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RESEARCH IN PROGRESS

Artificial Intelligence Research at General Electric

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Abstract

General Electric is engaged in a broad range of research and development activities in artificial intelligence, with the dual objectives of improving the productivity of its internal operations and of enhancing future products and services in its aerospace, industrial, aircraft engine, commercial, and service sectors Many of the applications projected for AI within GE will require significant advances in the state of the art in advanced inference, formal logic, and architectures for real-time systems New software tools for creating expert systems are needed to expedite the construction of knowledge bases. Further, new application domains such as computer-aided design (CAD), computer-aided manufacturing (CAM), and image understanding based on formal logic require novel concepts in knowledge representation and inference beyond the capabilities of current production rule systems Fundamental research in artificial intelligence is concentrated at Corporate Research and Development (CR&D), with advanced development and applications pursued in parallel efforts by operating departments The fundamental research and advanced applications activities are strongly coupled, providing research teams with opportunities for field evaluations of new concepts and systems. This article summarizes current research projects at CR&D and gives an overview of applications within the Company.

Advanced Inference and Logic

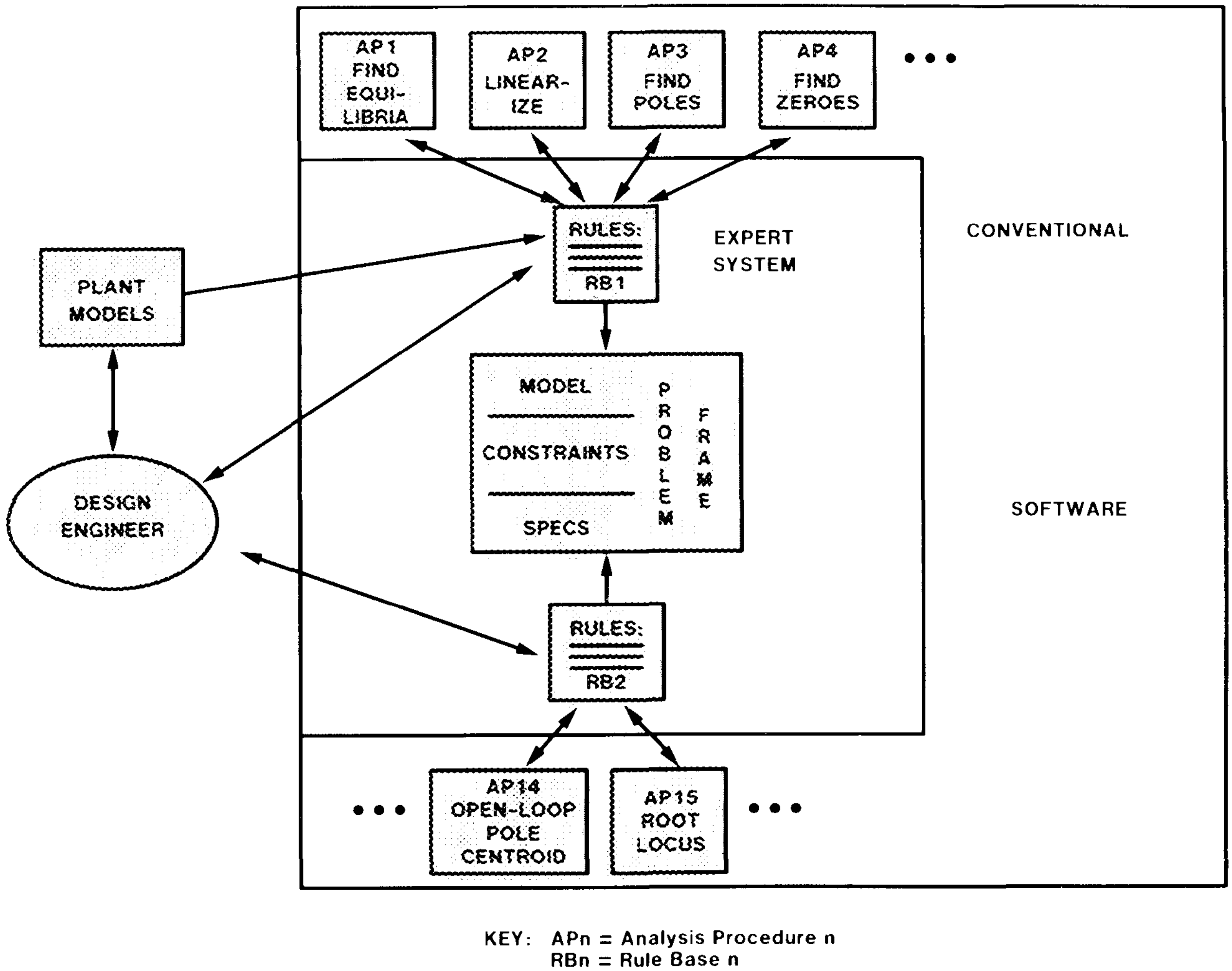
A majority of the product departments in General Electric's Aerospace Business Group are concerned with generation, integration, and interpretation of sensory information from satellites, radars, sonars, and similar hardware. The technical challenge today lies at the system integration level, in assessing the situation being monitored and providing assistance in selection of the most effective passive and active sensors at acceptable cost. The requirements of this domain exceed the capabilities of current production rule systems; consequently, approximately half of the research program in artificial intelligence is focused on extending the capabilities of current reasoning systems and on more powerful and efficient tools for knowledge representation.

Reasoning with Incomplete and Uncertain Information

To date, expert systems have shown most frequent success in diagnostic applications or on problems with similarly constrained data and results. Problem domains with less constraint such as military advisory systems will require more advanced reasoning techniques because the input data will have the following characteristics:

- Uncertain, incomplete, potentially erroneous, and time-varying.
- Specified quantitatively or qualitatively and must be interpreted in context.
- Contain information that is relevant but in a form unknown to the system.

The output of the expert system may be similarly unconstrained, in that there may not be a prescription for the form or the content; that is, the overall goals may be specified, but the form may not. For instance, it may be possible to say only that the output is "like" or "analogous to" an output that is specified. In fact, the output may be a composite of pieces (such as a plan composed of sub-plans), each of which may be similar to the specified set, while the composite is not similar to any of them. The objective of this project is to provide a richer environment



Structure of expert system for Computer Aided Control System design.

Figure 1.

in which to develop expert systems applications. Such an environment will allow the development of large systems whose complexity in both reasoning and inherent structure make current systems ineffective.

Fundamental research on reasoning with uncertainty is funded by the DARPA Strategic Computing Program, with an abstract battle management problem domain chosen as a model of this problem class. In parallel with the DARPA program is an internal effort focused on transition of this technology to future aerospace systems supported by a consortium of departments from GE's Aerospace Business Group. Interaction with these departments provides useful information, pertinent to this domain, in characterizing classes of uncertainty and defining realistic scenarios. From this information we are developing a test bed simulator for research experiments, which we refer to as a Battle Management Associate (BMA).

Reasoning with Uncertainty

A *representation of uncertainty* is used to describe the belief (or disbelief) in numeric and symbolic data. A numerical characterization represents uncertainty as scalars on an interval (bayesian approach, certainty factor), as intervals on a range (belief function, plausibility function, evidential reasoning), as distributions on a universe of discourse (extension of necessity and possibility), or as points in a space (evidence space).

Part of our research is directed to the establishment of the theoretical basis for defining the syntax and semantics of a small subset of calculi of uncertainty. Each calculus in this subset, defined by a negation operator, a Triangular norm, and its DeMorgan's dual Triangular co-norm, will be selected by context-dependent rules according to the type of constraints to be satisfied (evidence independence, evidence subsumption, etc.).

A term set of linguistic statements of likelihood will determine the *granularity* of the uncertainty that could be possibly specified by a user or an expert. This granularity will limit the ability of two similar calculi to produce notably different results. The meaning of each element in the term set will be defined by a fuzzy number on the [0,1] interval. Inconsistencies will be detected by interpreting the fuzzy interval as elastic lower and upper bounds of probability. Dempster-Shafer's theory will be extended to this case and its constraints will be used to detect conflicts during the aggregation. Entropy measures will also be used to quantify the magnitude of the conflicts.

Analogical Reasoning

Two approaches to reasoning with incomplete information are being pursued. The first, reasoning by analogy, addresses the issues of extensible representations for describing situations, evaluation of similarity between situations, partial matching of situations, reasoning from precedent, and learning new facts from constraint descriptions.

Reason Maintenance Systems

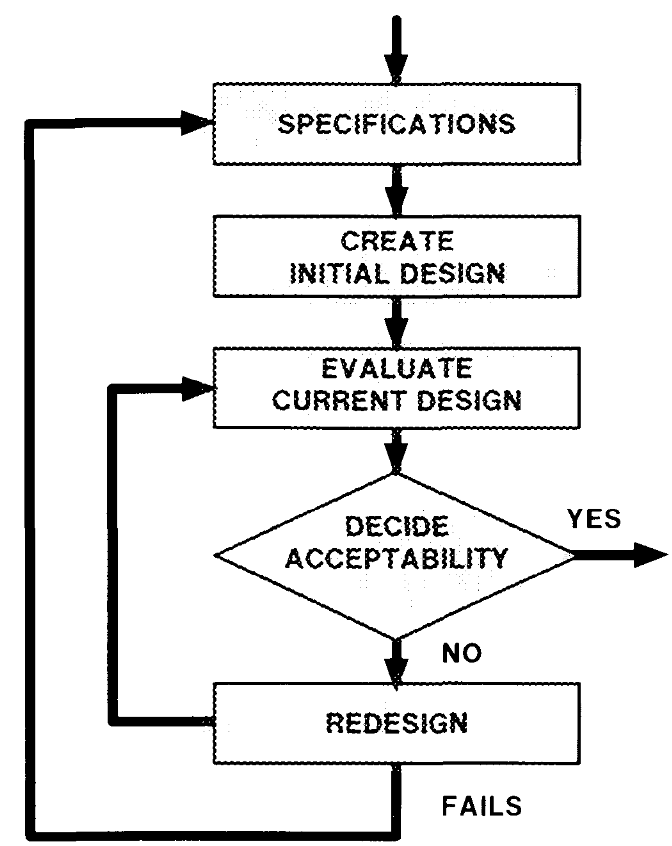
The second approach to reasoning about incomplete information is the development of a nonmonotonic logic specialized to reasoning about time, cause, and belief. This logic will be realized in a formally specified reason maintenance system that will maintain multiple hypothetical contexts, support a variety of inference rules (possibly nonmonotonic), automatically detect inconsistencies, and provide declarative control over the inference process.

Program Verification

The application of artificial intelligence to aerospace information fusion and situation assessment tasks imposes stringent requirements for software verification. Due to the complexity of many of these applications and the combinatorial explosion inherent to AI-based problem solving, verification through exhaustive testing is very costly and impractical in many cases. An alternative approach to this problem is verification procedures based on formal logic. GE has an ongoing effort to develop new methods of program verification and to apply them to real problems. Of particular interest is the use of these techniques as a part of the formal auditing procedure for software designs.

Several tools have been developed. Affirm-85 is an enhanced version of the Affirm program verification system that was developed during the past year. The Rewrite Rule Laboratory is an environment and set of tools for performing research on the rewrite rule method of formal reasoning. Developed jointly with MIT under NSF sponsorship, the Rewrite Rule Lab is now being used at six universities in addition to GE.

Contacts: Dr. Piero Bonissone (Uncertainty), Dr. Allen Brown (Reason maintenance systems), Mr. Gil Porter (Analogical reasoning), Dr. David Musser (Program verification).



The "Re-Design Model" for Engineering Design.

Figure 2.

Real-Time Systems

The problem domains described above generally impose requirements for execution in real time that are far beyond the capacity of commercially available computing hardware. To address this need, General Electric is active in developing new architectures specially designed for performing AI-based tasks, such as image processing and inference. Parallel research is underway on methods for programming such machines and for structuring software for efficient real-time execution.

Parallel Processing Computer Architectures

The Connection Machine, originally conceived at MIT, is a massively parallel Single Instruction, Multiple Datastream (SIMD) machine for real-time AI applications. The machine contains a quarter of a million simple processors with two different methods of interconnection. Each processor is locally connected to each of its eight nearest neighbors and can be globally connected to any other processor with a novel cross-omega routing network. For an image understanding application, for example, the nearest neighbor connection would be used to perform convolutions and other signal processing operations. After the signal-to-symbol transformations had been made (*e.g.,* some corners had been determined), the global interconnections would be used to process the symbols (*e.g.,* to find diagonal corners in a square). Programming is a key part of this project. To fully achieve the potential of this new highly parallel architecture, new languages, algorithms, and programming paradigms need to be developed and demonstrated on real applications.

Recently GE and MIT have established a joint project to build the machine and apply it to a number of problems including image understanding. MIT is responsible for the architecture, GE for the chip design and the actual assembling and testing of the machine, and MIT and GE are jointly responsible for programming and applications. Government funding is being sought for this effort.

In a parallel DARPA-sponsored program, the General Electric Military Electronics Systems Operation (MESO) is participating as a subcontractor to Carnegie-Mellon University to develop hardware for H. T. Kung's systolic array WARP machine.

Real-Time Control Systems

The objective of this research is the development of architectures and algorithms for use of artificial intelligence in real-time systems, in particular as applied to real-time control and signal-processing applications. This research includes identification of functions particularly suited to AI (in contrast to conventional control and signal processing methodologies) and partitioning of system architectures into AI-based and conventional subsystems for future hardware realization.

Work to date has focused on a rule-based approach to design of closed-loop control systems. Using the General Electric originated the *Delphi* expert system tool (described later), a knowledge base of approximately 300 rules was developed for application to a comprehensive set of existing routines used for CAD for control system design. The system, shown schematically in Figure 1, has been validated for single-input, single-output system design. Such a system has the potential for application to in-flight control system reconfiguration for flight or engine controls in response to battle damage or other degradation in plant or control system hardware.

Contacts· Dr. Piero Bonissone and Mr. Gil Porter (Real-time systems for AI), Dr. Kim Gostelow (Connection machine - software), Dr. James Taylor (Expert systems for control system design), Dr. James Wheeler (Connection machine - hardware).

Software Tools

Software tools used for expert system development in GE had their origins in the well-known CATS-1/DELTA system. DELTA was designed as a practical tool for locomotive troubleshooting. However, it has been found useful in other domains as well. DELTA is a forward and backward chaining system particularly suited for controlling dialogue with a user, including explanation, help, and graphical (video disk) displays. It provides a rich set of predicates and verbs in its rule language and implements a theory of "certainty factors" of facts and knowledge.

The experience gained during development of DELTA provided the basis for creation of software tools for building expert systems for a wide range of General Electric applications. The emphasis in designing these tools was improving the productivity of knowledge engineers to reduce the time and cost of implementing expert systems in the past. The two descendants of DELTA are GEN-X and Delphi.

GEN-X provides powerful and flexible user interfaces for both the knowledge engineer and end-user, using an IBM PC as a delivery vehicle. It includes GERULE, a spreadsheet format editor/interpreter for production rules, and GETREE, an interactive editor/interpreter/code generator for decision and and/or trees. Parallel expert systems applications projects are underway in numerous General Electric product departments using GEN-X.

Delphi extends lessons learned in DELTA into a more powerful and flexible expert system language embedded in LISP. Like DELTA, Delphi provides a forward and backward chaining inference engine and an ability to reason with and propagate uncertainty. However, Delphi includes a Rete algorithm and a hashing system for rapid matching of facts and goals to rules involving variables, and supports a wide variety of data types. A structure editor for Delphi has been developed to aid rule entry, modification, and checking. Delphi also provides a daemon facility for data-directed invocation of procedures.

The capability for user interaction during a session makes Delphi a viable tool for troubleshooting or advisor systems. Its ability to call other programs during execution has proven to be most useful in implementing expert systems for engineering design or sensor interpretation by several departments in General Electric.

Contacts: Dr. Peter Dietz (GEN-X), Dr. Mel Simmons (Delphi).

Application Domains

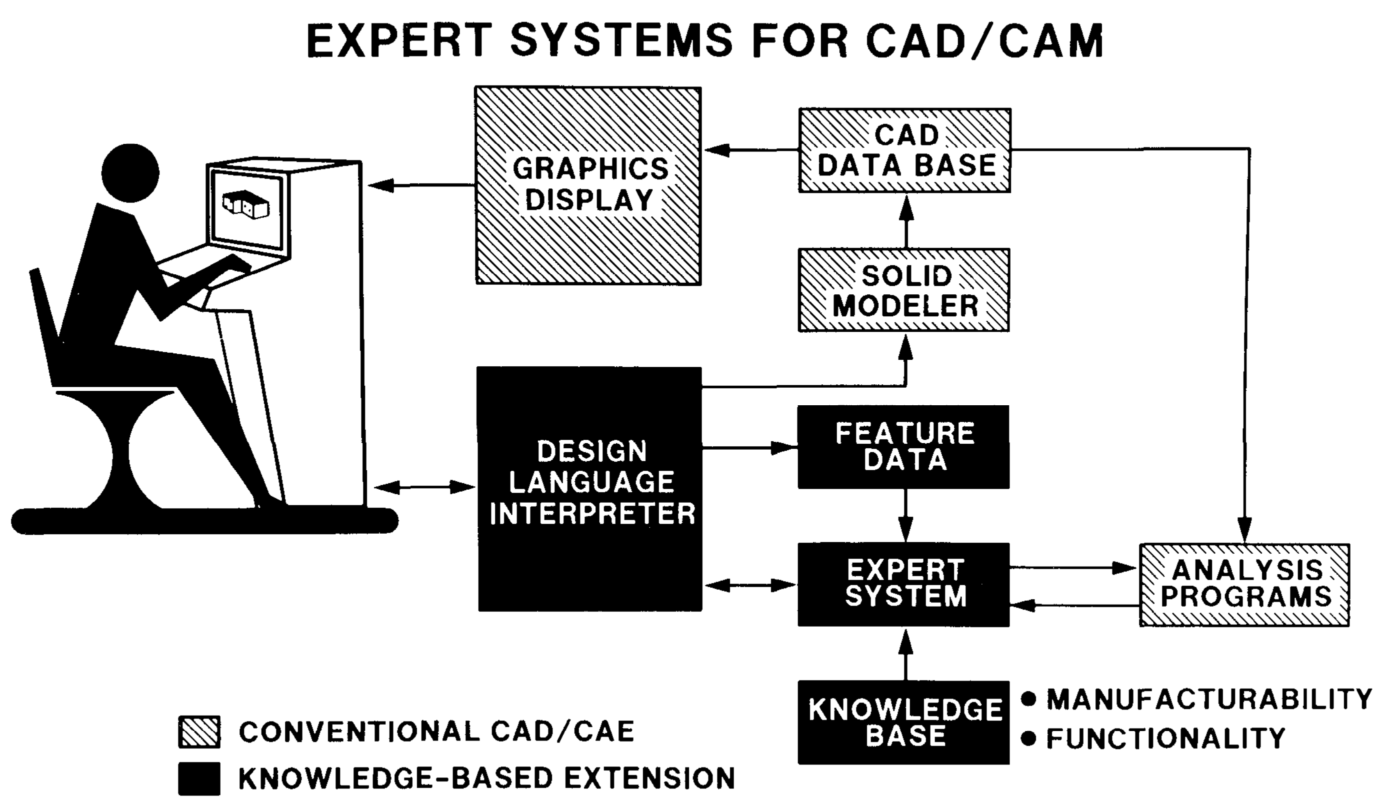
General Electric is active in development of applications of artificial intelligence in its commercial, industrial, and manufacturing sectors. These areas present interesting technical challenges, requiring new research in artificial intelligence coupled with understanding of the engineering and information processing requirements of the problem domain. Below are several examples of our current work.

AI for Engineering Design and Manufacturing

Research on AI for Engineering Design has been a collaborative effort between CR&D and a GE-sponsored program at the University of Massachusetts directed by Prof. J. Dixon. The objective of this research is to develop advanced inference, knowledge representation, and user input languages needed to enable application of expert systems to engineering design and automated manufacturing. Inherent to this objective are capabilities for reasoning with geometric information describing features of three-dimensional parts to be designed and manufactured, and for use of qualitative and quantitative information regarding the functionality and manufacturability of such parts. Knowledge-based systems for design would ultimately be integrated with conventional CAD systems in an architecture of the type shown in Figure 2.

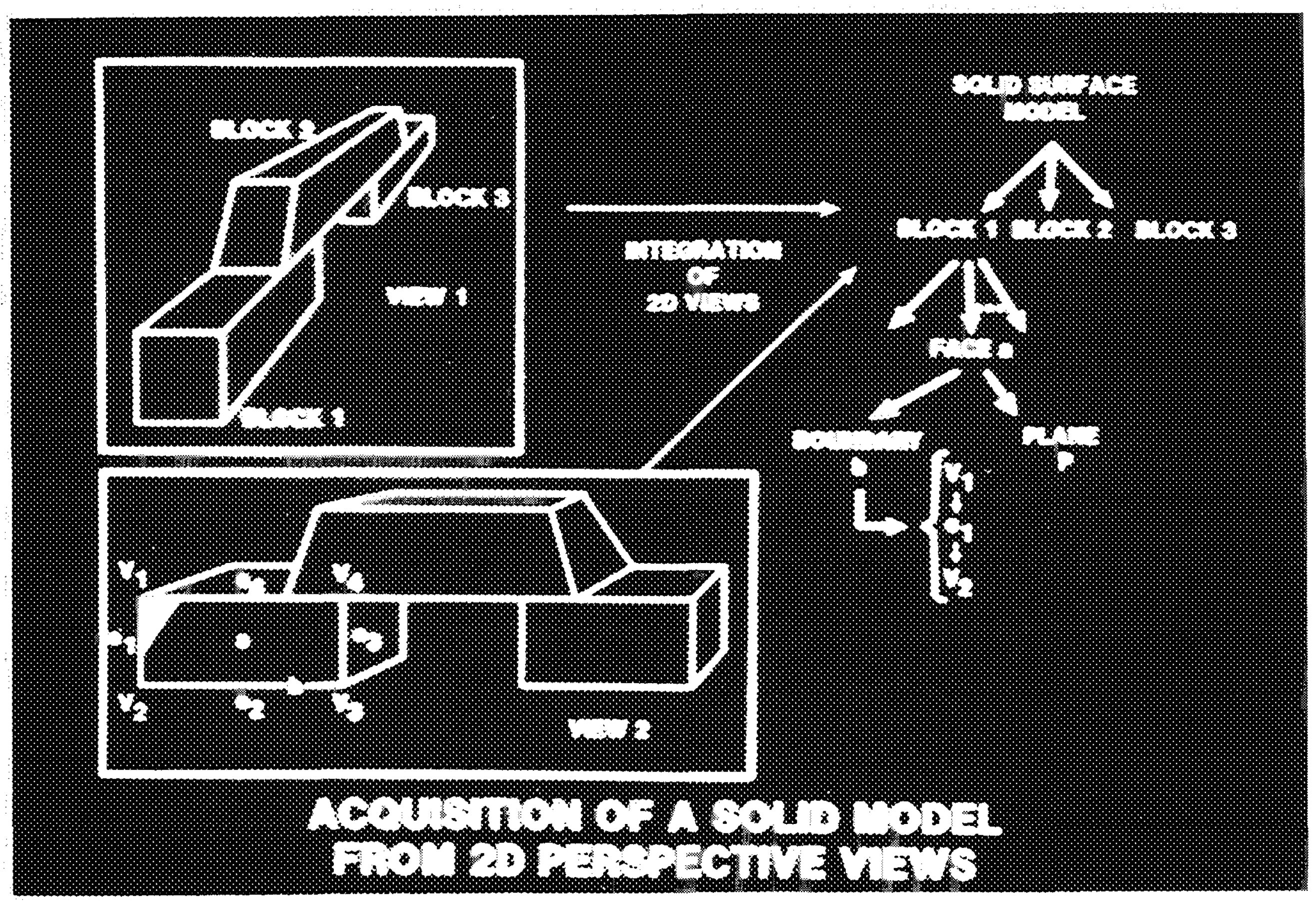
Our research has three major elements: the process of *redesign* and software architectures for implementing redesign strategies, the *decomposition* of complex design problems into simpler (partially independent) subproblems, and representation and reasoning about the *geometry* of designed objects (Figure 3). Throughout this effort our methodology is to start with small, specific problems selected from engineering domains so as to illuminate critical issues in our research agenda. A number of these problems are undertaken as student projects, generally as master's thesis projects. Working from these specific cases, we then try to generalize upon our experience and formulate concepts for next-generation software tools. Sample projects include plastic materials selection, design of aluminum extruded heat fins, injection-molded part design, and plastic extrusion design (in collaboration with GE Plastics Business Operations), and aluminum casting design (with Ordnance Systems Division).

Our research on AI for manufacturing is focused on modeling of qualitative reasoning about manufacturing processes. The motivation for this work is to provide tools for improving productivity in the process development phase of manufacturing, in particular for advanced manufacturing process technologies employed throughout the GE Aircraft Engine Group's highly automated factories. Processes such as curing of composite materials, casting, laser cutting and drilling, and welding require understanding of the underlying physical processes involved to efficiently design and debug tooling and process cycle parameters. The mental models used by humans in reasoning about and planning physical processes are quite unlike the quan-



Integration of a feature-level expert system for mechanical CAD with conventional CAD/CAE software tools.

Figure 3



Acquisition of a solid model of a three-dimensional object from two-dimensional perspective views.

Figure 4.

titative models used in numerical simulations of processes based upon exact physical principles. These mental models are qualitative, rather than quantitative, and represent only the most pertinent aspects of the many physical variables relevant to the situation.

Geometric Reasoning for Image Understanding

The object of this project is to develop new methods for reasoning about geometric concepts and to apply those methods to image understanding. (For example, an image understanding system sees some two-dimensional view which is a projective transformation of a three-dimensional scene. To understand what it sees, it must be able to reason about the effect of that transformation (Figure 4). Thus it should know under what conditions lines that are parallel in the three-dimensional scene remain parallel in the transformed two-dimensional view and under what conditions they appear to converge at infinity.) An initial goal of the project is to be able to create a three-dimensional model of an object from a number of two-dimensional views. A later goal will be to recognize a particular two-dimensional view as an instance of a transformed version of some three-dimensional model.

An important part of this project is to develop new methods for geometric reasoning. The basic approach is to express geometric constraints as algebraic expressions Then these algebraic expressions can be manipulated by various rewrite rule methods to perform the reasoning. The group has published several recent papers on the application of Groebner polynomials and Wu's method to this problem.

Diagnostic Systems

The diagnostic and repair capabilities provided by the orignal DELTA system are now being extended and distributed throughout the Company for use in addressing a range of problem domains. The locomotive diagnostic system, renamed CATS-1 (Computer-Aided Troubleshooting System), has been validated through field tests, with prototype units delivered to two railroad customers. New diagnostic systems are under development by GE product departments for application to gas turbines, aircraft engines, aircraft controls, and ordnance systems, based on the GEN-X expert system development tool.

Contacts: Dr. Peter Dietz (Diagnostics), Prof. John Dixon, Department of Mechanical Engineering, University of Massachusetts (Design), Dr. Joseph Mundy (Image understanding), Dr. Mel Simmons (Design and Manufacturing).

For further information please contact project leaders listed above or Dr Larry Sweet, Manager, Knowledge-Based Systems Branch, Building K-1, Room 5C17; (518)-387-5362.