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New Mexico State University's Computing Research Laboratory

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The Computing Research Laboratory (CRL) at New Mexico State University is a center for research in artificial intelligence and cognitive science. Specific areas of research include the human-computer interface, natural language understanding, connectionism, knowledge representation and reasoning, computer vision, robotics, and graph theory. This article describes the ongoing projects at CRL.

The Computing Research Laboratory (CRL) was founded in July 1983 as an autonomous unit in the College of Arts and Sciences at New Mexico State University (NMSU). The laboratory began as a part of the Rio Grande Corridor, a program funded by the state legislature, which links government laboratories, universities, and public-private research facilities across the state with the aim of fostering high technology development.

The laboratory currently employs a full-time director; 14 faculty members with joint appointments in the departments of computer science, electrical engineering, mathematics, and psychology; eight full-time researchers; four technicians; and over 30 research assistants. The administrative staff consists of a full-time business manager, a marketing adviser, and several clerks.

CRL's computing equipment includes a 64-module Intel Hypercube parallel processor; four Symbolics Lisp Machines; a Texas Instruments (TI) Explorer Lisp machine; a Xerox 1186 Lisp machine; seven Sun Microsystem UNIX workstations; and a number of IBM, Apple, and TI personal computers. An Ethernet provides a 10 megabit/sec communications link between CRL's equipment and the systems in other campus departments. Additionally, the network provides communications links to national networks (for example, CSNET and ARPANET) as well as to a regional backbone (TECHNET) that links universities and federal laboratories along a 300-mile stretch (the Rio Grande Research Corridor) of New Mexico.

Research at CRL is divided into four major groups: the Connectionism and Natural Language Processing Group; the Cognitive Systems Group; the Knowledge Systems Group; and the Vision, Robotics, and Graph Theory Group.

The Connectionism and Natural Language Processing Group

The Connectionism and Natural Language Processing Group has several main research directions that are apparent from the projects listed here. Our main approach is an outgrowth of preference semantics, where language understanding is semantic and knowledge based as opposed to syntax based. We have a strong interest in the connectionist approach to natural language processing and focus on the limitations of this approach. We have several projects in alternative parsing mechanisms, the traditional serial approaches, and coarse- and fine-grained parallelism. We also have dual efforts in the modeling of beliefs and points of view and have begun work on the use of a machine-readable dictionary (Longman's) in the automatic construction of lexicons. Finally, we have a substantial project in multilingual machine translation, primarily using Xiuming Huang's XTRA as a main front end. XTRA is based on a semantic definite-clause grammar written in Prolog, and its distinctive features are its treatment of conjunctions, phrase and clause attachment procedures (Wilks, Huang, and Fass 1985), and relaxation procedures for semantic constraints. Currently, we are improving XTRA's Chinese output as well as developing trial systems for Spanish, Japanese, and German.

Connectionism

Complex Data-Structure Manipulation in Connectionist and Neural Net-

works. Much of human cognition appears to involve the rapid processing of temporary, complex information structures, acting, for instance, as interpretations of utterances or representations of the current environment during commonsense reasoning or planning. The question of how data structures of appropriate complexity and expressive power might be realized in neural networks, and connectionist networks in general, is therefore raised. To examine this question, an abstract computational architecture is being investigated that can process complex data structures and be realized in a straightforward manner in neural or connectionist networks. The resultant mapping from data structures to neural-connectionist networks differs significantly from those previously entertained and successfully addresses some contemporary challenges to the field of connectionism. For instance, it accommodates processing rules with variables. The architecture has special psychological significance in its support of spatial-analog representation, where an arraylike medium acts as an internal model of an array of spatial regions. In particular, the spatial mental models studied by the psychologist Philip Johnson-Laird are easily accommodated. The architecture also readily supports Johnson-Laird's syllogistic mental models.
Participant: John Barnden.
References: Barnden (1985, 1986a, 1987).

Connectionist Models of Language and Learning. Our work centers on a psychologically driven model of natural language processing in which partial interpretations of sentences are simple processors that fight among themselves for superiority. The understanding of language emerges as the collection of cooperating partial interpretations that survive.

One of the differences between our work in connectionist modeling of natural language processing and the bounded-length work of others (Cottrell 1985; Selman 1985; Fanty 1985) is that we build the structure of the network "on the fly" as words are processed. In the past, we have used normal computer programs, such as a chart parser (Kay 1973), to dynamically construct networks, but we have been working on how dynamic reconfiguration can be achieved within the connectionist framework.

One method for achieving dynamic reconfiguration is through the use of multiplicative connections, simply having the ability to multiply the outputs of various units instead of linearly combining them with weights. This ability allows the weights between pairs of units to be varied by the output of other units.

Unfortunately, connectionist networks with multiplicative connections are not as easy to build or analyze as linear-derived systems. Accordingly, we have been working on the application of a new weight-learning technique (Rumelhart, Hinton, and Williams 1986) to the control of dynamic weights.

The organization of our learning technique is cascaded: We use the output from a context network to set the weights on a function network and errors on the weights of the function network as the error signals for the context network. This technique results in networks that can process multiple functions over the same set of processors. Furthermore, if the output of the function network is used as part of the input to the context network, then a machine emerges that is capable of sequentially processing grammatical strings of arbitrary length but bounded depth.
Participants: Jordan Pollack, Yorick Wilks, Tony Plate, Imre Balogh, and Srinivas Kankanahalli.
References: Pollack and Waltz (1982); Waltz and Pollack (1985); Pollack (1988, 1987); Wilks (1987).

Connectionist Modeling on a Hypercube. One of the advantages of connectionist models over traditional AI programs is that the parallelism does not have to be discovered; it is already present. We have begun design work on HYCON, a programmable connectionist simulator for CRL's 64-node Intel Hypercube to take advantage of this inherent parallelism.

Designed to handle several known connectionist configurations, the simulator runs in several phases: a computation phase in which each of the 64 nodes processes local subsets of the thousands of units needed for a large connectionist model, a communication phase in which each of the nodes is able to globally broadcast state information about their own units while it selectively caches information from the other 63 nodes, and a modification phase in which the weights of links can be dynamically adjusted.

HYCON has been successfully demonstrated running both back propagation and a distributed memory model. Current work is on improving its programmability and its user interface across a computer network. The practical importance of this simulator should not be undervalued because advances in the field of connectionism are tied to how it scales up to larger domains as well as to new theoretical breakthroughs.
Participants: Jordan Pollack and Tony Plate.
References: Plate (1987).

Studies in Parsing

Parsing in Parallel. The advent of real parallel machines such as the Intel Hypercube finally makes possible a real implementation of a model that investigates parsing of a natural language as a system of independent, modular, communicating processes. At CRL, we are developing a parallel model for natural language parsing. The parallel model is based on the semantic definite clause grammar formalism of Huang and integrates syntax and semantics through the communication of processes. The syntax in the XTRA parser is a definite clause grammar (Pereira and Warren 1980), and the semantics is a modification of Wilks (1975a, 1975b), along with relaxation mechanisms. The main processes contain either purely syntactic or purely semantic information, giving the advantage of simple, transparent algorithms dedicated to only one aspect of parsing. Message passing imposes semantic constraints on syntactic processes in order to avoid the combinatorial explosion of producing all legal syntactic possibilities. Both semantic and syntactic processes will be separated from the large lexicon in *Longman's Dictionary of Contemporary English* (LDOCE) (Proctor 1978), and all will be distributed over Hypercube nodes under Cubic Prolog, a new version of Prolog developed specifically for use in parallel parsing.

Cubic Prolog differs from most parallel implementations in that it is much less ambitious. The primary responsibility for gaining the benefits of parallelism lies with the user as opposed to some magical optimizing compiler or machine. The conceptual foundation of Cubic Prolog rests firmly in the technology of Sequential Prolog interpreters, and the main contribution that our version of Prolog offers lies in a new way of structuring message-based computation in a logic-programming language.

Essentially, Cubic Prolog allows the programmer to write programs that consist of multiple independent objects or nodes, each of which is a conventional Prolog program. Each Cubic Prolog object can send a query to another object, which will return all provable instantiations of the query. Each object has a unique name by which other objects can refer to it and by which classes of similar objects can be defined. Cubic Prolog combines the benefits of logic programming with the advantages of object-oriented programming for succinct and effective writing of concurrent programs.

This research has two independent strengths: a real implementation of independent but communicating syntactic and semantic processes and a clear implementation of Cubic Prolog that will also serve as a base for a range of new applications.

Participants: Ted Dunning, Teodor Przymusinski, Halina Przymusinska, and Xiuming Huang.
References: Huang and Guthrie (1986); Huang (1985).

Collative Semantics. A semantics for natural language processing, collative semantics (CS) is a development of Wilks' preference semantics. The main phenomena it addresses are lexical ambiguity and semantic relations. Seven kinds of semantic relations are investigated: literal, metonymic, metaphoric, anomalous, novel, inconsistent, and redundant. CS contains four components: two representations (sense frames and semantic vectors) and two processes (collation and screening). Sense frames are the knowledge representation scheme and represent individual word senses. In sense frames, word senses perform the functions of semantic primitives, although they are also part of the object language being represented. Collation matches the sense frames of two word senses and discriminates the semantic relations between the word senses as a complex system of mappings between their sense frames. Semantic vectors represent the systems of mappings produced by collation and, hence, the semantic relations encoded in these mappings (except for metonymic relations). Semantic vectors are a different kind of representation scheme from sense frames that we call a coherence representation (*coherence* is defined as the synergism of knowledge, where synergism is the interaction of two or more discrete agencies to achieve an effect that no agency can achieve individually). Screening chooses between two semantic vectors by applying rank orderings among semantic relations and a measure of conceptual similarity, thereby resolving lexical ambiguity. CS has been implemented in a natural language program called meta5 that analyzes individual sentences, discriminates the seven kinds of semantic relations between pairs of word senses in these sentences, and resolves any lexical ambiguity.

Participants: Dan Fass and Yorick Wilks.
References: Fass (1986a, 1986b, 1986c, 1987); Fass and Wilks (1983).

Automated Lexicon Building

Exploring LDOCE. CRL has access to a copy of LDOCE, written with syntactic codes and semantic definitions restricted to about 2000 primitives. We are exploring various approaches to making it a general, tractable, semantic English database for use with a semantic-based parser (see Lexical Semantics and a Preference Semantics Parser for Text) and the collative semantics analyzer (discussed earlier).

In connection with the work on collative semantics, our intention is to extract semantic information from dictionary entries in LDOCE to build sense frames. This method is feasible because the structure of a sense frame is similar to that of a standard dictionary entry, and in particular, there is no restriction on the basic vocabulary used in constructing sense frames.

The first step in this process is to construct sense frames for the 2000 word subvocabulary used by LDOCE (this process was begun manually and will be bootstrapped mechanically from a subset of the 2000 primitives). We then extract the semantic information we need using a rudimentary parser containing a list of templates for different forms of LDOCE dictionary definitions.

LDOCE is also being analyzed on the Hypercube parallel machine to extract clumpings of related words and pathways between them using forms of the Pathfinder algorithm developed by the Cognitive Systems Group.

Participants: Tony Plate, Brian Slator, Chenming Guo, and Yorick Wilks.
References: Wilks et al. (1987).

Lexical Semantics and a Preference Semantics Parser for Text. LDOCE dictionary definitions are converted to lexical semantic structures suitable for knowledge-based parsing. The first phase of frame construction uses the precise LDOCE grammatical categorizations to distinguish among word senses but only with general semantic and pragmatic information. When the needs of the knowledge-based parser increase beyond this initial representation (for instance, when resolving lexical ambiguity or making nontrivial attachment decisions), the frame representations are enriched by appeal to parse trees constructed from the dictionary entries of the relevant word senses; that is, the text of the definition entry itself is analyzed, further enriching the semantic structures.

The lexicon of frames is a text-specific knowledge source for a knowledge-based preference semantics parser for text (Wilks 1975a, 1975b, 1978), which is under development. We envision a goal-directed parser that keeps competing interpretations alive but only pursues the most highly preferred interpretation. Parsing will be robust in that some structure will be returned for every input, no matter how ill formed or "garden pathological." We anticipate macro-text structure formulations to be applied with global coherence measures derived from an analysis of preferred LDOCE

subject codes in the text (Walker and Amsler 1986).
Participants: Brian Slator and Yorick Wilks.
References: Slator and Wilks (1987).

Modeling Beliefs

Cooperation and Planning in a Multiactor System. The ViewGen project investigates theoretical issues in the area of belief systems that pertain to human-computer interaction (communication and cooperative planning). We are using the results to implement a system that reasons and interacts with people in a limited but real domain and incorporates the first perspicuous default algorithm for belief ascription in a concrete domain. Research has shown that effective communication between a computer and a human—in other words, the system and the user—requires modeling of the various beliefs which each has about the topic of conversation. This project is aimed at generating, from the system's own beliefs, the views of people on demand. These views can then be used in reasoning and cooperative processes. This project is the first to offer a theory of dynamic construction of nested belief structures, or viewpoints, and the heuristics associated with such constructions. We developed an initial program called ViewGen that generates nested viewpoints (what some person believes is another person's view of some topic), and the results and insights obtained from this program are being used to develop the larger belief system.
Participants: Afzal Ballim and Yorick Wilks.
References: Ballim (1986, 1987a, 1987b, 1987c); Wilks and Bien (1979, 1983); Wilks and Ballim (1987, 1988); Wilks (1986a, 1986b).

Fine Control in the Representation of Propositional Attitudes. In devising a formal representation scheme capable of ascribing beliefs and other propositional attitudes to agents, it is important to ensure that a wide enough range of ascription types is available. For instance, there are different types of de-reascription depending on what sort of referential idea the believing agent entertains. The variety-of-ascription issue is usually discussed only with respect to the referential aspects of beliefs but also arises for predicational aspects. Lack of variety as it relates to the predicational aspects can lead in a subtle way to potentially wrong ascriptions, especially when nested attitudes (such as beliefs about beliefs) are at issue. We are developing a representational approach which avoids this problem and which generally provides great control over, and freedom in, belief ascription. The approach is based on logic terms which denote putative mental structures or which denote templates whose holes can be filled to produce such structures. The approach seeks to minimize the number of assumptions made about the detailed nature of the structures.
Participant: John Barnden.
References: Barnden (1986b, 1986c, 1986d).

An Operating System Consultant. This project involves the construction of a natural language system called an Operating System CONsultant (OSCON). OSCON will initially be used to answer natural language queries on the UNIX and TOPS-20 operating systems. The system embodies the principle of separation between understanding and solving. The process of understanding a query is completed in a natural language front end, but the process of solving is located in a formal database. Parsed English queries are translated into formal queries with uninstantiated variables. Each formal query is instantiated by a database of operating-system concepts and returned to the front end where answers are produced in English. An important aspect of OSCON is that a purpose-built knowledge representation formalism called transfer semantics is used to formalize abstractions of database detail in the front end itself. Our work is separated from the Unix Consultant (UC) by Wilensky, Arens, and Chin (1984) and Wilensky et al. (1986) because we have designed a formal database and distinguished this database from the front end. Our methods of knowledge representation on operating systems differ, and the UC program is only intended to model UNIX.

We are providing a mechanism that handles situations where a new user might have a background in the use of one system but not another, for example, allowing the user to refer to an alternative system while asking queries about, say, UNIX. We will embody the belief-ascription work described earlier to provide this facility in OSCON. We intend to build representations of domain information, coding relationships between similar concepts that have different names on various systems. While building OSCON, we hope to examine the use of a semantic-driven parser over a syntax-driven one, and eventually, we will consider the incorporation of pragmatics into the system.
Participants: Paul Mc Kevitt, Yorick Wilks, and Stephen Hegner (University of Vermont).
References: Mc Kevitt and Wilks (1987); Hegner (1987); Hegner and Douglass (1984); Douglass and Hegner (1982); Mc Kevitt (1986a, 1986b, 1986c).

Machine Translation

Machine Translation: English-Chinese. We are currently modifying the XTRA parser, the generator, and the Chinese dictionary. The parser will be adapted to handle paragraph-to-paragraph translation (although the basic unit of analysis will continue to be the sentence). The English grammar will be modified in order to cover diverse language phenomena and make the parser robust. With the relaxation mechanism as a safety net, the system can handle sentences such as "My car drinks gasoline" that contain violations of selectional restrictions. It handles the violations by setting a flag when it fails as a result of the normal selectional restrictions and then reparsing the flagged sentences with the relevant restrictions relaxed. In the gasoline example, for instance, the verb drink allows its subject to be a thing instead of an animate object and, thus, satisfies the semantic match. No new word sense is forged.

With respect to generation, we are attempting to make XTRA a bidirectional system with a single analysis and generation grammar for English. The English dictionary for XTRA will be embedded in LDOCE, and a body of 200 English sentences with wide coverage of English structures will be kept as a test set. The system should always work for the sentences in the main body as increased coverage is sought. We are expanding the Chinese grammar's syntactic coverage and adding a semantics in order to ensure that the grammar is bidirectional and can be used for parsing and generating Chinese sentences. Connected with the English parser by a transfer phase, this grammar has proven more efficient than the earlier generation program and is of greater theoretical interest. This work is supported by Machine Translation Systems.

Participants: Xiuming Huang, David Farwell, Li Chen, Yiming Yang, Min Liu, and Yorick Wilks.

References: Huang (1985); Huang and Guthrie (1986); Huang (1986).

Building Embedded Learning Mechanisms for XTRA. Part of the early appeal of AI was that it applied knowledge and skill without studying how they were acquired. However, machine-translation systems built using an AI approach ought to be equipped with embedded learning mechanisms so that they can constantly update themselves and modify their behavior. Building such embedded systems will also speed the development of domain-specific or even general domain machine-translation computers because except for the syntactic component and the closed system of function words, machine-translation programs cannot be expected to have complete vocabularies at the time of installation.

Learning in the context of machine translation is defined as the improvement of machine-translation performance. The improvement is brought about by the modification of the system's memory. Depending on the nature of the data being modified and the processes that are affected, learning in the environment of machine translation falls into the following three categories: (1) *syntactic learning*, the acquisition or modification of syntactic information; (2) *semantic learning,* the acquisition or modification of conceptual information, such as new vocabulary items or new senses of old vocabulary items; and (3) *translation skill learning,* the acquisition or modification of transfer rules.

WLEARNER, an interactive word-acquisition device for learning new words and new word senses on line, has already been built for XTRA. The focus of the current research is embedding a word-sense learning mechanism in XTRA so that XTRA can consult LDOCE online.

Participant: Cheng-Ming Guo.

References: Guo (1987).

The Cognitive Systems Group

The Cognitive Systems Group is attempting to bring knowledge about human cognition to bear on the development of intelligent systems. For such problems as designing the user interface in computer systems or developing computer models for use in training and education, the importance of understanding human cognition is obvious. The modeling of human cognition also provides a general basis for building intelligent systems. The work in the Cognitive Systems Group approaches these goals through theoretical analysis, model building, application design, and empirical evaluation. The word systems in the Cognitive Systems Group is intended to emphasize that our work has practical, as well as theoretical, goals and, consequently, that the models we build are attempts to solve practical problems. These models are necessarily based on incomplete knowledge of human cognition. Thus, the models serve as hypotheses about human cognition and designs for computer systems. We hope to learn about both cognition and systems in the process.

Network Models.

Our work on deriving network representations of knowledge from proximity data was originally motivated by the desire to develop empirically based knowledge representation techniques that yield data structures of the kind found in psychological theory and AI systems. The Pathfinder network-generation algorithm for deriving network representations of knowledge from proximity data is based on the assumption that a link between a pair of entities is unnecessary if the proximity of the pair can be realized by another path connecting the entities. Pathfinder uses parameters that can accommodate different assumptions about the scale of measurement underlying the proximity data and different constraints on the density or sparsity of the resulting network. Research on Pathfinder has been concerned with the development of the theoretical foundations of network scaling and with validation studies investigating the value of Pathfinder networks as psychological models. We are currently working on techniques for defining substructures in networks (such as categories and schemata) and using the networks in reasoning and decision making.

The Pathfinder algorithm is used in several of the application projects concerned with user-interface design and knowledge engineering. Our extensive use of networks and graphs has led to a need for computer graphics for displaying and manipulating networks and graphs. Development of this tool has greatly assisted the layout work involved in displaying and interpreting networks. This work is supported by the National Science Foundation (NSF) and the Air Force Human Resources Laboratory.

Participants: Don Dearholt, Roger Schvaneveldt, Russell Branaghan, Nancy Cooke, and Tim Breen.

References: Cooke, Durso, and Schvaneveldt (1986); Dearholt et al. (1985); Dearholt, Schvaneveldt, and Durso (1985); Lawrence, Fowler, and Dearholt (1986); Schvaneveldt, Dearholt, and Durso (1988); Schvaneveldt, Durso, and Dearholt (1985).

Knowledge Elicitation and Representation.

We are developing a knowledge-acquisition tool kit, consisting of cognitive scaling techniques, that can be used to aid the knowledge engineer in extracting relevant expert knowledge and representing this knowledge. This tool kit will consist of techniques for concept elicitation, scaling, and relation identification (in other words, link labeling) and will become part of a formal methodology for expert system development. In addition, by formalizing the knowledge-acquisition process in this way, we will be able to automate it as well. An automated knowledge engineering system could be developed to take the place of the knowledge engineer in the preliminary stages of the knowledge acquisition. In our conception, the domain expert will interact with the automated system that will direct the expert through a series of tasks (such as listing concepts, sorting concepts, rating concepts for relatedness, and labeling links on a generated network) and apply psychological techniques to the expert's behavior to generate a cognitive profile of the expert. The knowledge engineer can then use this information as a starting point for further knowledge acquisition.

This methodology overcomes some of the problems inherent in the traditional, weaker methods of knowledge engineering. First, unlike other knowledge engineering tools, this formal methodology can aid in the initial stages of knowledge engineering in which expert knowledge is elicited. In addition, the techniques we propose elicit knowledge from the expert indirectly by asking relatively simple questions (for example, how related are these concepts?). Even though an expert might not be fully aware of the knowledge, it is often revealed through judgments, much as it is applied in the domain of expertise. Furthermore, because the proposed techniques suggest questions that need to be asked of the expert and because the techniques do not require answers from the expert in the form of if-then rules, the amount of interaction between the knowledge engineer and the expert is reduced, and the type of knowledge elicited from the expert is not constrained by a particular knowledge representation. Finally, the comparison of a variety of psychological scaling techniques might provide clues about the most compatible form of knowledge representation for the expert system. This work is supported in part by Sperry and TI.

Participants: Roger Schvaneveldt, Jim McDonald, Matt Anderson, Nancy Cooke, and Lisa Onorato.

References: Breen and Schvaneveldt (1986); Cooke (1985); Cooke and McDonald (1986); Durso et al. (1987); Onorato and Schvaneveldt (1986); Partridge et al. (1986); Schvaneveldt (1986); Schvaneveldt (1985).

User Models and Interface Design.

Recently, there has been a great deal of interest in how users develop and utilize mental models of devices. Unfortunately, the word model is a particularly vague and ambiguous word, even in the context of interface design. Several classes of models are important, particularly the conceptual models of system designers and the mental representations users form as they utilize a system. We theorize that users develop conceptual models of devices (systems) through use. Further, we believe that the conceptual models of experienced users can be characterized as memory schemata, or coherence models, which can be elicited and represented using empirical methodology. Finally, computer interfaces that reflect experienced user knowledge will facilitate learning and increase productivity.

We have been working on a methodology that allows us to build empirically derived, semantic-network models of users that are descriptive rather than analogical. Descriptions differ from metaphors in that they rely on general, rather than context-dependent, knowledge. Our methodology involves obtaining estimates of relatedness for pairs of system units (such as commands), subjecting the data to scaling analysis (for example, Pathfinder), and mapping the resulting solution onto some aspect of the interface. We are approaching our goal of developing a comprehensive interface design methodology by exploring a variety of promising applications, thereby extending and formalizing the methodology while obtaining useful knowledge about the design of particular interfaces.

One application of our methodology in progress is the development of an indexing aid for the UNIX online documentation system (the man system). This documentation will be highly flexible in that users will be able to seek help from the perspective of their functional knowledge of commands, procedural knowledge of tasks, or higher-level conceptual goals. Network representations will be displayed of appropriate subsections of the semantic-network-based user model. Users will be able to take advantage of whatever it is they already know in order to solve their current problem.

The basis for our documentation is empirically derived estimates of distance between system commands obtained from experienced UNIX users. We used both sorting and event-recording techniques to obtain the data necessary for scaling analysis. Judgments of functional relatedness provided us with declarative knowledge about UNIX commands, and event record data (user protocols) provided us with the basis for a procedural representation. By using clustering techniques, we were able to derive an abstract (categorical) representation of the sorting data, and similar techniques are being applied to the event record data in an effort to uncover task sequences. The next phase in this project involves building the documentation and validating its effectiveness under real-world conditions. This research is supported by a grant from the National Aeronautics and Space Administration (NASA).

Participants: Roger Schvaneveldt, Jim McDonald, Ken Paap, Don Dearholt, Matt Anderson, Rebecca Gomez, Linda Johansen, Bob Cimikowski, and Jerry Ball.

References: Bailey (1985); Gawron, Paap, and Malstrom (1985); Karat, McDonald, and Anderson (1986); McDonald et al. (1986); McDonald and Schvaneveldt (1988); Paap and Roske-Hofstrand (1986); Roske-Hofstrand and Paap (1985); Schvaneveldt, McDonald, and Cooke (1985); Snyder et al. (1985).

Rapid Interface Prototyping.

Mirage is a computer-based rapid interface prototyping (RIP) tool that allows designers to interactively mock up interfaces of various kinds in order to evaluate their usability. Mirage shares many of the characteristics of current spreadsheet programs in that individual cells, or interface units, can contain expressions which specify logical relationships. Mirage is a declarative, object-oriented programming language in the same way that spreadsheets are declarative programming languages. In addition, Mirage allows individual panels (analogous to individual work sheets) to be connected into systems that can be run as interface simulations. Although Mirage does not directly support all the programming capabilities of spreadsheet applications, it is considerably more flexible in its ability to specify the appearance and behavior of individual panels. Furthermore, Mirage supports interface input and output from devices typically associated with computer systems (in other words, touch screens, keyboards, graphic displays, tones).

We continue to use Mirage to conduct a number of studies into interface design. We have learned a great deal about RIP tools and are planning an enhanced version of Mirage. This work is supported by Sandia National Laboratories in Albuquerque and TI.

Participants: Jim McDonald and Paul Vandenberg.

References: McDonald, Vandenberg, and Smartt (1987)

Eye Movement Analysis of Information Retrieval.

Information retrieval is a common component in many tasks involving human-computer interaction. It is useful to view information retrieval as varying along a continuum ranging from a simple search for a specific chunk of information to a decision-making process that requires several separate chunks of information to be integrated and evaluated. The efficiency of retrieval is likely to be determined by the organization of the information in the computer system, particularly as it is presented to the user through the interface. One of our goals is to evaluate different organizational structures in tasks ranging from simple search to information integration. The optimal structure for various levels of task complexity can often be discovered or validated through eye movement analysis. We are tracing the sequences of fixations that occur as a user interacts with a computer.

Although eye movement analyses have contributed greatly to the understanding of skilled reading, they have not been applied to complex tasks that also require intermittent responding or problem solving. This observation is somewhat surprising because eye movement data can facilitate the decomposition of overall task time into components reflecting recognition, decision, response, search, and so on. These data also permit strong inferences concerning the subset of available information that is actually considered in arriving at a decision. This research is supported by a grant from NASA.

Participants: Ken Paap and Ron Noel.

Air Combat Expert Simulation.

The Air Combat Expert Simulation (ACES) is a computer simulation of the performance of expert fighter pilots in air-combat maneuvering. Currently, ACES is directed at selecting single air-combat maneuvers for particular airspace environments. ACES consists of a production system framework for selecting air-combat maneuvers, a graphic display showing the relative positions of two aircraft, a text display with information about the current state (for example, airspeed), and flight equations to produce realistic updating of airspace states as maneuvers are executed.

Currently, ACES is functioning effectively at the level of basic fighter maneuvers. The selections of ACES agree with the selections of experts about as well as experts agree with one another. Future work will be concerned with (1) incorporating high-level planning into the model, (2) defining basic action scripts that organize maneuvers around basic units of aircraft control, (3) evaluating the value of the model in training pilots in basic fighter maneuvers, and (4) integrating the development of the ACES model into the knowledge-acquisition work mentioned earlier. This work is supported by TI and the Air Force Human Resources Laboratory.

Participants: R. Schvaneveldt, T. Goldsmith, and S. Graves.

References: Goldsmith and Schvaneveldt (1985); Schvaneveldt and Goldsmith (1986).

The Knowledge Systems Group

The Knowledge Systems Group is researching a variety of issues in automated problem solving, ranging from designing less brittle expert systems to discovering the fundamental mechanisms of analogical reasoning. Although these projects require using different techniques and exploring different problem-solving architectures, one theoretical perspective unifies our research: problem solving and reasoning are best viewed as the cooperative attempt by procedurelike, active knowledge structures to achieve maximal coherence among themselves while they minimally disturb their own internal structure. In addition to its theoretical exploration, this theme is being applied widely in areas that include process control, scientific information analysis, sensor interpretation, and robotics.

Basic Research

Model Generative Reasoning. Current expert system technology performs effectively on well-defined problems within closed worlds. However, it is brittle when problems are ill defined, data are incomplete, and solutions require integration of knowledge from many different subject domains. These conditions characterize many real-world applications.

The model generative reasoning (MGR) system is a significant advance in existing technology. The MGR algorithm provides a general framework for constructing, comparing, and evaluating hypothetical models of queried events using *abductive assembly;* that is, models are assembled from definitions of general domain concepts to provide alternative explanations for the query and related assumptions.

Explanations are developed progressively through a generate-evaluate cycle. Assumptions are interpreted using concept definitions and then joined to form alternative descriptions (contexts) of the domain structures. Contexts are merged next with procedural information to form programs. These programs can then be run in an environment of facts (observations and necessary truths) to generate models. Last, models are evaluated for their parsimony and explanatory power, providing either a problem solution(s) or the assumptions for the next round of interpretation.

In contrast to much of the work on advanced problem solving within AI, MGR constitutes a theory of reasoning rather than simply a set of techniques. Important features of MGR include (1) the representation of all

knowledge at the conceptual level, (2) the incorporation of a situation calculus for reasoning about spatiotemporal relations between assumptions, (3) the dynamic composition of reasoning strategies from actors embedded in conceptual structures, (4) its constructive approach to event models that supports creative reasoning, and (5) its suitability for parallel implementation. This research is supported by TI and Sandia National Laboratoriesin Albuquerque.
Participants: Mike Coombs, Roger Hartley, and Eric Dietrich.
References: Coombs and Hartley (1987); Coombs and Alty (1984).

Wanton Inference Theory. One of the most interesting problem-solving strategies used by humans is taking information from one domain to solve a problem in another domain. This strategy has been studied extensively under the guise of analogical reasoning. Our research has revealed that this strategy has its greatest benefit when seemingly irrelevant information from one domain is applied to a problem in another domain. Indeed, in our view, information is relevant if it leads to a solution. Hence, given a problem, the information relevant to its solution can only be defined after it is solved. Therefore, the strategy for applying irrelevant information cannot be guided by any but the most general heuristics and is, therefore, somewhat wanton. Accordingly, we have dubbed this strategy wanton inference.

Wanton inference is a strategy for creative problem solving. It begins with the idea that creative solutions can be generated by ignoring the boundaries between the domains of knowledge and making connections between previously unassociated elements in one's knowledge base. The major consequence of using wanton inference is that the size of the search space is greatly increased. Hence, the wanton inference strategy is fundamentally at odds with the received view in AI that the essence of intelligent problem solving is limiting the search for solutions. Our view is that the problem of limiting search spaces is an artificial problem in AI which results from ignoring what can be thought of as the social aspect of creative problem solving: for any problem, virtually any agent can add something that will prove useful to finding a solution. Essentially, the different perspectives of different agents means that the search space is searched in a "massively, massively parallel" fashion. This social aspect of creative problem solving provides the key to managing the large search spaces generated by wanton inference.

Current work focuses on using statistical dynamics to explore the statistical nature of wanton inference and universal algebra to describe the semantic interactions of agents. Finally, we are developing two programs, AGL and CSE, for studying different kinds of interactions that agents might use when presented with a novel problem.
Participants: Eric Dietrich, Chris Fields, and Lizabeth Rachele.
References: Dietrich and Fields (1986); Fields and Dietrich (1987a, 1987b).

The Holmes Project. The Holmes Project is an investigation into the nature of scientific discovery. The central assumption is that the most important aspect of discovery is recognizing that a problem exists. Solutions to scientific problems are only possible after a problem is recognized. We also assume that the recognition provides the key context in which the solution is developed and that scientific discovery is primarily a theory-driven enterprise rather than a data-driven one. Thus, our approach contrasts interestingly with that of Langley, Bradshaw and Simon (1983) in the BACON set of programs.

Central to the Holmes Project are two programs: AGGLUT and COLLIDE. These programs implement two strategies for building new knowledge out of old knowledge (cf. the theory of wanton inference and the two programs AGL and CSE). The two strategies are called agglutination and collision. *Agglutination* binds knowledge within the same domain, and *collision* binds knowledge from different domains. Our hypothesis is that the scientific discovery of radically new scientific laws requires collision rather than agglutination, which is used in standard scientific discovery. We are testing these programs on cases from the history of science: Black's discovery of the law of specific heat; Ohm's discovery of the relation between current, voltage, and resistance; and Roentgen's discovery of X rays.
Participants: Eric Dietrich, Lizabeth Rachele, Chris Fields, and Mike Coombs.
References: Dietrich and Rachele (1987).

Programming Environment

A Conceptual Programming Environment. Research into conceptual programming (CP) aims to provide a conceptual representation and reasoning package that will provide the software environment for model generative reasoning by supplying the appropriate epistemological constructs. Thus contexts, programs, and models can be handled by basing them on types of conceptual graphs, as formalized in the work of Sowa (1984).

Two classes of information are represented in CP systems: definitions and situations. Reasoning strategies are tied into the structure of definitions because they apply to all instances of the appropriate concepts. Situations can be either externally given in the form of observed facts or internally generated by strategies such as hypotheses or deductions. Following Sowa, we use two mechanisms for definition. Concept types can be defined in an Aristotelian way, in other words, by a set of necessary and sufficient conditions; they can also be defined using schemata, which express alternative contexts in which a term can gain meaning. Procedural knowledge is represented in a CP program by the integration of relevant actors into the definitions.

Current research is focused on defining a clear epistemology for propositional types to support all phases of reasoning, especially abduction. Another area concerns the use of the different definitional types, in other words, how types and schemata can be incorporated into different strategic devices. A third area deals with the expression of complex strategies using compositions of lower-level actors. This work is supported in part by Sandia National Laboratories in Albuquerque and TI.
Participants: Roger Hartley, Heather Pfeiffer, and Mike Coombs.
References: Hartley (1986); Hartley and Coombs (1987).

Applied Projects

Task Planning for a Mobile Intelligent Robot. Autonomous intelligent robots are intended to undertake monitoring and diagnostic and manipulatory tasks in environments hazardous to a human operator. For routine operations, it is possible either to preplan tasks or to define a closed world in which they can be planned. However, many important applications do not permit preplanning or allow the closed-world assumption. A human expert faced with such a task would proceed empirically, carefully testing the accuracy of prior knowledge and revising it where necessary. Revision would be partly unilateral but might use advice from other external experts. Being able to communicate about reasoning and to use advice are, thus, important capabilities. However, it has been difficult to program these capabilities using existing automated-reasoning methodologies because these methodologies tend to rely on logical inference and the closed-world assumption.

The Knowledge Systems Group, in conjunction with the Robotics Group and Sandia National Laboratories in Albuquerque, are exploring the application of MGR to open-world problem solving and robot communication. Programming in CP, we want to provide a formalism for representing changing worlds, reasoning about exploration options, and integrating human and system knowledge through cooperative dialogue. We have tested our formalism by designing a conceptual planner for an inspection robot and aim to improve its performance by using MGR-like strategies. This work is supported by Sandia National Laboratory in Albuquerque.

Participants: Mike Coombs, Mike Roseborrough, Roger Hartley, Dan Eshner, and Cari Soderlund.

Optimizing the Use of Meteorological Databases. Weather forecasts must often be made using sparse, uncertain data. We are collaborating with meteorologists at the U.S. Army Atmospheric Sciences Laboratory (ASL) at White Sands Missile Range to develop an automated-reasoning system to assist forecasters in making optimal use of data from sensors of various types, predictions from numeric models of the atmosphere, and climatological databases for both nowcasting and forecasting applications. The Knowledge Systems Group will be developing a set of prototype systems for solving progressively more difficult data integration and comparison problems of interest to ASL.

Our approach is to use the MGR system to build and compare alternative weather scenarios based on data from different sources. The goal of the system is to generate a coherent model which satisfies the largest number of constraints imposed by the available data, where the constraints are weighted by reliability or relevancy, and which is strong enough to answer a given set of questions. The CP environment will be used for system development.

This project provides an excellent opportunity to assess the capabilities of MGR for reasoning tasks which require spatial, as well as temporal, reasoning and which involve the simultaneous satisfaction of constraints of different levels of hardness and different spatiotemporal scales. This project is supported by the U.S. ASL.

Participants: Chris Fields, Roger Hartley, Heather Pfeiffer, and Cari Soderlund.

Information Management for Acquired Immune Deficiency Syndrome Research. The Primate Research Institute (PRI) at NMSU is a major national center for the testing of candidate vaccines, including those for Acquired Immune Deficiency Syndrome (AIDS) in primates. In order to make the most efficient use of a limited chimpanzee population, chimpanzee immunization experiments at PRI must be carefully designed to yield the greatest possible information per animal immunized. In deciding which potential antigen-protocol combinations to test, PRI researchers must take into account, as potentially relevant, all current information on the AIDS virus, AIDS pathogenesis, and the host immune system.

We are collaborating with researchers at PRI to design an information-management system to support experimental design for AIDS vaccine trials. The current effort is directed toward developing a proof-of-concept system capable of representing and manipulating knowledge relevant to the structure and action of the AIDS envelope protein gp120. This system must represent knowledge at a set of descriptive levels ranging from DNA sequence data to antibody titer data on the host immune response; at each descriptive level, multiple classification systems must be used.

The MGR system is being used for this project, with CP providing the programming environment. This application provides a test of the ability of MGR to represent and manipulate knowledge at multiple levels of description in an environment in which interlevel constraints of various strengths are operative. This work is supported by PRI.

Participants: Chris Fields, Mike Coombs, Roberta Catizone, and Doris Quintana.

The Vision, Robotics, and Graph Theory Group

The Vision and Robotics Group at CRL is dedicated to establishing a first-rate, pure research program in selected areas of computer vision, robotics, and graph theory. Research results are integrated with other CRL research in AI, then directed toward selected applications and commercial developments, ultimately to develop a world class image-processing laboratory. The major research thrust is on mathematical models for vision and robotics. Differential calculus and geometry are used in edge analysis of images. Fourier transforms are used for shape analysis. Geometric modeling is used for robotics and three-dimensional (3-D) vision. Calculus of variations and control theory are used for integrated-path and energy planning, and kinematic control. Attention-expectation models are used for motion analysis and tracking. Graph-theoretic models are used for classification and computation, and the calculus of variations is used in integrated-path and energy optimization. Image-processing laboratory development is based on a highly interactive and modular system allowing researchers to implement algorithms without recompilation of entire packages, thereby giving immediate feedback for rapid analysis.

Vision

The Vision Laboratory Environment. In the design of a vision laboratory, we have made an environment that closely adheres to the general UNIX and C philosophy. UNIX provides the mechanisms necessary for highly interactive programming and development. The key to using this environment for vision research is the treatment of image files as ordinary data files. Individual files (images) can be "piped" from one program to another to achieve the desired processing. These programs, called filters, accept standard in and standard out files without regard to origin or destination. In this manner, command-line programming becomes the task of chaining small filters. For example, the sequence tell | clean | stretch | mark | show starts by submitting an image from a frame buffer (screen) with "tell," which sends the image downstream to "clean," which is a smoothing operator to reduce noise in the image. The "clean" filter then sends this new image to a "contrast stretch" filter, which in turn sends the stretched image to another routine "mark" that detects edges. Finally, the terminal program "show" displays the result. New capabilities developed by researchers plug into the environment with minimal recompilation. A large number of filters are available, spawning a new type of programming, that is, command-line programming. Programmers can mix filters in a new way, giving immediate results without coding. This stream processing acts as an image editor, and hence, our image-processing environment is called the Streamed Image Transformation Editor SITE© Another heavily used file-management feature of UNIX is that hardware devices appear to the system as ordinary files. This feature facilitates the use of different image-processing boards and processors in SITE©. We have SITE© operating on 1, 2, 8, 12, and 24-bit frame buffers under SUN 2s and 3s, IBM-AT-class machines, and Intel's Hypercube environment.

Participants: Scott Williams, Jeff Harris, Ted Dunning, and Patricia Lopez.

References: Williams (1987).

Fourier Analysis of Shape. In analyzing the content of a picture for pattern recognition or higher-level cognitive relations, it is important to have invariant descriptions of the shape of constituent parts of the scene. The picture is planar and so is the video or digital description of each object in it. The objects have one-dimensional boundaries or contours. Analysis of global properties of these contours, such as enclosed area, arc length, symmetry, convexity, and connectivity, is critical. The contours are initially described by data-intensive local coordinates or chain codes. These data are then converted and compressed by mathematical transforms into information amenable to analysis. Various transforms are used (such as moments and curvature trace), but perhaps the best is the Fourier transform of the contour. The closed contour can be thought of as a deformation or a mapping of a circle. The Fourier transform describes this mapping (and therefore the contour) as a sum of simple constituents or frequencies. Each of these building blocks—the Fourier coefficients—is the integral (or average) of the contour after multiplying by an algebraic homomorphism of the circle. Because the circle is invariant under these homomorphisms, the invariances of the contour are effectively analyzed using the Fourier coefficients. Behavior under rotations and translations in both domain and range can be effectively analyzed and used for orientation and normalization, which, in turn, are effective for classification and pattern recognition.

Participants: Keith Phillips, Nancy Gonzales, and Patricia Lopez.

References: Phillips (1986, 1987).

Edge Theory. An edge in a scene is a curve along which the scene changes in some way. Both natural and computer vision systems give structure to a scene by analyzing the edges in it. In cases in which the scene is simple, it is possible to find global contours or edges by simple thresholding and contouring methods or with the use of first-order linear differential operators. For complicated scenes, it is only possible to obtain local edges. These edges must be fitted together to give global structure in complicated ways. Local edges can be found as the zeros of second-order, nonlinear, covariant differential operators. The operators are of the general form $\langle Hf(p),q\rangle$, where f is the intensity function of the image, H is the Hessian, and p and q are variable directions. In particular, if p and q are both the gradient of f, we obtain the Q operator, similar to the Canny operator. These and various other edge operators are being studied.

Participants: Keith Phillips, Warren Krueger, Scott Williams, Zhi-Yong Zhao, and Ted Dunning.

References: Phillips et al. (1984); Machuca and Phillips (1983).

Surface Theory and Vision. Given an image in which for each point x there is a number h(x), Krueger and Phillips have proposed predicates such as

Q(x), S(x), and C(x) , the truth of which signal the occurrence of a differential geometric event at x. Event curves for each of these predicates—that is, the curves of points x which satisfy one of the predicates—have structural significance for the surface whose equation is z = h(x). For example, Q finds asymptotic lines of curvature on the surface, S finds geodesic lines of curvature, and C finds lines that are transversely critical for Gaussian and mean curvature. Sequential programs have been written to implement each of these predicates. All these programs require second differences of h, and C implicitly uses third differences. When the granularity of the image data h(x) is coarse, the second differences become ill conditioned. Real image data (as opposed to geometric image data) are typically coarse and fractal in nature. A pressing problem is how to mediate between the coarseness presented by real data and the fineness required by the predicates. Smoothing convolutions is one alternative; another is to investigate fractal conditions of boundaries. We are also obtaining useful results with piecewise cubic surface fits.

Participants: Warren Krueger, Keith Phillips, and Scott Williams.

References: Krueger (1986); Krueger et al. (1986).

Agricultural Aerial Monitoring. CRL serves as the system developer and research and development lab for Earth Resources Development Corporation (ERDC). This company takes aerial photographs of agricultural areas and analyzes them for use in making agricultural decisions. We have designed a SUN-based image-processing lab for ERDC that is compatible with the CRL system. We are developing a variety of algorithms for improving image acquisition and digitization on board aircraft and matching images taken from aircraft at different orientations, times, lighting, or altitudes. We have also developed a projective geometry transformation that matches a collection of points in one image with the same collection in another. This method is being refined and tested. A variety of contrast stretching and histogram enhancement algorithms are in place, all important for the kind of analysis required for ERDC customers. Other research goals that will fit into ERDC applications are the development of fast and accurate local edge-detection algorithms; pattern recognition and shape analysis using Fourier series or entropy and maximal likelihood estimates; and estimation of water content in the soil from infrared images. In the long term, the image analysis is to be combined with economic irrigation scheduling models to form an automated agricultural planning model.

Participants: Scott Williams, Roberta Catizone, Ted Dunning, and Jeff Harris.

Automated Insect Classification and Counting. A computerized system for classifying and counting large, diverse samples of insects quickly and accurately is under joint development with the Entomology and Plant Pathology Department at NMSU. Field testing of the first-generation insect classification and counting system was done during the summer of 1986. The system is implemented on a microcomputer and includes a charge coupled device (CCD) camera fitted with a color wheel and lights. The complete unit can be installed and removed from a van with ease, permitting on-site analysis of insect populations in agro-ecosystems. The counting and classification system is based on similarities of size, shape, and color. Fourier transforms are used for the analysis of shape. A complexity involved in pattern matching of biological organisms is the variability of shape depending on the position of appendages. We have dealt with this problem by implementing a mathematical appendage-chopping algorithm. The database currently in use was generated using 100 examples each of seven insect genera in different growth stages (adult and nymph) and orientations (dorsal, ventral, and side), resulting in 25 database nodes. Templates derived by means of statistical analysis of the attribute values within each sample set are used in the pattern matching. The best match is that node for which the probability is greatest that an insect of this type would exhibit the descriptor values computed for the unknown. If no node has a probability greater than some fixed minimum, the result is no match.

Participants: Nancy Gonzales, Keith Phillips, Edward Plumer, and Scott Williams.

References: Gonzales, Ellington, and Phillips (1987); Gonzales (1986); Dearholt et al. (1985).

Contaminant Detection. A computerized system for detection and statistical description of contaminants on spacecraft parts is being developed under contract to a division of Lockheed Corporation. The contaminants are contained on a 47-mm filter paper that is placed under a microscope. A series of 400 magnified images are taken, with particulate matter being detected by gray-level thresholding or contouring. Areas are computed using simple pixel counting. Maximal and minimal diameters are determined using elliptical approximations based only on area and the length on the contour. The blobs are sparse on the filter paper, and the real challenge in the project is efficient scanning and file management to increase speed and reduce storage.

We have also developed software for computerized inspection and grading of cotton for the Southwest Cotton Ginning Laboratory. A feasibility study is complete, and we are working on the design of the next phase. We hope to include real-time edging and particle counting and carry software implementations into hardware.

Participants: Jeff Harris, Edward Plumer, and Scott Williams.

References: Harris and Plumer (1987).

Computerized Archaeology. CRL has developed and implemented a computer vision system for the Archaeological Research Lab at NMSU. In the production system, the Fourier series of the contours of artifacts (lithics and prehistoric ceramics) are calculated, and elementary measurements such as diameters are taken. Interactive tools allow archaeologists to manipulate and compare artifacts on the screen, thereby reducing hand-held analysis. Classification schemes for projectile points based on the Fourier transform are being developed. Both local and global classification is promising. A system for taking three-dimensional measurements using structured lighting is also being developed.

Participants: Keith Phillips, Nancy Gonzales, Alice Bertini, Roberta Catizone, Ted Dunning, Wojciech Golik, Niall Graham, Jeff Harris, Patricia Lopez, Bruce Rowen, Scott Williams, and Zhi-Yong Zhao.

References: Phillips et al. (1987a); Phillips et al. (1987b).

Neural Networks. We are exploring mechanisms for associative memory, pattern recognition, and abstraction that appear as emergent properties of networks of neuronlike units with adaptive synaptic connections. It has been most fruitful to explore the continuous limit, in other words, to let the number of neurons go to infinity (a neural field model). We have shown that because of the variation of synaptic conduction with integrated experience, the network might learn, in other words, display associative memory and categorization behavior. We have proposed a nonlinear optical analog for the neural field equations, consisting of a phase-conjugating resonator loaded with a volume holographic recording medium.

Theoretical advances have involved including the effects of higher-order correlations by expanding the requisite perturbation theory to higher than cubic order. Some of the effects include group pattern recognition, the ability to store and recall temporal sequences, and logical search and inference capabilities. We are also exploring soliton solutions for reconstruction of temporal sequences by chains of binary correlations. This process, too, can lead to group invariant recognition.

Experimental advances have been obtained in work with Los Alamos National Laboratories (LANL) in Los Alamos, N.M., and the Joint Institute for Laboratory Study of Astrophysics (ILSA) in Boulder, Colo. Exhaustive studies of phase conjugators have been done at Los Alamos. Ring resonators that store and reconstruct images have been set up at ILSA. Phase-conjugating resonators capable of storing and reconstructing multiple images are the next step. Our theory then indicates how to program logical functions within such hardware. This work is supported by a grant from NSF.

Participants: Marcus Cohen, Wojciech Golik, Robert Fisher (LANL), and Dave Anderson (ILSA).

References: Cohen (1987, 1985).

Robotics

Cognitive Modeling in a Robotics Environment. There are two major objectives of this research project: (1) the implementation of biologically based cognitive models and (2) the development of algorithms for adaptive industrial robots. With respect to the first objective, we are investigating models of visual perception and hand-eye coordination and, at a general level, models for the learning of these fundamental skills. Our experimental setup is that of a hand-eye-coordinated robot performing tasks in a reasonably restricted environment. One current subproject is the design and implementation of an attentional algorithm for rapid object identification and scene analysis. Such an algorithm facilitates image analysis and scene understanding by flexibly integrating low-level, sensory, data-driven information with high-level, knowledge-driven information in order to achieve the visual-processing speeds required by a real-time robotics system where feature extraction is performed on a need-to-know basis. Another subproject is concerned with the integration of learned local constancies of an environment with known, perhaps innate, principles of apparent motion for motion understanding. Data from human subjects are used to generate the parameters for the apparent motion algorithm.

We are currently concentrating on the tracking of multiple objects in simple environments with simple interactions between objects, with the goal of generalization to complex environments and interactions. Objects in motion are videotaped, and the individual frames serve as input to motion correspondence. Although the current system is necessarily a simulation, a variety of strategies can be tested, and algorithms that use the most system time can be optimized and targeted for hardware implementation. Images are 512 x 480 pixels, with 256 gray levels. The implementation language is C.

Participants: Victor Johnston, Patricia Lopez, and Derek Partridge.

References: Partridge, Johnston, and Lopez (1988); Johnston et al. (1986).

Mobile Robots. Joint research into the kinematics and path planning of mobile robots is being conducted with the Intelligent Machines Division at Sandia National Laboratories in Albuquerque. Most path planning for mobile robots has been straight line as opposed to continuous; for example, if a robot must move through an environment with obstacles, the strategy has typically been a model of the environment combined with a sequence of intermediate positions that can be achieved linearly. Clearly, an important research issue in path planning is the generation of paths for continuous motion through the obstacles. Mathematically, this generation of paths means making the derivatives of the path continuous to some order.

Another research issue is describing the motion of the contour of the robot, resulting in a mathematical model with differential equations for strategic points on the robot. The problem is a combination of geometric constraints, for example, getting a three-dimensional object through a door and describing continuous motion. A third research issue is driving the motors to obtain the correct acceleration and velocity to follow the prescribed path. We have developed one method by showing that an omnidirection vehicle can be represented by the motion of the coupler link in a four-bar, closed kinematic chain. The concept of linkage representation is quite attractive because once the transform is defined, steering control is straightforward. Both steering position and rate can be continuously defined by making certain positions on the robot follow circular paths. Further research in this area should include the integration of the representation topology of the environment and path generation, the application of linkage synthesis techniques, and analytic and computational solutions of the resulting differential equations. This work is supported by Sandia National Laboratories in Albuquerque.

Participants: Michael Roseborrough, Jeff Harris, Keith Phillips, Sunil Desai, and Kelly Perryman.

References: Roseborrough and Phillips (1986).

Geometric Pattern Recognition for Robots. In joint research with the Intelligent Machines Division of Sandia National Laboratories in Albuquerque, the Fourier series-based pattern-recognition methods are being integrated into a recognition system for regular-shaped geometric objects such as triangles, ellipses, rectangles, and tools that closely resemble these shapes. The geometry of elementary shapes is reflected well in the Fourier transform, making machine geometric analysis, as opposed to template matching, a viable method. This work is supported by Sandia National Laboratories in Albuquerque.

Participants: Keith Phillips and Nancy Gonzales.

References: Phillips (1988).

Energy Optimization Energy. Consumption of a multiple-degree-of-freedom robot, either mobile or fixed, can be approximated by an integral expression in several variables. Energy minimization is an optimization problem for this integral. The classical calculus of variations is being used to solve this problem, and several approaches are being tried. The most general formulation is an optimization problem in an infinite-dimensional Banach space. A finite-dimensional approximation can be formulated and LaGrange multipliers and other techniques of nonlinear optimization used. Optimal path planning has received much attention in AI and robotics literature, but energy optimization has received little. Integrating path planning with energy control considerations should lead to efficient robots.

Participants: Richard Colbaugh, Keith Phillips, Michael Roseborrough, and Kelly Perryman.

References: Colbaugh (1987); Perryman and Roseborrough (1985).

Graph Theory

Graph Theoretic Models. Research into graph theoretic models in computer science is being conducted at CRL. The primary research interest is the hypercube graph and its properties. The hypercube characterizes a topology of structures as diverse as parallel computers and finite Boolean lattices. The most significant result has been Harary's theorem that the hypercube is the best architecture for "parallel gossiping," that is, the exchange of information between all processors. The problem of embedding arbitrary graphs in hypercubes has also been investigated, as have problems pertaining to the reliability of the hypercube graph when faced with processor or interconnection failure and the optimal packing of a hypercube with subcubes. Unsolved problems abound, and some of those under investigation have applications in very large scale integration design, computer networks, and parallel processing. Several other problems that are pertinent to the programming or designing of hypercube computers are also being analyzed. These problems include a criterion that identifies the trees which span the hypercube (which is partially solved), the crossing number of the hypercube when embedded in the plane, optimal graphs for broadcasting messages from one node to all others (the hypercube is one of them), the derivation of reliability polynomials for hypercubes, and the characterization of the minimal cut sets of a hypercube. Some theoretic properties pertaining purely to graphs are also under investigation, such as the number of perfect matchings of a hypercube and alternative characterizations of hypercubes. A thorough survey has been prepared and serves as a comprehensive guide to the important unsolved problems in the theory of hypercubes. The Intel hypercube is being programmed to determine the number of nonisomorphic hamiltonian cycles on a hypercube.

Participants: Frank Harary and Niall Graham.

References: Harary (1988a, 1988b); Graham and Harary (1988, 1987, 1986).

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