ENGINEERING DESIGN KNOWLEDGE RECYCLING in NEAR-REAL-TIME

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ABSTRACT

It is hypothesized that the capture and reuse of machine readable design records is cost beneficial. This informal engineering notebook design knowledge can be used to model the artifact and the design process. Design rationale is, in part, preserved and available for examination. Redesign cycle time is significantly reduced (Baya et al, 1992). These factors contribute to making it less costly to capture and reuse knowledge than to recreate comparable knowledge (current practice). To test the hypothesis, we have focused on validation of the concept and tools in two "real design" projects this past year: 1) a short (8 month) turnaround project for NASA life science bioreactor researchers was done by a team of 3 Mechanical Engineering graduate students at Stanford University (in a class, ME210abc "Mechatronic Systems Design and Methodology", taught by one of the authors, Leifer; and 2) a long range (8 to 20 year) international consortium project for NASA's Space Science program (STEP: satellite test of the equivalence principle).

Design knowledge capture was supported this year by assigning the use of a Team-Design PowerBook. Design records were catalogued in near-real time. These records were used to qualitatively model the artifact design as it evolved. Dedal, an "intelligent librarian" developed at NASA-ARC, was used to navigate and retrieve captured knowledge for reuse.

INTRODUCTION

The Engineering Design Notebook (EDN®) concept has evolved rapidly. Whereas costly high performance workstations were used in the past to implement EDN, the concept has now been migrated to laptop PowerBooks (Appendix-B) for portability, ease of use and designer "ownership". Commercially available software (Appendix-C) replaced custom software used in our earlier research. In this form, the EDN concept of design knowledge capture was adopted by the SHARE project (see Appendix-A). In this context, EDN has been extended to support multiple, mobile and distributed design teams through use of the PowerBook as a notebook medium. The project is also informed by active collaboration with the ASK systems project, PACT (Palo Alto Collaborative Test-bed (for distributed design), and the NSF Synthesis Coalition (8 universities dealing with engineering knowledge capture and reuse in undergraduate education).

Deep engagement with real design activity, in parallel with the research program, has been a special feature of the NASA-Stanford collaboration on Generation and Conservation of Design Knowledge (GCDK). This strategy assures the utility of our results and keeps the research grounded in constant feedback from real designers. Last year, the FORD motor company sponsored "Continuously Variable Damper" a project in Stanford's Mechatronics Systems Design & Methodology course (ME210abc) was used post-facto to develop Dedal, an informal document navigation aid. This year we do real-time design knowledge capture and near-real-time reuse on the NASA-Bioreactor project. We have also captured "proof of concept" hardware development activity in the STEP project where rationale capture is particularly important during the proof-of-concept phase. This paper reports some of our findings in the ME210 test-bed environment.

ME210: a design research test-bed environment (Leifer, 1993)

The GCDK rapid prototyping environment is ME210abc (Figure-1), a 9-month long graduate engineering course in which teams of designers conceive, design and prototype substantial electromechanical systems for industrial

sponsors. The designers are typically first year graduate students with one to three years of industrial experience. They typically work in teams of three with coaching by faculty, staff and consultants from industry. The industry sponsored projects are usually multi-disciplinary, combining thermal, mechanical and electrical systems, sensors, actuators, and software. As in industry, the teams have tight deadlines, and must manage equipment and development budgets, engage in frequent design reviews, negotiate with the sponsors, vendors, and fabrication job-shops, etc.
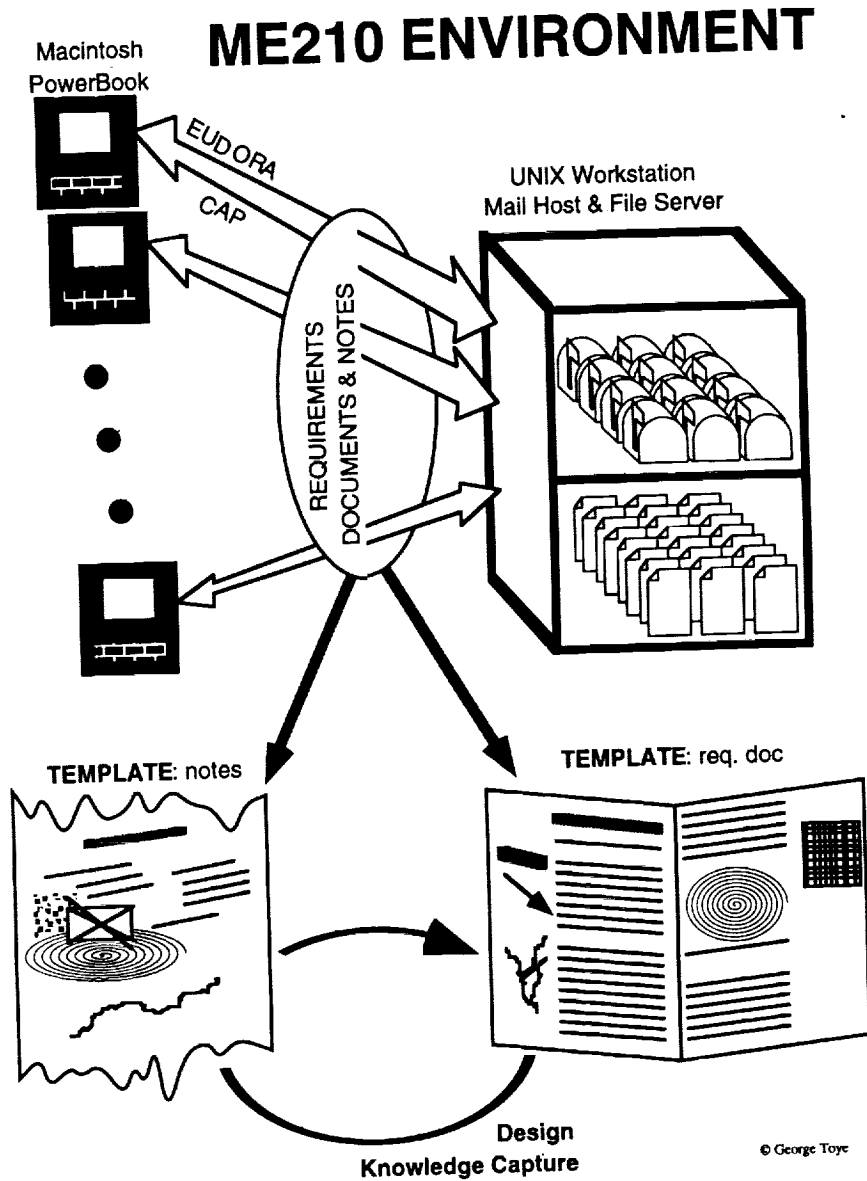
ME210 ENVIRONMENT

Figure 1: PowerBook mediated, network supported, capture and reuse of informal engineering knowledge.

The design process goes from requirements definition and conceptual design to a working prototype and final report in 9 months. The report, often running over 200 pages, is typically of more value to the sponsoring companies than the prototype because it not only documents the design, but also captures the students' experience, decision making process and knowledge relating to the project. Roughly 60% of the report consists of appendices of calculations, catalog pages and data sheets, test results, materials properties, contact logs and meeting notes, and a wealth of other information extracted or generated during the design. The remainder documents the decisions and rationale behind the final prototype as well as ideas pursued and ultimately abandoned.

The design process begins with extended negotiation and clarification with the sponsor about the design requirements and constraints. A requirements document is among the deliverables early in the course. However, as with all real design processes, the generation and clarification of requirements and constraints continues throughout the design. As design continues, information is continually gathered, sifted, sorted, and reorganized for presentation. The report is generated incrementally and submitted for review at the end of each academic quarter. Sections are reviewed more frequently as part of regularly scheduled design reviews. Each submission contains revised and reorganized information from the previous versions. As the teams are each working on different projects and not competing directly, there is more incentive to share knowledge than to hide it. Indeed, a class consensus rapidly develops concerning which tools, consultants, and handbooks are most helpful.

The engineering design course provides the GCDK project with important resources. First, it is a test-bed for evaluating tools, methodologies and concepts that we develop. The rapid turnover and aggressive design schedule allow us to obtain considerable empirical evidence over just a few years. The tight deadlines also ensure that designers will employ a new tool or method if and only if it is demonstrably helpful.

Second, the course provides a rich stream of design examples that cross multiple disciplines and levels of detail, from component design and fabrication to sub-assembly integration. Extensive interaction takes place not only among team members but also with other teams and with the "extended team" of sponsors, consultants, vendors, etc. The net result is a flood of information that must be captured and organized in near-real time. This coupling to real design activity provides a distinctive direction for tool development.

The course also provides many opportunities for observing and abetting design reuse. Often, sponsors come back with variations on a theme that appeared during previous years. For example, a client may ask for a packaging system one year and a materials handling and inspection system to go with it the next. Today, the main source of information about previous projects is a chronologically arranged library of final reports. Searching for relevant information is a tedious and inexact process. If a team needs information about precision assembly devices it is up to the faculty, staff and sponsors to recall which projects from which years are likely to yield something germane. Based on testimony by our industry sponsors, we know that this scenario is also typical on the job.

As part of GCDK, all delivered documents will be stored on CD ROMs and used to form an electronic design library for subsequent years. As we develop more tools for sorting, browsing, retrieving and querying the information, the electronic library will develop into the unified design representation and hyper web that we ultimately envision.

Share: a concurrent engineering vision (Toye et al, 1993)

Today's CAD systems do not adequately support the tasks on which engineers spend the most time: gathering and organizing information, communicating with clients, suppliers and colleagues, negotiating tradeoffs, and using each others' services. Engineers spend days or weeks locating catalog items, consultants, analysis tools, and production facilities. Often, they redo analyses and manufacturing plans because it is difficult to retrieve relevant examples from the past, or because the examples lack sufficient context or detail to adapt them to the circumstances. Sometimes, they forego analysis altogether because the cost of learning new tools exceeds their apparent worth. Then, when the parts are back from fabrication, it is all too often back to the drawing board because of an earlier failure to communicate some interface convention or constraint. The consequences of all these difficulties are well known, and include costly engineering change orders (ECOs), delays in procurement and fabrication of new prototypes, high reject rates, high maintenance costs and lost time to market.

To overcome these difficulties, we propose an open, network-oriented environment for concurrent engineering. The environment enables engineers to participate on a distributed team using their own tools and data bases. Specifically, it should provide:

- familiar displays that put useful information at the engineers' fingertips, including on-line notebooks, handbooks, requirements documents, and design libraries;

- collaboration services, including multimedia mail and desktop video conferencing, that enable team members to communicate and share tools and data;

- on-line catalog ordering and fabrication services, with information about pricing and shipping schedules and bid solicitation, leading to delivery of components without numerous phone calls to clarify the designers' intent;

- access to specialized network services for simulation, analysis and planning, (e.g., cost estimation, dynamics simulation) and access to shared engineering knowledge bases;

- a distributed product data management service that accepts postings from on-line tools and services, and maintains dependencies so that when changes occur, the right people are notified, the right tools invoked and the right sources consulted;

- an integration infrastructure that enables heterogeneous design tools and data bases to interoperate transparently across platforms, creating a shared project environment.
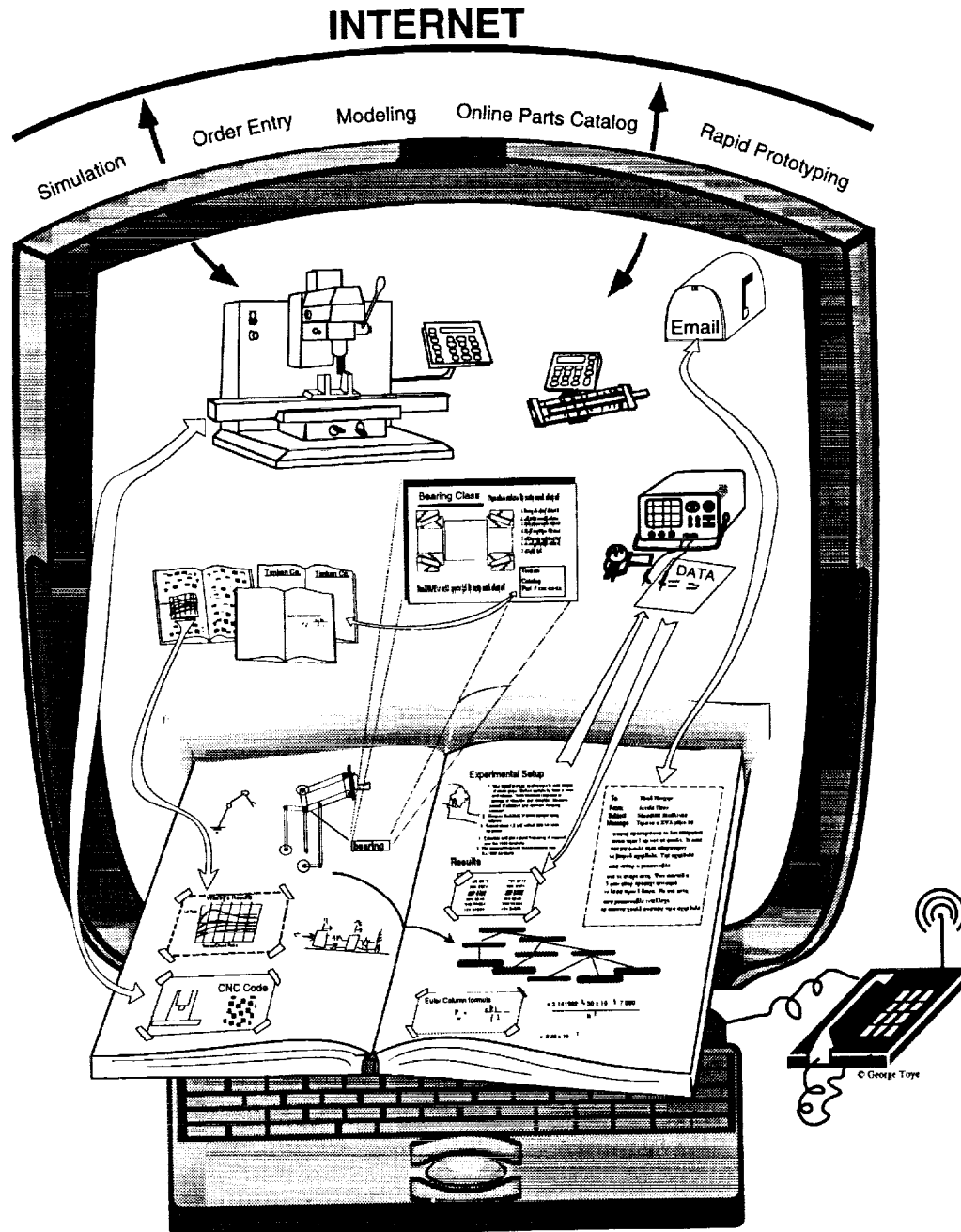
INTERNET

Figure 2: SHARE vision of the personal design notebook integrated into the world wide internet product development enterprise.

The windows on this world of networked resources and services will be multimedia "notebooks" in which to capture and organize information about a project: CAD drawings and solid models, audio notes, sketches, spreadsheets, pages from handbooks and catalogs, animated simulations, mail, excerpts from video conferences, and so forth. The goal is

a system that becomes one's preferred work environment for collaborating on everything from proposals to detailed designs.

What will life be like for an engineer on the Internet? He or she will browse on-line handbooks for relevant components or design models, and submit them to remote services for simulation or analysis. Interesting designs will be copied and pasted into the notebook, and annotated by adding hypertext links to related specifications, data, analysis tools, and components. These links represent constraints, rationale, and dependencies, some of which may point to entries in colleagues' notebooks. Notebook pages will be exchanged with colleagues and inserted into shared project notebooks. Users will navigate this distributed information web using browsing and search tools. Alternatively, they can invoke agents to keep track of dependencies and alert them (or other agents) to changes. Design conflicts that require negotiation will be resolved using multimedia e-mail or a notebook video conference. When a design is ready for fabrication, its specifications will be shipped over the network, perhaps through a broker, to the appropriate production, and procurement services.

Dedal: an informal multi-media document navigator (Baudin et al, 1993a)

Information retrieval systems that use conceptual indexing (Tong et al, 1989) to describe the information content perform better than syntactic indexing methods based on words from a text. However, since conceptual indices represent the semantics of a piece of information, it is difficult to extract them automatically from a document, and it is tedious to build them manually. We implemented an information retrieval system that acquires conceptual indices of text, graphics and videotaped documents. Our approach is to use an underlying model of the domain covered by the documents to constrain the user's queries. This facilitates question-based acquisition of conceptual indices: converting user queries into indices which accurately model the content of the documents, and can be reused. We discuss Dedal, a system that facilitates the indexing and retrieval of design documents in the mechanical engineering domain. A user formulates a query to the system, and if there is no corresponding index, Dedal uses the underlying domain model (Figure-3) and a set of retrieval heuristics to approximate the retrieval, and ask for confirmation from the user. If the user finds the retrieved information relevant, Dedal acquires a new index based on the query. We demonstrate the relevance and coverage of the acquired indices through experimentation.
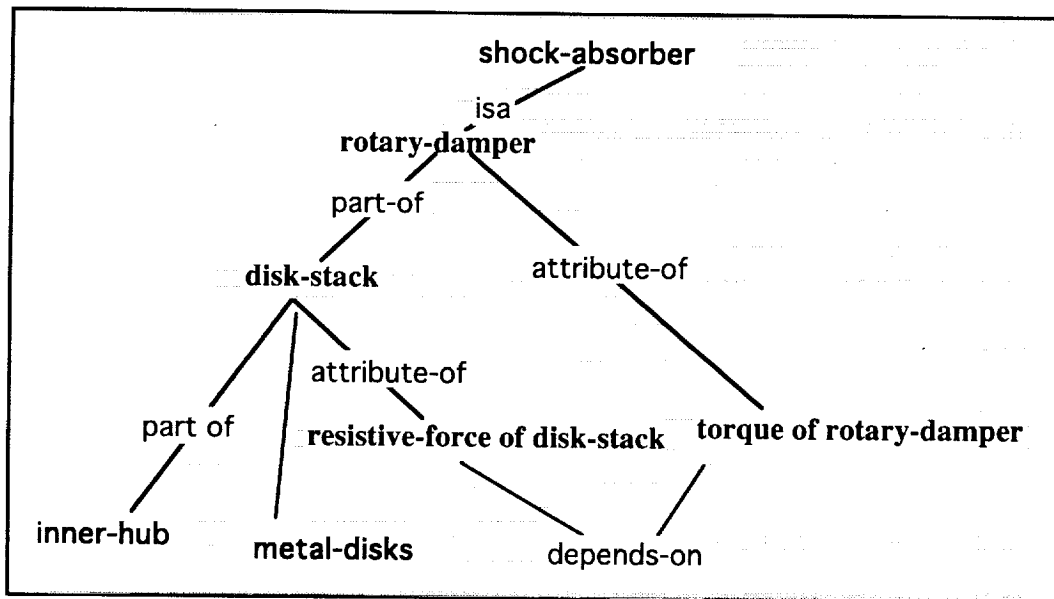

Figure 3: Objects and relations in the domain model

Our approach is to use a conceptual query language plus feedback from the user on the relevance of the documents retrieved in response to a query, to incrementally acquire new conceptual indices for that document. The user formulates a query to the system. If no document description exactly matches the query, the system approximates the retrieval and prompts the user for feedback on the relevance of the references retrieved. If a reference is confirmed, the query is turned into a new index. This extends relevance feedback techniques (Salton et al. 88) to the acquisition of conceptual indices.

This approach uses a question-based indexing paradigm (Osgood et al. 91)(Schank 91)(Mabogunje 93) where the query language and the indexing language have the same structure and use the same vocabulary. The assumption is

that the questions asked by users indicate the objects and relationships that are relevant to describe the content of the documents at a conceptual level appropriate for a class of users. However, in order to use the queries to acquire new indices the following conditions must be met by the query language:

Reusability: The query language must be general enough to create indices that will match a class of queries.

Relevance: The query language must be able to describe the information that the user is interested in articulating queries to acquire information in order to achieve a goal is in general a difficult task (Croft et al. 90). In our approach, the query formulation is constrained by a model of the domain covered by the documents and a model of the type of information designers are interested in.

Context independence: The query language must be able to generate indices that can be reused in different situations, for different users and different tasks.

The retrieval module takes a query from the user as input, matches the question to the set of conceptual indices and returns an ordered list of references related to the question. The retrieval proceeds in two steps: (1) exact match: find the indices that exactly match the query and return the associated list of references. If the exact match fails: (2) approximate match: activate the proximity retrieval heuristics.

Dedal currently uses fourteen proximity retrieval heuristics to find related answers to a question. For instance, segments described by concepts like "*decision* for lever material" and "*alternative* for lever material" are likely to be located in nearby regions of the documentation. The heuristics are described in detail in (Baudin et al. 92b).

Each retrieval step returns a list of references ordered according to a set of priority criteria. The user selects a reference and if the document is on line, goes to the corresponding segment of information (using the hypertext facility that supports the text and graphics documents). A user dissatisfied with the references retrieved can request more information and force Dedal to resume its search and retrieve other references.

CONCLUSIONS

Our work is based on the view of design as a process of gathering, organizing and exchanging information. The process begins with notes and concept sketches, catalog pages and evolves to encompass more formal representations as models are generated, tested and communicated to others and as the individual and group design records are annotated with decisions, revision notices, and fabrication orders. As the proportion of formal structured information increases, the ability of automated mechanisms to help people manage it also increases. However, even toward the end of a design, the proportion of informal to formal information remains disproportionately high.

Consequently, we focus our efforts on providing tools to help people capture and organize the multimedia e-mail messages, annotations and scratch work that make up the bulk of typical design records. These tools will have immediate applicability in the graduate design course that grounds the context of our work. We want to help design teams organize their personal notebooks and use the resulting documents for redesign during the term and in subsequent years. Our focus stems directly from our commitment to provide tools that are demonstrably useful in real design environments.

The graduate design course sequence provides us with a critical test-bed in this regard. It also provides a rich stream of information to capture and analyze. Our goal is to capture as much as feasible, on a continuing basis. In return, we will provide designers with automated retrieval, indexing and organization as these capabilities become available. We also acquaint designers with the potential of electronic design notebooks that serve both as personal and group design records and as windows to a world of services and resources on the Internet.

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ACKNOWLEDGMENTS

APPENDIX-A: Related work

The GCDK team is a unique component of the SHARE and PACT consortia on concurrent engineering. NASA's GCDK project has taken the leading position in regards to indexing, navigation and reuse of large, informal knowledge records. Of the following, it is the only project focused on NASA space science engineering applications.

SHARE (a scalable methodology and framework for concurrent engineering) is ARPA funded and jointly directed by Professors Leifer and Cutkosky in collaboration with Enterprise Integration Technologies Corporation (Dr. Jay Tenenbaum). PACT is a broad consortium of Palo Alto area laboratories. It includes the assembly laboratory lead by Prof. Latombe in computer science at Stanford; the logic Design World project supported by Hewlett-Packard and lead by Prof. Genesereth at Stanford; the How Things Works project lead by Dr. Tom Gruber and Professor Richard Fikes at the Stanford Knowledge Systems Laboratory; the NVisage program at Lockheed Corporation's AI laboratory lead by Dr. Bill Mark; and members of the Stanford Manufacturing Systems Engineering Program (MSE). Professor Leifer is also co-PI with Professor Sheri Sheppard on the NSF sponsored National Engineering Education Synthesis Coalition. Consortia members include: Cornell University, Hampton University, Tuskegee University, Southern University, Cal Poly San Luis Obispo, University of California at Berkeley, Iowa State University and Stanford

University. These collateral associations promote widespread dissemination of NASA sponsored work and assure that the work itself is well informed by the activity of others.

APPENDIX-B: EDN laptop computer hardware configuration

Apple Computer PowerBook 160 (adequate may go to Duos next year)
8 MB memory (minimum)
80 MB hard disk drive (adequate with file server backups)
Global Village Silver PowerPort fax-modem (adequate)

The design environment included some additional hardware, including: 4 Hewlett-Packard CAD stations, 4 Macintosh IIci workstations, 1 Microsoft DOS compatible Intel PC. In addition to computer hardware, a full complement of rapid physical prototyping equipment was available.

APPENDIX-C: EDN laptop computer software configuration

FrameMaker 3.0: a document processor
Microsoft Excel 4.0: a spreadsheet processor
Aldus Persuasion 2.0: a presentation environment
Eudora 1.3: a public domain electronic mail manager
AOS System 7.0: the Apple Macintosh operating system

A variety of engineering software tools were available in the laboratory on desktop workstations: e.g., CAD, CAM, CAE, Symbolic Math Modeling. The environment was networked using Local Talk (to be upgraded next year to ethernet) and supported by an file server on the Internet for file backup and electronic mail.