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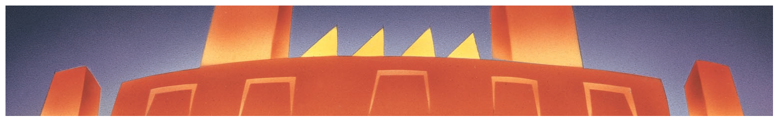


Rapid Design and Manufacture of Wearable Computers

Wearable devices bring new meaning to the field of mobile computing. Yet designing such small machines calls for speed as well as preciseness.

Advances in computational science and engineering have changed profoundly both the artifacts we can realize and the processes by which we realize them. This article looks at the impact of these new technologies on the design of wearable computers covering three main areas: new design tools and approaches, new manufacturing technologies, and new uses of information technologies. We will show how we at the Engineering Design Research Center (EDRC) at Carnegie Mellon have used the wearable computer project as a testbed in which to integrate research on rapid design and manufacturing. In our research, we have designed, manufactured, and used our own tools as well as observing their use by others—where the tools include wearable computers, design analysis programs, and information organization tools. Through this process, we have learned about design education and design practice, and we have uncovered new issues for design research.

Case Study: Wearable Computer Design Class

Interdisciplinary design teams of up to 20 students each have designed and fabricated six generations of wearable, mobile computers: VuMan 1 [1], VuMan 2 [12], VuMan 2R,[1] VuMan 3, Navigator 1 [11], and Navigator 2 (see Figure 1). The computers are designed and built by an interdisciplinary design class which draws students from all the departments affiliated with the EDRC. The development time for each new generation of mobile computer is between four and six months. Each generation provides a learning experience and experimental testbed enabling advancement toward the next generation.

We have developed an interdisciplinary concurrent design methodology that is constantly revisited and revised as we design new artifacts and processes. (This methodology is described in more detail in [11].) This methodology has its roots in electronic design, which has been the driving factor in the design of wearable computers. The goal of the design methodology is to allow as much concurrency—in both time and resources—as possible in the design process. The semester is divided into three phases; activities within a phase proceed in parallel and are synchronized at phase boundaries. Resources consist of personnel, hardware platforms, and communications. Members of the design team are dynamically allocated to groups that focus on specific problems. Groups and individuals communicate informally between the synchronization points as well as formally during progress reviews.

[1] VuMan 2R and VuMan 3 have identical housings but differ in electronics.

The design process starts with an initial site visit to assess customer needs. During this first phase, students perform a technology survey, identifying and evaluating major components. Since electronic technology changes so rapidly, what might have been infeasible six months ago may now be possible. During the technology survey phase, students identify alternatives for each subsystem. Currently the students read trade magazines, identify suppliers, and contact suppliers to obtain literature on product features. Since the formats of the literature vary, designers often must contact the supplier directly to consult an application engineer. Further phone calls to marketing are required to establish an availability date for the product.

During the second phase, the students configure the product to produce the first concept of the total system. They create a conceptual approach by illustrating the concept with "story boards" and simulated walkthroughs that are presented during a second site visit. During this phase, interactions and interfaces between subsystems are identified and inconsistencies between subsystem alternatives are detected. The information used during this phase is derived from product literature. However, the students learn that two products that claim to adhere to the same standard may not be compatible. For example, we recently lost two weeks because a DOS-based speech recognition product would not run on the DOS version on our laptop. Resolution of this discrepancy required a trip to the supplier's home office.

Each month for the next four months, an incremental build of system capabilities provides feedback on the design. Components are evaluated for compatibility, purchased, and integrated with a laptop computer. In addition, the team creates prototypes of alternative shapes for the housing. These prototypes are usually made of wood or styrofoam because even the best rapid manufacturing processes are too slow and expensive during this phase when many alternatives are generated, evaluated, modified, rejected, and resurrected until one is finally selected. During the third site visit, in which we acquire final reactions and suggestions, both the physical and the computer prototypes are evaluated by the customers.

Once the functionality of the unit has been frozen, the team begins a detailed design phase. As the design becomes more completely defined, more analytical tools, such as stress analysis, thermal analysis, and assembly analysis, are used. During this phase, the components in the final system are acquired and fabrication of the electronic and mechanical systems commence.

Currently, fabrication of wearable computers requires multiple visits to the supplier. We have developed a network of over 30 component and service suppliers to support the wearable computer project. Our supplier chain encompasses a variety of vendor capabilities ranging from small machine shops to large corporations. Knowledge of our suppliers is essential to on-time delivery of our products. For example, to reduce fixed costs, one vendor produces head-mounted displays in batches after enough orders have been received. Missing a fabrication run can add more than a month to the acquisition of the head-mounted displays. In another example, a software vendor had been promising a critical software tool for over two weeks. Delays were due to "manufacturing." After numerous inquires, we discovered that the vendor was waiting for a new batch of manuals to be returned from the printer. We were able to convince the vendor to ship the software immediately with an older manual. Several weeks were lost due to lack of knowledge of the supplier's schedule.

Figure 1. Five generations of wearable computers

Regular design reviews are held to ensure that interface specifications are not violated. At the end of the last phase, the final system is fabricated, assembled, tested, and delivered to the customer.

A significant increase in design complexity characterizes the design and evolution of each new generation of wearable computers. For example, the sixth generation has multimedia, speech recognition and generation, image transmission, wireless communication, and global position sensing capabilities. The metric of complexity for wearable computer design for factors in the complexity of the software, the electronics, and the mechanical design. The metric reflects the complexity of both functionality and the implementation of functionality. When applied to the first four generations of wearable computers, the design methodology has demonstrated an increase of two orders of magnitude in design and efficiency [13].

Rapid Design

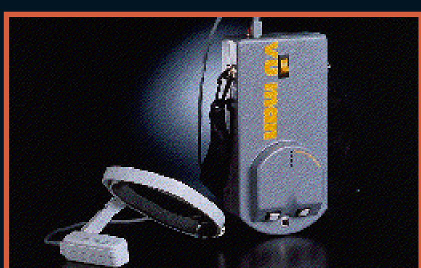
From our case studies of the wearable computers and other artifacts, we have learned that engineers use a variety of techniques in their work. These techniques may be formal, informal, ad hoc, experimental, verbal, qualitative, quantitative, precise, or approximate. Because designers usually operate under tight deadlines, the easiest, quickest tools (often pencils and telephones) get used most frequently. For most designers, the key is simple pragmatism; anything that works gets used [5]. For computational tools to be used in practice, designers must have access to them and must be able to acquire knowledge about them rapidly.

Another lesson from our design testbed is that interdisciplinary groups collaborating on a design project do not necessarily make a team. People need practice and time to develop trust and to develop a working relationship. Designers need to understand and appreciate how different disciplines approach problems, how they talk about problems and solutions, and what tools they use to solve problems. The unpredictable interactions that occur between designers and between disciplines are essential in interdisci-

VuMan 1

VuMan 2

Navigator 1



Navigator 2

VuMan MA

plinary design. The solution to interdisciplinary design is not connecting discipline-specific computer-based tools together; it is creating an interdisciplinary team of people who can work together, aided by tools that support the design process.

We have learned that we must create design tools in the context of design work. For example, a thermal design methodology for wearable computers, developed in response to the needs of the designers, is described in [2]. In the wearable computers, the thermal properties depend on the electronics (and hence, indirectly, the software), the housing shape, and the manufacturing process. The designers did not have appropriate thermal analysis tools available. Therefore, they had a vested interest in the success of this new analysis methodology. The researchers and the designers worked together. The resulting methodology allows the designers to evaluate the thermal properties of the wearable computers at different levels of detail and from different points of view depending on the current state of the design.

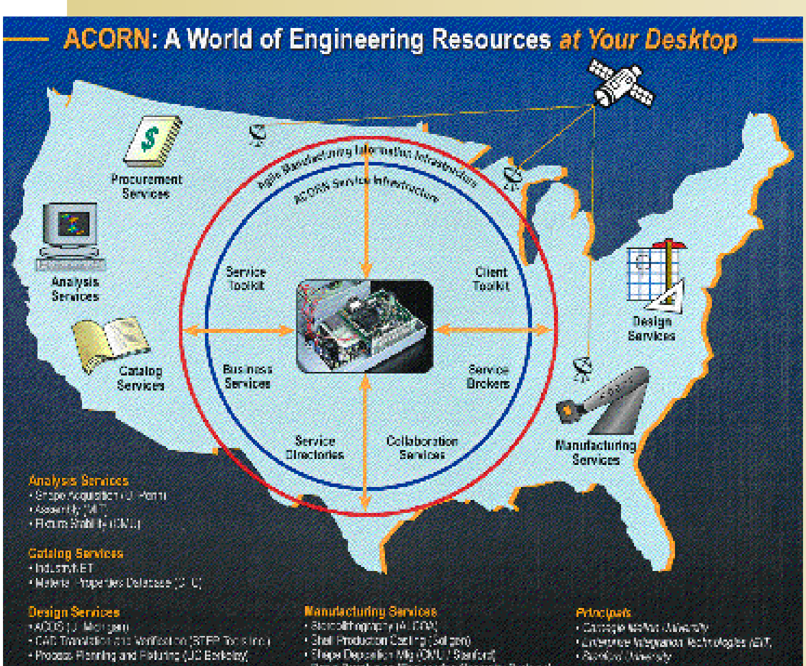
For each generation of wearable computer, we have been capturing the design process. We capture both the informal electronic communications of the team members and the formal design documents produced by each subteam. Much of the design history is not captured because it occurs in chance meetings in the halls, on the phone, and in paper sketches. We have been working to create a system called *n*-dim to integrate a variety of efforts to capture a design as it progresses. (Among the research that *n*-dim builds on are [3, 6, 10].)

Based on experience from observations of designers at work, the primary motivation of *n*-dim is to create facilities that allow designers to organize and retrieve product information in multiple ways. *n*-dim does not impose a representation or abstraction technique on engineers. The space of *n*-dim objects can be viewed in multiple, overlapping hierarchies. This flexibility promotes information exchange between people with different worldviews and different models of the information. Other aspects of the project include creating a task-level view for configuring and managing the design process and creating an infor-

ACORN: Access to Network Services

The goal of the ACORN project is to create a testbed for investigating the ad hoc linking of corporations, universities, and small businesses into distributed engineering design and manufacturing teams.

ACORN builds on the emerging Agile Manufacturing Information Infrastructure [7] efforts such as EINet, which are aimed at exploiting Internet technologies for multimedia documents, wide-area information services, information agents, and electronic commerce. ACORN has been extending and testing these technologies to facilitate engineering and manufacturing on the Internet, concentrating specifically on the creation and use of design and manufacturing services. ACORN has been developing toolkits for engineering service providers and customers to ease the process of installing and using ACORN services. We and other ACORN team members have developed and demonstrated WWW interfaces to services at ALCOA, Cleveland Advanced Manufacturing Program, MIT, the University of Michigan, and the University of Pennsylvania. This technology will be made available to the community as part of the ACORN software repository.



In addition, we have been testing the performance of these services and toolkits within the context of wearable computer design to simulate and understand the interactions between the design team and their external suppliers. Some of the important issues that are examined in these experiments include support for varying degrees of interaction between designer and supplier and support for modeling, capture and reuse of Internet- based interactions with external services. These experiments help highlight the benefits and shortcomings of the current and emerging Internet technology as applied to real product development efforts.

For more information on ACORN see website at http://acorn.eit.com:9001/

mation-management system for defining and displaying a user's current design context. The approach is based on providing a uniform paradigm for structuring and modeling varied data objects including text, drawings, artifact models, and human and computational agents [14].

Rapid Manufacturing

Rapid prototyping, whether in virtual or physical artifacts, is important in the design process because designers alternate between the abstract and the concrete. For a mechanical design, a team's first ideas are turned into rough sketches, these sketches are evaluated, new ideas emerge, and more precise drawings are generated. This iterative process continues with soft mock-ups, appearance sketches, computer prototypes, and physical prototypes until finally the product is fabricated. An important part of this process is evaluation of prototypes. Both users and designers are better at responding to and criticizing an object rather than an abstract description they cannot hold or manipulate. Prototypes help the participants to redefine, evaluate, and analyze their needs and requirements.

Development and low-batch production of wearable computers rely on rapid manufacturing technologies. For example, rapid prototyping processes are used to create prototype housings quickly. Rapid prototyping services currently available, such as stereolithography, use solid freeform fabrication, in which solid CAD models of the part are first decomposed into cross-sectional layers and each layer is then selectively deposited to build up the desired shape. These processes have matured to the point that they are available as distributed, data-driven services.

The wearable computer project requires rapid manufacture and assembly of final designs as well as intermediate prototypes. The users of the wearable computers require greater functionality in smaller housings that are easier to wear. These needs have motivated another area of research, *shape deposition manufacturing* (SDM), which permits the creation of multimaterial structures with embedded electronic components.

Rapid manufacturing requires a direct interface between the CAD model and the manufacturing processes. A key bottleneck for the interoperability of manufacturing services on the Internet is a common representation of the artifact design. Major progress has been made during the last decade through the definition of a common representation through STEP [9], the international standard for product data exchange.

The need of design teams for better access to services over the Internet has led to the creation of an Advanced Collaborative Open Resource Network (ACORN), which is a cooperative project with colleagues from many other institutions [4]. This network provides a mechanism for rapidly accessing technical information and exchanging it between members of a

Wearable Computers

Wearable, mobile computers move with the user. They can track the user's motions in both time and space, providing real-time information that can extend the user's knowledge and perception of the environment. Users have greater interaction with the physical environment because the wearable computers provide real-time information directly relevant to the current state of the workspace.

These computers can remove the traditional need for oversized blueprints or volumes of manuals to use as references for construction and maintenance information. Support for augmented perception provides the user with a means of viewing details of the work environment that are otherwise invisible. For example, a maintenance worker can view what is behind a wall by displaying the appropriate blueprint and can record maintenance actions as they are made.

The close interplay between the user and the computer is the distinguishing characteristic of wearable computers. The need to create a computer that is an extension of its user drives the design process, requiring the integration of the diverse issues and disciplines involved in making the extension to the user's movement and activity as complete and transparent as possible. Rapid design and manufacture of wearable computers presents many challenges, due to the need for high functionality in a small complex package shape, the demand for affordable prices, and the shorter product lifetime. These products require an approach that integrates the application, the artifact, the design environment, and manufacturing.

This figure illustrates an application of the VuMan 3 wearable computer for aircraft inspection. All items on the heads-up display screen are in a list that are accessed by toggling with a rotary dial and pressing selection buttons that surround the dial. The computer's mechanical controls are an intuitive interface to the linear list and can be operated in any orientation by the user wearing gloves or even through the cloth of an overall pocket.

SDM of Heterogeneous Structures

Solid freeform fabrication (SFF) is the rapid and automatic production of arbitrarily complex shapes. The methodology underlying SFF manufacturing processes is to first decompose a 3D solid CAD model of the shape into cross-sectional layers, then use material deposition techniques to physically build up these layers to form the object. Sacrificial supporting layers may also be simultaneously built up to fixture the object.

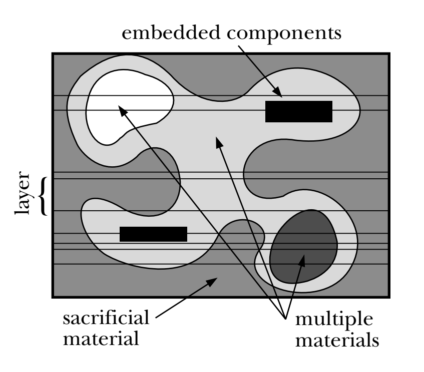


Figure A. Heterogeneous structure

SFF processes were originally developed for rapid prototyping applications. Forming shapes by selective incremental material deposition has other potential benefits including the capability to build heterogeneous structures. A heterogeneous structure can include multi-material regions and prefabricated devices embedded into the growing shapes (see Figure A).

Shape deposition manufacturing (SDM) is a new SFF process that builds heterogeneous structures. Along with shape complexity, these capabilities effectively expand and extend the design space by reducing manufacturing constraints. One application is to rapidly build an electronic housing and simultaneously embed and interconnect circuitry within it, forming a rugged, compact package. Another application is to manufacture custom tooling, such as an injection mold die, composed of an outer steel shell for strength and a copper interior for uniform heating/cooling, as well as embedded thermocouples for process control.

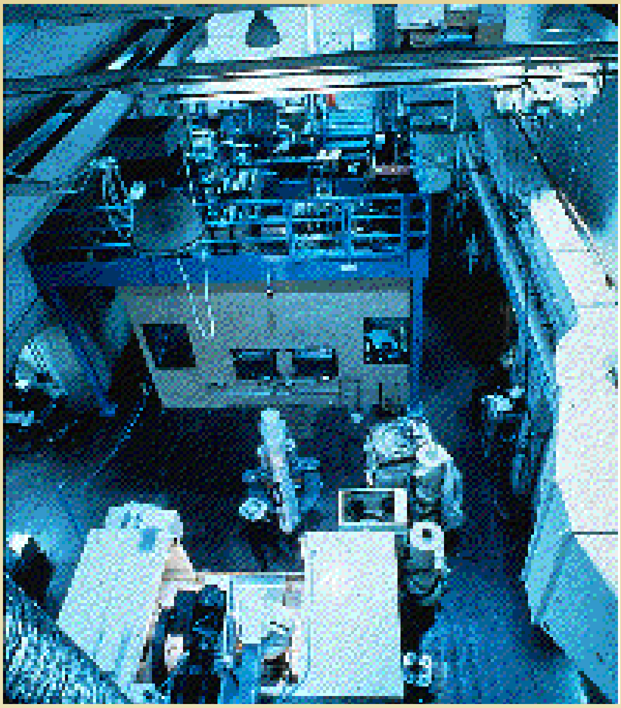


Figure C. SDM testbed facility

SDM integrates material deposition with material removal techniques, as well as other intermediate processing operations performed on each layer (see Figure B). Individual layer segments are deposited as near-net shapes and then accurately machined to net-shape before depositing additional material. The thicknesses of the layers will vary depending on the local geometry. Each layer is further decomposed into layer segments such that undercut features are not machined, but formed by previously shaped segments. Each material in each layer is then deposited as a near-net shape, using one of several available deposition processes. The sequence for depositing the primary and support materials is also dependent upon the local geometry.

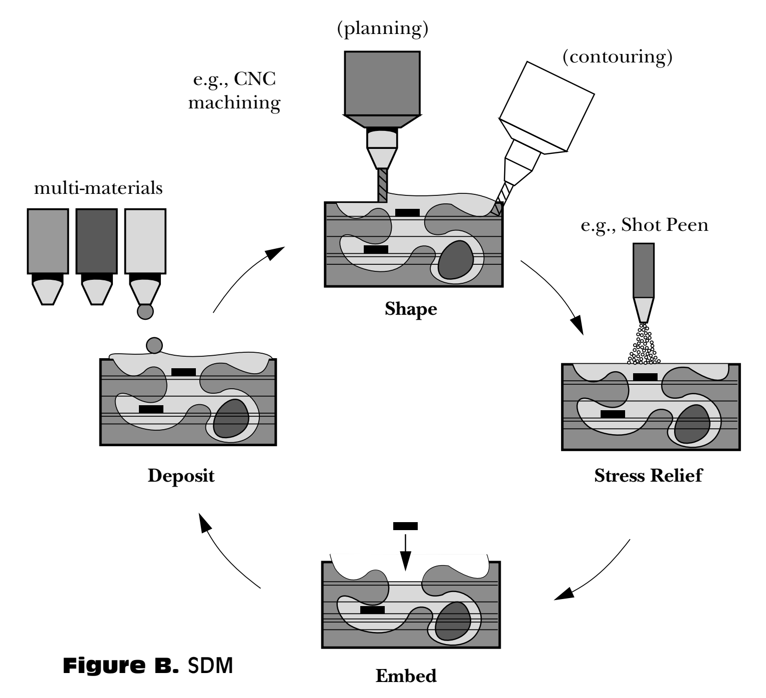


Figure B. SDM

In the SDM testbed facility (Figure C), the growing parts are built on pallets that are transferred to different processing stations using a robotic palletizing system. A robotic deposition station includes alternative sources of depositing metals (e.g., welding), ceramics (e.g., thermal spraying), waxes (e.g., hot extrusion), and plastics (e.g., two-part epoxy mixers). Stainless-steel structures, for example, are built up with a sacrificial material, which is removed with nitric acid when the part is completed. A shot-peening station is also provided to control the build-up of internal stresses in thermally deposited shapes. Polyurethane shapes, such as our wearable computers, are built up with wax sacrificial material, which is removed by heating.

distributed design team. As a result of this research we have uncovered a new set of challenges faced by users of these services. In many cases, the benefits of being able to access a wider range of services are outweighed by the effort required to choose among a large set of alternatives and by the risks involved with working with suppliers of new or novel technology. The ability to access and exchange data rapidly must be coupled with protocols and tools for making rapid business decisions and the ability to filter the increasing amount of information that is available.

Open Issues

In this article, we have provided an overview of our experience in the design and manufacture of wearable computers. Our experience highlights two areas in which computer science plays a critical role: the growing importance of embedded software in end-use products and the role of computation in the design and manufacture of products.

Embedded software has become common in a variety of products, from household appliances to customized and specialized electromechanical devices such as wearable computers. For the wearable computer project, design tools for single-board computer design were adapted for synthesis of embedded software. However, the task of creating appropriate user interfaces still requires a significant amount of paper-based prototyping and customization. The primary need is for tools that promote rapid development of software prototypes, to be embedded within hardware prototypes, in order to obtain user evaluation and feedback. The research issues are the same as those for rapid prototyping in software engineering and in codesign of hardware and software.

The cost and time required to assemble systems that support collaborative multidisciplinary design, especially for products with short design and manufacturing cycles, are prohibitive. Development of comprehensive design systems requires not only expertise in software engineering but also an understanding of the context and of product-specific design and manufacturing methodologies [8]. The problem becomes even more complex when the required resources do not exist within the same organization, leading to the need to integrate geographically distributed suppliers and manufacturing firms. Our experience in producing wearable computers using rapid prototyping technology has spotlighted the lack of design tools and our inability to create comprehensive design systems.

Producing successive generations of a product requires the retention and consolidation of expertise over time. This need is especially acute in an academic design effort, because each year we begin with a workforce of new students. For now, we have overcome these difficulties by organizational means rather than through computational means of maintaining history and rationale of product design. Meanwhile, we have been exploring these issues through the development of software support environments such as n-dim and experiments such as ACORN.

Conclusions

The design process for engineering products has changed substantially over the last decade. It is moving from sequential to concurrent, from hierarchical to parallel, from paper data exchange to electronic data exchange, from standalone tools to integrated tools, from limited design alternative exploration to comprehensive exploration. To illustrate this evolution, we have presented our experience with the design of wearable computers. These computers have a short design cycle, are manufactured in small batch sizes, close interaction with the customers, and require several modes of rapid prototyping. The manufacture and procurement of components are distributed over several internal and external vendors. Often the suppliers and vendors change within a single design cycle. In this article, we have identified the types of computational support needed for rapid design and manufacture of this class of products.

One lesson from this effort has been the appreciation that the context of each product design is unique, requiring a unique composition of computational tools. Through experiments with different classes of products, we hope to be able to define a composable set of computational design support tools for specific product design contexts. The issue of rapid configuration of design and manufacturing environments, especially for novel products, remains an open issue. To address this issue, we must continue to study the needs of design teams in different contexts, to develop rapid design and manufacturing prototyping technologies, and to work on the evolution of exchange standards such as STEP and on the development of business process standards.

In light of these observations and preliminary experiments in supporting rapid design and manufacture, we have identified the following critical research areas for the future of rapid design and manufacture of products:

- Architectures and standards for easy composition of design systems
- Collaboration tools to achieve intradesign organization integration
- Reference architectures for interorganization interactions at different levels, from single transactions to continuous collaboration
- Facilities for interoperability of design tools, including legacy, evolving, and future tools
- Tools for context-based retrieval of design product and process information
- Tools to enable engineers to create their own application environments with minimal support from software developers
- An infrastructure to capture information, design

rationale, history, and intent
- Training and educational systems within design systems to enable rapid introduction of new team members
- Tools for visualization and simulation of rapid prototypes—for evaluation by both designers and customers
- Tools for visualization and simulation of process models that include multiphenomenon modeling.

This list is by no means exhaustive but reflects some areas of research that the EDRC is currently addressing in the *n*-dim, ACORN, SDM, and other projects. We hope this exposition of research problems in the context of multidisciplinary, multiorganizational rapid design and manufacture will foster the development of a community that is multidisciplinary, multiorganizational, and cooperative in addressing the complex challenges of integration of information technology into the design and manufacturing workplace of the 21st century.

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References
1. Akella, J., Dutoit, A., and Siewiorek, D. P. Concurrent engineering: A prototyping case study. In *1992 International Workshop on Rapid System Prototyping*. IEEE, Research Triangle Park, N.C. (1992) 138–160.
2. Amon, C. H., Nigen, J. S., Siewiorek, D. P., Smailagic, A., and Stivoric, J. Concurrent design and analysis of the Navigator wearable computer system: The thermal perspective. In *Proceedings of the 1994 4th Intersociety Conference on Thermal Phenomena in Electronic Systems (I-THERM)* (Washington, D.C., May) 1994. 133–142.
3. Conklin, J., and Begeman, M. L. gIBIS: A hypertext tool for exploratory policy discussion. *ACM Trans. Off. Info. Syst. 6,* 4 (1988), 303–331.
4. Coyne, R., Finger, S., Konda, S., Prinz, F. B., Siewiorek, D. P., Subrahmanian, E., Tenenbaum, M. J., Weber, J., Cutkosky, M., Leifer, L., Bajcsy, R., Koivunen, V., and Birmingham, W. Creating an Advanced Collaborative Open Resource Network. In *Proceedings of the 6th International ASME Conference on Design Theory and Methodology* (Minneapolis, Sept) 1994, 375–380.
5. Finger, S., and Subrahmanian, E. Exploring the relationship between research, practice, and education: An EDRC view. In *Proceedings of the International Conference on Engineering Design, ICED'95* (Prague, Aug.) 1995, 44–49.
6. Garg, P. K., and Scacchi, W. ISHYS: Designing an intelligent software hypertext system. *IEEE Expert 4,* 3 (1989), 52–63.
7. Goldman, S.L., and Nagel, R.N. Management, technology and agility: The emergence of a new era in manufacturing. *Intern. J. Tech. Manag. 8,* 1–2 (1993), 18–38.
8. Konda, S., Monarch, I., Sargent, P., and Subrahmanian, E. Shared memory in design: A unifying theme for research and practice. *Res. in Eng. Design 4,* 1 (1992), 23–42.
9. Laurance, N. A high-level view of STEP. *Mfg. Rev. 7,* 1 (1994), 39–46.
10. Sanvad, E. Hyper-Object System for Software Engineering. Tech. Rep. DAIMI-280, Dept. of Computer Science, University of Aarhus, Denmark, 1989.
11. Siewiorek, D. P., Smailagic, A., Lee, J. C. Y., and Adl-Tabatabai, A. R. Interdisciplinary concurrent design methodology as applied to the Navigator wearable computer system. *J. Comput. Softw. Eng. 2,* 3 (1994), 259–292.
12. Smailagic, A., and Siewiorek, D. P. A case study in embedded-system design: The VuMan 2 wearable computer. *IEEE Des. Test Comput. 10,* 3 (1993), 56–67.
13. Smailagic, A., Siewiorek, D. P, Anderson, A. Kasabach, C., Martin, T., and Stivoric, J. Benchmarking an interdisciplinary concurrent design methodology for electronic/mechanical systems. *ACM/IEEE Design Automation Conference* (San Francisco, June) 1995, 514–519.
14. Subrahmanian, E., Konda, S. L., Levy, S. N., Reich, Y., and Westerberg, A. W. Equations aren't enough: Informal modeling in design. *Artif. Intell. Eng. Des., Anal. Manuf. 7,* 4 (1993), 257–74.

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