

Rapid Prototyping of Parallel Robot Vision Systems Using Virtual Reality and Systems Simulation

Final Report, NSF CDA-9401142

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October 1999

1 Introduction

1.1 Institution

The University of Rochester is a small, private University established in 1850. During the early 20th century, the University grew significantly, in part due to the efforts of George Eastman, the founder of Eastman Kodak. During this period, the Medical School, the Institute of Optics, and the Eastman School of Music, all currently nationally known, were established. Today, the University is home to approximately 4000 undergraduates and 2500 graduate students, and operates with a philosophy of providing the academic opportunities of a renowned research institution in an environment scaled to the individual.

The Department of Computer Science at the University of Rochester offers an intense, research-oriented program leading to the degree of Doctor of Philosophy, with particular emphasis on the areas of computer vision and robotics, knowledge representation and natural language understanding, systems software for parallel computing, and the theory of computation. The focused research interests reflect our desire to achieve excellence in a core of important issues, rather than to try to cover all areas. Undergraduate BA and BS programs, now in their fifth year, explicitly emulate the intensity and research focus of the graduate program, though at a less advanced level.

1.2 Project

The main focus of our research is a laboratory that combines sensory interaction with simulated physical environments (otherwise known as virtual reality), physical and sensory interaction with mixed physical and simulated environments (otherwise known as augmented reality), and the reconstruction of physical environments from sensory inputs (otherwise known as computer vision), with execution-driven simulation of complex parallel systems in the design and control of visually-controlled robotic systems. We also develop systems

tools to manage large parallel computing applications and development environments. This RI-supported research leverages Rochester's unique combination of expertise in active vision systems, behavioral robotics, virtual reality, and parallel programming environments and systems. (see <http://www.cs.rochester.edu/research/iip/>).

Our laboratory has two parts: one is for building working systems in the *real world*; the other part is for prototyping and experimentation in the *virtual world*. The components of the real-world laboratory are the effectors and sensors for interacting in the real world, and the computational machinery required to run the control algorithms. The virtual-world laboratory includes the hardware and software for creating the virtual world, (models of sensors, effectors, and their interaction with an environment). System support includes the large parallel computers used for computation-intensive applications and simulations, and research software systems for running them.

2 Participants

2.1 People

As noted on the cover page, the grant had five PIs or co-PIs. Two years into the work, Tom LeBlanc was promoted to Vice Provost and Dean of the College Faculties, effectively removing him from day-to-day participation. That same year we hired Sandhya Dwarkadas as an assistant professor, and she began to function as a de facto co-PI. The next year we hired Kyros Kutulakos into a joint assistant professor position in Computer Science and the Medical Center. Kyros, too, functions as a de facto co-PI. Liudy Bukys, who is a part-time Research Scientist in the department and part-time Associate Vice Provost for Computing at the University, has also played a major role in several facets of the work.

A total of 52 graduate students have been directly involved in research on the project. Names, degrees, and post-graduation placements can be found in figures 1 and 2.

Many undergraduates have also participated in the project. Unfortunately, our records here are incomplete. The following is a partial list of students playing an active role in the labs in the last two years: Anand Bahirwani, Elliot Barnett (BS, 1998), Josh Drake (BA, 1998), Aaron Gerega (BS, 1999), Craig Harman, Peenak Inamdar, Craig Harman, Fred Marcus Henry McCauley, Yasser Mufti (BS, 1999), Sean Rodgers, and Kari Sortland (BA, 1998).

2.2 Organizations

As described on the web page form, we have had significant technical interactions with at least four industrial partners.

Digital Equipment Corporation (now **Compaq**) provided two major equipment grants, totaling over \$1.5M, toward acquisition of a state-of-the art 32-processor AlphaServer cluster, connected by a high-performance Memory Channel network. Approximately \$370K in NSF funds were expended on those clusters. We also collaborated on papers with members of technical staff at Compaq's Cambridge and Western (Palo Alto) Research Labs.

Ph.D. graduates

Ricardo Bianchini (Rutgers Univ.)
Michał Cierniak (Intel Corp.)
Corinna Cortes (Bell Labs)
Mark Crovella (Boston Univ.)
Virginia de Sa (Sloan Center, San Francisco)
Olac Fuentes (Mexican National Institute for Astrophysics Optics, and Electronics)
Galen Hunt (Microsoft Research)
Martin Jägersand (Johns Hopkins)
Jonas Karlsson (Xerox Webster Research Center)
Leonidas Kontothanassis (Compaq Cambridge Research Lab)
Andrew McCallum (Just Research, Pittsburgh)
Wagner Meira (Federal University of Minas Gerais, Brazil)
Maged Michael (IBM T. J. Watson Research Center)
Ramprasad Polana (Microstrategy, Inc.)
Polly Pook (IS Robotics)
Rajesh P. N. Rao (Salk Institute)
Ray Rimey (Lockheed Martin Astronautics)
Justinian Rosca (Siemens Corp. Research Center)
Garbis Salgian (Sarnoff Research Center)
Ramesh Sarukkai (Kurzweil Assoc.)
Jeff Schneider (Carnegie Mellon Univ.)
Rob Stets (Compaq Western Research Lab)
Jack Veenstra (Silicon Graphics)
Jim Vallino (Rochester Institute of Technology)
Bob Wisniewski (IBM T. J. Watson Research Center)
Lambert Wixson (Sarnoff Research Center)
Mohammed Zaki (Rensselaer Polytechnic Institute)

Figure 1: Students receiving Ph.D.s resulting from the sponsored research.

We worked with **SensAble Devices, Inc.** to develop a large-scale version of their Phantom force-feedback device, and to configure a pair of these devices to provide a thumb-and-forefinger grip workspace spanning almost a cubic meter.

We worked with **Virtual Research Systems, Inc.** and **ISCAN, Inc.** to integrate the latter's eye-tracking mechanism into the former's VR4 virtual reality helmet. This provided us with the first immersive visual environment capable of fine-grain tracking of gaze and attention. The design has since been copied by labs around the world.

M.S. graduates

Nikolaos Hardavellas (Compaq)
Sotirios Ioannidis (Ph.D. program at UPenn)
Michael Marchetti
Alex Poulos (Silicon Graphics)
Peter von Kaenel

continuing students

Rajeev Balasubramonian	Jessica Bayliss
Rahul Bhotika	Rodrigo Carceroni
DeQing Chen	Melissa Dominguez
Chris Eveland	Isaac Green
Chris Homan	Bo Hu
Grigorios Magklis	Srini Parthasarathy
Umit Rencuzogullari	Brandon Sanders
Andrea Selinger	Amit Singhal
Nathan Sprague	Yiyang Tao
Mike VanWie	Zuohua Zhang

Figure 2: Other graduate students involved in the sponsored research.

3 Activities and Findings

The infrastructure constructed over five years with this award has been a significant factor in producing an environment that has allowed us to attract top notch faculty and graduate students, and carry out state-of-the-art research. As described in sections 2.1 and 4.1, 27 Ph.D.s and more than 300 publications, over half of them in refereed forums, have been produced with direct support of the infrastructure grant. Many of the original visions were achieved; and as is the case in creative endeavors, some lines of research took unanticipated directions. For example, the virtual reality component took off dramatically in ways not originally envisioned, especially regarding study of human performance in virtual environments, and in development of augmented reality technology.

3.1 Research and Education

Over the course of three consecutive five-year awards, the Research Infrastructure program has played a crucial role in shaping almost every facet of our research program. NSF funding has allowed us to build a laboratory that has unique capabilities to support research into perceptual intelligence through robot vision, psychophysics and cognition, and photo-realistic and touch-realistic simulations for advanced computer control. Almost all our infrastructure funding was spent on highly-leveraged, unusual hardware that has helped us attract and retain the best students and faculty as well as carry out our work. With the infrastructure resources, we have been able to develop a number of successful applications in which the

real and simulated worlds were effectively married, realizing improved testing, performance, debugging, and human experimental interfaces.

The just-completed grant has helped us retain our position as a leader in active paradigm, biologically-motivated vision and robotics research, and in shared-memory parallel computing. It has helped us recruit and train the very best graduate students (consistently the best in the College on standardized tests), and place them at the best institutions upon their graduation.

Our emphasis on interdisciplinary work was a major factor in attracting Sandhya Dwarkadas, now in her fourth year as an Assistant Professor, and Kyros Kutulakos, who now has a dual post in Computer Science and the Medical Center. Both Sandhya and Kyros have landed NSF CAREER awards. Sandhya is a leading expert in the interplay of compilers, runtime systems, and computer architecture for high-end parallel computing. She was appointed this past year to a secondary position in Electrical and Computer Engineering. She is the heaviest faculty user of the AlphaServer cluster acquired through a combination of Infrastructure funding and leveraged equipment donations from Compaq.

Infrastructure funds were also used for hardware to support Kyros's early work in augmented reality and interactive 3-D representation construction. He won the best paper award at CVPR94 for the Purposeful Viewpoint Control paradigm for reconstructing the surface of complex curved 3D objects. His "Space Carving" reconstruction technique is the only provably-correct method capable of extracting the 3D shape of an arbitrary scene from an arbitrary collection of input photographs taken inside or around the scene.

3.2 Findings

Our most recent RI award focused on simulation and the creation and analysis of large intelligent systems. We had several notable successes in which real-time graphics were used as input to controllers. The real-time graphics were generated by virtual reality technology, which we also used for psychophysics. Dana Ballard's use of virtual reality technology to improve the monitoring of human performance has raised the standard of complexity possible in psychophysical experiments and has created new tools (such as eye-trackers in head mounted displays). The use of simulated input to computational perception systems was key to this work, and has advanced the state of computer learning. Under the RI, we were the first lab with an eye tracker inside of a virtual reality helmet, and the first lab to integrate two Phantom haptics robots for the ability to grasp virtual objects between two fingers. We discovered that deictic codes play a crucial role in cognition, and are the first lab to study EEG evoked potentials obtained while a subject drives freely in a virtual environment. We developed the best genetic programming algorithms for subroutine discovery and heuristic components: Evolutionary Divide-and-Conquer and Adaptive Representation. We extended reinforcement learning to deal with up to 10,000 states while still dealing with the hidden state problem. We created the first visual routines for autonomous driving in virtual photo-realistic and real environments based on driving behaviors observed with eye-tracking. We developed a robust Kalman filter framework that learns both measurement and state matrices. We unified the Kalman filter, neural net, and sparse distributed memory formalisms into a hierarchical model of the visual cortex.

Our most recent award also concerned robotics and computer vision. Using our 16 DOF

Utah robot “hand”, Randal Nelson and students made the first demonstration of model-free dextrous manipulation, and the first demonstration of learning of dextrous manipulation primitives. Using cooperating robot arms and the hand, we made the first demonstration of high degree of freedom adaptive visual servoing to allow robot motion programming by showing the desired result. We also have the best known algorithm for general 3D object recognition in cluttered environments.

Chris Brown’s work led to the first run-time environment allowing soft real-time AI to be supported at a system level along with hard real-time control functionality. We developed the best Learning methods for real-time control of highly non-linear plants and systems. We built an influential and novel purposive, active vision system driven by decision theory and Bayes nets. We reformulated Lowe’s famous pose detection algorithm for much better accuracy and speed. With SRI, we are making the first use of novel real-time stereo hardware for tracking and monitoring pedestrian traffic.

Finally, our most recent award supported research in parallel systems. Particularly noteworthy was our work in software distributed shared memory (S-DSM—Dwarkadas and Scott’s Cashmere and TreadMarks projects), software synchronization (Scott and students), and parallel program performance analysis and prediction (the Carnival system of LeBlanc and students). During the last grant period we developed scalable busy-wait synchronization mechanisms that can be used successfully on a multiprogrammed system, along with several new atomic data structures, among them the fastest known parallel queue. We constructed the Coign automatic distributed partitioning system, which creates minimal-communication-cost distributed applications from non-distributed, shrink-wrapped commercial code. We evaluated several key tradeoffs, including the choice between programmable and hard-wired network interfaces, for multiprocessor cache controllers. We developed *waiting time analysis* to explain the performance of parallel applications.

Our Cashmere project demonstrated that fast, user-level access to remote memory can dramatically improve the performance of software distributed shared memory (S-DSM), at very low dollar cost. Cashmere runs on an AlphaServer cluster connected by Digital’s Memory Channel network. It incorporates the first scheme to avoid expensive TLB shutdown operations while combining hardware coherence within multiprocessor nodes with software coherence between nodes; this scheme is the subject of a pending patent. PI Dwarkadas participated in the development of TreadMarks, an S-DSM system now in use at over 20 university and industry sites. The parallel FASTLINK package that Dwarkadas was instrumental in developing was used in conjunction with TreadMarks to obtain the results that led to the recent discovery of the gene believed responsible for Parkinson’s disease. As part of the TreadMarks project, we developed innovative techniques to adapt the memory coherence protocol to the sharing behavior of a given application. We also developed one of the first integrated compiler and run-time systems to exploit static (compile-time) and dynamic (run-time) information for improved performance on shared-memory programs.

We have collaborated with researchers in several disciplines on parallel application development. Within the department, work with Prof. Mitsunori Ogihara and Henry Kyburg has made datamining a major focus of department expertise. Across departments, we are currently very excited about collaborations with Prof. Adam Frank of Astrophysics in the area of computational fluid dynamics.

3.3 Training and Development

Section 2.1 lists graduate and undergraduate students active on the project. Graduate education is the core of our department’s mission, and we work hard to integrate undergraduates into the research labs as well. Infrastructure provided by the grant has significantly enhanced opportunities at both the graduate and undergraduate levels.

In the fourth year of the grant we collaborated with Electrical and Computer Engineering, Optics, and several other departments on a successful proposal to the NSF Coordinated Research and Curricular Development (CRCRD) program, on the subject of Electronic Imaging.

3.4 Outreach

Project participants have engaged in a variety of outreach activities. We have visited local high schools, made presentations to the local ACM and IEEE chapters and to undergraduate groups at other institutions, and been featured prominently in the popular press. This past summer, one of our graduate students, Jessica Bayliss, ran a summer course for high school students on the interdisciplinary aspects of computer science (unofficial title: Computer Science is not just for Geeks).

4 Publications and Products

4.1 Papers

The final 18 pages of this report list over 300 papers reporting on work supported by the grant. These include 40 journal articles, 163 conference or workshop papers, 16 books or chapters, and 83 technical reports. Almost all explicitly acknowledge funding from the grant.

4.2 Internet Dissemination

Links to extensive information on work supported under the grant can be found at

<http://www.cs.rochester.edu/research>

in the subsections entitled “Robotics and Vision Research” and “Systems”. The three most directly relevant subprojects are described at the following addresses:

<http://www.cs.rochester.edu/research/iip/>

<http://www.cs.rochester.edu/research/robotics.html>

<http://www.cs.rochester.edu/research/cashmere/>

5 Contributions

5.1 Contributions Within Computer Science

At the national and global level, work supported by the grant has its impact through the influence of our papers on other researchers, and through the work of our alumni. Our work

is heavily cited. Some of our laboratory techniques have been widely copied (e.g. verging binocular cameras, fast execution-driven simulation, scalable synchronization algorithms) and others are still on the leading edge (eye trackers in VR helmets, oversize haptic hardware, uncalibrated augmented reality, low-latency software distributed shared memory, real-time vision algorithms implemented on special hardware).

5.2 Contributions to Other Disciplines

Our vision and virtual reality researchers interact heavily with colleagues in cardiology, dermatology, neurology, neurosurgery, ophthalmology, psychology, and radiology. Dana Ballard's NIH Center for the Study of Neural Models of Behavior has co-PIs in experimental psychology, ophthalmology, and neurology. Our work has led to major insights into the nature of cognition.

Our systems group interacts with colleagues in several branches of computational science, including astrophysics, computational biology, and radiology, where we are helping to expand the frontiers of simulation, genetic linkage analysis, and real-time volumetric imaging.

5.3 Human Resource Development

Our work contributes to human resource development primarily through the mentoring of students. Graduate and undergraduate students directly involved in the sponsored research are listed in section 2.1. As noted in section 3.3, we worked with several other departments last year to launch a major new educational initiative in Electronic Imaging, with funding from the NSF Coordinated Research and Curricular Development (CRCDD) program.

5.4 Resources for Research and Education

Over the course of the past five years, the grant has been one of the principal sources of funds for departmental infrastructure. Almost every project in the department has relied, at least in part on the devices, servers, and networks purchased with these funds.

Research funded under this grant played a major role in our first-year "immigration" course for graduate students. Each year of the grant we have used the funded infrastructure as the basis of at least one, and often two, of the major course projects. Several of the students listed in section 2.1 first became involved in the project in this way. The infrastructure has also been used in several other courses, including Sensory Motor Systems, Networks, Visual Computing, and The Computational Brain.

5.5 Contributions Beyond Science and Engineering

Our work in virtual reality is helping to shape the next generation of therapeutic techniques and prosthetic devices for persons with neurological disabilities.

Sandhya Dwarkadas has made major contributions to the parallel FASTLINK package for genetic linkage analysis, and to the TreadMarks system for shared memory emulation on clusters of machines. Three years ago these two packages were instrumental in the discovery at NIH of the gene believed responsible for Parkinson's disease.

IIP-Related Publications List (CDA-94-01142)

July 1994 – June 1999

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Amza, C., A.L. Cox, S. Dwarkadas, L-J. Lin, K. Rajamani, and W. Zwaenepoel, “Adaptive protocols for software distributed shared memory,” *Proc., IEEE* 87, 3, 467–475, March 1999.

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Araújo, H., R.L. Carceroni, and C.M. Brown, “A fully projective formulation for Lowe’s tracking algorithm,” TR 641 (replaces TR 610), Computer Science Dept., U. Rochester, November 1996.

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Barnett, E., C.M. Brown, and C. Harman, “A preliminary Hough transform class for the IUE,” internal report to the Image Understanding Environment Technical Committee, August 1997.

- Bayliss, J.D. (Ed.), "Introduction to the Department," Dept. Guide 2, Computer Science Dept., U. Rochester, August 1998.
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