices. Stereoscopic images are displayed with a Crystal Eyes™ stereoscopic shutter in conjunction with a 120 Hz. monitor. The shutter's design allows multiple shutters to be used with one monitor, thereby encouraging consultation among clinicians and researchers. A SpaceBall™ serves as the 3-D direct manipulation mechanism.

Fig. 2. Original cross-sectional MR image

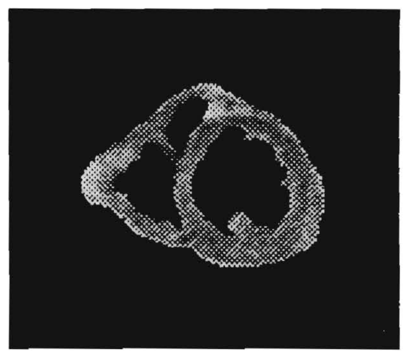


Fig. 3. Masked region of MR image

3. METHODS

Three inputs are needed to generate the model: the volume data, the volume mask, and the sampling geometry parameters

3.1 Volume mask

A volume mask is required for defining the chamber contours as well as the external wall boundaries of the cardiac MRI data. A physician "paints" mask images over the cardiac MRI slices to identify the heart muscle areas (see Fig. 2 and 3). The mask image is then processed with a contour extraction algorithm. The resultant multiple contours (chamber definitions and organ outline) are used in defining the graphical model of the heart as well as opaque image areas to be rendered.

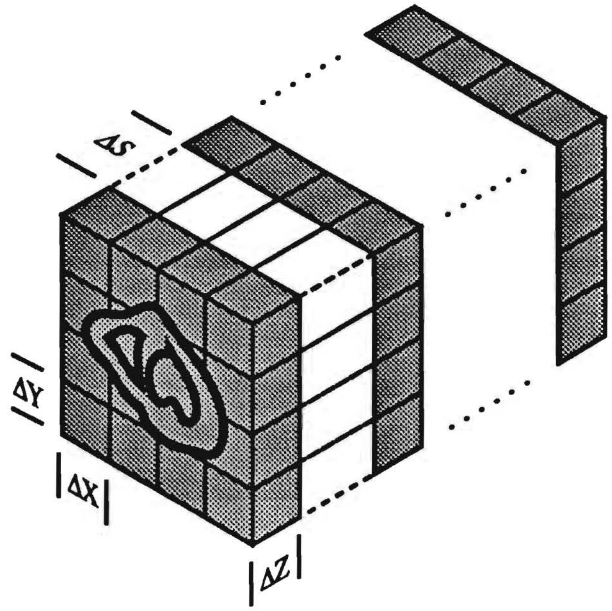


Fig. 4. Sampling geometry parameterized by ΔX, ΔY, ΔZ, and ΔS (slice separation)

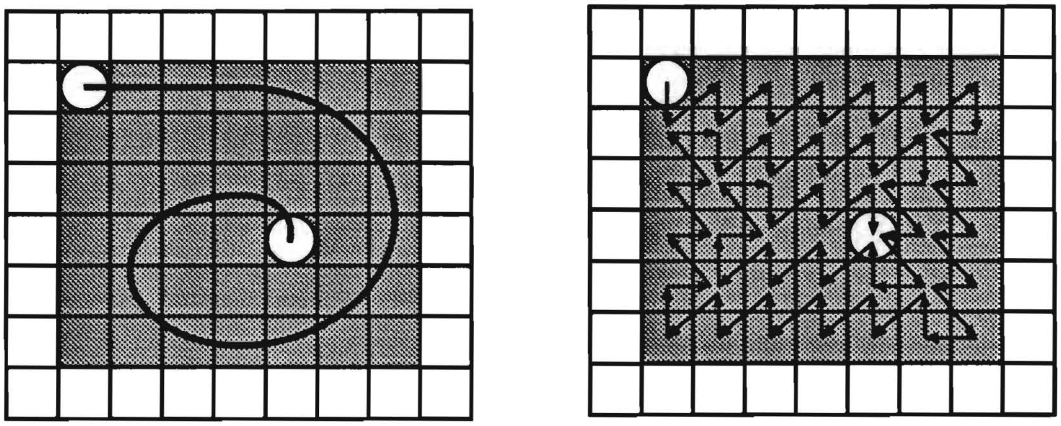
3.2 Geometry

Four geometry parameters are required. The sampling geometry defines the physical positioning of the sampling planes when the patient is scanned. Sampling geometries can be defined and parameterized by dx, dy , dz, and ds . The dx, dy, and ds variables specify the planar resolution and relative positioning of slice data, respectively (see Fig.4).

Since a volumetric data set is composed of infinitesimally small points, a slice from this data set is similarly thin. In actuality, the sampling geometry is not so ideal. Almost all scanners sample over a volume for every data point produced. Therefore the geometric model representing the volume must account for this reality. Our model solves this problem by rendering "thick" planar contours for each slice. This representation gives each component of the model an extruded quality reflecting the actual spatial conversion, and enhances the physical realism.

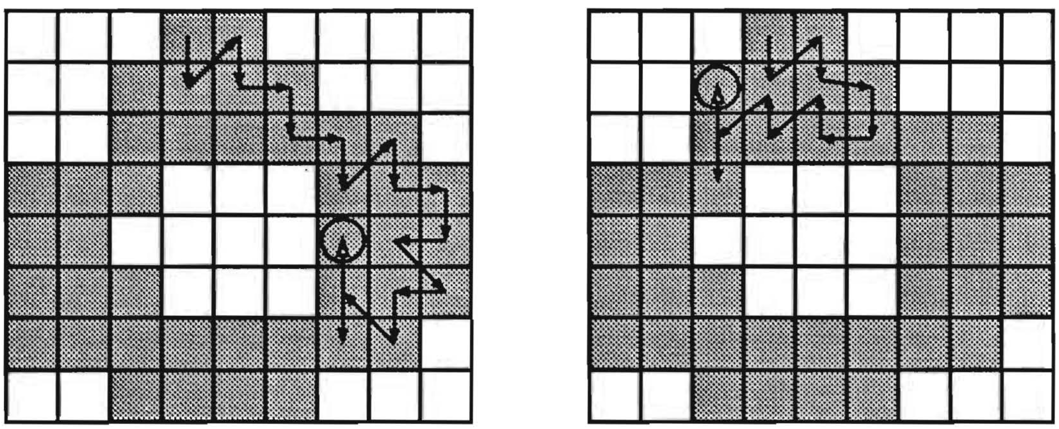
The scalar values in the volume data, or some processed version of this data, are mapped onto the geometric model (derived from the mask volume). The mapping process is the most critical aspect of the rendering since it determines the complexity of the graphical model. Texture mapping is not practical in this situation since the contours have non-rectangular, arbitrary areas, and holes.

The most efficient means of rendering the model is a triangular mesh. Most high-performance graphics workstations implement triangular meshes with a constraint on vertex ordering. In order to avoid redundant vertex calls these systems require a sequential ordering of the mesh triangle vertices. This constraint may, in general, speed up the rendering computations but it adversely affects our needs, as will be shown.



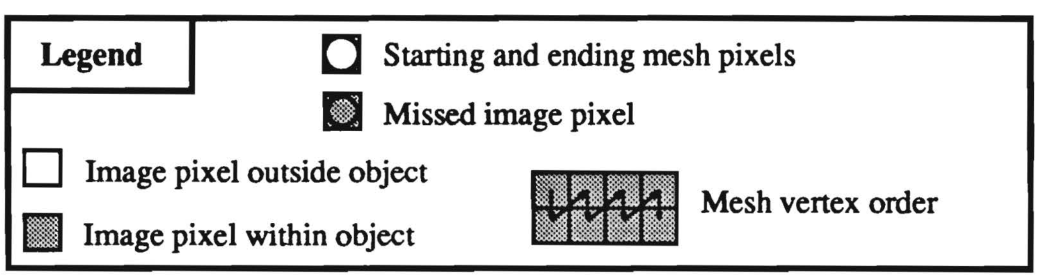
(a) (b)

Fig. 5. (a) & (b) represent a square image contour without holes and it's resultant mesh ordering. All data points from (a) are captured in (b) without redundancy from the start pixel to the end pixel. (a) shows the general mesh order for circumnavigation. (b) is the resultant mesh vertex ordering.



(a) (b)

Fig. 6. (a) & (b) illustrate the data loss problem when the image contour has holes. (a) is a circumnavigated mesh construction . Note the missed data point. (b) is an area or top down ordering of the same image contour with holes. Again, note the missed data point.



Scan line	# of meshes
0	1
1	1
2	1
3	2
4	2
5	2
6	1
7	0

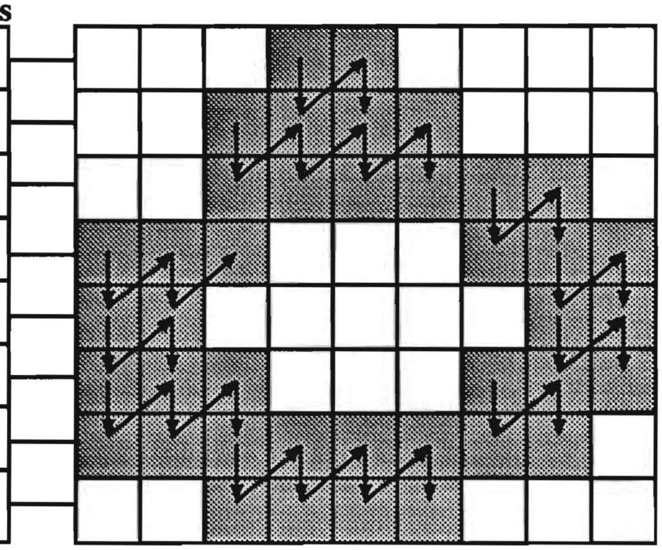


Fig. 7. Scan line method for meshing the image contour. All data points captured without redundancy.

A circular meshing of the data is trivial (Fig. 5a) and results in an area traversal as shown in figure 5b. Generalizing the contours to include holes introduces a potential data loss situation. For example, if such contours were meshed by circumnavigation, some pixel areas would be omitted (see Fig. 6a). If an area or top-down mesh approach is taken the same situation is possible (see Fig. 6b). The problem is caused by thin contour structures. It is possible to include these data points in the meshing traversal but at the cost of introducing collinear points in the geometric model. Though this problem may occur with any type of scanned volume it is unavoidable in cardiac MRI. Whether the meshing algorithm is top-down or circular this problem will cause volume data to be lost. The mesh traversal problem was solved by using a scan line approach (see Fig. 7) insuring the inclusion and rendering of all image elements identified for display and exclusion of collinear points.

4. RESULTS

When the model is rendered the heart chambers appear hollow (see Fig. 8). This rendering gives a realistic view of the chamber volumes. The jagged appearance of the planar components follows from a strict adherence to the physician-generated mask data. The rendering process must minimize modification of the volume of interest .

Each planar component of the model is bounded by the volume of interest region coincident on the sampling plane, producing a planar object whose border is a contour of the volume of interest. If a surface-based algorithm were used, the contour edge points would be the data used to reconstruct the 3-D surface. In those methods the 3-D surface is created from the contour edges, which are 2-D curve approximations, by interpolation. Therefore, the only canonical data points used in the surface reconstruction are the contour edge points. Our geometric model is only defined within the sampling space (canonical data), free of interpolated data. The slices are not connected geometrically in order to keep the rendering free of interpolated data. Volume techniques resample the volume data before rendering, introducing interpolation errors as well. One of the benefits of building the geometric model on top of the sampling geometry is that we avoid introducing sampling errors. Assuming that the scanner adhered to the Nyquist frequency of the volume signal, our model will not introduce false data.

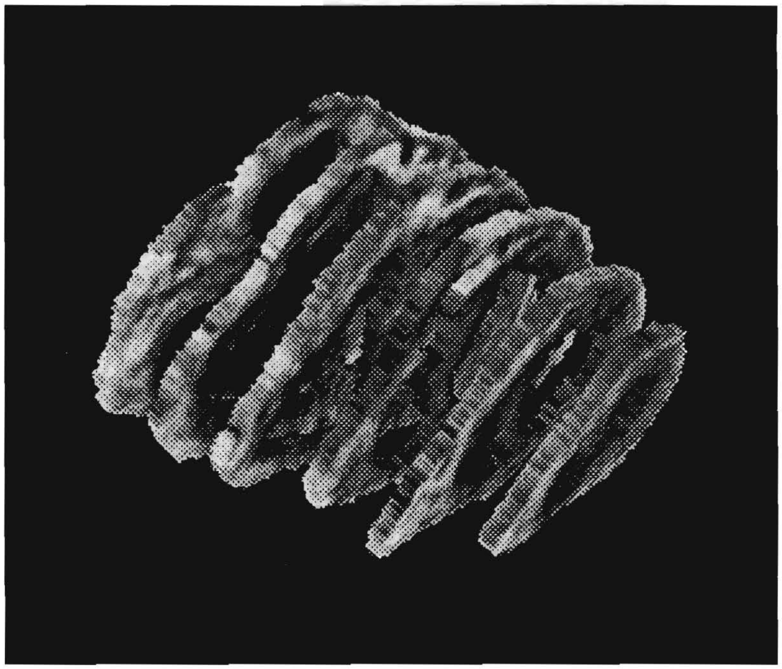


Fig. 8. Rendered MRI volumetric data

Our model images the whole volume without occluding the interior volume data. It differs from volume techniques because data points are either opaque or transparent, as specified by the mask data. In addition, it is geometrically simpler than surface-based models yet has the same structure defining quality while capturing a greater amount of volume data.

4.1 Performance

The model works well for our cardiac studies because it is effective for high planar resolution, low slice density data. The model is even more effective when the volume of interest consists of cavities. The more surfaces (cavities create surfaces) in the volume of interest the better the performance of our volume renderer. The cavities provide three benefits: they help define and highlight structural attributes in the volume data, they create ports in the data for greater views of physical relationships and data, and they reduce the rendering load by reducing the data set size.

The model uses the reduced graphical complexity gained from the planar components to allow the user to interactively manipulate the model while it is being animated. The quality of the animation and the response to real-time manipulation is dependent on the complexity of the volume of interest geometry. We have achieved acceptable performance for six thick slices, with each slice containing approximately 16K data points. The addition of real-time stereoscopic animation degrades performance on a SGI GTX120 graphics workstation.

We have looked at several means of increasing our rendering speed and interactivity for more complex images without increased hardware costs. One approach embarked upon was to apply adaptive refinement techniques to the rendering.[9,10] Unfortunately, these methods cannot be used because of the inherent temporal constraints. Basically, such methods involve refining the image over time. But the animation may have a higher frame rate than the adaptive refinement sequence. In addition, the spectral characteristics of an inferior medical image would obviously cause problems in a clinical setting.

5. CONCLUSION

We have developed a volume rendering technique that aids the clinician in visualizing anatomical, physiological and temporal characteristics of MRI data. The technique avoids resolution loss and other problems outlined above by maintaining the slice image character of the original data set. In addition, through interactive animation, multiple spatial visual perspectives of the heart in 3-D can be generated. Relevant portions from the grayscale Cardiac MR volume are transformed geometrically to correspond to their size and locations in space as would be seen by an observer at a specified location. Contour data is used to restrict this transformation to certain desired structures in the images, while making other structures in the images completely transparent as desired by the observer. Thus, this technique displays the geometric continuity of the structures of interest and allows the observers to investigate complex, abnormal, and previously undefined geometric interrelationships. Information about the sampling geometry is incorporated in the rendering by displaying each slab with an appropriately scaled thickness, instead of an infinitesimally thin plane.

The volume rendering method uses a graphical model that reduces the levels of visual mappings between the original sampled volume and the displayed image. In addition, the system creates true 3-D, interactive, real-time, animated renderings of the data, unlike other volume rendering techniques which create movie loops of the data off-line.

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