Final Report

Resourceful Computing in Unstructured Environments
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Summary

This report describes, in general terms, the results of basic research conducted in five areas in which resourceful computing is critical for defense applications.

- Engineering apprentices for resourceful repair, design, and specification.
- Sensing prototypes for recognition, navigation, and manipulation.
- Hardware and software solutions for ultra-large scale computing problems.
- Analogical and common sense reasoning for analysis and design.

The remainder of this report provides a bit more detail in each area. Fully detailed accounts of the research results are accessible through the lists of technical reports and publications.

Special Publication Note

Much of the work performed under this contract was reported on in a massive two-volume collection titled *Artificial Intelligence at MIT: Expanding Frontiers*, edited by Patrick H. Winston with Sarah A. Shellard (1990). Copies are available through the MIT Press.

Engineering Apprentices

Model Based Reasoning Systems

Professor Davis, Dr. Shrobe, and their associates have built knowledge-based systems that use models of structure, function, and causality to perform a wide range of problem solving and reasoning tasks. The systems they have built can reason about how a device works and how it fails in a manner similar to an experienced engineer. This is an important advance in the art of knowledge-based systems construction, because it provides the system with a more fundamental understanding of the device than is possible using traditional approaches.

In particular, the members of Professor Davis's group have built a troubleshooting system that deals with devices that include memory and complex time-dependent behavior; a system that generates diagnostics from a circuit description, capable of generating tests for devices considerably more complicated than those handled by existing test generators; a system that functions as an assistant in design for testability; a system that designs devices by reasoning from fundamental principles of qualitative physics and qualitative mathematics; a system to demonstrate how a program can learn from experience, using two different forms of generalization along with a set of guidelines that indicates when to remember and generalize, and when to simply re-derive the result; and a system capable of designing representations for an interesting class of analytical reasoning problems.

Work during the final year of the contract produced two new systems. One assists with consensus knowledge acquisition, the task of assisting two or more experts in coming to consensus on the knowledge base necessary for a specific task. The second explored the fundamental problem of model selection: how does an engineer decide which model (that is, which approximation) to use when solving a problem.

St-A per telecon Dr. Meyrowitz,
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Work to be carried on in the future is focused on understanding how things work in a variety of domains, including simple mechanical devices like four-bar linkages, and mechanistic explanations of biological phenomena. Examples of understanding include the ability to produce descriptions of device behavior from a description of their structure, the ability to predict behavior under unusual circumstances, and the ability to redesign to fit those new circumstances.

Engineering Problem Solving and Design

Professor Ulrich and his students have worked on computational tools for product design and manufacturing. One project was aimed at encoding and exploiting product development information as it is discovered and modified in the course of a product development effort. This research is being conducted in the context of the actual development of a new power tool.

Another project focused on the problem of enforcing producibility constraints during the specification of the geometry of structural parts. This work was motivated by the needs of large engineering projects, commercial airframe development for example, involving thousands of structural parts.

The Programmer's Apprentice

Dr. Rich, Dr. Waters, and other members of the Programmer's Apprentice group used programming as a domain for studying and attempting to duplicate human problem solving skills. They produced a system, called the Programmer's Apprentice, which provides intelligent assistance in various phases of the programming process. During the final year of the contract, they completed a demonstration of automated program optimization (using a library of reusable software abstractions). They also worked on automated reverse engineering (reconstructing the design of a program from just the source code) and intelligent assistance for software design.

Sensing Prototypes

Object Isolation and Identification

Work directed by Professor Ullman explored the problem of three-dimensional object recognition without three-dimensional models. This research was divided into two main topics. The first topic was that of image partitioning and selection. The goal of this processing stage is to select from the image a portion that is likely to contain an object of interest. The selection process gives the recognition system a capacity that is similar to the use of selective attention in human vision: it allows the system to concentrate its computational resources on the selected structure and apply to it additional processing stages that will lead eventually to recognition. Professor Ullman has developed a method for grouping together image edges and contours that are likely to correspond to a single object. This method appears to capture some basic properties of the grouping processes used by the human visual system.

The second topic was the representation of three-dimensional objects in memory, and the matching of these memory models with two-dimensional objects in the image. Towards this end, Professor Ullman has developed two approaches. The first, called the alignment method, finds and compensates for the transformations separating the viewed object and a given stored model prior to a matching operation. The second approach is novel in that objects are recognized without storing any three-dimensional object models. Instead, objects are recognized by using combinations of two-dimensional views. The method is based on a theory that shows that any view of a three-dimensional object can be approximated by the linear combination of a small number of its views.

Other work on object recognition, directed by Professor Grimson, was centered on the development of systems for recognizing objects in cluttered, noisy, unstructured environments. Such systems have been demonstrated in a variety of environments, using visual, laser, sonar, and tactile sensors. They have also been incorporated as part of a hand-eye system, as part of a navigation system for autonomous vehicles, and as part of an inspection and process control system for industrial parts. Recent efforts have focused on establishing a formal theory on which to judge the efficacy and robustness of recognition methods, on exploring alternative matching schemes for recognizing objects, on grouping methods for preprocessing the input data into salient sets of features, on the role of visual attention in recognition, and on the use of current recognition systems in practical applications.

Motion Vision, Low-Level Integration, and Photogrammetry

Professor Horn and his students worked on problems in motion vision. While one can get good motion information from just two image frames, distances to objects are determined only rather coarsely. One difficulty with using many frames is that one cannot generally assume that the motion is constant from frame to frame. It is possible, however, to incorporate a dynamic model of the vehicle carrying the camera to constrain the likely changes in motion over time. This enables application of the well-known techniques of Kalman filtering, although the problems here are highly non-linear and the equivalent "state" has an enormous number of degrees of freedom, typically one per picture cell, which prevents application of traditional direct approaches. In a related development, methods from computer graphics are used to predict the shape and position of an object at the next image frame time, based on the estimated shape and position and the estimated motion at the present time. Dramatic improvements in the accuracy of the reconstructed object shape are attained in this fashion, although after about ten frames the errors introduced by the prediction phase begin to balance out the improvements obtained from continuing the solution in time.

Because recovery of information about the world from a single cue such as motion parallax, binocular stereo disparity, or shading in images tends to not be very robust, there was a great deal of interest in integrating information from multiple cues. The intimate integration of early vision modules will be required for most practical applications of vision systems. Professor Horn's approach to the problem focuses on intimate integration at the lowest level of vision modules. In the simplest case, this means interlacing iterations of different schemes for recovering shape, or more formally, constructing a compound functional that contains penalty terms for mismatching information available from both cues being considered. Preliminary results in integrating motion vision and shape from shading, and in integrating binocular stereo and shape from shading show great promise.

Visual Motion and Human Vision

Professor Hildreth's research addressed the analysis of visual motion with special emphasis on biologically plausible theories. Her work in the final year of the contract focused on the recovery of the three-dimensional motion and structure of objects, and followed three directions. The first is the computation of qualitative or partial information regarding 3-D structure and motion for tasks such as navigation. She developed a model that uses simple estimates of time-to-collision, based on the changing image size of moving objects, to reconstruct their 3-D trajectories through space, and is conducting perceptual experiments to test whether such a strategy is used by the human visual system. Second, she explored the integration of 3-D structure-from-motion recovery with the overall process of surface reconstruction. This latter project has led Professor Hildreth to study the interaction between motion analysis and binocular stereopsis. She pursued a model that computes the 3-D positions and velocities of features over an extended time, through incremental improvement, by combining constraints both from the projected 2-D motions of the points in the image and the temporal changes in their stereo disparity.

The Vision Machine

The main project of Professor Poggio's group was the Vision Machine—a computer system that attempts to integrate several visual cues to achieve high performance in unstructured environments for the tasks of visual recognition and navigation. The Vision Machine became a test-bed for measuring progress in the theory of early vision algorithms, their parallel implementation and their integration, up to recognition of 3-D objects. They developed and implemented several parallel early vision algorithms computing edge detection, stereo, motion, texture, and color in close to real time. The integration stage attempts to derive a map of the surface discontinuities in the scene, with a partial labeling of the intensity edges in terms of their physical origin. They interfaced the output of their integration stage with a parallel recognition algorithm.

During the final year of the contract, one of the main achievements was the design and fabrication of an analog VLSI chip embedding one of the earliest Vision Machine algorithms—edge detection—integrated with a CCD imager on the same chip.

Hardware and Software

Message-Passing Semantics

The Message-Passing Semantics group, under the guidance of Professor Hewitt, developed the foundations for Open Systems that perform robustly in changing environments. An Open System is one that is always subject to unanticipated communications from outside and whose operations are subject to indeterminate results. Robustness means the ability to keep commitments in the face of conflict and indeterminacy, which are ubiquitous in Open Systems. Robust computer systems are needed to meet the challenge of Open Systems to gain from the advantages of openness while meeting the requirements that are imposed by openness. Open Systems undergo continual change: some change coming from within, through communication among internal parties, some from without through interaction with the environment. The primitives of ultraconcurrent systems are called ACTORs. These can be organized into systems of ORGs (Organizations of Restricted Generality). The Actor model provides a scientific and technological basis for Open Systems because it supports dynamic reconfigurability, compositionality, and extensibility. The ORG model provides a scientific and technological basis for organizational systems because it supports teamwork, management, liaison, and organizational representation. The group's research focuses on theoretical, architectural, and linguistic aspects of organizational systems composed of humans and telecomputer systems.

Symbolic Parallel Architectures

The Symbolic Parallel Architecture group, under the direction of Professor Knight, has developed a design for a uniform, large scale, parallel symbolic supercomputer called *Transit*. Unlike most parallel machines, this architecture has been explicitly designed to support a wide range of parallel programming models with excellent performance. The key realization is the critical importance of low latency in the processor-to-processor communications path. This low latency communications is used as a substrate for coherent caches and processor-to-processor message passing. The implementation of *Transit*, now underway, will be done in three phases: construction of the routing network, coherent cache implementation, and finally processor design. The routing network is currently under detailed design and simulation. Its construction involves novel three-dimensional packaging and cooling technology, novel VLSI techniques for chip-to-chip communications, and a very simple, high speed routing component. The initial prototype is expected to yield a remote memory access latency of about 300ns and a per-port peak bandwidth of 800 megabaud. The aggregate switch bandwidth approaches a terabaud.

Analogical and Formal Reasoning

Learning from Analogous Precedents

Professor Winston's group concentrated on developing representations that enable learning and reasoning by analogy. During the final year of the contract, considerable progress was made on the particular problem of representing decision rationals. The key problem was to find a suitable, framelike vocabulary for describing decisions. By capturing a decision rational in a form that facilitates symbolic reasoning, subsequent decisions need not go over the same ground. Additionally, decision can be seen from a variety of perspectives, providing a sort of symbolic what-if capability, leading to a better understanding of how biases influence conclusions.

Other work in Professor Winston's group has focused on the problem of representing change qualitatively, such that a remembered sequence of changes can be used as a precedent for understanding how some subsequent situation is evolving. The experimental domain was that of encyclopedia-style texts describing, for example, how rockets work.

Automated Formal Reasoning

Professor McAllester concentrated on building and testing automated formal reasoning systems. These formal reasoning systems incorporate a variety of new algorithmic techniques that allow effective automated reasoning about topics that are beyond the scope of any previous reasoning system. For example, the new reasoning systems have been able to verify proofs, starting with only the axioms of Zermelo-Fraenkel set theory, of the Stone representation theorem in lattice theory. This theorem involves an ultrafilter construction and is similar in complexity to the Tychonoff theorem that a product of compact topological spaces is compact. The novel algorithmic techniques include the integration of congruence closure into general theorem proving, monotone closure for reasoning about semantic types, focused forward chaining, and the incorporation of universal generalization into constraint propagation. In addition to evaluating automated reasoning systems in terms of their ability to verify abstract mathematical theorems, Professor McAllester has studied the application of automated reasoning systems in software verification. In particular, during the final year of the contract, Professor McAllester began to concentrate on the special case of verifying computer programs to be "uncrashable."

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