**Annual Report for Period:** 03/2006 - 02/2007
**Submitted on:** 03/28/2007
**Principal Investigator:** Laidlaw, David H.
**Award ID:** 0093238
**Organization:** Brown University
**Title:**
CAREER: Shape Capture and Modeling for Wrist Dynamics and Ancient Pottery Analysis using Manifold Surfaces and Signed-Distance Volume Images

## Project Participants

**Senior Personnel**

**Name:** Laidlaw, David
**Worked for more than 160 Hours:** Yes
**Contribution to Project:**

**Name:** Grimm, Cindy
**Worked for more than 160 Hours:** No
**Contribution to Project:**

**Post-doc**

**Graduate Student**

**Name:** Andrews, Stuart
**Worked for more than 160 Hours:** Yes
**Contribution to Project:**

**Name:** Marai, Georgeta
**Worked for more than 160 Hours:** Yes
**Contribution to Project:**

**Name:** Demiralp, Cagatay
**Worked for more than 160 Hours:** Yes
**Contribution to Project:**

**Name:** Zhang, Song
**Worked for more than 160 Hours:** No
**Contribution to Project:**

**Name:** Wald, Andrew
**Worked for more than 160 Hours:** No
**Contribution to Project:**
Just beginning to work on shape modeling of wrists.

**Undergraduate Student**

**Technician, Programmer**

**Name:** Thomas, Leor
**Worked for more than 160 Hours:** No
**Contribution to Project:**

**Name:** Horani, Morriah
**Worked for more than 160 Hours:** Yes
**Contribution to Project:**

**Name:** Gang, Joshua
**Worked for more than 160 Hours:** No
**Contribution to Project:**

**Other Participant**

**Research Experience for Undergraduates**

## Organizational Partners

**Rhode Island Hospital**
Bioengineering faculty and staff and orthopedic surgeons have collaborated on development and application of scientific tools for shape modeling of carpal bones and kinematics

**Washington University**
Cindy Grimm, formerly a PhD student and then a postdoc here at Brown in Computer Science continues to collaborate and support our efforts to apply manifold surface technology to shape modeling.

**Brown University**
As part of a previousliy funded KDI grant, engineering, applied math, and archaeology faculty and students have collaborated on developing tools for analyzing pottery sherds.

## Other Collaborators or Contacts

COLLABORATORS

Joseph Crisco, Assoc. Prof., Rhode Island Hospital/Brown Orthopedics applications.

James Coburn, Research Staff, Rhode Island Hospital/Brown Orthopedics applications.

Douglas Moore, Research Staff, Rhode Island Hospital/Brown Orthopedics applications.

Drs. Akleman and Weiss, RI Hostpital/Brown, Orthopedic Surgeons

Martha Joukowsky, Brown Archaeology, applications.

David Mumford, Prof., Applied Math

David Cooper, Prof., Engineering

Benjamin Kimia, Assoc. Prof., Engineering

Martha Sharp Joukowsky, Prof., Archaeology

Cindy Grimm, Asst. Prof, Computer Science, Wash U, St Louis

CONTACTS

n/a

## Activities and Findings

**Research and Education Activities: (See PDF version submitted by PI at the end of the report)**

**Findings:**
See activities section for both activities and findings.

**Training and Development:**
Laidlaw's cs237, ``Interdisciplinary Scientific Visualization.'' course was approved as a full-fledged course, not just a ``topics'' class. Three undergrads attended, together with graduate students. Work started in the class led to one paper accepted to IEEE Visualization conference with two undergraduate coauthors. Two of the ugrads from the class started doing research in Laidlaw's research group and attended weekly research meetings, expanding their learning as described in the PI's education plan.

Laidlaw's course was totally redesigned for Fall 2002. Participants included 8 visual design students (mostly from neighboring Rhode Island School of Design) and 8 computer science students. They learned how to collaboratively create scientific visualization application in a virtual reality environment. The course explored how to collaborate acress disparate disciplines, and created a better understanding of that process both for the instructors and the students. The class was briefly described in Science Magazine's ``Random Samples'' column and in a Brown publications, the George Street Journal. The course was run again in 2004 with 13 students, some visual design and some computer science.

The 2001 version of the class was taught again in 2003, with ten participants, including several undergraduates. Several of the projects from the class are continuing and will likely lead to publications. I believe that some of the students are now more likely to continue on in science than they were before.

Based on a practice session in Laidlaw's course, a course at the main graphics conference, SIGGRAPH, was proposed and accepted. In it, about 80 students spent about 2 hours using traditional art media to create exploratory visualizations of multi-valued 2D fluid flow data. The course was highly rated and participants produced some excellent results.

CS137 evolved this last year to involve no programming and mostly individual assignments. Students from both computer science and visual design were able to imagine and execute designs for virtual reality interactions and visualizations using an authoring tool created by PhD student Dan Keefe. This effort trained a new cohort of 13 students in the overlap between visual art, visualization and biological modeling and data analysis.

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The PI's research group has been firmly established within the department. It meets weekly, with participants from CS as well as facutly, students, and staff from other sciences, from application areas, and, on occasion, from the arts. The group employs a Rhetoric and Writing Fellow to help instruct on public speaking and on writing skills. Her help has been invaluable in raising the overall level of oral and written communication within the group. Talks are aimed at a lay-science level, in general, so that they can be more broadly accessible to an inter-disciplinary audience.

The PI received tenure during year 3, one year early, partly due to the work made possible by this funding.

**Outreach Activities:**

Laidlaw spoke about this work at a Dagstuhl Scientific Visualization seminar in Spring 2003, at Princeton Computer Science and Siemens Corporate Research also in Spring 2003, at a SIAM geometric modeling conference in Fall 2003, and at an NSF-sponsored conference 'Imaging in 2020' also in Fall 2003.

Science magazine profiled some of the PI's educational achievements in ``Random samples: Painterly data.'' Constance Holden. Science Magazine, 298(5594):739, Oct. 2002. Brown's local weekly newspaper described the educational work in more detail in ``Brown-risd course unites two disciplines, two institutions.'' Elizabeth Miller. George Street Journal, 27, November 2002.

Marai presented results at the IEEE Visualization '04 conference, Oct. '04.

Collaborator Crisco presented results at a conference in Feb. '03 and at two more conferences in '04.

Laidlaw spoke at UNH in Oct '02 and at the Frauenhofer Center for Computer Graphics in Feb '02.

Andrews presented results at the 18th Nat'l Conf on AI, Aug. '02.

Collaborator Cooper presented results at Int'l Conf on Pattern Recognition 2002 and at a conference on tools for archaeology, VAST 2001.

Marai presented findings at the World Congress on Biomechanics, Jul. '02.

Demiralp presented results at the IEEE Visualization '02 conference, Oct. '02.

Laidlaw, Demiralp, and collaborators made an award-winning presentation athte Am. Soc for Surgery of the Hand 56th Annual Meeting, Oct. '01. The exhibition was recognized with ``Best Scientific Presentation'' and ``Best Layout'' awards at the conference.

Laidlaw spoke at CMU in Nov. '01, at the MIT Image and Meaning Conference in Jun. '01, and at the University of Edinburgh in Apr. '01.

A SIGGRAPH course described in the Education section reached out to the computer graphics community.

**Journal Publications**

G.E. Marai, C.M. Grimm, D. H. Laidlaw, "Arthrodial Joint Markerless Cross-Parameterization and Biomechanical Visualization,", IEEE Transactions on Visualization and Computer Graphics, p. , vol. , ( ). Accepted

Joseph J. Crisco, Douglas Moore, G. Elisabeta Marai, David H. Laidlaw, Edward Akelman, Arnold-Peter C. Weiss, and Scott W. Wolfe., "Effects of Distal Radius Malunion on Distal Radioulnar Joint Mechanics. An In Vivo Study.", Journal of Orthopedic Research, p. , vol. , ( ). Accepted

G. ElisabetaMarai, David H. Laidlaw, and Joseph J. Crisco., "Super Resolution Registration Using Tissue-Classified Distance Fields.", IEEE Transactions on Medical Imaging, p. 177, vol. 25 (2), (2006). Published

G. Elisabeta Marai, Joseph Crisco, and David H. Laidlaw, "A Kinematics-Based Method For Generating Cartilage Maps and Deformations in the Multi-Articulating Wrist Joint From CT Images.", In Proceedings of the IEEE International Conference of the Engineering in Medicine and Biology Society, (EMBS), New York, NY,, p. 252, vol. Sept, (2006). Published

G. Elisabeta Marai, Cindy Grimm, and David H. Laidlaw., "Articulated Bone-Shape Cross-Parameterization and Biomechanical Visualization.", IEEE Transactions on Visualization and Computer Graphics, p. , vol. , ( ). Accepted

G. Elisabeta Marai and David H. Laidlaw, "Markerless inter-subject bone shape matching using 2D projections.", MICCAI short papers, p. 54, vol. , (2005). Published

G. Elisabeta Marai, Cagatay Demiralp, Stuart Andrews, and David H. Laidlaw., "JointViewer an interactive system for exploring orthopedic data.", IEEE Visualization 2004 Poster Compendium, p. 101, vol. October, (2004). Published

Andreas Wenger, Daniel Keefe, Song Zhang, and David H. Laidlaw., "Interactive rendering of multivalued volume data with layered complementary volumes.", IEEE Transactions on Visualization and Computer Graphics, p. , vol. , ( ). Accepted

Song Zhang, Mark E. Bastin, David H. Laidlaw, Saurabh Sinha, Paul A. Armitage, and Thomas S. Deisboeck., "Visualization and analysis of white matter structural asymmetry in diffusion tensor MR imaging data.", Magnetic Resonance in Medicine,, p. 140, vol. 51(1), (2004). Published

Joseph J. Crisco, G. ElisabetaMarai, David H. Laidlaw, DouglasMoore, and E. Akelman., "Kinematic and mechanical changes in the distal radioulnar joint (DRUJ) of patients with malunited distal radius fractures.", In 49th Annual Meeting of the Orthopaedic Research Society, New Orleans, LA. Orthopaedic Research Society, February 2-5 2003, p. 115, vol. , (2006). Published

G. ElisabetaMarai, David H. Laidlaw, James J Coburn,MohammadA Upal, and Joseph J. Crisco., "A 3d method for segmenting and registering carpal bones from ct volume images", In Proceedings of Annual Meeting of the American Society of Biomechanics,, p. 421, vol. Sept, (2003). Published

GeorgetaMarai, David H. Laidlaw, Cagatay Demiralp, Stuart Andrews, Cindy Grimm, and Joseph J. Crisco., "In vivo measurement of contact areas and ligament lengths in the distal radioulnar joint.", IEEE Transactions on Biomedical Engineering, 2002., p. 33, vol. , (2002). Published

Cindy Grimm, Joseph J. Crisco, and David H. Laidlaw, "Fitting manifold surfaces to 3D point clouds.", Journal of Biomechanical Engineering, p. 136, vol. 124(1), (2002). Published

Stuart Andrews and David H. Laidlaw., "Toward a framework for assembling broken pottery vessels.", In Proceedings of the 18th National Conference on Artificial Intelligence,, p. 945, vol. July/A, (2002). Published

David
B. Cooper, AndrewWillis, Stuart Andrews, Jill Baker, Yan Cao, Dongjin Han, Kongbin Kang,Weixin Kong, Frederic Leymarie, Xavier Orriols, Senem Velipasalar, Eileen Vote,Martha Joukowsky, Benjamin B. Kimia, David H. Laidlaw, and David Mumford., "Bayesian virtual pot-assembly from fragments as problems in perceptual-grouping and geometric-learning.", Proceedings of ICPR,, p. 30297, vol. 3, (2002). Published

David B. Cooper, An-drew Willis, Stuart Andrews, Jill Baker, Yan Cao, Dongjin Han, Kongbin Kang, Weixin Kong, Frederic Leymarie, Xavier Orriols, Eileen Vote, Martha Joukowsky, Benjamin B. Kimia, David H. Laidlaw, David Mumford, and Senem Velipasalar., "Assembling virtual pots from 3D measurements of their fragments.", VAST, p. 365, vol. , (2001). Published

Georgeta Marai, David H. Laidlaw, Cagatay Demiralp, Cindy Grimm, J. J. Crisco, D. C. Moore, and E. Akelman., "Contact areas and ligament lengths are abnormal in patients with malunited distal radius fracture despite normal radioulnar kinematics", World Congress Biomechanics, p. 125, vol. , (2002). Published

Cagatay Demiralp, Georgeta Marai, Stuart Andrews, David H. Laidlaw, Joseph J. Crisco, and Cindy Grimm., "Modeling and visualization of inter-bone distances in joints.", Visualization ?01 Work in Progress Proceedings, p. 24, vol. October, (2001). Published

J. J. Crisco, Cagatay Demiralp, David H. Laidlaw, A-P. C. Weiss, E. Akelman, and S.W. Wolfe., "Interactive visualization of 3D carpal kinematics and bony anatomy.", Am. Soc. for Surgery of the Hand 56th Annual Meeting,, p. 236, vol. October, (2001). Published

## Books or Other One-time Publications

## Web/Internet Site

**URL(s):**

http://www.cs.brown.edu/research/vis

**Description:**

This is the top-level link for the scientific visualization and modeling work of my group. Under it are this project and a number or others that inter-related. Datasets are also made available under this link for sharing by other researchers.

## Other Specific Products

## Contributions

**Contributions within Discipline:**

We have begun to develop methodology for quantifying the changing relationships among articulated bones. The methodology builds on different complementary shape representation and on numerical modeling techniques that use the different strengths of the different representations. Within computational modeling, this may suggest general modeling approaches that will go beyond the specific archaeological and orthopedic application areas in which we have deployed early solutions.

**Contributions to Other Disciplines:**

In orthopedics our methodological developments may change how surgeons approach surgery for malunited forearm fractures. They are also changing how other injuries and diseases can be quantified and

understood, particularly in the wrist. Some of our results are now being generalized to other skeletal kinematics application areas, including the study of flying bats, flying birds, and swimming fish.

**Contributions to Human Resource Development:**

Students and staff working on these projects, both within CS and in application areas, are developing valuable skills in inter-disciplinary scientific research.

**Contributions to Resources for Research and Education:**

We have developed tools for more quickly prototyping visualization applications in virtual reality. These have been used by students in our joint Brown/RISD (Rhode Island School of Design) class that teaches about design in virtual reality for science.

**Contributions Beyond Science and Engineering:**

## Special Requirements

**Special reporting requirements:** None

**Change in Objectives or Scope:** None

**Unobligated funds:** $ 0.00

**Animal, Human Subjects, Biohazards:** None

## Categories for which nothing is reported:

Any Book

Any Product

Contributions: To Any Beyond Science and Engineering

## 2.1 Activities and Findings

**YEARS ONE TO SIX**

**Shape Modeling for Archaeology**

Our revised scope of work removed one of the applications areas, archaeological analysis. However, over the first two years of the grant we have been able to complete all of the proposed work as well as extending into some of the work proposed for year three. In year three, however, we shifted to focus only on the wrist shape and kinematics modeling work.

Graduate student Stuart Andrews, in collaboration with the PI as well as faculty and students in several other Brown departments, developed a methodology for assembling pottery sherds into complete pots. The methodology used implicit and explicit geometric shape representations as well as loosely modeling the process that archaeologists use for assembling pots by hand. His results were reported in a student paper listed in the products section. A parallel collaborative effort with the engineering department also led to related results using an alternate methodology. These efforts and results are equivalent to the first 2 years of proposed effort with some clustering of sherd triples, which was expected in year 3.

**Shape modeling for Orthopedics**

We have completed most of the proposed goals for the first four years of the grant, with some substitutions of year four goals for earlier ones.

Our year-one goals of fitting both manifold surfaces and signed-distance functions to CT data have been realized. During the first two years, we also proposed to reduce the human interaction time needed for this process by automating the initial interactive step of drawing contours in serial CT sections. Instead, we re-ordered our plans and automated the following nine interactive segmentation steps, reducing interaction time by almost ninety percent and permitting many more subjects to be processed. This reduction has had a significant impact on the power of the statistical results that can be generated because subject numbers can be larger. It also permited the study of more problems, and we have begun expanding our efforts into modeling the entire carpus, not just the distal radial ulnar joint (DRUJ). The method builds on unsupervised partial-volume Bayesian classification of the CT data following by automated registration of manifold models to the CT data.

In parallel with the automation, we have processed DRUJ patient data, producing both shape models, visualizing the resulting relationships in the motion between the bones in multiple poses, and creating a set of scalar measures that help to capture and quantify that motion. The measures capture the distance between articulating surfaces on the bones, the size of the contact areas, their location on the bones, the likely lengths of ligaments, and the deflection in those ligaments due to bone/ligament interactions.

These measures are producing results that suggest a new theory of deficits due to malunited radius fractures. Our collaborators demonstrated that no bony impingement was responsible for limited motion and pain; we went further to show that certain soft-tissue bone-bone alignment issues are likely to be responsible. This application of the new technologies we have developed demonstrates their utility, and our orthopedic surgeon collaborators are studying the consequences in surgeries that they are currently carrying out.

We have also developed an interactive tool for visualization of articular relationships. It was part of an award-winning presentation at a national hand surgery meeting.

We have deployed the segmentation and registration to Rhode Island Hospital researchers, who have applied it to over 80 joints. Together we created a database of normal wrist shape and motion. We have also developed a framework for validation of registration accuracy.

We have extended the registration method to wrists in which one bone had been completely fractured (scaphoid non-union). We have deployed the technology to Rhode Island Hospital researchers, who are currently applying it to a collection of injured joints. We intend to run the wrist motion model (currently under development) on both the normal and injured database and contrast the findings.

In parallel with the wrist motion work, we have proposed additional bone shape measures based on the distance between articulating surfaces on the bones. These measures account for the location of the contact area centroid, the size of the contact area, and the bone curvature at the centroid. We have processed over 20 scapho-lunate joints. The findings should help our orthopedics collaborators develop a wrist bone shape atlas.

We have developed a non-invasive, subject-specific method for estimating cartilage maps (location and thickness) directly from in vivo kinematic data and computed tomography (CT) volume images. The methos inferrs cartilage lo-

cation and thickness from inter-bone joint spacing measurements across the kinematic range of motion. We have also developed a novel algorithm for computing cartilage surface deformations. Our cartilage model, a meshless incompressible heightfield captures the physical properties important for estimating the shape, contact area, and deformation magnitude of cartilage at each articulation. Incompressibility is achieved by transferring volume from compressed locations to locations not in contact.

We have extended our ligament model so that ligament fibers can wrap around multiple bones. We can also handle now multiple fibers per ligament bundle, multiple kinematic poses for each ligament, and multiple ligament bundles.

We have assembled a kinematically driven model prototype of the wrist using in vivo bone surfaces and kinematics, and synthetically defined cartilage maps and ligment insertion sites. The cartilage maps (location and thickness) were generated using inter-bone joint spacing measurements across the kinematic range of motion. The prototyoe allows computation of cartilage and functional ligament length across the range of motion.

Also, we have developed an automated technique for transferring ligament insertion sites and cartilage maps from in vitro dataset to in vivo datasets. Central to our approach is a computer-vision inspired markerless method for establishing pairwise correspondences between individual-specific geometry. Manifold models are subsequently defined and deformed from one individual-specific geometry to another such that the markerless correspondences are preserved while minimizing model distortion. The resulted mutually-consistent parameterization allows our users to combine complementary geometry acquired through different modalities, and thus overcome current imaging limitations.

PRODUCTS

G.E. Marai, C.M. Grimm, D. H. Laidlaw, Arthrodial Joint Markerless Cross-Parameterization and Biomechanical Visualization, IEEE Transactions on Visualization and Computer Graphics (in press).

Joseph J. Crisco, Douglas Moore, G. Elisabeta Marai, David H. Laidlaw, Edward Akelman, Arnold-Peter C. Weiss, and Scott W. Wolfe. Effects of Distal Radius Malunion on Distal Radioulnar Joint Mechanics. An In Vivo Study. Journal of Orthopedic Research, 2006. In Press.

G. Elisabeta Marai, David H. Laidlaw, and Joseph J. Crisco. Super Resolution Registration Using Tissue-Classified Distance Fields. IEEE Transactions on Medical Imaging, 25(2):177-187, 2006.

G. Elisabeta Marai, Joseph Crisco, and David H. Laidlaw. A Kinematics-Based Method For Generating Cartilage Maps and Deformations in the Multi-Articulating Wrist Joint From CT Images. In Proceedings of the IEEE International Conference of the Engineering in Medicine and Biology Society (EMBS), New York, NY, September 2006.

G. Elisabeta Marai, Cindy Grimm, and David H. Laidlaw. Articulated Bone-Shape Cross-Parameterization and Biomechanical Visualization. IEEE Transactions on Visualization and Computer Graphics, 2006. In Press.

G. Elisabeta Marai and David H. Laidlaw. Markerless inter-subject bone shape matching using 2D projections. In MICCAI 2005 short papers, 2005

G. Elisabeta Marai, Cagatay Demiralp, Stuart Andrews, and David H. Laidlaw. JointViewer an interactive system for exploring orthopedic data. IEEE Visualization 2004 Poster Compendium, October 2004

Andreas Wenger, Daniel Keefe, Song Zhang, and David H. Laidlaw. Interactive rendering of multivalued volume data with layered complementary volumes. IEEE Transactions on Visualization and Computer Graphics, in press.

Song Zhang, Mark E. Bastin, David H. Laidlaw, Saurabh Sinha, Paul A. Armitage, and Thomas S. Deisboeck. Visualization and analysis of white matter structural asymmetry in diffusion tensor MR imaging data. Magnetic Resonance in Medicine, 51(1):140-147, 2004.

Joseph J. Crisco, G. Elisabeta Marai, David H. Laidlaw, Douglas Moore, and E. Akelman. Kinematic and mechanical changes in the distal radioulnar joint (DRUJ) of patients with malunited distal radius fractures. In 49th Annual Meeting of the Orthopaedic Research Society, New Orleans, LA. Orthopaedic Research Society, February 2-5 2003

G. Elisabeta Marai, David H. Laidlaw, James J Coburn, Mohammad A Upal, and Joseph J. Crisco. A 3d method for segmenting and registering carpal bones from ct volume images. In Proceedings of Annual Meeting of the American Society of Biomechanics, September 2003.

In vivo measurement of contact areas and ligament lengths in the distal radioulnar joint. Georgeta Marai, David H. Laidlaw, Cagatay Demiralp, Stuart Andrews, Cindy Grimm, and Joseph J. Crisco. IEEE Transactions on Biomedical Engineering, 2002. In review

Fitting manifold surfaces to 3D point clouds. Cindy Grimm, Joseph J. Crisco, and David H. Laidlaw. Journal of Biomechanical Engineering, 124(1):136-140, February 2002.

Toward a framework for assembling broken pottery vessels. Stuart Andrews and David H. Laidlaw. In Proceedings of the 18th National Conference on Artificial Intelligence, pages 945-946, July/August 2002.

Bayesian virtual pot-assembly from fragments as problems in perceptual-grouping and geometric-learning. David B. Cooper, Andrew Willis, Stuart Andrews, Jill Baker, Yan Cao, Dongjin Han, Kongbin Kang, Weixin Kong, Frederic Leymarie, Xavier Orriols, Senem Velipasalar, Eileen Vote, Martha Joukowsky, Benjamin B. Kimia, David H. Laidlaw, and David Mumford. In Proceedings of ICPR, volume 3, pages 30297-30302, 2002.

Assembling virtual pots from 3D measurements of their fragments. David B. Cooper, An-drew Willis, Stuart Andrews, Jill Baker, Yan Cao, Dongjin Han, Kongbin Kang, Weixin Kong, Frederic Leymarie, Xavier Orriols, Eileen Vote, Martha Joukowsky, Benjamin B. Kimia, David H. Laidlaw, David Mumford, and Senem Velipasalar. In Proceedings of VAST, 2001. Contact areas and ligament lengths are abnormal in patients with malunited distal radius fracture despite normal radioulnar kinematics. Georgeta Marai, David H. Laidlaw, Cagatay Demiralp, Cindy Grimm, J. J. Crisco, D. C. Moore, and E. Akelman. In World Congress Biomechanics, 2002.

Modeling and visualization of inter-bone distances in joints. Cagatay Demiralp, Georgeta Marai, Stuart Andrews, David H. Laidlaw, Joseph J. Crisco, and Cindy Grimm. In Visualization '01 Work in Progress Proceedings, pages 24-25, October 2001.

Interactive visualization of 3D carpal kinematics and bony anatomy. J. J. Crisco, Cagatay Demiralp, David H. Laidlaw, A-P. C. Weiss, E. Akelman, and S.W. Wolfe. In Am. Soc. for Surgery of the Hand 56th Annual Meeting, October 2001.