PRAGMATIC AND THEORETICAL STUDIES IN AUTOMATED REPAIR

Final Technical Report

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Total: $900,000

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1. PRODUCTIVITY MEASURES OVER THREE YEARS

• Refereed papers submitted but not yet published	7
• Refereed papers published	74
• Unrefereed reports and articles	4
• Books or parts thereof submitted but not yet published	6
• Patents filed but not yet granted	0
• Patents granted	0
• Invited presentations	47
• Contributed presentations	31
• Honors received (fellowships, technical society appointments, conference committee role, editorship, etc.)	15
• Prizes or awards received	4
• Promotions obtained	6
• Graduate students supported >25% of full time	16
• Post-docs supported > 25% of full time	4
• Minorities supported (include Blacks, Hispanics, American Indians and other native Americans such as Aleuts, Pacific Islanders, etc, Asians, and Indians)	0

STATMENT "A" per Dr. A. Meyrowitz
ONR/Code 1133IS
TELECON 7/3/90 VG

2. OVERVIEW OF TECHNICAL ACTIVITIES OVER THREE YEARS

In the Executive Summary of the proposal for this project, we opened with the following problem statement. "The use of robots to diagnose and disassemble defective equipment during and after manufacture, to detect faulty parts and replace them with properly functioning parts, and then to reassemble a total system and make it operational, is a potentially important application of robotic technology. However, present robotic technology only provides very immature approximations to the capabilities required to accomplish operations of such sophistication."

The proposal was to study the ... "essential subcapabilities and develop demonstrations which aim to show how these separate capabilities can be integrated to realize important repair processes for industry and maintenance shops."

To respond to this challenge, we have integrated five essential components of engineering science:

1) graphical simulations of assembly, repair and manufacturing,
2) automated manufacturing of parts,
3) dextrous manipulation of parts,
4) computer vision for scene analysis and inspection of parts,
5) system integration and real-time operating systems.

Our individual research efforts have focussed on the first four areas because we believe they are the basic scientific ingredients that must be set in place prior to integration for the scenario in figure 1. Automated repair is dependent on realistic graphical simulations, deterministic manufacturing procedures and dextrous robots that can manipulate the manufactured parts produced in the remote manufacturing situation. Computer vision is likewise essential to provide the scene analysis of such a remote manufacturing station, and the automated inspection of manufactured parts.

As a final point of emphasis, the integration of the form a complete system, depends on using *de facto* emerging standards in the areas of computer hardware operating systems and programming languages. In general, we have used the Sun/VMEbus/Unix/C configuration for (respectively) our hardware/hardware extension/operating system/language needs. This has allowed dramatic portability within our laboratory and, futhermore, it allows knowledge transfer to other universities and industry. As an example, the Open-Architecture Manufacturing System (described in section 4.2.) was constructed and operational in only 12 man-months (2 engineers working from December '88 to May '89) because of our use of *de facto* standards. The Sun/VMEbus/real-time-Unix/C environment already available in figure 2 was readily used as the platform for figure 3. The importance of such portability cannot be emphasized enough. The economic success and reliability of future autonomous robotics and manufacturing systems will depend on the ease with which sensors and software can be added to a flexible, open-architecture environment.

3. SUMMARY OF MAIN TECHNICAL FINDINGS

In this section 3, we list the main achievements of the work and then present details in section 4.

As research test-beds for "studies in automated repair" we have constructed the two laboratory workcells shown in figures 2 and 3:-

- **Figure 2** - the Utah/MIT hand, held by a Puma 560, operated by a VPL Dataglove and an electromagnetic wrist Polhemus. This enables studies in dextrous manipulation for automated repair.

- **Figure 3** - an open-architecture manufacturing system in which CAD tools, expert systems, sensors and quality control routines can be integrated. This enables studies in autonomous repair-part manufacturing for the scenario in figure 1 below.

Imagine a computer controlled machine tool that is in a geographically remote land-based facility. Alternatively the machine might be on board an aircraft carrier serving as the resource base for a fleet on manuevers. Without warning, a telephone call is received, urgently requesting the manufacture of a part that has failed on an aircraft or a ship. If a rich source of information is available, describing both the part and the way it should be manufactured, then it can be made on the spot. From a library in a central land base, such information would be sent over a network to the machine tool at the remote location. It would contain CNC programs and instructions on fixture selection, stock size, initial setup, ordering of CNC subroutines, and machining technology. Then, an engineer who had general skills, but not specific machining skills, could work with this detailed information and produce the part. It would be as if an expert machinist, located many miles away in the central land base, were looking over the engineer's shoulder and describing the actions.

Figure 1. A scenario for rapidly producing and/or assembling a repair part on an aircraft carrier. A rich source of machining and repair information arrives to instruct an inexperienced machinist or maintenance engineer. In the future, increased automation of such a facility will require the autonomous manipulation routines being developed in figure 2 and our findings in model-based vision

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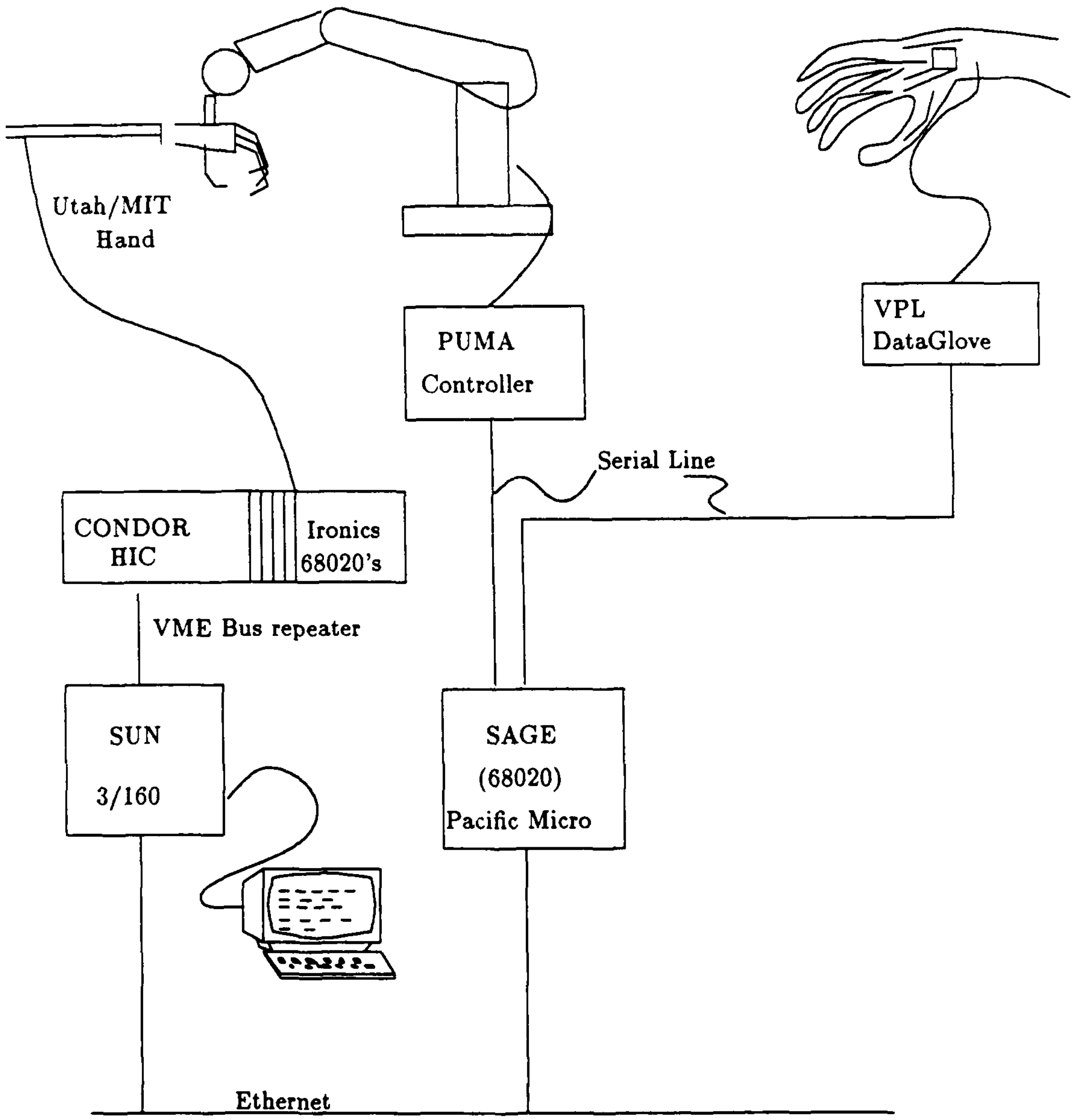

Figure 2. Dextrous Manipulation Cell

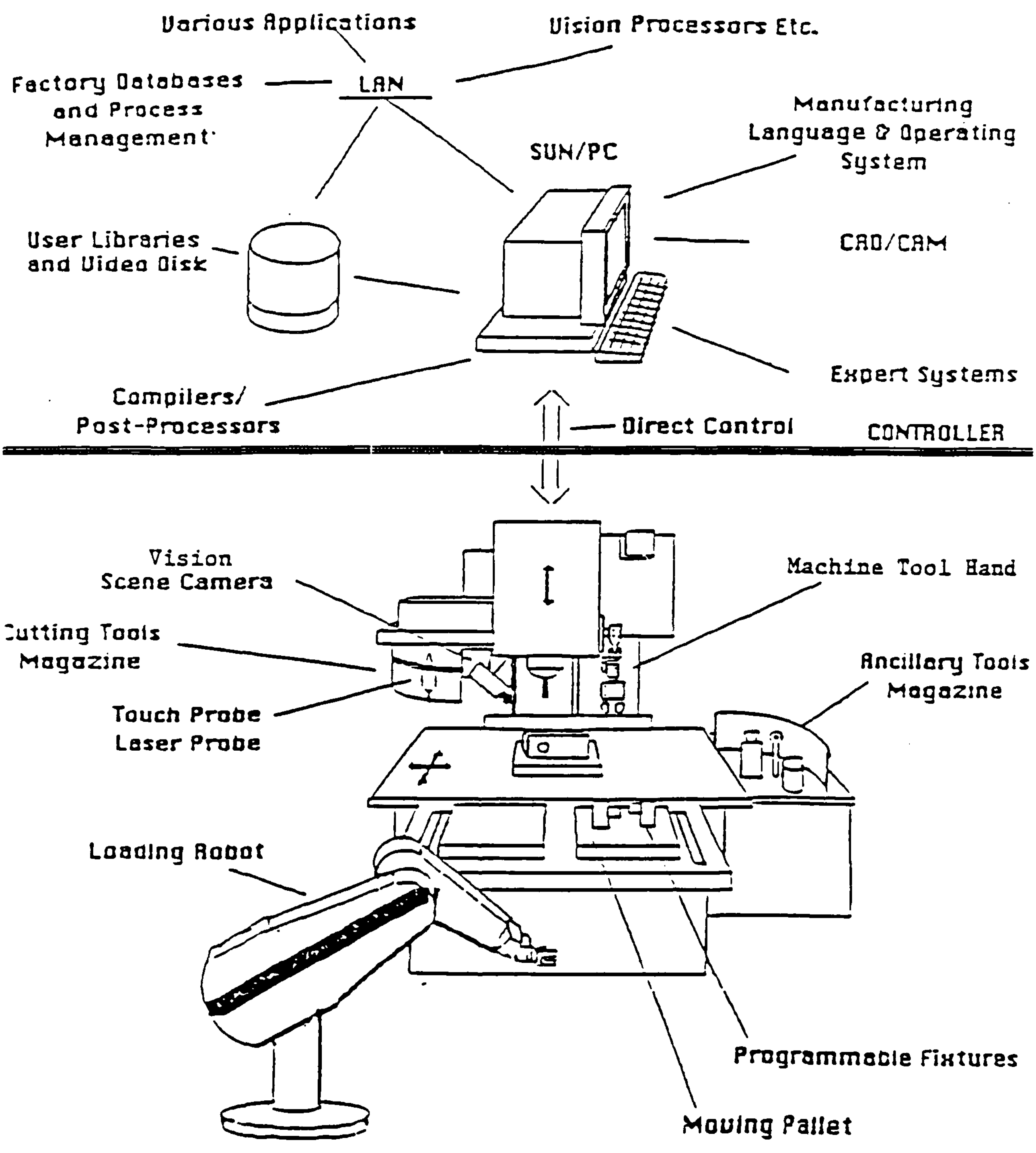

Figure 3. Autonomous Manufacturing Cell

Specific Contributions

Within the context of applying the basic sciences of graphics, automated manufacturing, dextrous manipulation and vision to these work cells, our major contributions have been:

i) Graphics and Simulation

- New CAD software for creating convincing representations of gaseous, liquid and solid objects (the **Pixel Steam Editing (PSE)** language)

- New CAD software for modelling kinematic objects such as the Utah/MIT hand (**Motion Editor**)

- Simulation software for robotics and manufacturing processes, allowing a designer to "sketch events and device activities over time" (**Scratch**)

- Multilevel search software for manufacturing and robotics (**Pad**)

ii) Manufacturing

- Quantitative models of the **mechanics of fixturing**, tool interactions and machining technology for providing CAD information on how to setup and organize automated repair.

- Heuristic models of more complex setup situations that have now been combined into a working expert system called **Machinist**. This adds to the above quantitative models for wider applications in automated repair. In both cases, work is on-going with more situations being analysed.

- An introductory version of the **Machinist Guiding System** that is an interactive, multimedia, on-line help system for the scenario described in figure 1.

- Basic studies and implementations of **Open Architecture Manufacturing**. The cell in figure 3 in an example of radically new technology for the machine tool industry and remote repair operations, enabling the integration of CAD tools and sensors.

iii) Dextrous Manipulation

- Development of position, force and **hybrid-force-position** control algorithms for dextrous repair tasks. These were first carried out on our custom-made four finger manipulator.

- Algorithms for **motion planning** and determining the **degree of goodness of grasps** in the context of general arm/hand designs and specific designs such as the Utah/MIT hand.

• Development of the **Open-Architecture Dextrous Manipulation Cell** shown in figure 2 that allows the integration of sensors (including vision) and the hardware shown in the figure.

• Development of **static grasp taxonomies, homogenous manipulation routines** and **hierarchical control methods** for artificial hands.

iv) Computer Vision

• Development of 2-D and 3-D model-based vision methods especially **geometric hashing algorithms** and **affine invariant point, line and curve matching**.

• Further refinement of general 'low-level' vision algorithms such as **relaxation labelling methods** and the **zero-crossing data** methods.

4. A MORE DETAILED REPORT OF PROGRESS

4.1. Graphics for Automated Repair

During the three year period, work in graphics was developed as a "front-end" to our open-architecture manufacturing system and dextrous manipulation experiment.

In the early part of the grant (1987) we focussed on the static modelling of objects and their textures. This enabled us to develop basic methodologies.

Initially, well behaved stochastic functions were created to yield a rich set of visual textures. In order to be able to write, compile and run the programs efficiently, a **Pixel Stream Editing** language (**PSE**) was developed to facilitate creation of convincing representations of clouds, fire, water and solid objects. The algorithms developed within this research paradigm are generally extremely fast, highly realistic and asynchronously parallelizable at the pixel level.

This initial work was extended in our **Hypertexture** system, which makes it possible to obtain visually realistic representation of such shape+texture (hypertexture) combinations as hair, fur, fire, glass, fluid flow and erosion. This is done, first by describing a set of base level functions to provide basic texture and control capability, then by combining these to synthesize various visual effects. Using such software we developed models and digitized photographs of "downstream" manufacturing devices such as robot hands and machine tool fixtures that can be displayed in a SUN-window of the designers CAD station. This motivates the designer to create part designs that are sympathetic to downstream manufacturing and assembly constraints. In addition, recent work has developed animation sequences for such devices. For a given machine tool or manipulator type the designer can employ our high-level interaction graphics, whereby frequently used machine tool actions or robot hand gestures are simply referenced and brought out of a library of commands, rather than recreated.

After some experience, the user develops a set of basic grasping motions (pinch grasp, circular grasp, lateral grasp) which can be stored graphically. This would not be practical in a scripted system, where the user would need to store such iconic gestures symbolically, and would then quickly lose track of them for purposes of interactive recall. A number of tools are provided for extending, blending, rearranging, or otherwise combining and editing motions. These are in a sense the heart of the system, since they provide the user with the power to create an ever richer library of gestures.

The graphical system developed by 1990 at the end of the contract (**Scratch**) aims to allow its user to "sketch things over time" with the same immediacy with which one can now compose a letter, draw a picture, or improvise at a piano. Using the **Scratch** program one can describe gestures, time-dependent logical relationships, facial expressions, overlapping temporal events, etc., very easily and rapidly, without being forced to resort to text or other analytic abstractions.

This line of research is opening a path to a fundamentally new mode of communication that will, in important ways, be more expressive than verbal or written descriptions. Such research has great potential for simulating the flow of events in factories and manufacturing processes and as a means of engineer-to-engineer and engineer-to-administration communication. We propose to extend the current **Scratch** system extensively and combine it with **Pad** which is just beginning to be developed as a search tool for multiple levels of representation.

4.2. Manufacturing in Automated Repair Facilities

In the three year period we studied the planning of manufacturing, its modelling and various implementations to prove out our concepts. All of our efforts have been focussed on the following problem:

In today's systems, a designer, working at a CAD system preparing the manufacturing instructions, generally has a poor understanding of the setups and machining practices appropriate to actual manufacture of the object which he designs geometrically. Thus the designer is currently obliged to prepare only an approximate and/or imperfect plan, needing crucial 'shop-floor' editing, and forcing work that is both costly and prone to quality-control ambiguities. And obviously this set of ambiguous data cannot be tolerated for the scenario in figure 1. This situation has justified our research in setup planning, fixturing design, and the physics of processes as they relate to accuracy and general quality control.

Two approaches have been pursued. The first, more quantitative line of work has involved analysis of the mechanics of fixturing, tooling selection and machining technologies for rapid-prototyping. Typical situations include: a) for toe-clamping, force equilibrium equations have been developed that relate clamp positions and pressures to cutting-path-angles-of-attack and resistance to slip. The results allow the designer to use as few toe-clamps as possible - thereby maximizing the surface area of the part that can be machined in any one setup - while not damaging the integrity of the part by bearing down too heavily with the few clamps used nor allowing tangential slip to occur during machining; b) for parallel-sided vises, we had analyzed the possible movements and/or buckling of plates clamped by the vise and then the additional movements of the same plate as different cutting tools and tool paths interact with it. The results allow the designer to clamp for maximum rigidity, and hence part quality, while not obscuring the part in the vise nor damaging it.

The second analysis method involves heuristics and qualitative data. In a future "mechanical MOSIS" like facility (or the scenario in figure 1) the remote users will need to use standardized rules and databases on machining technology (especially fixturing) in order that the parts made on remote systems will be safely and accurately provided. Deterministic models of machining and other manufacturing processes are thus a prerequisite. **Machinist** is an expert system that provides step by step instructions on the ordering of events on the "downstream" machine tool. **Machinist** has been constructed by interviewing skilled machinists and CNC programmers. Approximately 300 OPS5 rules formulate stock-squaring operations, avoid feature interactions that might create an out-of-tolerance part, and advise on proper clamping procedures. The geometric modeller in **Machinist** contains nine primitives (thruhole, slot, angle, pocket, etc.) enabling prismatic parts to be described. The program is given a description of the part, the stock from which to make it and a list of tools and fixtures. As the program runs two plans are produced - one for squaring the stock and one for obtaining the features. Using further heuristics (now in the program as rules) these two sub-plans are merged as efficiently as possible to produce a final setup plan that is as short as possible. This program is of great potential for automated process planning and we have made good plans for a wide variety of part styles that compare well with plans made by humans. Nevertheless, new parts often present problems that our current program cannot handle and new rules have to be sought from the experts and put into the program. Further work is highly desirable to create a broad based reliable system and to produce generalities that extend to other domains of manufacturing planning. Connections to PDES for the specifications of features is also needed in the future.

In the area of **control**, for automated repair we have focused on basic research that leads to a radical redesign of today's factory floor machinery. The new results and software tools that are emerging from the basic research above "push" in a direct way, the redesign and construction of conventional machine tools. Until recently, the integration of the new CAD tools and on-machine sensors was frustrated by the "closed" architecture of typical machine tool controllers: these are still based on the programmable logic controllers (PLCs) of the 1970s. Thus to accommodate our new directions it has been necessary to propose an Open-Architecture Machine Controller. It is based on a general purpose computer (a SUN Workstation) running a standard operating system (a real time version of Unix) programmed in a standard language (C) and having a standard hardware (VMEbus). This provides a flexible environment that can drive the 3-axis machine tool, manipulator and sensors. For example, the CAD files merged with **Machinist** will lead to the creation of toolpaths in APT that can then be directly interpreted. This is done in real-time, eliminating the need for traditional post-processing. The "open" design of this CADCAM/Rapid-Prototyping system is its strongest attribute in terms of future expansions in sensors, hardware and expert system software. The new design is sufficiently radical that we chose (with New York University funding) to build a prototype of our design during 1989. The new system is now a viable system and is attracting attention from Martin Marietta, Hurco, Pratt and Whitney, and other companies as a prototype of the Next Generation Controller.

4.3. Dextrous Manipulation for Automated Repair

Significant results have been obtained in the control of dextrous hands and arms. In our laboratory workcell, a PUMA 560 carries the MIT/Utah hand which is a 16 joint mechanical hand having great flexibility. In recent work, we have teleoperated this system in the following way. A human programmer wears a VPL dataglove and a wrist Polhemus. The dataglove is a cloth glove that the human wears in a the normal way but which carries optical fibers on its back to monitor the human gesticulations. The Polhemus sensor is a magnetic sensor mounted on the back of the wrist that measures the 6-degrees-of-freedom of the wrist location. With these two sensors it is possible to control both the robot arm and the fine manipulations of the Utah/MIT hand. Videotapes show that we have successfully used this setup for simple domestic and industrial tasks such as insertion, screwing a nut onto a bolt, and light assembly tasks. At present, our research in this area is moving in the direction of autonomous manipulations rather than teleoperation. We have been building homogenous manipulation primitives that allow our robot hand to function independently on small sub-tasks. The concatenation of such primitives (now being established in a library) will allow a user to build more complex extended tasks. Between such sets of concatenated primitives transitions occur, during which the overseeing human needs to resume teleoperation control temporarily. As we integrate tactile sensors with the hand and also incorporate some of the vision algorithms mentioned in section 4.5 these transition recoveries will become increasingly automated.

It is also important to mention dextrous manipulation work on the planar, four-finger manipulator designed especially to test algorithms for hybrid force/position control. Each of the digits in this system can be moved in an *xy* plane and is compliant. Strain gauges and motor encoders provide the information required for force, position, or hybrid force/position control. An example of our control algorithms, involves the continuous rotation of a suspended disc by cooperating fingers. This is an exercise in simultaneous force control and controlled rotation.

4.4. A Note on Real-Time Operating System Development during this contract

Improved real-time operating systems were developed to support work on the four finger manipulator and Utah/MIT hand. Our SAGE system is an extension of Bell Labs' NRTX system designed specifically for real-time robotics supervisory control. It incorporates multi tasking, memory management, low overhead synchronization and provides network communication capabilities. After its development in a robotic setting it was adapted for use in our open-architecture machine tool project. An additional hierarchical control system (HIC) was developed for use in implementing low-level control systems under the supervisory control of SAGE. HIC, which is very fast, provides the inter-processor communication, the user interface, the timer interface and the debugging support for the Utah/MIT hand attaining a 4 msec control cycle.

It is important to conclude that SAGE has been the crucial element in the speed with which the integration of the **Open-Architecture Manufacturing** system has taken place. (2 project engineers completed this work in the duration of 6 months.)

4.5. Computer Vision for Analysing Automated Repair Scenes

During the three year period we continued to develop new efficient algorithms for model-based object recognition, with the main emphasis on the more complicated problem of object-recognition in the presence of partial occlusion. There were two major interrelated objectives in our research. One was to develop shape representations, which are informative enough to allow object identification and location in the presence of occlusion. The other was to develop computationally efficient algorithms to match the representations of the model objects against the representation of the sensed scene data. This required the shape representations to be terse.

We developed a new general object recognition scheme, the *Geometric Hashing* paradigm, which enabled a unified treatment of the object recognition task under various viewing transformations. The paradigm was based on an intensive off-line model preprocessing (learning) stage, where model information was indexed into a hash-table using minimal transformation invariant features. This enabled the on-line recognition algorithm to be particularly efficient. (The new technique was presented as a long paper at the 2nd International Conference on Computer Vision.) Special attention was given to recognition of general 3-D objects from a single intensity image. The affine invariant recognition technique is especially suitable for aerial photograph matching and interpretation.

We also evaluated the performance of the *Geometric Hashing* technique in the presence of substantial sensor noise. We developed a theoretical noise model, and a series of experiments on simulated data to evaluate the expected performance. Recognition of objects in 'real' scenes was successfully performed.

5. PERSONNEL INVOLVED WITH THE PROJECT

5.1. Faculty

James Demmel, Asst. Prof. of Computer Science
Robert Hummel, Asst. Prof. of Computer Science
Zexiang Li, Asst. Prof. of Computer Science
Stephane Mallat, Asst. Prof. of Computer Science
Bhubaneswar Mishra, Asst. Prof. of Computer Science
Kenneth Perlin, Visiting Asst. Prof. of Computer Science
Eric Schwartz, Adj, Asst. Prof. of Computer Science
Jack Schwartz, Prof. of Mathematics and Computer Science
Micha Sharir, Research Prof. of Computer Science; Assoc. Director, Robotics
Paul Wright, Prof. of Computer Science, Director, Robotics

5.2. Research and Technical Staff

Marc Bastuscheck (experimental work with three-dimensional sensor systems)
Sanghamitra Basu (visitor from CUNY; synthetic pattern recognition)
Jiawei Hong (manipulation, vision, theory);
Gerardo Lafferriere (control theory and experimentation)
David Meyer (visitor from U. of Virginia; control theory and experimentation
Xiaonan Tan (manipulation, vision, theory)
Haim Wolfson (image analysis; real-time software and development)

Other

Hank Alvstead (electronic and mechanical technical support)
Jiachun Cai (visitor from Queens College; electronic engineering
Dayton Clark (manager of system software development)
Joseph DePillis (image analysis software)
John Deragon (electronic and mechanical technical support)
James Fehlinger (system and control software)
Israel Greenfeld (mechanical engineering and implementation)
Fred Hansen (electronic and mechanical technical support)
Andrew Howell (computer systems support)
Louis Pavlakos (engineer)
Shidan Tavana (laboratory technical support)
Estarose Wolfson (computational geometry and neuroscience; vision)

5.3. Administrative Support

David Lugowski, Administrative Assistant
Karen Ostberg, Administrative Manager/Faculty Service Officer
Evelyn Rosario-Fernandez, Sr. Terminal Systems Operator/Admin. Secretary
Phyllis Talley-Mejia, Terminal Systems Operator/Admin. Secretary
Robin Simon, Terminal Systems Operator/Admin. Secretary

5.4. Students

Pankaj Kumar Argawal (computational geometry)
Patricia Bedard (robotics)
Grigore Burdea (development of 'programmable compliance')

David Epstein (computer graphics)
Chirstopher Fernandes (dextrous manipulation and control theory)
Robert Goldberg (model-based vision)
Yaron Hecker (computer vision for manufacturing systems)
Maw-Kae Hor (control hardware and software)
Alain Jacquot (visiting from ENST, France; AI, control algorithms)
Alan Kalvin (shape recognition software)
Eyal Kishon (robotics, image analysis)
Yehezkel Lamdan (object recognition)
Yu Lu (computer vision)
Deepak Mohan (dextrous manipulation and control theory)
Eyal Kishon (image processing hardware and software)
Jean-Gabriel Nyguyen (low-level representation of images)
Paul Pederson (computational geometry)
Adi Perry (texture segmentation)
Isidore Rigoutsos (computer vision)
Nicolas Rougon (visiting from ENST, France; computer vision)
Lou Salkind (control of multi-arm systems)
Naomi Silver (dextrous manipulation and control theory
Xue-Dong Yang (image processing hardware and software)
Sifen Zhong (computer vision)
Qun Zuo (automated manufacturing)

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6b. J. T. Schwartz

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