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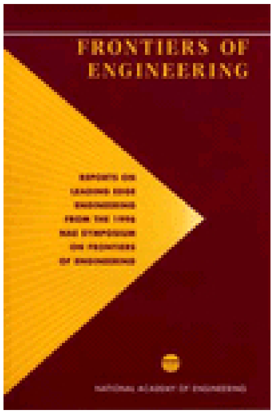

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

SECOND ANNUAL SYMPOSIUM ON FRONTIERS OF ENGINEERING

NATIONAL ACADEMY OF ENGINEERING

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Preface

On September 19–21, 1996, the National Academy of Engineering (NAE) convened the Second Annual Symposium on Frontiers of Engineering at the Academies' Beckman Center in Irvine, California. This volume is a collection of abstracts of the papers presented at that symposium. Its intent is twofold: (1) to describe the content and underpinning philosophy of this unique meeting and (2) to highlight the kinds of pioneering research and technical work being done by some of this country's emerging leaders in engineering.

ORIGINS AND GOALS OF THE ACTIVITY

The Frontiers of Engineering Symposium series was initiated by the NAE Council in 1994, and the first symposium was held in September 1995. The concept for the meeting was borrowed from the National Academy of Sciences' Frontiers of Science program, which brings together scientists ages 30 to 45 to discuss leading-edge research in a variety of scientific disciplines. NAE saw several compelling reasons for undertaking a similar activity for engineers.

Primary among these reasons was the recognition that advances in engineering are moving increasingly across many facets of the profession. Thus, bringing together outstanding young leaders of engineering developments from disparate fields, and challenging them to think about the developments and problems at the frontiers of areas different from their own, may facilitate collaborative work as well as the transfer of new techniques and approaches across fields.

Examples of the increasingly interdisciplinary nature of engineering are plentiful. For instance, computational fluid dynamics allows both chemical engineers to simulate complex chemical processes without altering actual production processes and mechanical and aerospace engineers to simulate flow processes in power and vehicular systems. Also, information technologies are having broad impacts outside of the telecommunications industry—from the design of highway systems to the management of complex manufacturing processes. And advances in data analysis and molecular modeling in biotechnology combine research topics in biology and chemistry with topics in computer science and applied mathematics. Although there has always been "cross-fertilization" among engineering fields, the nature of today's emerging technologies and the challenges of an increasingly competitive environment have sharpened the need for engineers to understand each other's disciplines and have enhanced the value of that interaction.

To optimize the objectives of this meeting, the participants selected represent all sectors where engineering research and technical work is carried out: industry, academia, and government laboratories. Moreover, the participants, who were invited to attend after a competitive nomination and selection process, represent some of the country's "best and brightest" engineers. Another important component of the meeting is that the number of participants was kept relatively low: at 90 to 100. Finally, the content of the meeting—the selection of topics and speakers—was determined by an organizing committee composed of engineers in the same 30- to 45-year-old cohort as the target participants.

CONTENT OF THE SECOND ANNUAL SYMPOSIUM

The September 1996 meeting included presentations and discussion of leading-edge research and pioneering technical work in four areas: (1) design research, (2) visualization for design and display, (3) microelectromechanical systems (MEMS), and (4) innovations in materials and processes. Presentations covered such topics as performance-based seismic design procedures, applications of virtual reality and augmented reality in aircraft design and manufacturing, the challenges of large-scale production of MEMS, and silicon satellites (see Appendixes for complete program). Because of the diversity of the participants' areas of engineering expertise, presenting a talk to this audience proved a challenge. Speakers had been asked to tailor their talks to a technically sophisticated but nonspecialist audience and to cover such specific issues as follows: What are the frontiers in their field? What experiments, prototypes, and design studies are completed and in progress? What new tools and methodologies are being used? What are the current limitations on advances? What is the theoretical, commercial, societal, and long-term significance of the work? Despite the varied backgrounds of the participants—or perhaps because of it—lively exchange followed each presentation and carried beyond the formal sessions. Often, the discussions focused on specific technical aspects of the presentation; at other times it covered broader, more policy-oriented issues.

On the first night of the symposium, John A. Armstrong, retired Vice President for Science and Technology of IBM Corporation, gave an insightful and provocative talk, urging the audience of relatively early-career engineers to keep in mind the importance of achieving their individual career goals within, and sometimes in spite of, the institutional cultures in which they work. His paper is included in this volume as well.

Participants' responses to this second Frontiers of Engineering symposium confirmed the value of these meetings. Many attendees appreciated that the symposium drew together engineers at a relatively early point in their careers from a range of engineering fields and sectors and that the meeting focused on the spectrum of activities and concerns of engineers. Several participants were particularly grateful for the chance to interact with engineers from other sectors, noting that it allowed them to meet engineers and potential collaborators they would not have met at their institutions or in their usual rounds of professional meetings. Many said that because of the quality of the presentations and the caliber of the participants, they felt a renewed sense of pride in their profession and respect for the activities of other engineers.

Funding for the Second Annual Symposium on Frontiers of Engineering was provided by the National Science Foundation, the U.S. Department of Defense, the National Institute of Standards and Technology, and the Engineering Foundation. The National Academy of Engineering would like to express its appreciation to these groups for sponsoring this activity as well as to the members of the Symposium Organizing Committee for their work in planning and organizing this event. A special expression of gratitude is due Robert A. Brown, Dean of Engineering at the Massachusetts Institute of Technology, who contributed greatly to this activity by chairing the organizing committees of the first and second Frontiers of Engineering symposia.

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DESIGN RESEARCH

Designing Vehicles in Changing Times

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The primary commercial change in society of the last decade is the impact women have had in the marketplace. There are 56 million women employed in America today, representing 45 percent of the total work force, and three-fourths of all women between the ages of 35 and 44 hold jobs outside the home. Even more important, women now own nearly 8 million companies in America—a number that has escalated an astounding 78 percent from just 10 years ago.

This coalition of working women has become increasingly independent both financially and intellectually. Women earned more than one trillion dollars in 1995, a fivefold increase from 1975. Increased household income over the last two decades is due almost exclusively to the number of married women working outside of the home. What do women do with this newfound wealth? Not only do women influence consumer purchases, but they often are the primary decision makers in the purchase process—whether that purchase is an automobile, real estate, soft goods, hardware, or health care.

Industry must refine its perspective of the female customer. Since men and women obviously are different physically, emotionally, and socially, strategies for product engineering cannot be gender neutral. Designers cannot construct a single model, and engineers cannot design to a single standard and then expect that their results will best serve all consumers. The basic differences between men and women must affect design in order for the end result to be practical, efficient, effective, and beautiful—all of the attributes for which we engineers strive.

PRIMARY, SECONDARY, AND TERTIARY DESIGN

A closer examination of primary, secondary, and tertiary design issues as applied in the automotive industry illustrates these gender differences. Primary design issues concern unique physical differences, such as size and shape, body proportions, reach (arm and leg length), and strength. Secondary design issues focus on the following: usage, which addresses not only practicality but also such safety and security concerns as antilock brakes, airbags, power locks, delayed lighting, cellular phones, and child seats; functionality, which includes such things as ease of entry and egress; and affordability, which includes quality, perceived value and price, and motivation. Finally, tertiary design issues focus on social and cosmetic characteristics. Those include clothing and overall fashion orientation.

Let us investigate some examples of primary design issues. For years, an average-size American Caucasian male was the accepted “model” of the typical customer. Women tend to be shorter than men, so arm and leg reach—to a brake pedal or gearshift, to instrument panel controls, or to a shoulder harness—have become primary gender-design issues. When researching door handles and door handle heights for the Windstar, for instance, we discovered that there can be as much as a 2-inch difference between the hand width of a small female and a large male. These different dimensions therefore dictated the design and placement of the Windstar handles. Visibility over an instrument panel or rear seat is another primary design issue. Windshield wipers on the Ford Ranger, for example, were reengineered after we determined that the wiper blades could impair the vision of shorter-than-average drivers.

Secondary issues are less tangible because they focus more on consumers’ differing motivations and usage patterns. Focus groups confirmed that women place great importance on functionality and affordability. The success of the minivan design, for example, can be attributed to prominent, but simple, functional design features. These include the large side door that opens and allows easy access for children, infant car seats, pets, groceries, and other cargo, as well as cupholders that are strategically placed and designed to hold children’s juice boxes and bottles, which have proven to be real benefits for children and, therefore, for mothers.

Another secondary gender-design issue that underscores the differences between men and women is emphasis on safety. Women consistently request safety-related design features, such as power locks, power windows, and delayed interior lighting systems. They want integrated cellular phones and child seats. Women clearly understand the benefits of functional safety items such as airbags and antilock brakes, and they have been instrumental in creating a demand for such features to be standard, even on entry-level vehicles.

Finally, there are the tertiary design issues. Traditionally, it is these tertiary issues—cosmetic design issues—that companies have found easiest to address. For example, through the 1960s and 1970s, cars were equipped with vanity mirrors for the right front passengers. When the auto companies recognized the growing prominence of women in the marketplace, vanity mirrors were installed on the left-hand visor as well, since more and more women were driving. It was a relatively simple, but superficial, solution. The stereotypic treatment of tertiary design issues can be seen in the introduction in the 1950s of La Femme, a car designed "for women only." With its tea-rose brocade interior and matching hat and handbag, La Femme designers and engineers addressed fashion or tertiary gender-design issues only, and they failed to understand what women really wanted and needed.

OTHER INDUSTRIES FACE SAME ISSUES

Today, many companies are responding to the increasing impact of women in the marketplace.

Razors

About 5 years ago, Gillette discovered, through focus groups and in-home tests, that although both men and women shave, there are clear differences in primary and secondary gender-design issues in razors. Men shave in front of well lit mirrors; women usually shave in dimly lit showers. Men use short shaving strokes for the face, whereas women use long strokes for legs, which is an awkward task with traditional T-shaped razors. Women tend to see shaving as a chore. Men see it as a skill—a rite of passage—especially among teenage boys. Armed with a new thought process, Gillette developed the Sensor for Women. It has a uniquely shaped handle and head, better suited for a woman's hand and for making long strokes. Now, more than half of all razors sold to women are Sensors, and Gillette's market share has risen to over 67 percent, up from 55 percent just 2 years ago.

Athletic Shoes

Ten years ago the term "women's athletic shoe" meant generic aerobic models that were simply smaller versions of men's cross-trainers. According to an industry spokesperson, "the only thing that classified it as a woman's shoe was a pink stripe . . . and little else." Nike's research and development team developed shoes—men's shoes—based on pressure points, shape, weight, padding, and size and then scaled down these shoes for women. In reality, though, a woman's foot is shaped differently from a man's and has different pressure points. It took a complete rethink by Nike and a new focus on women consumers to react, but Nike did it. Building on research, Nike began designing separate molds to ensure a better fit and greater comfort for its female customers.

Computer Software

Although there are positive examples, there is still a great deal of refinement to be done, even in such a high-tech industry as computer software. According to Trendata, 50 percent of personal computers are bought by women—up from 30 percent just 15 years ago. As a result, the computer industry has revised the software bundles it loads into home computers. For example, PCs are packaged with many more programs keyed to women: programs that plan a family vacation and that keep track of key dates and financial records, as well as programs to support home-based businesses, which Trendata acknowledges that women are more likely to own than men.

Nevertheless, although the computer industry appears to be addressing women's needs on a secondary level, the extremely lucrative videogame software market is still searching for the key. The majority of videogame buyers are young males between the ages of 10 and 25. Is this because young women simply are not interested in videogames? Or is it because today's games, which are primarily designed by men for men, do not appeal to women? In general, what appeals to men does not necessarily appeal or sell to women. Software companies need to investigate the motivators. It is known that women shy away from confrontation and violence, but to what other factor does this technology lend itself? There is clear market growth potential here for the first companies that calculate the correct formula.

WOMEN'S MARKETING COMMITTEE FORMED

To better understand the female customer and to guarantee that women's needs are addressed, Ford formed the Women's Marketing Committee (WMC) in 1987. The WMC's mandate is to educate designers and engineers about the far-reaching effects of the choices they make. The committee is composed of volunteers representing all operational areas of Ford Motor Company, gathering input from design, engineering, manufacturing, finance, and sales. Although the word "marketing" is prominent in its name, marketing is not the committee's primary focus.

Working through eight subcommittees, WMC confronts a variety of design and engineering issues. Its Product Review Team is composed of hundreds of employees—mostly women—who review advanced design concepts. Members also participate in test drives of current and future models, which adds balance and depth to decision making in all facets of design.

Addressing secondary gender-design issues requires a different, more expansive thought process. It requires recognizing what motivates consumers, appreciating their specific needs and wants, and defining those needs and wants in the end products. In an effort to move toward this goal, the WMC completed an extensive women's market Pulse Study, which was the most comprehensive survey ever conducted specifically with women buyers. The study revealed not only what women want in terms of design, products, and services, but it also uncovered women's attitudes—the reasoning behind their choices.

The study concluded that product quality is the number one buying consideration among women. This is no surprise, since women perceive mechanical breakdowns as personal security concerns, whether they are driving alone or with young children. Because of this, it was assumed that women defined "quality" largely as "reliability," primarily because of their fear of breakdowns. But our Pulse Study data also showed that women are just as concerned about paint flaws and body margins. They are critical about instrument panel fit and finish and about wiper blades that do not streak or smear. Obviously, details get noticed.

Performance is also part of the total package. Power represents both safety and fun to women. They believe increased horsepower will help them pass safely or enter a freeway with more confidence and that better-handling vehicles will improve their ability to avoid accidents. The study also confirmed that women enjoy driving for driving's sake. Women's focus groups have made this point repeatedly: "You don't have to be a man to enjoy quick acceleration or hanging out in the left lane."

A vehicle's performance and its styling are the overwhelming motivators for men, allowing them more easily to "tradeoff" or forego such other attributes as ease of entry and package space. Conversely, our Pulse Study proved women see vehicles as a whole. Women tend to be complex as well as practical. Sacrificing one design feature for another lessens their perception of that vehicle's overall quality.

IMPACT ON OTHER CONSUMERS

Designing cars and trucks with women in mind will not turn away male customers, nor will it hurt other market segments. In fact, this approach almost always enhances products for all consumers. The lumbar seat support that is now popular in many models originally was designed for the comfort of pregnant women. The Windstar's easy-lift hood, easy-access engine maintenance points, low step-in height, and exterior door handles are features that reflect gender-based design. While they appeal to women, these features benefit older drivers, shorter drivers, and, not surprisingly, most men.

These are changing times. Women are more independent and are making important purchasing decisions. This sea change is very evident in the automotive industry. In the United States in 1995, women purchased 4.3 million new vehicles. They now buy almost 50 percent of the cars and one-fourth of all the light trucks sold. That translates into $83 billion in new vehicle sales every year.

The impact of societal evolution is not confined to the automotive industry. All companies—and the designers and engineers whose jobs are to create commercially successful products—must be both attentive to changing demographics and vigilant in addressing their customers' evolving demands and desires.

Development of Performance-Based Seismic Design Procedures

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Construction in the United States is regulated by a variety of codes. Although most members of the general public do not know details of the local electrical or plumbing codes, they are secure in the knowledge that compliance provides the required level of safety for typical residential construction. Within structural engineering, building codes define the forces used in design and the procedures for calculating the nominal strength of members.

The intent of building codes (BOCA, 1993; ICBO, 1994; SBCCI, 1993) is clear concerning design of a structure to resist gravity loads. Buildings are expected to support intended loads without structural damage or loss of integrity. With a few notable exceptions, such as the Hyatt Regency walkway in Kansas City, this goal is accomplished easily because the magnitudes of gravity loads are well defined. In addition, the loads applied during construction often exceed those expected during normal use; therefore, most buildings have been subjected to a significant load test before being occupied.

But the intent of building codes is not as straightforward when forces induced by earthquakes are considered. Although the general public may assume that compliance with the seismic provisions of the code provides the same level of structural performance that is achieved for gravity loads, the aim of the code actually is quite different. For a structure with an average occupancy, such as an office or apartment building, the objective of the current building codes is "to safeguard against major failures and loss of life, not to limit damage, maintain functions, or provide for easy repair" (SEAOC, 1990). It is not economical, nor is it architecturally feasible, for buildings other than extremely critical facilities to be designed to resist forces induced during the maximum credible earthquake without damage. Therefore, the force levels used to design most buildings are consistent with an expectation of structural damage, and buildings in the epicentral area are expected to sustain damage, even during moderate events. Clearly, the differences in the performance expectations of the general public and the structural engineering profession are significant.

Experience from recent earthquakes in California demonstrates that U.S. building codes have been successful in meeting the primary objective of limiting the loss of life (Table 1). However, many of the buildings that structural engineers consider to have performed successfully during an earthquake represent a substantial economic loss for the owner. Although it is usually possible to repair a structure damaged by an earthquake, often it is not practical to do so, especially considering the often high replacement cost of nonstructural equipment, finishes, and contents. Consequently, the economic impact of building damage in terms of interruption of business, loss of housing, and disruption to the community can be staggering.

It is obvious that successful structural performance during an earthquake can no longer be defined merely in terms of preventing collapse. Funds available for disaster relief are not limitless, and the 1994 Northridge earthquake provided convincing evidence that an economic crisis could develop if a major earthquake occurred near a densely populated area of the United States.

The concept of performance-based design was developed in an attempt to narrow the gap between the expectations that society places on building performance during an earthquake and the philosophy that structural engineers use to develop the building codes. In 1995 the Structural Engineers Association of California issued an overview of the objectives of performance-based seismic design. Although actual design procedures have not been developed, target levels of structural response are defined relative to the anticipated condition of the building after earthquakes of varying intensity.

TABLE 1 Direct Losses from Recent Earthquakes in California

Date	Location	Magnitude	Deaths	Damage (million $ 1994)
1983	Coalinga	6.5	0	50
1987	Whittier Narrows	5.9	8	450
1989	Loma Prieta	7.0	63	6,870
1992	Petrolia	6.9	0	70
1992	Landers	7.3	1	100
1994	Northridge	6.7	57	20,000

Source: OTA (1995).

TABLE 2 Performance Objectives for Buildings

Earthquake Designation	Return Period (years)	Probability of Exceedance	Condition of Standard Occupancy Building
Frequent	43	50% in 30 years	Fully operational
Occasional	72	50% in 50 years	Operational
Rare	475	10% in 50 years	Life safety
Very rare	970	10% in 100 years	Near collapse

Source: SEAOC (1995).

Again considering an average building, four states of damage have been related to four earthquake intensities (Table 2). Expected levels of damage to structural members, architectural elements, mechanical systems, and the building contents also have been defined for each damage condition. During the design process, the engineer would consider each earthquake level, and check that the calculated structural response is consistent with the expected performance.

Although the objectives of the performance-based design procedures are well defined, implementation is not a simple matter of considering a few more load cases during design. The structural engineering community must address a large number of technical issues for which consensus opinions have not emerged. Of primary importance is the development of a clear understanding of what aspects of structural response trigger damage. Building codes have traditionally defined force levels, but damage levels more often are defined related to displacements, and the influence of earthquake duration cannot be ignored. Therefore, reliable analytical tools are needed to calculate the distortion of the structure when it is subjected to various levels of earthquake excitation. Specialized nonlinear analytical models have been used in research for more than 20 years, but they are not sufficient to accomplish the objectives of performance-based design. The results of these analyses are extremely sensitive to the choice of input parameters, most algorithms are limited to modeling two-dimensional response, the influence of nonstructural elements typically is ignored, and the nonlinear analysis models are computationally intensive.

Even if the structural engineering community were able to develop comprehensive and efficient modeling tools, determination of the earthquake risk at a given location would remain a major concern. Seismologists continue to develop new theories about source mechanisms (Allen, 1995), earthquakes occur along previously unidentified faults, and large-amplitude velocity and displacement pulses have been identified in near-field ground motions (Iwan, 1995). In addition, the 1985 Mexico and 1989 Loma Prieta earthquakes have highlighted the influence of local soil conditions on building response.

In addition to the technical challenges, performance-based design represents a new relationship between the structural engineering community and society. Structural engineers are attempting to predict the performance of complex structural and nonstructural systems that may be subjected to highly variable earthquake forces years after construction is completed. Building owners are being given the opportunity to select appropriate performance levels for a facility and the option to design the structure to stricter performance levels, with the belief that disruption to normal operations will be less immediately after an earthquake. The ambiguity of the design process is thereby reduced, and expectations are stated explicitly, but the complexity of the process is increased exponentially.

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Information in the Design Process

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Intelligent Real Time Design (IRTD) is a framework that explicitly considers the cost of resources consumed during the design process (e.g., the value of the design team's time; the cost of further information gathering, analyses, or experimentation; and "time-to-market" opportunity costs) and trades these off against the optimum of the design solution found. Such a process dynamically takes into account the "real-time" aspect of the design process. IRTD helps designers focus their information-gathering efforts on reducing uncertainty in areas of the design that have the greatest impact on the design objectives (Bradley, 1993; Bradley and Agogino, 1991, 1992, 1993, 1994).

Uncertainty and ambiguity are greatest in the early conceptual stages of design, where the greatest potential for design improvement lies. Sources of uncertainty can be found in the design constraints, objectives, and parameters; evaluation models; and customer preferences. IRTD provides a prescriptive methodology for transforming the design space over the course of the design process. The results of an IRTD analysis are a set of expected costs associated with the uncertainty in each design decision. The designer must decide whether the impact of reducing uncertainty—by updating preference functions, design models, or design parameters—is worth the cost of information gathering (Wood, 1996; Wood and Agogino, 1996a).

The fundamental theory behind IRTD is the decision-analytic notion of the *expected value of information* (EVI). A design decision must be formulated as a nonlinear programming problem, with both objectives and constraints, as well as probability measures on the uncertain variables or parameters. EVI is a relatively simple concept, representing the expectation of the objective function over the uncertain variables with the new information, minus the expected value of the objective with the current state of information.

Definition: Expected Value of Information (EVI) is the

expected value of the objective function with the new information

minus

expected value of the objective given the present state of information

In equation form (Wood, 1996): it is

$$\text{EVI}\,(v_j) = \int_{v_j} \left\{ \max_{i} \left(E\left[obj \mid dec_i, v_j, \mathbf{c} \right] \right) - E\left[obj \mid dec^*, v_j, \mathbf{c} \right] \right\} P\left(v_j, \mathbf{c} \right) dv_j$$

where

v_j is an uncertain design variable,
obj is the value of the objective function,
dec^* is the current (best) decision,
dec_j is one of the set of possible decisions,
c is the constraint vector, and
$P(v_j, \mathbf{c})$ is the probability of the value of the design variable and constraint set.

Given the mathematical basis for the IRTD method, one might question its usefulness in conceptual design, where analytical models often are limited to those that can be written on the "back of an envelope." Although the "envelope" in today's world of information technology is more likely to be an e-mail message, a document written on a word processor, a notation in a design database, a CAD drawing, or a sketch in a graphics program, the information in conceptual design is not likely to be in a form convenient for applying IRTD.

Research on case-based reasoning, "data mining," and information retrieval (Dong and Agogino, 1996; Dong et al., 1995; Varma et al., 1996; Wood, 1996; Wood and Agogino, 1996a) is providing the tools needed for exploiting this structured and unstructured design information. These algorithms and techniques provide the theoretical engine for the UC Berkeley Concept Database Project (Bradley et al., 1994), aimed at supporting the conceptual design process by (1) identifying good prototype designs, (2) obtaining or deriving engineering models and uncertainty measures associated with the models, and (3) evaluating the value of reducing the uncertainty in the model (applying IRTD).

The Concept Database methodology provides "smart navigation" through a hypermedia database of linked design concepts. Such a system expands the amount of information available to the designer and other members of the product development team in a manner that is selective, using search techniques that are based on heuristic, deterministic, and decision-analytic methods. Prescriptive design methodologies are used to develop the structure of the search in order to guarantee that the full range of life-cycle issues is considered and to provide a framework for making design decisions that take into account multiple and often conflicting life-cycle objectives.

Mechatronic design, the domain of our first prototype system, is an area of key strategic importance, playing an important role in the design of consumer products, computer peripherals, automation systems, and aerospace and defense systems. It is also an area where off-the-shelf component selection is essential and is one in which expertise crosses departmental boundaries: electronic design, mechanical design, interface design, supplier coordination, packaging, logistics, and support all are involved in the realization of a good mechatronic system design.

Research from the Concept Database Project has been integrated also into the curricular reform efforts of the NSF-funded Synthesis Engineering Education Coalition, providing tools for developing educational case studies of engineering design and a database for archiving, searching, and retrieving engineering courseware (Agogino and Wood, 1994; Wood and Agogino,1996b).

ACKNOWLEDGMENTS

I wish to acknowledge the team of students I have worked with over the past 5 years, who have contributed to various aspects of this research, as listed in the References below. Steve Bradley was the first to suggest that my previous work in using information value theory in diagnostics and supervisory control might be modified effectively for use in real-time design environments, and he developed the first IRTD framework. Bill Wood brought in the notions of case-based reasoning, data mining, and information retrieval. Andy Dong continued this work by developing text analysis algorithms for constructing design representations for "smart drawing" documentation and concept retrieval. Anil Varma is extending this work to include neural network approaches to automated design classification, association, and retrieval.

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Product Modularity: A Key Concept in Life-Cycle Design

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The goal of life-cycle design is to maximize the values of the manufacturer's line of products while containing the products' costs to the manufacturer, the user, and society (Figure 1). Engineers must consider performance, cost, and any environmental impact of their designs. Our research develops systematic methodologies that apply to the early stages of product development in integrating life-cycle quality (Ishii, 1995). We address not simply one product but entire product families and changes over product generations.

I focus here on the concept of product modularity: a key concept in achieving life-cycle quality. Modularity is particularly important for electromechanical products, such as computers, telecommunication devices, and peripherals. The short technology life-cycle of many of the functions in these products, combined with customer demand for a wide variety of features, necessitates that designers optimize the modularity of components and subassemblies for manufacturability and serviceability. More recently, recyclability of durable products has also become an important consideration. For the past several years we at Stanford University have been developing evaluation metrics of modular designs from different perspectives. Such metrics should lead to design charts that enable engineers to achieve modules with an optimum life-cycle balance.

Our current research focuses on three perspectives that drive decisions on modularity. The first perspective is manufacturability. Engineers must address not only one product but the entire product family. They must design the product line in such a way that it has maximum market coverage; at the same time its modularity minimizes the cost of providing variety. This is

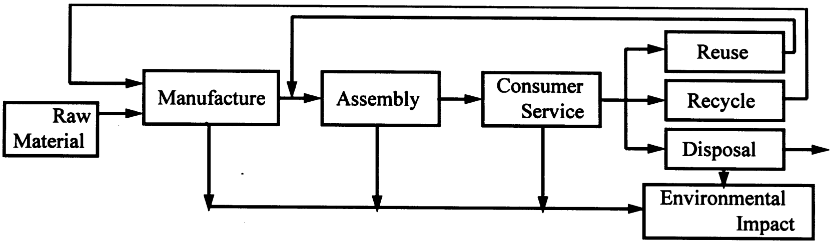

FIGURE 1 Material flow in the life-cycle of a product. Source: Ishii.

referred to as design for variety (DFV). Designers must critically evaluate what features require variety, they must identify core platforms with standard features, and they must modularize the design for efficient supply chain and manufacturing. Our research has identified several key metrics (Ishii et al., 1995):

- Voice of the customer that characterizes the variety requirements (VVOC).
- Commonality of components and manufacturing processes.
- Differentiation sequence in the manufacturing process.

Figures 2 and 3 show design charts for variety manufacturability of microwave ovens. Figure 2 plots commonality against VVOC, a number derived from quality function deployment. The chart shows that designers should (1) standardize core components that do not require variety and (2) contend with low commonality for features that require variety. Figure 3 plots commonality against stages in the manufacturing line. Empirical data show that one can reduce the cost associated with variety (e.g., inventory and logistics) by commonizing the early stages of manufacturing and long lead-time components and then differentiating variety at the final stages of assembly using short lead-time items. Figure 3 illustrates this concept of late point identification (LPI). The charts pinpoint weaknesses in a product line and guide the designers to improved modularization. Ongoing work attempts to quantify more accurately the cost of providing variety.

The second perspective addresses both serviceability and reliability. Users must be able to service easily the components requiring routine maintenance or those features that it would cost too much to make highly reliable. This is referred to as design for ownership quality (DFOQ). During the design process, the engineer needs to break into priorities the serviceability in terms of functional importance. A thorough functional analysis, combined with function-based failure modes and effects analysis, guides engineers to an appropriate modularization (DiMarco et al., 1995). Pertinent factors include the following:

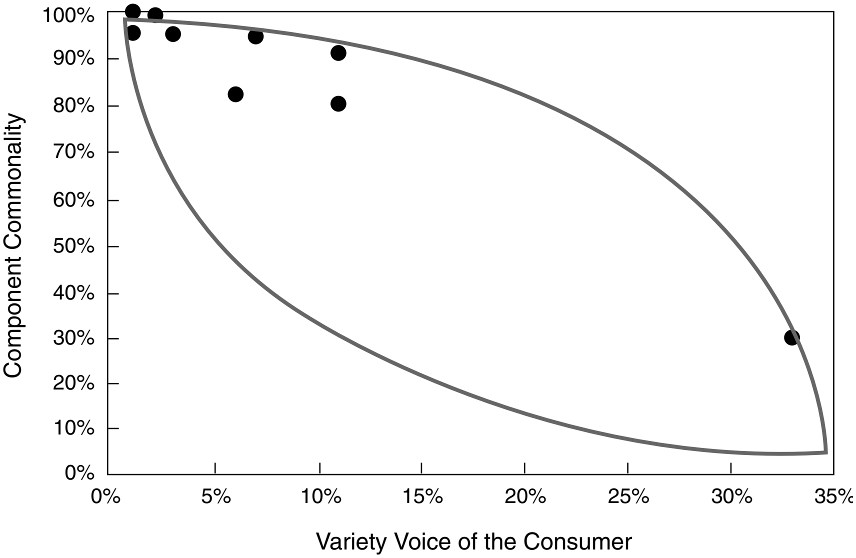

FIGURE 2 DFV Chart 1—Component commonality versus variety voice of the customer. Source: Ishii.

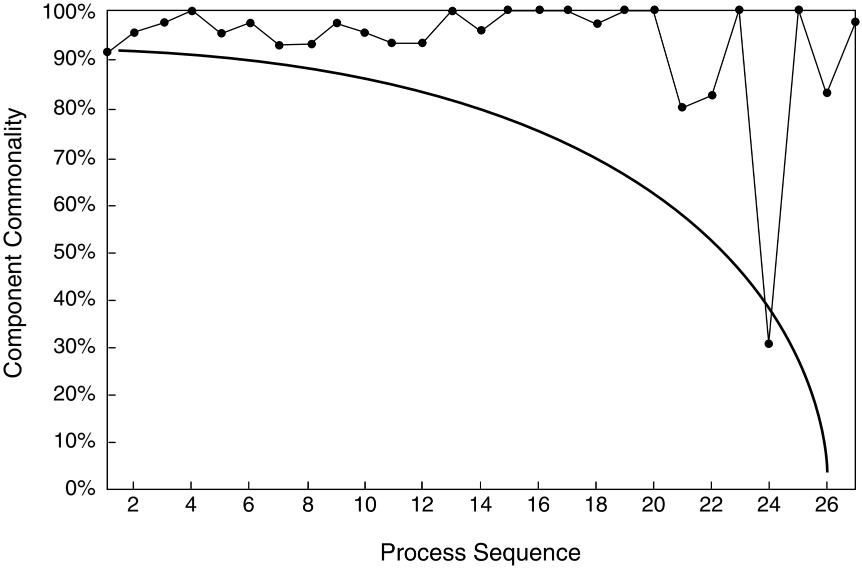

FIGURE 3 DFV Chart 2—Commonality versus manufacturing process sequence. Source: Ishii.

- Availability (up-time) requirements and warranty cost targets.
- Reliability versus maintenance trade-offs.
- Accessibility of components requiring service.

A good example of a modular design for serviceability is the toner cartridge of personal copiers. Companies have opted to embed several key components in the cartridge that require regular maintenance and service. As a result, the end-user can perform most of the service needs simply by replacing the cartridge. Although the service frequencies of various components may vary, the cartridge concept works extremely well for the usage profile of the personal copier. As is illustrated in this example, the service modularity of a product depends heavily on how the product is used.

The third perspective is design for recyclability (DFR). To enhance component reuse and the recycling of materials, engineers must embed strategic modularity into the product, and they must reduce the cost to the recycling organizations. Such efforts will lead to overall improvement of industrial ecology through reduction of raw material use, reduction of energy use throughout the product life-cycle, and reduction of solid waste. The key issue is an up-front consideration of recycle modularity at the early stages of product design that addresses product families and their generations. We have proposed several metrics for the complexity of the product demanufacturing process:

- Variety complexity: commonality of parts in a product family (similar to DFV).
- Material complexity: number of types of materials used in a product.
- Sort complexity: levels of disassembly.

We now know that the *total number of sort bins* required for a retirement process of a product family is a good overall indicator of all three of the metrics listed above. In general, more sort bins indicate deeper levels of disassembly, higher material count, and low commonality. A good design for recycle modularity should lead to fewer sort bins. Figure 4 maps the sort bins required for each major module against the average scrap rate of the material recovered from the bins. In this example of a family of ink-jet printers, the I/O paper tray included several types of plastic material and metal fasteners that required four sort bins and resulted in nearly a 40 percent scrap rate. This analysis led to a redesign that cut down the sort bin count to two and the disassembly time to one-third and that improved the scrap rate to 20 percent. Thus, the chart helps designers to select materials, processes, and assembly methods for various components, as well as to make advanced plans for the recycling process. We are now applying the chart to product families from different industries to validate its usefulness.

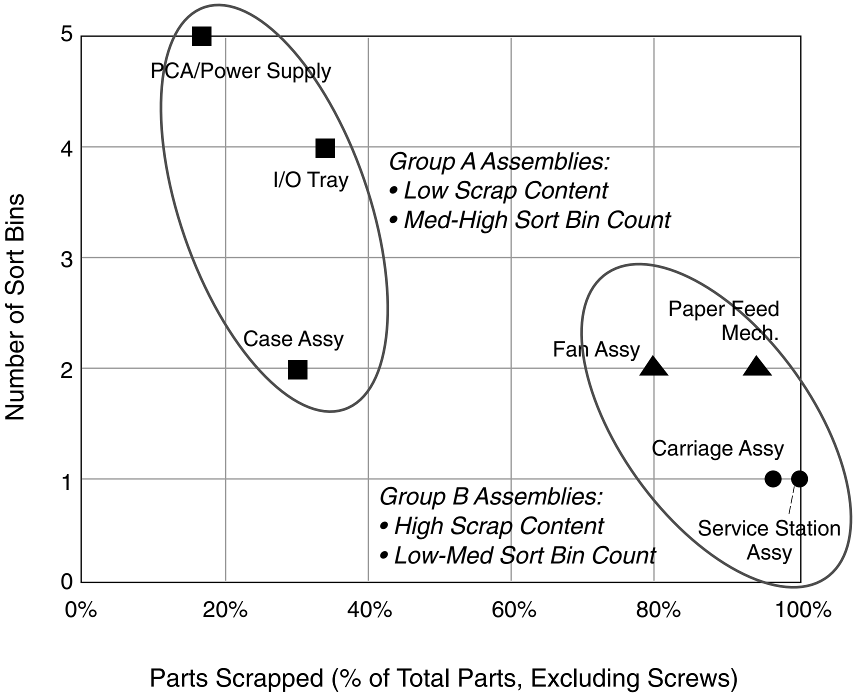

FIGURE 4 DFR evaluation chart. Source: Ishii.

The metrics and design charts described above guide engineers in formulating modular constructions addressing the issues of: manufacturability, serviceability, and recyclability. These methods also have provided guidance for student design teams in Stanford's graduate course on design for manufacturability. Although the teams felt the metrics and charts helped them analyze current weaknesses and generate improvements, they felt they fall far short of a general methodology for modular designs. We must address the issue of overall evaluation of modularity beyond such simplistic measures as the dismantling cost. However, I feel that such an overall life-cycle evaluation is too complex and inappropriate for early stages of product development. Rather, further work should focus on identifying other criteria for modularization and on developing a trade-off method among the different criteria. To this end, we are developing a computer environment that allows engineers to quickly input rough information about the product family, to evaluate the modularity measures, to plot the design charts, and to also allow iterative trade-off analysis (Ishii et al., 1994).

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VISUALIZATION FOR DESIGN AND DISPLAY

Visualizing Aircraft Aerodynamic Design

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The virtual wind tunnel (VWT) is the result of the application of virtual reality (VR) interface techniques to the visualization of the results of computational fluid dynamics (CFD) simulations. CFD is used to simulate the airflow around aircraft, thus allowing engineers controlled exploration of various aerodynamic concepts without their having to resort to expensive time in real wind tunnels. CFD simulations often result in complex, time-varying flow patterns, the details of which can be critical in determining the aerodynamic properties of the aircraft being simulated. Understanding these complex patterns is one of the challenges of aircraft design and development. The VWT helps address this challenge by providing the user an environment for the rapid investigation of CFD simulations in a fully three-dimensional control and display context, using a variety of visualization tools. However, several serious problems, determined by the engineering requirements of the simulations, have had to be addressed during development of the VWT.

VR interfaces use a variety of interface technologies in order to allow the user to interact with the computer-generated environment in a fully three-dimensional context. There are two basic components to the VR interface used in the VWT: display and interaction. The VR display is based on the use of a head-tracked stereo display to provide an image from the user's point of view, with an update rate of at least 10 frames per second. When combined with conventional three-dimensional graphics, this technology provides to the user various three-dimensional structure and depth cues, most particularly head motion and stereo parallax. By moving around in the scene, the user gets a very strong sense of the three-dimensional structure of objects in the virtual environment. The resulting, greatly enhanced three-dimensional perception allows CFD researchers to see the complex three-dimensional structures in their simulations much more accurately and easily than in conventional visualization systems.

VR interaction is based on the use of three-dimensional tracking systems, which provide the user's hand position and orientation, along with simple command information. This hand position and orientation data allow the user to move visualization objects about in the environment, exploring the flow simulation in near-real time. To support such exploration, visualizations must be recomputed continually based on the user's current hand position. In order to provide good responsiveness, these recomputations should occur with delays of less than one tenth of a second.

Thus, the VR interface implies strict performance requirements of both a 10-frames-per-second (or faster) rerendering of the entire scene as well as delays of less than one-tenth of a second between user control of a visualization and when that visualization is displayed. Meeting these performance demands has been one of the primary challenges in the design of the VWT. These performance demands are encountered in the computation of visualizations, the rendering of the visualizations, any network traffic involved in the operation of the system (not addressed in detail in this abstract), and access to the data being visualized.

Computations arising in typical visualization problems include the integration of vector fields to produce streamlines and moving particles, the computation of isosurfaces and cutting planes, and the extraction of geometry reflecting various derived features of interest to the CFD researcher. These computations are performed by a choice of algorithms, which typically involve an inverse relationship between speed and accuracy. Although modern workstations may be able to compute and render a very few simple visualizations within the performance requirements described above, the complexity of modern CFD simulations makes complex visualization environments, with many active visualization techniques in the scene, highly desirable. The resulting computational burden typically saturates the computational power of even the most powerful modern workstation, particularly for time-varying simulations where all visualizations must be recomputed with every frame.

In order to meet the computational performance requirements, the time required to complete the computation must be controlled so that it is not too long. This time may be controlled in a variety of ways, depending on the details of the computation. Typical control options include the choice of more or less accurate algorithms and the number of times the algorithm is iterated for extended visualization objects. When asked, many CFD researchers have indicated that they would rather have a fast and less-complete or less-accurate answer in order to rapidly explore the simulation. When they then identify an interesting feature, that feature can be verified with a slower, more-accurate algorithm. The challenge for the VWT then becomes deciding how to control the time required for a computation while delivering the most complete and accurate answer within the specified time constraint. This is done using time-critical computation techniques, where each visualization is given a time budget. That time budget and the time taken in the previous computational frame is used to determine the parameters of the computation so that the computation does the best job possible in the time available.

The geometry resulting from time-critical computations typically can be rendered much more quickly than it was computed, so a time-critical graphics approach has not proven to be necessary for the VWT.

By far the most difficult challenge in development of the VWT has been the very large sizes of data sets encountered in time-varying CFD simulations. These simulations can range in size up to 300 gigabytes, as of 1996, with each time step containing 60 megabytes of data. In order to maintain a time-varying animation rate of 10 frames per second, each time step can take no longer than one-tenth of a second to load, implying a bandwidth from wherever that data is stored of 600 megabytes per second. The only storage medium with the required bandwidth is the physical memory inside the computer, yet the largest memory available in graphics workstations is only 16 gigabytes. This remains an unsolved problem, and it will only worsen as simulation sizes increase. Existing compromises include restricting the data set to allow more time steps to fit into physical memory and using widely striped disks for increased bandwidth (NASA Ames has a disk system that has attained bandwidths in excess of 300 megabytes per second). Approaches based on loading only the data required for a visualization run into the problem of disk latency, which proves to be unacceptably long for VR applications. Data compression also has failed to address this problem, since compression schemes that cause losses such as subsampling or Fourier-based methods intolerably distort the data, while compression schemes without loss such as run-length encoding often increase the size of the data set. At this time multiresolution compression schemes such as those based on wavelets provide some hope, but they have yet to be demonstrated for CFD-type data.

Another set of challenges for the VWT involves the design of the user interface. Most visualization systems are based on an "external command model," where the user specifies a visualization using either text or a graphical user interface, which is then computed and rendered. The nature of the VR display requires that the user interface be imbedded in the visualization environment, and the three-dimensional interaction capability strongly suggests a direct manipulation interface. A direct manipulation interface implies mapping the user's hand position to the specification of a visualization. These considerations have led to the concept of a "local visualization," which uses the value of a data field at a point in space to generate the visualization. Using local visualizations, a CFD researcher can explore the phenomena in a simulation by "waving the visualization about in space," rapidly sampling features in a volume of data. The visualizations are controlled by interactive tools, which "emit" collections of visualizations. It is these tools the user manipulates directly.

There are several features of the VWT architecture critical to its success: the computation and graphics are implemented in separate, asynchronous, concurrent processes so that a slowdown in the computation does not impede the head-tracked aspects of the display; the visualizations and tools are implemented in an object-oriented class hierarchy designed so that new visualizations or tools may be added without having to modify existing visualizations or tools; and a number of display and interaction technologies are supported, ranging from conventional workstation and mouse through head-mounted displays and gloves, with a unified interaction paradigm.

The VWT currently is under evaluation release at a number of NASA sites, with a general release expected in early 1997. For more information on the VWT, contact the Web at www.nas.nasa.gov/NAS/VWT. For papers on the VWT, contact the Web at www.nas.nasa.gov/~bryson/home.html.

Virtual Reality and Augmented Reality In Aircraft Design and Manufacturing

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At Boeing all new aircraft designs, starting with the 777, as well as new derivatives of older aircraft designs, are being specified as three dimensional solid models. The projects I discuss below belong to a group of several advanced computing and human-computer interface R&D projects going on within Boeing's research and technology groups. These projects all exploit the fact that our products now are being defined both digitally and three dimensionally.

VIRTUAL REALITY

The focus of our virtual reality (VR) project is on visualizing and interacting with aircraft CAD geometry, thus providing a VR environment almost identical to that inside of the full-scale physical mockups once built for each aircraft during the design phase. We believe that VR alone allows a person not only to visualize a set of CAD representations of parts but to "physically" interact with them—that is, move parts into and out of their installed positions, reach around obstacles, and so on. Several beneficial applications of this capability include the following:

- flight deck design,
- maintainability/accessibility verification,
- assembly planning,
- maintenance training, and
- the creation of maintenance training animations.

The primary goal of our work for the past two years has been to develop and demonstrate what we call the "egocentric human model." By this we mean a VR capability whereby a participant perceives himself/herself, from a first-person point of view, to be inside the aircraft geometry, "wearing" a graphical human body whose positions and movements closely mimic his/her own. Position/orientation sensors on the participant's limbs, torso, and head provide the necessary information to the computer, enabling it to draw the graphical body (sometimes called an "avatar") in a corresponding position. Real-time collision detection software informs the participant if he/she has bumped into an obstacle. Someday, haptic feedback systems may enable the user actually to feel such a collision. In the meantime, we provide sound cues and make the object change color to notify the user of the collision.

The fundamental problem we face in trying to use aircraft CAD geometry as our virtual environment is one of scale. CAD geometry is orders of magnitude more complex than the scenes usually portrayed in VR systems. Any subset of interest to the aircraft engineers is likely to contain millions of polygons worth of geometric data, and rendering such data sets in stereo at 25 to 30 frames/second is a daunting challenge. Providing on-the-fly collision detection among such complex geometry is equally daunting. Our approach probably could best be characterized as "use every trick in the book," because all are probably necessary to handle geometry of this scale. The algorithmic techniques we are trying to combine include

- parallel rendering algorithms,
- upstream occlusion culling,
- object simplification and level-of-detail control, and
- substitution of texture maps for geometry.

AUGMENTED REALITY

Independently of the VR project, we are working on another technology involving a VR-style head position/orientation tracker; a see-through head-mounted display; and a belt-mounted, battery-operated computer. This combination makes up the hardware platform for our Augmented Reality (AR) system. Since the display is see-through, the AR system can be used to superimpose computer graphics on the surface of a real object the user is viewing. Because we employ a position/orientation tracking system, the computer can change the display whenever the user moves his/her head, making the graphics appear to be fixed on specific coordinates of the real object. Our goal is to have people who perform touch labor manufacturing tasks use this technology. At every step of a manufacturing or assembly procedure, the diagrams or text a worker needs to perform that step quickly and accurately will appear to him/her as if they were painted on the surface of the workpiece.

The critical technical issue for AR is the head position/orientation tracker. Current commercially available trackers are not adequate for factory use.

Typically, they only have an accurate range of about a meter, and they lose accuracy in the presence of metal or radio frequency (RF) energy, both of which are abundant in factories. The ideal tracker for AR use would be

- untethered;
- accurate to .01 inch and .1 degree over 25+ feet of range;
- able to provide position and orientation measurements at 25 Hz or better, with minimal latency;
- impervious to metal, RF, or acoustic interference;
- lightweight and low power so as to be body worn and battery operated; and
- inexpensive.

Our strongest candidate so far is a prototype “videometric” tracker built for us by Honeywell and TriSen, Inc., of Minneapolis. This videometric tracker entails a head-mounted videocamera, with some image-processing capability included in the wearable computer. The tracker finds fiducial marks (visible spots at known coordinates) on or near the workpiece and computes the user’s head position and orientation relative to them.

We also are experimenting with a simpler wearable computer system—without a head tracking system—for applications where the user needs to be mobile, must have his/her hands-free, and needs to see a computer or enter data into a computer while performing his/her job. The classic example for the aircraft industry is being able to refer hands free to a digital maintenance manual while performing the maintenance operation.

The Frontiers of Virtual Reality Applied to High Performance Computing and Communications

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Our nation is now designing the architecture of the Global Information Infrastructure (GII), yet it is using standard keyboard and pull-down menu interfaces for computing that are inadequate, particularly when the computers can reside anywhere in the world and when there is an emphasis on moving from human/computer dialog to human/computer/human collaboration, with the computer providing real-time data in a shared, collaborative environment. Virtual reality (VR) is, at its most useful, a mode of information display that encourages intuitive navigation and exploration. VR provides views of data and computation that are hard to prespecify in the way currently required by two-dimensional workstation visualization interfaces, and it has garnered interest as an intelligent user interface to the GII. However, its real-time, interactive, high-resolution displays are pushing the limits of today's high-performance computing and communication (HPCC) technologies.

The Electronic Visualization Laboratory (EVL) at the University of Illinois at Chicago, in partnership with the National Center for Supercomputing Applications (NCSA) at the University of Illinois at Urbana-Champaign and the Mathematics and Computer Science Division of Argonne National Laboratory (ANL), is involved in a multiyear, national-scale effort to develop collaborations using supercomputers, high-speed networks, VR, and scientific visualization. EVL, NCSA, and ANL have, for several years, created national testbeds—notably at the SIGGRAPH 92, SIGGRAPH 94, and Supercomputing 95 conferences—to showcase distributed scalable computing and visualization and virtual environment applications from academia, national supercomputer laboratories, and industry.

The partnership designed these testbeds as experiments to help ferret out the right research questions, as well as to be a cyberlaboratory in which to work out answers to these questions and to formulate new questions in turn. How can we integrate HPCC technologies and VR devices seamlessly? What are the current limitations of these technologies? How do computational scientists and engineers want to use them? What tools do computational scientists and engineers need in order to use VR for problem solving? As partners, we firmly believe that application requirements should drive our research agenda; accordingly, we have been using the testbed concept to create the needed teams, tools, hardware, system software, and human interface models on an accelerated schedule in order to facilitate solutions to National Challenge and Grand Challenge problems.[1]

In 1991 EVL began developing projection-based VR graphical displays for use by computational scientists and engineers. Such a VR display had to help the users get to scientific discoveries faster, without compromising the color, resolution, and flicker-free qualities those users have come to expect when using workstations. Most important, the VR display had to link remote data sources, supercomputers, and scientific instrumentation in a functional way. In all, the VR system had to offer a significant advantage to offset its packaging. The CAVE,[2] introduced at SIGGRAPH 92, basically met all these criteria and has been successful in attracting serious collaborators in the HPCC community.

The CAVE (Cave Automatic Virtual Environment) is a 10 × 10 × 9 foot, room-sized, multiperson, high-resolution three-dimensional video and audio environment. Other VR graphical displays include the ImmersaDesk, introduced in 1995, which is a drafting-table format virtual prototyping device designed as a single-user application development station. The Infinity Wall, also introduced in 1995, is a paneled, large-screen, high-resolution stereo projection display well suited for large audiences. EVL then extended its CAVE library and desktop simulator software package to work with all three displays so that projects designed in any one of these virtual environments could be displayed in the others.

EVL, NCSA, and ANL most recently completed a major experiment for Supercomputing 95: the Information Wide-Area Year (I-WAY), an experi-

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[1] National and Grand Challenges were defined by the National Science and Technology Council, established by President Clinton in 1993 to coordinate the federal research and development agenda. Grand Challenges are fundamental problems in science and engineering (e.g., environmental science, computational chemistry, and computation astrophysics) that have broad economic and scientific impact; National Challenges are fundamental applications that have broad and direct impact on the nation's competitiveness and the well-being of its citizens (e.g., manufacturing, health care, education, and access to information). Finding solutions to these problems can be advanced through the use of HPCC technologies and resources.

[2] The CAVE, ImmersaDesk, and Infinity Wall are trademarks of the University of Illinois Board of Trustees.

mental high-performance network linking dozens of the nation's fastest computers and advanced visualization environments. The I-WAY experiment laid the groundwork for scientific community-based access to heterogeneous distributed computing resources, high-speed networks, and immersive VR environments. More specifically, the I-WAY was an effort to provide a wide-area ATM (Asynchronous Transfer Mode) network to support various experimental activities at Supercomputing 95—notably, interactive video, distributed applications, and remote computations for interactive virtual environments and scientific visualization.

Much of I-WAY's physical networking made use of existing smaller ATM research networks, including AAInet (ACTS ATM Internetwork), ACTS (Advanced Communications Technology Satellite), ATDnet (Advanced Technology Demonstration Network), CalREN (California Research and Education Network), CANARIE (Canadian Network for the Advancement of Research, Industry and Education), CASA (Gigabit Testbed), DREN (Defense Research and Engineering Network), ESnet (Energy Sciences Network), MAGIC (Multidimensional Applications and Gigabit Internetwork Consortium), MREN (Chicago Metropolitan Research and Education Network), and vBNS (Very High-Speed Backbone Network Service). The separate networks were linked with the help of several major network service providers, including MCI, AT&T, Sprint, Ameritech, and Pacific Bell.

The EVL, NCSA, and ANL partnership also staged a unique conference event, the GII Testbed, during which 60 scientific and engineering application groups demonstrated solutions to Grand Challenge and National Challenge problems. These groups used the I-WAY for remote computation and the CAVE, ImmersaDesk, and Infinity Wall for local presentations of results. Overall, the HPCC community showed tremendous enthusiasm, supporting our interest in wide-area, high-performance distributed computing. Now that Supercomputing 95 is over, the partnership seeks to establish a Persistent I-WAY to provide computational scientists and engineers with a model nationwide facility for both production and research.

EVL continues to enhance its VR displays. Primary criteria for these VR systems are that they be network based and that human sharing and collaboration, data distribution, and computational heterogeneity be the core foci. An important evaluation criterion is that these systems are sought after and used regardless of distance; they should be a part of science regardless of whether the researchers are in the same room or spread across the nation.

EVL also continues to track developments in the simulation and graphics industry. EVL is interested in problems with unique human/computer interface needs—from navigation intensive (i.e., lots of user interaction) to collaboration intensive (i.e., multiple VR sites participating). We do not yet know how new machine architectures (e.g., distributed shared-memory machines with hundreds of processors), advanced user interfaces (e.g., gazedirected, gesture recognition), and next-generation graphics engines (capable of rendering more polygons/second and real-time volume visualization) will stress test network bandwidth and latency. The research community is just beginning to have enough polygons and texture memory to function at all in VR, as well as to harness the real-time power of supercomputers. With no exaggeration, computational scientists need four orders of magnitude improvement in graphics and processor performance to do in real-time VR what they now do in frame-at-a-time scientific visualizations. Similarly, 155Mb networking is barely enough for intense point-to-point VR with supercomputing; upgrades to OC-48 and OC-192 experimental networks clearly are desirable, especially for multiple VR sessions.

The 10- to 20-year challenges in VR/visualization applied to scientific problem solving are as follows:

1. Providing enough anti-aliased image resolution to match human vision (roughly 5,000 pixels at a 90-degree field of view) at rates of 10–48 frames/second.
2. Providing audio output matched to the dynamic range of human hearing as well as mostly flawless voice recognition.
3. Developing haptic (touch and force feedback) devices.
4. Storing, retrieving, and playing back visualization/VR sessions.
5. Filtering and compressing massive amounts of data for presentation and storage.
6. Connecting to remote computations and data sources in collaborative "tele-immersion" experiences via high-speed networks.
7. Developing algorithms to portray complexity in meaningful ways.
8. Providing the security necessary to distribute computing and data at very high speed.

Our goal is to integrate heterogeneous distributed computing environments—that is, supercomputers, remote instrumentation, networks, mass storage devices, and advanced real-time three-dimensional immersive interfaces—into computational science workspaces so that scientists will depend on these systems to discover, communicate, and transmit results.

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Digitizing the Shape and Appearance of Three-Dimensional Objects

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There is a growing interest within the design, manufacturing, and graphics communities in building a device capable of digitizing the shape and appearance of physical objects. Depending on the type of object digitized, the resulting computer model may have many uses. For small objects, applications may include product design; reverse engineering; museum archiving; and creation of models for visual simulation, movie making, videogames, and home shopping. For large objects, applications may include architectural preservation, engineering retrofits, virtual reality flythroughs, and recording of such cultural artifacts as sculptures, historic buildings, and archeological sites. If the object is small enough and the computer model is of high enough quality, a physical replica of the object can be produced using a rapid prototyping technology such as stereolithography. This type of system, if inexpensive enough, rightfully could be called a “3D fax machine.”

Together with my students in the Stanford Computer Graphics Laboratory, I have been building a prototype for such a machine. In this paper I describe how we obtain range images of small objects using a laser-stripe triangulation scanner, how we combine these range images to produce a watertight computer model, and how we fabricate a physical replica from the model. I also summarize some preliminary results on digitizing color. Finally, I outline the future of this project and comment briefly on some possible economic implications.

PASSIVE VERSUS ACTIVE SENSING

I restrict the discussion here to optical sensing technologies—that is, those technologies that employ visible light. Hence, we are concerned only with the external surfaces of objects. In this domain, acquiring the shape and appearance of an object requires solving an inverse rendering problem: given a set of images, one must solve for scene illumination, sensor geometry, object geometry, and object reflectance. This is a central problem in the computer vision field, and if the images are acquired using passive sensing, such as a video camera, it is a hard problem. The difficulty arises in large part from the necessity of finding corresponding features in multiple images, each of which may in itself be very complex.

However, if the images are acquired using active sensing—for instance, with a light-stripe scanner—the problem is greatly simplified. In particular, by limiting the problem domain to a stationary scanner for small objects, we can control sensor geometry and scene illumination, thereby eliminating several variables from the problem. By employing active sensing using structured light, we can independently measure geometry and reflectance, eliminating yet even more variables. Finally, by providing computer control over the operation of the scanner, we can acquire redundant data, improving the robustness (i.e., error tolerance) of the system. To bypass the many difficulties associated with passive sensing, we employ active sensing in our work.

DIGITIZING SHAPE

The goal of shape digitization is to produce a seamless, occlusion-free, geometric representation of the externally visible surfaces of an object. Restricting ourselves now to active optical sensing technologies, we are aware of many devices on the market that can digitize the shape of one side of an object. These devices are generically called range finders, and their output is called a range image—a rectangular lattice of pixels, each of which contains a distance from the sensor to the object (Besl, 1989). The system we are building in the Stanford Computer Graphics Laboratory employs a modified Cyberware laser-stripe triangulation scanner as shown in Figure 1.

A harder task is to digitize objects having multiple sides and self-occlusions (i.e., parts that obscure other parts). Several methods have been proposed to solve this problem, involving scanning the object from several directions and then combining data from the individual scans. In our laboratory we have investigated methods based on fine-grained polygon meshes (Turk and Levoy, 1994) and fine-grained voxel arrays (Curless and Levoy, 1996). The second method has given us our best results, so I describe it here briefly.

Working with one range image at a time, we first convert the image to a signed distance function defined over 3D-space. In other words, for each point in space, this function gives an estimate of the distance forward or backward from that point to the surface of the object. In places where the laser did not see the object because of occlusions, this function will have gaps in it. We then sample this function on a lattice, producing an array of voxels

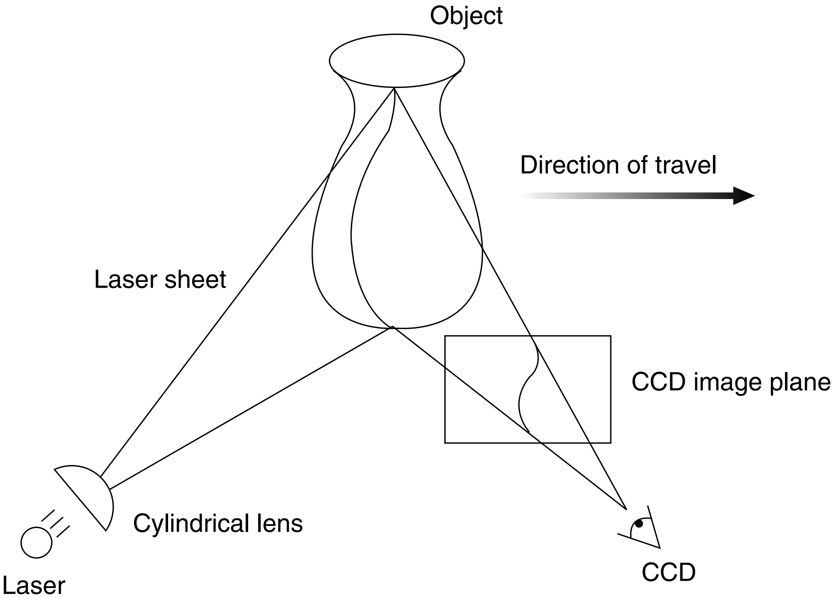

FIGURE 1 Range finding using laser-stripe triangulation. An object is affixed to a precision-motion platform and translated through a thin sheet of laser light. The resulting reflection takes the form of a moving line, which is digitized by a charge-coupled device (CCD) video camera and analyzed in real time. In the case of our Cyberware range scanner, the output is a 512 × 512 pixel grid of depth values, each accurate to 0.25 mm. Figure is at http://www-graphics.stanford.edu/~levoy/images/cyber_triang_geom.tif.

(literally, volume elements), and combine it using a simple additive scheme with a voxel array representing everything we have seen so far. Digitizing a complicated object may require 50 or more such scans. This takes several hours, but since our motion platform is partially automated, only a few minutes of human interaction is necessary. The result is a voxel array densely populated with signed distances. Finally, we extract a contour surface (also called a level set) at the zero-distance level. We typically represent this contour surface as a mesh of tiny polygons, frequently numbering in the millions. This mesh is our best estimate of the object's surface.

The meshes created using this algorithm have two desirable properties. First, because they arise from the addition of many overlapping scans, they are relatively free of sensor noise. Second, because they are contour surfaces, they are watertight, having no holes or self-intersections. Mathematically, we say that they are manifolds. This property allows us to fabricate a physical replica of the model, as shown in Figure 2.

FIGURE 2 The Happy Buddha, from original to 3D fax. (a) This is a photograph of the plastic and rosewood statuette, which stands 20 cm tall. (b) Here we show a smooth-shaded computer rendering of one range image of the statuette. This figure illustrates the limited and fragmentary nature of the information available from a single range image. After digitizing and combining 58 such scans, we obtain a 2.6 million polygon mesh representing the entire statuette. The process takes several

hours. (c) This is a colored (see website) and smooth-shaded rendering of this model. (d) Here is a photograph of a physical replica made from the computer model; the replica was manufactured by 3D Systems, Inc. which used a rapid prototyping technology called stereolithography. This process also takes several hours. Figures can be viewed in color at http://www-graphics.stanford.edu/projects/faxing/happy/, figures (1), (3), (5), (6).

DIGITIZING APPEARANCE

The amount of light reflected from a surface depends on both the direction of illumination and the direction of reflection. Each of these two directions consists of two angles. The resulting four-dimensional function is called the bidirectional reflection distribution function (BRDF; Nicodemus et al., 1977). BRDF typically varies with the wavelength of the illumination, and, for textured objects, it also varies from point to point on the object's surface.

Construction of the BRDF for a given material can be done analytically—by mathematically modeling the underlying physics—or empirically—by measuring the light reflected from samples of the material. Where analytical models are available, this method is preferred. One example is the Cook-Torrance-Sparrow reflection model for metals and simple plastics. Some of the most realistic computer graphics pictures to date have been produced using this model (Cook and Torrance, 1981). But for compound materials, materials subjected to extensive surface finishing, or materials of unknown composition, analytical methods may be infeasible. Unfortunately, this is true for many materials used in design and manufacturing applications, and in these situations empirical methods are necessary.

A device capable of measuring the light leaving an object as a function of the angles of illumination and reflection is called a scatterometer or gonioreflectometer (Hunter and Harold, 1987). Such a device typically is accurate but expensive and slow. In keeping with our goal of building inexpensive devices, we are designing a new generation of handheld gonioreflectometers that employ wide-angle optics, high-resolution sensor arrays, and commodity multimedia chips to compress the digitized reflections. Our goal is to build a device that is capable of quickly characterizing the reflectance of an unknown material to an accuracy sufficient to generate computer animations of objects covered with that material. Of course, we would love to build a color 3D fax machine, but no such technology as yet exists. A preliminary result of our work in digitizing object appearance is shown in Figure 3.

FUTURE DIRECTIONS

There are several directions this project might take in the future. First, our present scanning methods are time consuming and not fully automated. We need algorithms that, given a partial computer model, can determine the "next best view" to acquire unseen portions of the object. Such an algorithm would drive a robot arm that holds either the object or the camera, making scanning completely automatic.

Second, although colored dense polygon meshes suffice for some of our applications, other applications require a higher-level representation. For applications in computer animation and computer-aided design (CAD), we have

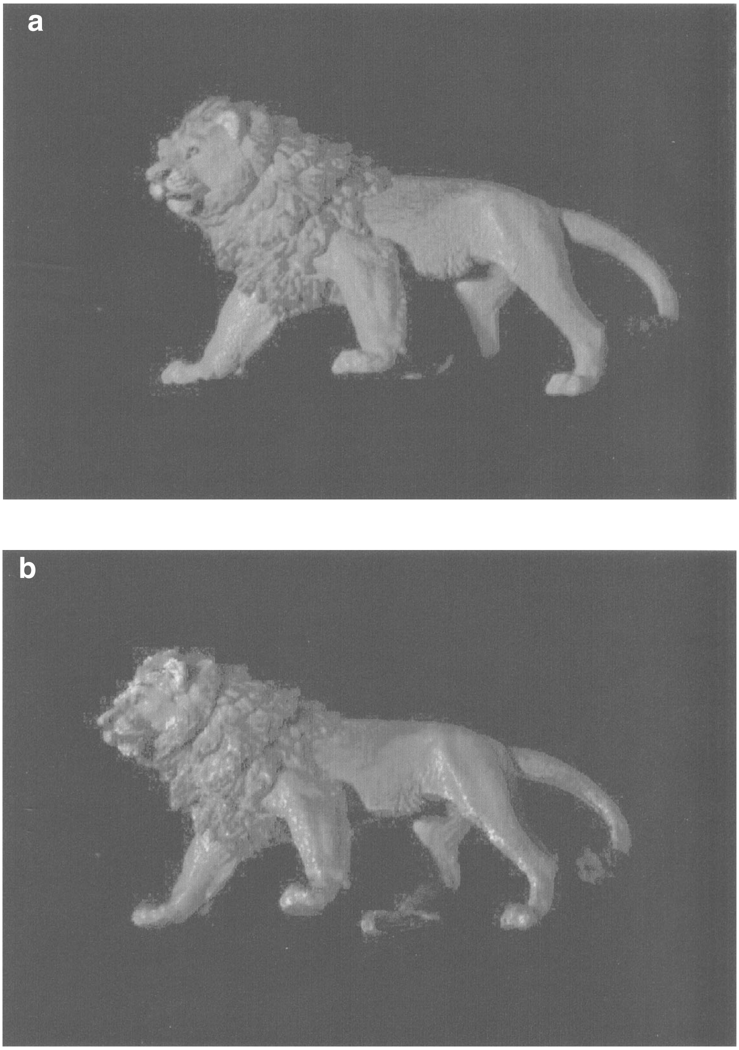

FIGURE 3 Toy lion. (a) This is a photograph of a hand-painted plastic toy lion that stands 10 cm tall. The BRDF of a painted surface typically contains two components: a mirror-like but colorless reflection from the surface of the paint carrier and a diffuse but colored scattering of light from dye particles embedded in the carrier. We measured surface radiance using a color video camera, and then we used the known object and lighting geometry to correct for surface orientation, shadows, and specular highlights. (b) This shows a computer rendering of the polygon mesh. Of course, since this is a computer model, we could easily have moved the lights or changed the viewpoint. Figures with digitized color can be viewed at http://www-graphics.stanford.edu/~levoy/lion.html.

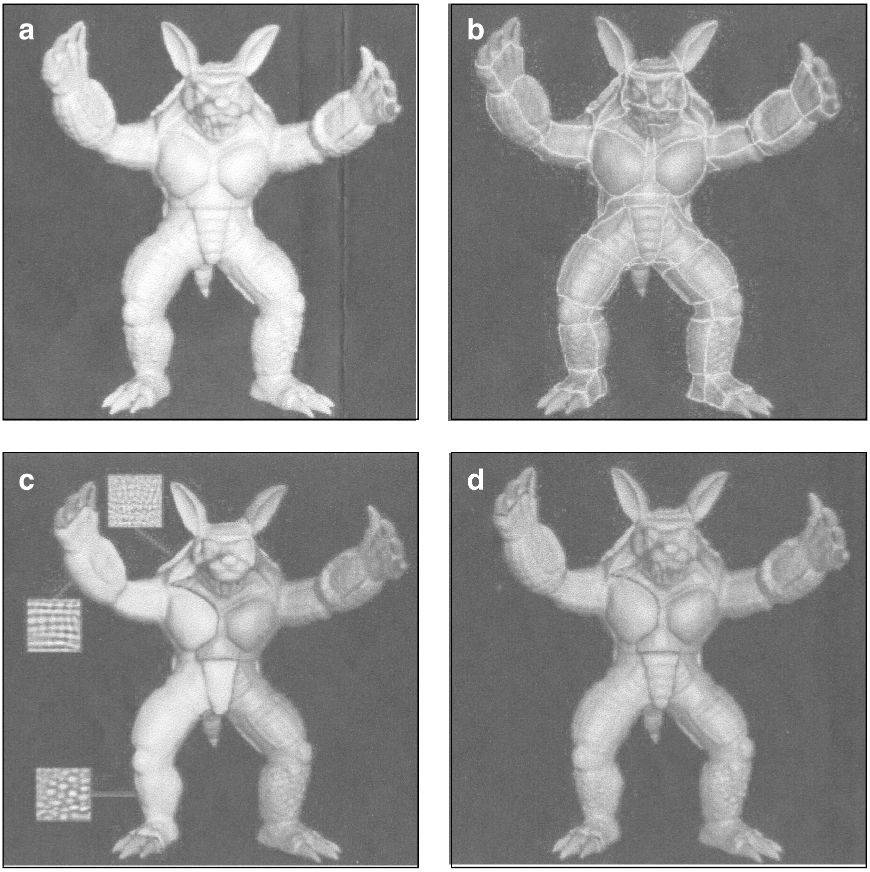

FIGURE 4 Fitting surfaces to Armadillo Man. In this figure (a) is the polygonal model (350,000 polygons, 75 scans), (b) shows manually specified B-spline patch boundary curves, (c) shows a split view of the B-spline surfaces smooth shaded on the left with the polygon mesh on the right (a few displacement maps are given alongside their corresponding patches), and (d) shows a split view of the displacement-mapped spline patches on the left with the original polygon mesh on the right. Figures can be viewed in color at http://www-graphics.stanford.edu/papers/surfacefitting/, the banner image.

developed a representation that combines both B-spline surface patches to capture overall shape and displacement maps (sometimes called offset functions) to capture fine surface detail (Krishnamurthy and Levoy, 1996). This hybrid representation yields a coarse but efficient model suitable for animation and a fine but more expensive model suitable for rendering. An example is shown in Figure 4.

Third, recent advances in time-of-flight laser range-finding technology permit us to scan accurately such large objects as cars, buildings, engineering sites, movie sets, and so on. Combined with our present system, this technology allows us to build virtual environments of unprecedented complexity. Of course, increases in the complexity of computer models must be accompanied by improvements in the software needed to manipulate these models as well as improvements in the rendering engines needed to display them.

ECONOMIC IMPLICATIONS

As a technology become less expensive, it can be applied in an increasing number of areas. We have already seen commercial applications of 3D digitization emerging at the professional and retailer level. For example, shoe and clothing manufacturers, with an eye on the custom-fit market, have begun installing range image scanners in their larger stores. Some of these scanners are capable of digitizing an entire body at once, and many of them have our software embedded in them.

Another example can be found in several museums, which are evaluating this technology for scanning their most precious sculptures. If someone ever again should attack Michelangelo's Pieta with a hammer and chisel (which will hopefully never happen), there might be a 3D backup from which to restore it. On a more positive note, museums could use these 3D archives in conjunction with emerging rapid-casting technologies to make perfect replicas to sell to the public. These copies, authorized by the museum, would revolutionize the art reproduction industry, which currently is pervaded by poor-quality replicas often made from photographs of the original.

It is doubtful that this technology will be cheap enough—or fast enough—to appear in homes anytime soon, much as my children would love to own a Lego® duplicator. But even if consumer applications are unlikely, we at Stanford have been driven in this project by the image of a popular consumer device: the microwave oven. In our dreams we see a fax machine about that size; we put the object in, close the door, press a button, and a few minutes later we have a computer model. We then punch in a telephone number, and a few minutes later our collaborator across the country opens the door of his box and retrieves a physical replica of the object.

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MICROELECTROMECHANICAL SYSTEMS

Microelectromechanical Systems (MEMS)

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As information systems increasingly leave central control areas and appear in distributed systems, they are getting closer to the physical world, thus creating new opportunities for perceiving and controlling the physical environment. To exploit these opportunities, information systems will need to sense and act as well as compute. Filling this need is the driving force for the development of microelectromechanical systems (MEMS).

Using both the fabrication techniques and materials of microelectronics as a basis, MEMS processes are used to construct both mechanical and electrical components. Mechanical components in MEMS, like transistors in microelectronics, have dimensions that are measured in microns and numbers measured from a few to millions (Figure 1). MEMS is not about any one single application or device, nor is it either defined by a single fabrication process or limited to a few materials. More than anything else, MEMS is a fabrication approach that conveys the advantages of miniaturization, multiple components, and microelectronics to the design and construction of integrated electromechanical systems. Potential applications include miniature inertial measurement units for competent munitions and personal navigation; distributed unattended sensors for asset tracking and environmental/security surveillance; mass data storage devices; miniature analytical instruments; a range of embedded pressure sensors for passenger car, truck, and aircraft tires; noninvasive biomedical sensors; fiberoptic components and networks; distributed aerodynamic controls; and on-demand structural strength sensors.

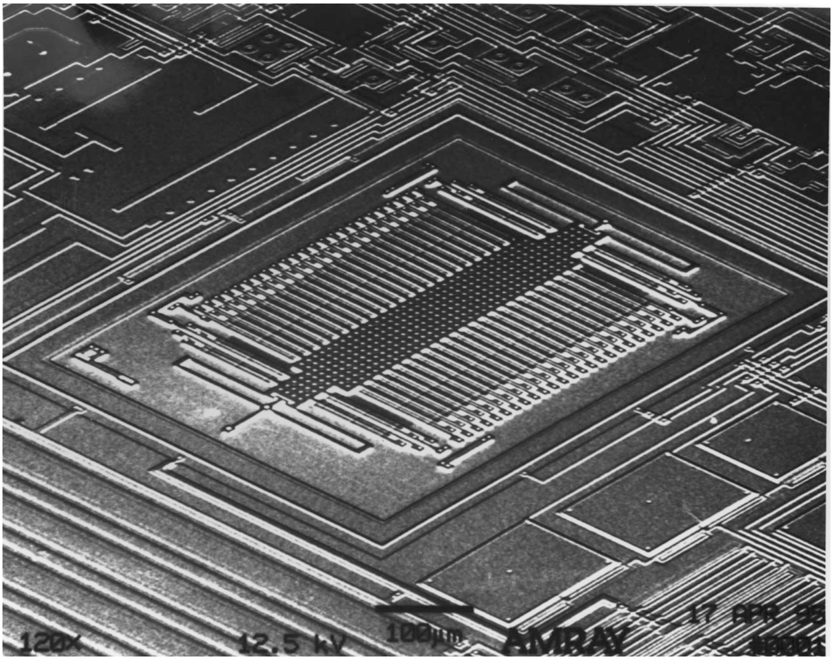

FIGURE 1 Typical MEMS structures are very planar, but they can be several hundred microns in area. This structure is about 2 microns thick in polysilicon. Source: Analog Devices, Inc.

MEMS FABRICATION TECHNOLOGIES

Although MEMS fabrication uses many of the materials and processes of bulk and surface micromachined semiconductor fabrication, there are important distinctions between the two technologies. The most significant distinctions between MEMS fabrication and semiconductor fabrication are in the process recipes (the number, sequence, and type of deposition, removal, and patterning steps used to fabricate devices) and in the end-stages of production (bonding of wafers, freeing of parts designed to move, packaging, and testing). The fundamental challenge of using semiconductor processes for MEMS fabrication is not in the type of processes and materials used but in the way those processes and materials are used.

Wafer-to-wafer bonding, a versatile fabrication technique that yields high quality interfaces and bonds, is commonly employed to get around the restrictions in the type of structures that can be fabricated using bulk micromachining. Because anisotropic etching, by definition, only removes material, bonding of wafers allows for the addition of material to the bulk micromachining repertoire. Thus, wafer-to-wafer bonding (bonding under pressure or a combination of pressure and a high voltage across the wafer) of two or more micromachined wafers is used to construct MEMS. Constituent wafers can be bulk micromachined wafers, wafers with prefabricated electronics, or wafers micromachined by other techniques. In many cases, the bonded wafers are silicon-to-silicon, but silicon-to-quartz and silicon-to-pyrex bonds are also common.

Despite the usefulness of bulk micromachining and wafer-to-wafer bonding (and their continuing commercial importance), these micromachining techniques are limiting in the type of features that can be sculpted. Bulk micromachined structures and features are defined by the internal crystalline structure of the material. Fabricating multiple, interconnected electromechanical parts of free-form geometry using bulk micromachining is often difficult or impossible. Although wafer-to-wafer bonding gets around some of these limitations, truly free-form geometries and integrated multicomponent (multiple, interconnected, and cofabricated components) electromechanical structures presently are produced by a relatively new micromachining approach, surface micromachining, that is fundamentally different from bulk micromachining and wafer-to-wafer bonding.

MEMS PROGRAM AT DARPA

The long-term goal of DARPA's MEMS program is to merge information processing with sensing and actuation in order to realize new systems and strategies for both perceiving and controlling systems, processes, and the environment (Department of Defense, 1995). There are many opportunities for insertion of MEMS devices into DOD systems across a number of technologies and products. These include:

- inertial navigational units on a chip for munitions guidance and personal navigation;
- distributed unattended sensors for asset tracking, border control, environmental monitoring, security surveillance, and process control;
- integrated fluidic systems for miniature chemical/biological analysis instrumentation, hydraulic and pneumatic systems, propellant and combustion control, and printing technology;
- weapons safing, arming, and fuzing to replace current warhead systems (to improve safety and reliability);
- low-power, high-resolution, small-area displays for tactical and personal information systems;
- embedded sensors and actuators for condition-based maintenance of machines and vehicles, and for on-demand amplified structural strength in lower-weight weapons systems/platforms and disaster-resistant buildings;

- mass data storage devices for storage densities of terabytes per square centimeter;
- integrated microoptomechanical components for identify-friend-or-foe (IFF) systems, displays, and fiberoptic switches/modulators; and
- active, conformal surfaces for distributed aerodynamic control of aircraft, adaptive optics, and precision parts and material handling.

Chemical and Biological Agent Detection As the 1994 chemical-agent attacks on the Tokyo subway system demonstrate, chemical and biological agents are a continuing and pervasive threat. User-friendly miniature devices are needed that can be used to perform key missions, such as nuclear, biological, and chemical (NBC) operations; treaty verification; cargo inspections; and detection/identification of fuels, explosives, and illegal drugs. MEMS research and development progress in the next 5 years may result in a variety of small, low-cost, low-power portable analytical instruments having compact versatility and a built-in self-test/calibration feature. For example, an ideal MEMS NBC detector, with a small display, could be developed that would be an integral component of each gas mask. A detector of this type could be mounted as well on other items of military equipment. These MEMS devices would enable the quick detection, alarm, and identification of threat agents, and thus could also verify that decontamination efforts were effective. Such capabilities would eliminate the need for many specialized teams that currently must be dispatched to a reported contamination site.

Mass Data Storage Mass data storage requirements continue to increase as the military moves toward increased digitization. Future tactical computing systems must be small, light, and often low power to be useful to highly mobile forces. For example, a dismounted reconnaissance team would need a system that could hold several digital maps, photographs, field manuals, and databases—potentially requiring 10 gigabytes or more of storage. No portable battery-powered data storage system exists that can support this need.

Both MEMS-enhanced conventional magnetic disk drives and future atomic-resolution data storage systems fabricated on silicon substrates and integrated with signal processing electronics substantially will decrease the size, weight, power requirements, latency of access, failure rate, and cost of data storage. Advanced tunneling-based write-once, read-many-times (WORM) devices offer as much as 100,000 times the storage density of a current CD-ROM. Microdisks, when coupled with advances in low-power computing and displays, would enable major advances in portable electronic devices. If this technology were applied only to portable devices, one could easily envision one digital assistant (with an embedded MEMS disk drive) being issued to each service member. This would result in a minimum DOD market of 1.5 million units.

Aircraft Performance Aircraft development requires continued efforts to squeeze every possible ounce of performance into a design enabling an aircraft to travel faster and farther, and with greater payload, greater maneuverability, and higher efficiency. These goals could be realized through use of distributed MEMS sensors and actuators on the wing flaps, controlling the separation of leading-edge vortices. Active deferrable surfaces also could be applied to rotor blades on helicopters to achieve greater lifting efficiency, on submarine surfaces to reduce noise, and as advanced sonar with multiple arrays.

Structural Strength In weight-critical applications, increasing the strength-to-weight ratio of structural components offers improvements in performance. MEMS devices can be surface mounted or embedded into advanced and conventional structural members both to monitor static and dynamic loading conditions and then to react as required in order to provide localized strengthening. With distributed sensors and actuators injecting the right amount of energy at the critical time and place, structural components will become stronger for just those few necessary microseconds. The potential exists to create materials that are six to ten to theoretically a hundred times stronger than what the Euler buckling theory would predict. These materials then could be used in aircraft as well as earthquake-resistant buildings.

MEMS R&D Strategy

The MEMS research and development strategy at DARPA is as follows:

- Invest in advanced MEMS devices and systems, leading toward MEMS with higher levels of functional capability, higher levels of integrated electronics, and greater numbers of mechanical components. Activities in this area will accelerate both the development of actuator-enabled applications and the shift from discrete MEMS component manufacturing to the manufacturing of integrated MEMS devices. Focused thrusts include the development of new materials, devices, systems, fabrication processes, and interfacing/packaging techniques.
- Invest in the development of a MEMS infrastructure by developing support and access technologies, including electronic design aids and databases, shared fabrication services, and test/evaluation capabilities. Infrastructure development activities will increase and broaden the pool of MEMS designers; will enable rapid, timely, and affordable access to MEMS technologies for evolving needs; and will create a national mechanism for cost-effective MEMS prototyping and low-volume production. An ongoing project supported by DARPA offers regular, shared access to a single common MEMS fabrication process, which already has been employed by over 300 users at service/federal laboratories, domestic companies, and universities. More than half of the users (and all of the small businesses) are getting their first and only access to MEMS technology through this shared fabrication service.

- Invest in activities to accelerate the insertion of presently available or near-term commercial MEMS products into military systems and operations; examples include munitions safing and arming and condition-based maintenance. In this area investments focus on improved and affordable manufacturing resources, assembly/packaging techniques, and methods of assessing and qualifying device performance and reliability. Activities encourage and are aligned with industry-formed teams that speed the introduction and use of MEMS fabrication processes and products.
- Coordinate and complement federal programs by establishing a DOD and interagency MEMS specialists group that is chaired by a representative of DARPA. Examples of ongoing activities in this area include coordinated projects in fluid dynamics and integrated MEMS fluidic devices (Air Force Office of Scientific Research and DARPA) and in materials standards and databases (National Institute of Standards and Technology and DARPA), as well as a project to broaden MEMS education and training programs, to increase the number of qualified MEMS instructors, and to couple these instructors with shared fabrication services (National Science Foundation and DARPA).

MARKET TRENDS

Forecasts for MEMS products throughout the world show rapid growth for the foreseeable future. Early market studies projected an eightfold growth in the nearly $1 billion 1994 MEMS market by the turn of the century, but more recent estimates are forecasting growth of nearly 12 to 14 times today's market, reaching $12 to $14 billion by the year 2000. Whereas sensors (primarily pressure and acceleration) are the principal MEMS products produced today, no single product or application area is set to dominate the MEMS industry for the foreseeable future, since the MEMS market is growing both in the currently dominant sensor sector and in the actuator-enabled sectors. Furthermore, because MEMS products will be embedded in larger non-MEMS systems (e.g., automobiles, printers, displays, instruments, and controllers), they will enable new and improved systems with a projected market worth approaching $100 billion in the year 2000. Although MEMS devices will be a relatively small fraction of the cost, size, and weight of these systems, MEMS will be critical to their operation, reliability, and affordability. MEMS devices, and the smart products they enable, increasingly will be the performance differentiator for both commercial and defense systems.

MEMS ROADMAP

Figure 2 illustrates the central concept of this technology, which is the merger of computation with sensing and actuation. As we view the breadth

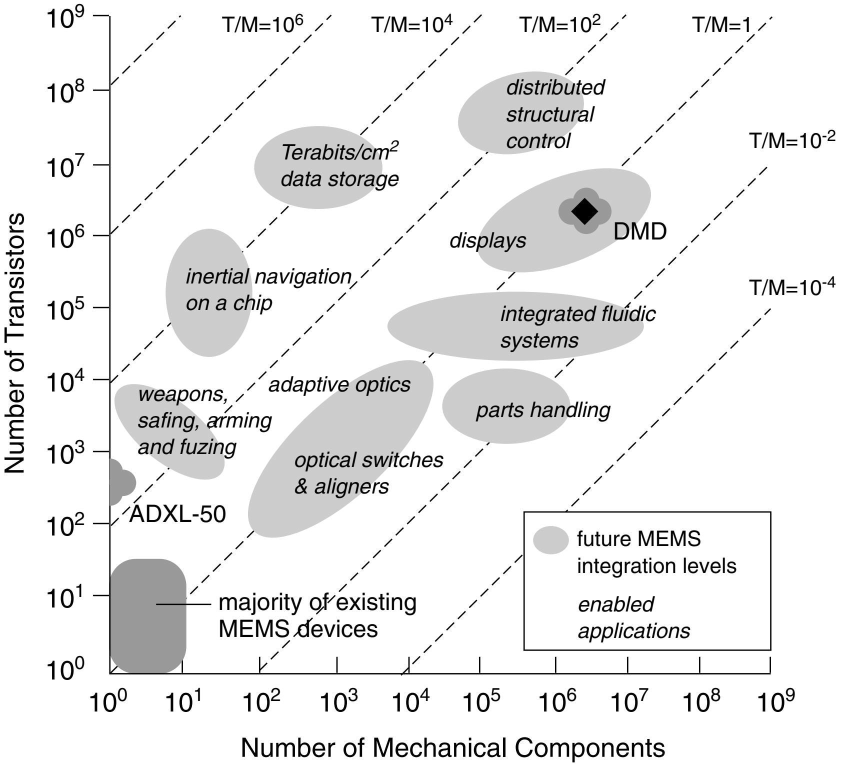

FIGURE 2 MEMS technology trends and roadmap. Log-log plot of number of transistors merged with number of mechanical components for MEMS devices and systems. Contours of equal transistors-to-mechanical-components ratios (T/M) are lines of 45° slope. Lines representing T/M ratios ranging from 10^{-4} to 10^{6} are shown for reference. The resulting map represents a quantitative way to measure and track MEMS technology advances across different application areas. Source: Reprinted with permission from Scientific American (Gabriel, 1995).

and spectrum of applications, it is important to understand the underlying similarities of all of these different application areas. Along the vertical axis is the number of transistors, which is a rough measure of the increasing ability to compute. Along the abscissa is the increase of the log plot of the number of mechanical components, which is the increasing ability to sense and act.

The majority of existing MEMS devices are down in the lower left-hand corner, where devices have a few mechanical components with a few transistors. The real potential and application area is going to be as we move out from the corner and explore increasing levels of integration and increasing levels of sensing and actuation. Two representative examples are the ADXL-

50, an integrated surface micromachined accelerometer that is a single mechanical component with a few hundred transistors, and the digital micromirror display (DMD), which in its high-definition version has two million mirrors and about twelve million transistors. There is a lot of space left to explore. The DARPA program is pushing the edges of the envelope to explore the application possibilities.

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Fabrication Technology and the Challenges of Large-Scale Production

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As the commercial and military implementation of microelectromechanical systems (MEMS) technology solutions moves further up the line from research to consumer and commodity applications, the need for a robust manufacturing technology base for MEMS continues to increase. MEMS, the merging of computation with sensing and actuation into an integrated system-based solution for problems pertaining to the physical world, has benefited greatly and grown rapidly out of the widespread manufacturing infrastructure existing in the United States. The U.S. approach to MEMS involves applying the repetitive-layering, batch-processed wafer methods of the integrated silicon circuit manufacturing industry (the IC industry) in order to achieve revolutionary strides in mechanical miniaturization and system integration (Figure 1). This outgrowth from the IC industry has both benefits and pitfalls; capitalizing on the benefits and navigating the pitfalls will determine our success in moving from current low or sporadic MEMS volumes to high-volume successes demanding large-scale production capabilities.

One of the many benefits MEMS technology derives from its common base with the IC industry is the methodology behind its fabrication sequences. Most MEMS processes can be decomposed into a repeating series of material deposition, patterning, and subsequent removal of specific areas of the material. This layering is repeated until the basic structure is created either on or within the silicon wafer. However, although many of these steps, or unit processes, are similar to those used in IC processing, the mechanical nature of MEMS puts additional stringent requirements on the processes. Beyond the fabrication of the basic wafer structure, the releasing of the structures, the handling of these released wafers or die, the packaging, and the testing of the

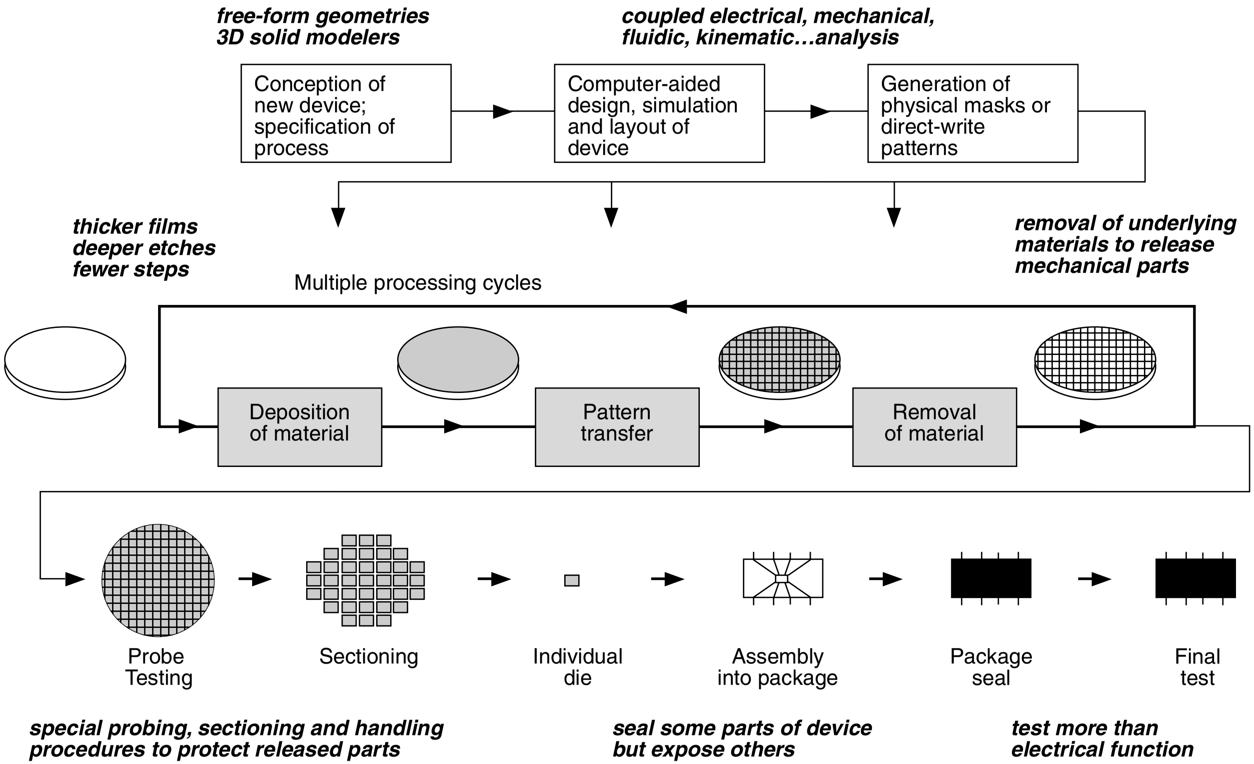

FIGURE 1 MEMS technology builds from the basic silicon ICs manufacturing process flow. Some of the significant distinctions between MEMS and ICs are noted in bold italics. Source: Electronics Technology Office, DARPA.

MEMS devices all can challenge even the most sophisticated and technically advanced manufacturing line.

Examples of some of the areas in which MEMS processing differences continue to challenge the norms established by both the IC fabricators and equipment manufacturers include the following.

DESIGN AIDS

Creation of new ICs normally entails employing fully integrated computer-aided design tools, from creation through completion. For MEMS, however, these tools are just beginning to be developed for commercial activities, and they exist as discrete, stand-alone programs relevant to only a small piece of the design-simulate-fabricate-validate cycle. One of the most challenging aspects of CAD for MEMS is the multidomain nature of the devices. Whereas electronic circuits function almost exclusively in the electrical domain, MEMS device operation transcends boundaries among thermal, fluid, electrical, mechanical, magnetic, and optical domains. MEMS' need for coupled solutions over several domains challenges the state of the art in CAD.

LITHOGRAPHY

Whereas ICs are pushing the limits of optical lithography down below 0.35 m, MEMS are pushing the same equipment base not to smaller feature size but rather to greater depth of focus. Typical surface micromachined MEMS devices can exhibit 8 microns of topography by the end of the process, compared with 0.5–1.0 micron for advanced IC processes.

ETCHING

This topography generally is created using thicker deposited materials that serve as the active mechanical layers. Once they are patterned lithographically, these thick layers must undergo robust etch processes that have the capability to etch through the layers selectively and anisotropically while still maintaining critical line size dimensions and edge profiles.

PARAMETRIC TESTING

A production IC process is monitored by a regular, well-characterized set of parametric test structures. These structures are designed both to screen the health of the integrated process during fabrication and to act as a prefunctional testing screen. Such a set of parametric test structures is yet to be developed, characterized, and implemented in most of the critical MEMS processes. Although many of the basic resistance, capacitance, and defect density test structures utilized in IC processing can be used, the mechanical nature of the materials for MEMS provides a challenge to the MEMS process engineer attempting to monitor the outcome of the fabrication run. How does one nondestructively measure, monitor, and characterize Young's modulus, residual stress (including gradients), Poisson's ratio, and other material parameters of a deposited film that is intimately affected by both the processing and testing conditions? Does one stack several of these layers together and monitor them?

FUNCTIONAL TESTING

Functional testing of ICs generally is performed at the wafer level, and sometimes again after packaging, and is achieved mostly through the use of high-speed electronic testers capable of producing an input voltage (generally 5V or less) or current and then measuring the state of various output nodes. The driving forces in IC testing have been both the number of electrical inputs and outputs necessary to operate the chip (pin count) and the speed of operation. For MEMS testing, the pin count tends to be extremely low: a few to a few tens of pins. Voltages, however, can range into the hundreds of volts for some actuators. Additionally, with the exception of such notables as the Analog Devices ADXL-50 and the Texas Instruments Digital Light Processors (DLP), most MEMS devices produced today have little if any electronics integrally processed with the mechanical devices. This means that the tester must provide the necessary control and feedback functions as well. Similarly, if the device function is to sense a fluid or chemical presence, a severe "shock," or an optical signal, full functional testing of these devices requires the presence of the appropriate environmental factor.

PACKAGING

Currently, packaging is the Achilles' heel of MEMS manufacturing. Unlike IC packaging, MEMS packaging is an application-specific task and can completely destroy a potential product's ability to reach the marketplace. Generic methodologies for the packaging of classes of MEMS structures currently do not exist, but they are essential to the continued growth of the field. Every company, large or small, that enters the field cannot afford to travel the long route of learning that some of the early MEMS product pioneers have had to traverse. MEMS packages must have the ability to meet at least one or more of the following criteria:

- isolate nonsensing areas from sensing areas, often in harsh, corrosive, or mechanically demanding environments;
- not impede mechanical action, such as tilting, twisting, rotating, sliding, or vibrating;

- allow the transfer of fluids from one region to another;
- allow the coupling of energy, motion, or momentum from one region to another; and
- not transfer mechanical strain, heat, pressure, moisture, outgassing, performance restriction, and so on to the part in the package.

EQUIPMENT

A great majority of those companies currently involved in MEMS fabrication are performing their processing in facilities previously outfitted for IC processing and on equipment that the fast-growing IC industry has outgrown. The extremely large wafer sizes and cutting-edge lithography processes that are the norm in the IC industry currently are not required for MEMS, which allows MEMS fabricators to capitalize their facilities at a fraction of the cost of the newest IC fabs by using "last-year's" refurbished equipment. The down side to this is the limited influence that the MEMS technologists have on the semiconductor processing equipment manufacturers in urging them to develop innovative manufacturing solutions.

The movement of MEMS technology from its current position of "little sister" of the IC industry to dominant force in system manufacturing will require considerable effort on the part of MEMS manufacturers to overcome the impediments to large-scale manufacturing. The closer the MEMS process is to that of the IC process, the easier this transition will be. An example is the Analog Devices (ADI) surface micromachined accelerometer. This MEMS device, rather than being more different, has more in common with the IC technology from which it evolved. For ADI the transition from pilot-line project to major commodity product has been a well-defined path, with reasonable levels of support from existing manufacturing infrastructure.

In contrast are the long growth and development cycles experienced by manufacturers of bulk silicon micromachined devices, which share far less of their processing sequence with ICs than surface micromachining. Although bulk micromachined products have been successful in the marketplace for processing generations longer than surface micromachining, there has been little advance in the state of the art for bulk micromachining. Only recently has advanced reactive ion etching technology been introduced, which will enhance the yield, design, and performance of bulk devices, and this is because this technology is an offshoot of the DRAM market's trench etching requirements. Lithography equipment capable of supporting enhanced two-sided alignment and multiple-wafer aligned bonding has been developed only recently.

These basic perturbations on silicon IC manufacturing technology both enable the field and threaten to hold it back. Silicon IC technology evolved from specialized high-cost tools to low-cost consumer products (smart toasters!?) as a result of the drive exerted by advanced large-scale manufacturing. MEMS technology has received a considerable leg up from the manufacturing equipment, testing, and process engineering technology base established by the domestic IC industry. But unless the key differences and challenges that drive MEMS are adequately addressed and supported through both innovation and manufacturing resources, MEMS will be relegated to a position of "niche market item" rather than the enabling, revolutionary technology toward which it is evolving.

Frontiers in MEMS Design

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From automobiles to operating rooms, microelectromechanical systems (MEMS) products have quietly become a part of our lives. As the capabilities of these devices become more widely recognized, the biggest obstacle to growth of MEMS applications is the design-cycle time. For example, meetings such as this one are both wonderful and frustrating. Tremendous opportunities are presented, with clear importance and immediate impact in other fields of engineering and science, and yet only a handful will be pursued. An hour's worth of technical discussion can generate several man-decades' worth of research ideas. MEMS engineers are in the enviable position of regularly having to choose from dozens of research or development projects, each of which is clearly worthy of effort and will clearly lead to new and useful products or tools. Unfortunately, choosing only some leaves the remainder—the vast majority—of projects unexplored.

The reasons for this are simple. There are not enough MEMS designers, and the design-cycle time is very long. Most major universities are working to rectify the former problem by educating a new wave of MEMS-capable students, and these are being snapped up by U.S. industry as quickly as they earn their degrees. Solving the latter problem, however, is not so simple.

To a large extent, MEMS design is still an art. Many of the products in production today were designed, with essentially no computer support, by intuition and "back-of-the-envelope" calculations. This, in itself, is not such a bad (or unusual) thing, for all design requires creativity. The problem in MEMS is that the validation or rejection of ideas typically must be done by fabrication rather than by simulation, with the result that one iteration of the design loop can take months.

The goals in MEMS design, therefore, are clear: (1) shorten the MEMS design cycle, (2) make MEMS technology easily accessible to engineers in different disciplines, and (3) lower the barriers to entry.

MEMS DESIGN

Because MEMS fabrication is based on integrated circuit (IC) fabrication, the design of MEMS devices ultimately comes down to two tightly coupled tasks. The designer must specify the light and dark shapes on a collection of glass plates, and he or she must specify the sequence of material deposition and removal to be used in conjunction with the transfer of these designs. The designs are transferred from the masks to the materials by photolithography and etching. This sequence of material deposition, photolithographic pattern transfer, and etching is applied repeatedly to build up the desired materials and shapes. The collection of glass plates is known as the mask set, and the specification of deposition and etching parameters is known as the process flow. Together, the mask set and process flow define the materials, geometry, and, ultimately, the performance of the device.

Because there is such a variety of materials and etchants (a chemical or method for material removal) available, and since dozens of masks may be used in sequence in a given process flow, even the shape of the finished parts can be hard to predict, let alone the physical properties of the materials. For example, with three materials and three etchants to choose from in a 10-mask process, there are over three billion ways in which the process can be run. The geometry and material properties of a given layer are affected not only by the parameters of their own deposition and etching but also by the subsequent processing of other layers.

Once the geometry and the material properties are known, the device physics then must be modeled. This task is complicated by the fact that MEMS devices store and exchange energy with their environment in many different ways, including electrical, mechanical, thermal, and fluidic. For a variety of reasons, the coupling among these energy domains typically is stronger for MEMS than for macrosystems, which makes it difficult either to predict device performance based on simulation of a subset of the energy domains or to know which energy domains form the necessary set for simulation.

As MEMS capabilities expand, single-device products have become less common, and collections of devices have been developed as integrated microsystems. Integration of electromechanical elements with active electronics is a typical example of this. Such integration requires an additional stage of modeling, where the individual device models must be linked together and simulated to determine system performance.

DESIGN CONSTRAINTS ARE A "GOOD" THING?

The biggest successes for computer-aided design (CAD) have been in the field of IC design, which would practically cease to exist without CAD. There is valid concern that CAD for "normal-scale" mechanical systems has not progressed as far or as fast as was originally hoped, and it is unrealistic to expect that micro-scale mechanical systems will be any different. This is an important point, and it indicates that we should be cautious in those areas where we hope to apply CAD for MEMS. Certainly, the MEMS design problem described above is a formidable one.

Fortunately, from the perspective of the CAD system designer, the constraints of IC-like fabrication operate in our favor. Although there are many material, deposition, and removal options in MEMS process design, the way in which they are used is very structured and is virtually identical from process to process. This imposes a structure on the problem that can be exploited for process simulation and even process synthesis.

An even more ideal constraint is the use of a single process, with the only design variable being the geometry on the masks. This is very close to the situation in IC design, where two or three classes of process have become dominant. The basic devices (transistors) fabricated in each process are qualitatively similar and differ only in the parameters needed to fit their performance with a standard ordinary differential equation (ODE) model. This imposes a serious constraint on circuit designers, who must work only with the devices available to them in a particular process. On the other hand, it imposes a structure on the IC design problem that has led to tremendous success in that field.

THE FRONTIER

Currently, there are two main thrusts in CAD system design for MEMS. The first is a process-and device-oriented approach, and the second is a systems-design approach. Both approaches promise to greatly decrease the design-cycle time and to increase the probability of generating working devices in "first silicon," the first attempt at production, even for the novice designer.

The Holy Grail for the process and device CAD is the ability to take a mask set and process flow, simulate the three-dimensional geometry and material properties, and solve the partial differential equations (PDEs) describing the device physics in order to determine the static and dynamic performance of the device. These tools will have an immediate impact in the MEMS industry, where much of this work currently is done by hand, and they will also open up MEMS design to a broader audience, enabling engineers to iterate through many generations of virtual prototypes in a period of hours instead of weeks or months.

The systems design approach is based on the existence of several commercially available standard MEMS processes offered by MCNC and MOSIS.[1] Within a standard process, the PDEs that describe devices can be reduced to ODEs given parameters by key dimensions. These dimensions can be used to generate mask geometry automatically from parametric description. Networks of devices can be simulated by creating a graph with device dynamics at the nodes and energy flow through arcs connecting the nodes. This nodal analysis approach is the basis for some of the most successful electrical circuit simulation tools (SPICE, SABER). In this way, complex systems can be designed and simulated from previously tested parameter-given components. Design-cycle times can be reduced to minutes, and the probability of a functional part increased dramatically.

The intent of this latter approach is to bring MEMS design to a point comparable to IC design, which will enable first-year graduate students or senior undergraduates to learn significant MEMS design skills in a single semester course. More than anything else, this wave of students and the products they design will make MEMS a ubiquitous part of our daily lives.

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[1] MCNC, located in Research Triangle Park, North Carolina, offers a polysilicon MEMS process, among many other services. MOSIS, located at the University of Southern California's Information Sciences Institute in Marina Del Ray, California, provides access to several IC processes that can be used for MEMS.

Large-Market Applications of MEMS

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After the initial overhype in the early 1980s, the return to realism in the late 1980s, and the persistency of the early 1990s, the field of microelectromechanical systems (MEMS; Petersen, 1982) is, from a commercial viewpoint, entering an era of maturity, where the largely academic research of yesterday is now unmistakably making the transition into ever-growing numbers of industrial and commercial ventures. The entire field of MEMS has been enabled by the massively parallel fabrication methods established in the semiconductor industry, but the economy of scale and other economic models governing the semiconductor markets are still transposed too often without sufficient differentiation to make rational predictions about the markets for MEMS-based products. And although these parallels are both undeniable and enabling, the successful MEMS venture today is likely to be the one that focuses on differences rather than parallels with mainstream semiconductor markets. It is essential to recognize that the primary challenges in the MEMS field, as well as the barriers obstructing its advancement, are both on a technical and a business level disparate from the classic semiconductor problem set.

BUSINESS CHALLENGES

Key business issues characterizing the MEMS field are volume/cost, time to market, and infrastructure. The single most important distinction between a MEMS and a Very Large-Scale Integration (VLSI) mindset is the lack of a MEMS "transistor"—that is, the lack of a generic element allowing one to build extremely diverse, function-spanning application areas, essentially by implementing appropriate interconnection patterns within a large collection of the generic elements. The ideal VLSI paradigm holds almost perfectly for digital circuitry, which operates in a single boolean domain where the system operation is described in terms of a single-state variable (V) and where there is, in first order, no cross-term coupling via other domains between the elements. For analog circuitry, however, the paradigm holds to a lesser extent, because a first-order description of the interaction between the elementary circuit elements requires a second variable (V,I). The one additional variable introduces the issues of input and output impedances, mutual loading of circuit elements, linearity, and so on, which accounts for the longer design cycle, the slower time to market, and the higher cost per function characteristic of analog circuits. The generic elements are less generic and more application specific than in digital circuits, and analog-automated design is challenging research rather than the routine research tool that digital-automated design is.

These considerations are taken to an entirely new level in the context of MEMS-based devices, which operate not only in the electrical domain but, by definition, in the mechanical domain, as well as often in a third or fourth energy domain (thermal, optical, etc.), and, typically, are mutually coupled and analog. For all practical purposes, there is no MEMS generic component, and there never will be one. This should not be a show-stopper, but it does have far-reaching consequences on time to market, cost/volume, and infrastructure, as well as on markets that can reasonably be addressed with MEMS-based products.

Because the design and, to a certain extent, the fabrication of MEMS-based products are largely application specific and do not comply with the VLSI paradigm, the development cycle for MEMS is typically long. Also, in the typical case, several cycles are still required to meet all design specifications because of the current unavailability of a complete set of mature simulation tools for coupled domain modeling. The time to market of existing MEMS products, therefore, often is reported to be 10 years or longer (Walsh et al., 1996), and the associated development cost can be recovered only if a large volume market exists for the product. The economy of scale that rules the semiconductor industry in general obviously also requires the existence of large volume markets because of the high infrastructure investment cost, but the subtle difference is that MEMS, unlike mainstream electronics, requires a large market for the product, not just for the technology. This is clearly a much harder criterion to meet. To date, successful cases include mechanical sensors for the automotive (pressure and acceleration) and medical industries (disposable pressure sensors) and thermal inkjet (TIJ) printheads. Emerging markets seem to be in optical displays and in microfluidics handling systems for the medical industry.

The common scenario after introduction of the MEMS devices into the mass markets for which they were initially developed, is cross-fertilization of a variety of smaller markets such as consumer electronics. Examples are the pressure sensors in altimeters, scuba diver wrist watches, or vacuum cleaners, and accelerometers in washing machines, toys, or golf clubs. Currently, the most viable approach to entering niche markets directly with custom-developed MEMS devices is to "piggyback" on an established technology, design within the given limits of that technology, and target such high-margin markets as biomedicine or the military. This is the avenue pursued by a multitude of small MEMS startups. Again owing to the inherent application specificity of MEMS, a "silicon foundry" concept is much more difficult to implement than it is for mainstream semiconductor work, although promising efforts are being undertaken in the United States (DARPA and MCNC), as well as in Europe (NEXUS) and Japan. It is clear, though, that MEMS foundry processes will never aspire to reach the same levels of generality and breadth of applicability as the standard semiconductor foundries, simply because of the different nature of the problem. For practical purposes, MEMS development is, unlike custom integrated circuit design, less of a "software" activity and much more of a "hardware" activity, where most of the added value is realized at those locations having a strong internal development capability. The balance is likely to shift in the future, but the scale is unlikely to tip.

TECHNICAL CHALLENGES

The technical challenges of the field are threefold; there are important science barriers, engineering barriers, and design barriers. The main science barriers in the MEMS arena are related to material properties. The effective material properties of the materials used to produce these micromechanical components depend not only on the actual material used but also on the way the material is deposited, as well as on the whole series of subsequent treatments. Often, the structural properties, such as E-modulus and built-in stress, are not only dependent on the deposition parameters but on the actual equipment used, and possibly even the history of the equipment. Predictability and reproducibility can be serious issues depending on the design and materials choices; they are typically less of a concern for single-crystal silicon microstructures because of the inherent predictability of this material but remain major concerns for polysilicon, metal, or polymer structures. Currently, the best defense is tolerant design.

The main engineering barriers are related to multidomain optimization and packaging. The coupled domain operation that is so characteristic for these devices is not only an issue in MEMS design but is equally a concern in MEMS fabrication. Combining electrical functionality with mechanical functionality in a single component/structure/material requires compromising between optima in different domains (e.g., the optimum deposition conditions for "electrical" polysilicon can be different from the optimum conditions for "structural" polysilicon). In general, this has the effect of narrowing process windows; sometimes, no window can be found. In practice, however, packaging of MEMS devices is often the main engineering challenge. Packaging is not a trivial matter, since the primary purpose of the package (i.e., protecting the die from the environment) is in direct conflict with the purpose of the MEMS die (i.e., sensing or actuating the environment). In addition, the package is highly application specific and often does not benefit from economy of scale in case the packaging is not based on batch processes. As a general rule and with few exceptions, packaging is the cost-dominating factor in producing MEMS products. This is a strong incentive to incorporate as many packaging functions as possible in the MEMS die itself. Examples are overrange protection, stress decoupling, electrical shielding, and connectors.

Currently, the main design barrier in the MEMS field is the lack of mature coupled domain modeling tools, which keeps multiple-iteration "trial-and-error" design as well as multiple iteration prototyping methods alive. Modeling tools generally are recognized as a high priority for the advancement of the MEMS field, though, and progress is being made rapidly.

THERMAL INKJET CASE STUDY

A success story concerning the introduction of MEMS technology in a high-volume market involves the disposable printheads in the TIJ printer products now dominating the low-end color printing market (Courtney et al., 1994). Part of the reason for this success is that the specific problem set of the application was positioned favorably with regard to the MEMS business and technical barriers outlined earlier.

Operating Principles and Xerox Implementation

TIJ printers operate by the application of a short electrical pulse to a resistive microheater, which then rapidly heats a thin layer of ink at the heater surface. During heating, the ink in contact with the heater surface superheats, and a vapor bubble is nucleated. The nucleation of the vapor bubble is dependent on the heater surface and the ink composition, as well as on the form of the thermal input. As the vapor bubble grows, it transmits momentum to the surrounding fluid and ejects ink out the channel nozzle in the form of a well-defined drop. After completion of the heating pulse, the vapor bubble collapses, and ink refills the channel from the ink reservoir.

Xerox' TIJ implementation consists of wafer-level bonding a bulk-micromachined silicon "channel wafer" to a metal-oxide semiconductor (MOS) "heater wafer" with an intermediate polyimide spacer layer, as shown in Figure 1. The channel wafer contains an array of bulk-micromachined fluid-flow channels, local ink reservoirs, and ejector nozzles. The heater substrate is a MOS wafer containing polysilicon heater elements, power drivers, and addressing logic.

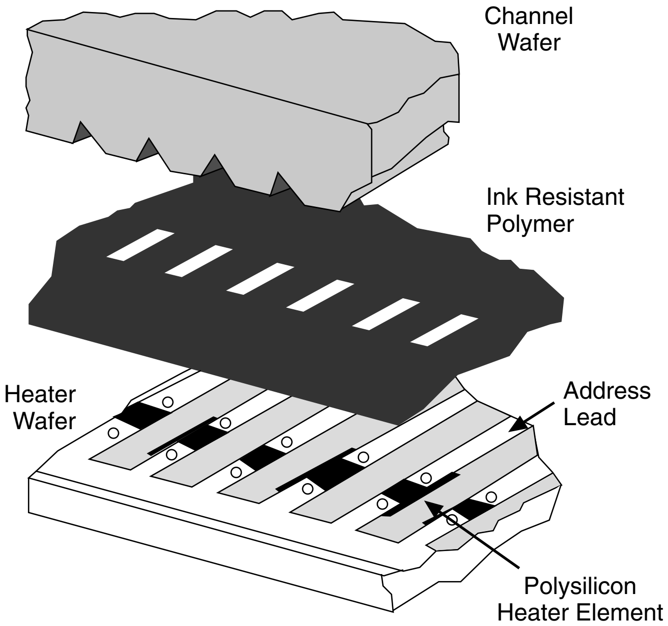

FIGURE 1 Xerox Corporation's Thermal Inkjet (TIJ) printhead implementation. Source: Xerox Corp.

Business Challenges

The large market was "bootstrapped" in this case by the introduction of color printers with unprecedented performance/cost ratios. MEMS technology was the enabler for the product that created the large volume market required to sustain the MEMS investment. The market volume has been further sustained over time because the TIJ printheads are disposable—that is, the MEMS components are embedded in consumable supplies. Time to market is typically not excessive in these applications, because TIJ heater wafers can be piggybacked readily on slightly modified baseline MOS processes and because the fluid-flow pathways are relatively uncomplicated micromachined parts. In addition, the first-order coupling between domains (electrical-thermal-fluid dynamics) is fairly well understood in this case, and mature thermofluidic simulation tools are commercially available. The MEMS-specific infrastructure investment can stay moderate because the application does not demand state-of-the-art linewidths or feature sizes. Depreciated process lines can be revived and can deliver another life-cycle of perfectly acceptable service.

Technical Challenges

Important material-related challenges in TIJ are cavitation and corrosion. Without cavitation protection, the lifetime of a polysilicon film is very limited when the film is exposed to the cyclic and focused pressure pulses of up to 100 atm that occur during vapor bubble collapse. A Tantalum barrier is deposited over the polyheaters for cavitation protection. Other customizations of the heater wafer baseline process satisfy requirements of thermal efficiency, heater stability, and protection from the ionic ink environment. Thermal efficiency is achieved through a thicker-than-usual field oxide to avoid thermal losses to the substrate, and the MOS circuitry is protected from the ionic ink environment with an extra polyimide passivation film. The ink cartridge (i.e., packaging) is typically the cost-dominating factor in disposable TIJ printheads. One approach to reduce packaging/interconnect expense is to integrate addressing and multiplexing logic onto the ejector die to minimize the external lead count.

ACKNOWLEDGMENTS

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INNOVATIONS IN MATERIALS AND PROCESSES

Cellular Materials: Structure, Properties, and Applications

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Cellular materials—in the form of either honeycombs, with two-dimensional prismatic cells, or foams, with three-dimensional polyhedral cells—are widespread (Figure 1). Processes now exist for making these cellular materials from almost any solid material, including polymers, metals, ceramics, and glasses. Their cellular structure gives rise to stress-strain curves with a characteristic shape: initial linear elasticity, caused by cell wall bending, is followed by a period of roughly constant stress, resulting from cell collapse, and then a final sharp increase in stress at the point at which opposing cell walls touch and the material densifies (Figure 2). Also, the properties of a foam for a particular application can be controlled by the engineer by suitable selection of the solid material from which the foam is to be made, the volume fraction of the solid, and whether or not the cells are open or closed.

The low density of cellular materials is widely exploited in the production of buoyancy devices and of lightweight cores of structural sandwich panels. The combination of low compressive strength and high strain capacity makes cellular materials ideal for absorbing the kinetic energy of impacts—they can absorb large impact energies while generating only low stresses on a packaged object. For this reason, they are the materials of choice for impact protection in everything from crash helmets to packaging for electronic devices. Also, the high volume fraction of low thermal conductivity gas within the cells of a closed-cell foam makes them valuable for widespread use as thermal insulation, and open-cell foams can be used as filters and membranes.

Our research has focused on modeling the mechanisms of deformation and failure in cellular solids to give expressions for their mechanical properties, such as stiffness and strength. We have used these models to improve

FIGURE 1 Scanning electron micrographs of engineering cellular materials: (a) polyethylene, (b) copper, and (c) mullite. Source: Gibson and Ashby, 1988.

techniques for selecting the optimum foam for the core of a structural sandwich panel as well as for energy absorption devices (Gibson and Ashby, 1988).

To improve our understanding of the mechanical behavior of a variety of widespread natural cellular materials, including wood, cork, and trabecular bone (Figure 3), we have used the models developed for engineering honeycombs and foams. For instance, wood is much stiffer and stronger when loaded along the grain than across it; we have found this anisotropy arises, in part, from the composite nature of the cell wall in wood and, in part, from its cellular structure: loading along the grain axially compresses the cell walls

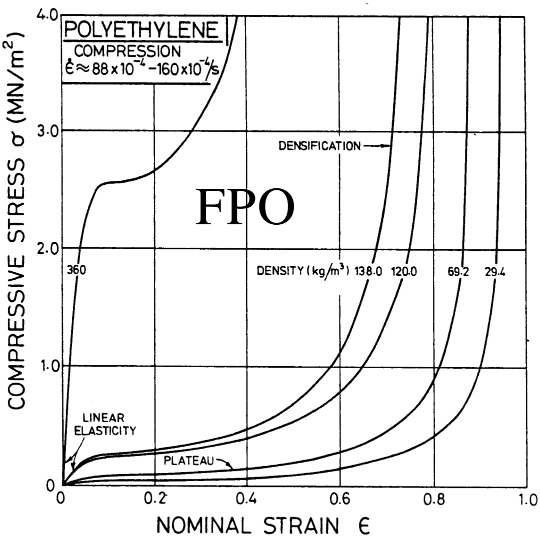

FIGURE 2 Compressive stress-strain curves for flexible polyethylene. Source: Gibson and Ashby, 1988.

a

b

FIGURE 3 Scanning electron micrographs of (a) Norway spruce and (b) human vertebral trabecular bone. Source: Gibson and Ashby, 1988.

while loading across the grain bends them. Currently, we are studying progressive damage, by creep or fatigue, in trabecular bone, which is the porous bone occuring at the ends of the long bones and making up the bulk of the vertebrae. Patients with osteoporosis are at increased risk of hip, wrist, and vertebral fractures, all of which largely involve trabecular bone. About 10 percent of hip fractures and 50 percent of vertebral fractures are thought to be the result of the activities of daily living rather than a sudden impact such as a fall, and understanding how this progressive damage occurs in osteoporotic bone is essential for evaluation of fracture risk.

Here, we briefly describe models for the mechanical behavior of cellular materials, compare the models with data, and note some of the remaining questions to be answered. Two applications of cellular materials, in sandwich panels and in energy absorption devices, then are discussed. Finally, we describe new directions for research on cellular materials.

MODELING MECHANICAL BEHAVIOR

The mechanical properties of cellular solids can be described by using structural mechanics to analyze their mechanisms of deformation and failure. The stress-strain curve is characterized by three regimes (Figure 2): (1) Initial linear elastic behavior is caused by bending of the cell walls. (2) At sufficiently large stresses, the cells begin to collapse, either by elastic buckling, plastic yielding, or brittle fracture of the cell walls; cell collapse begins at a weak layer and then propagates through the rest of the material, giving an almost constant stress plateau. (3) Finally, at large strains, all of the cells have collapsed; further strain then loads the cell walls against each other, leading to a rapid increase in stress at densification. The simplest cellular material in which to analyze this is a two-dimensional honeycomb with repeating hexagonal cells (Figure 4a). Its properties can be described by ana-

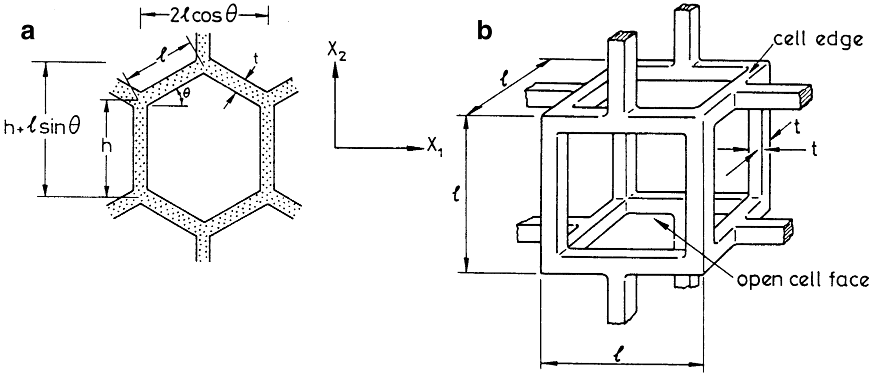

FIGURE 4 (a) Hexagonal unit cell of two-dimensional honeycomb. (b) Cubic cell used for dimensional analysis of a foam. Source: Gibson and Ashby, 1988

lyzing the response of a unit hexagonal cell. The elastic moduli, the compressive strength, and the brittle fracture toughness depend on the properties of the solid from which the honeycomb is made, the volume fraction of the solid (raised to some power), and the geometry of the cells. For instance, the Young's modulus, E^*, of the honeycomb with the unit cell shown in Figure 4a is

$$\frac{E^*}{E_s} = \left(\frac{\rho^*}{\rho_s}\right)^3 \frac{8\cos^4\theta(h/\ell+\sin\theta)^2}{(h/\ell+2)^3\sin^2\theta},$$

where E_s is the Young's modulus of the solid from which the honeycomb is made, ρ^*/ρ_s is the density of the honeycomb divided by that of the solid from which it is made (i.e., the relative density of the honeycomb), and h/l and θ (shown in Figure 4a) describe the cell geometry.

The more complex geometry of three-dimensional foam materials makes analysis more difficult. We have used dimensional arguments to give the relationship between foam properties and those of the cell wall material and the relative density; they do not give the dependence of foam properties on cell geometry (Figure 4b). Comparisons of typical results of the dimensional analysis with data are given in Figure 5.

More recently, numerical techniques have been used to give more detailed analyses. For instance, the unit cell analysis of a two-dimensional honeycomb does not allow the effect of irregularities in the cell geometry or defects in the structure (such as missing cell walls) to be modeled. Finite element analysis of a honeycomb with a random cell structure shows that the random cell structure has little effect on the elastic moduli but reduces the strength of the honeycomb by about 25 percent compared with that of an

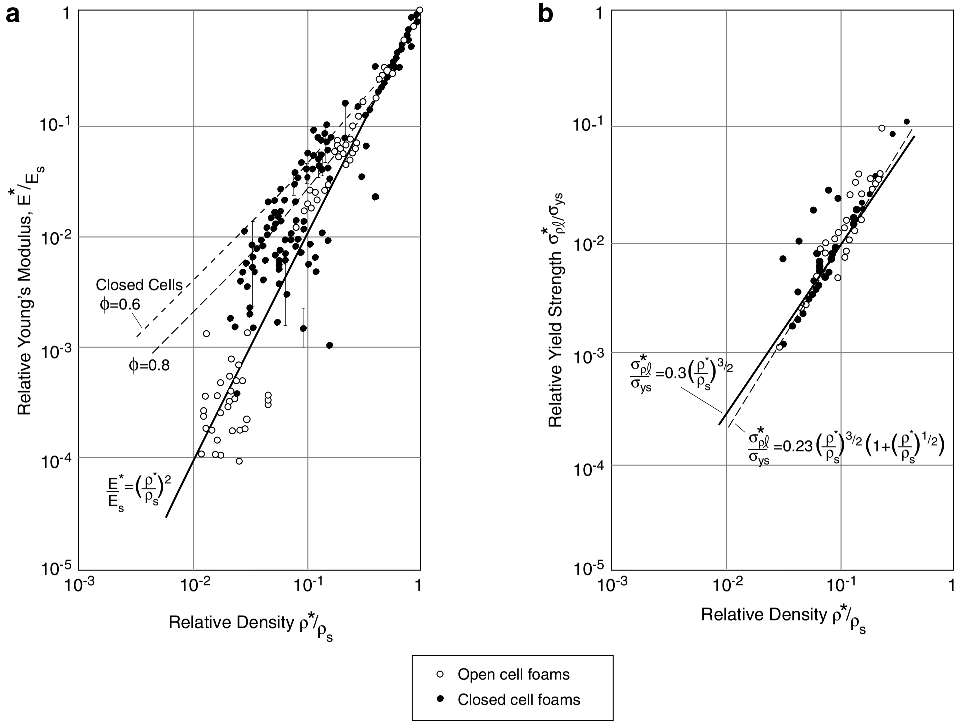

FIGURE 5 (a) The Young's modulus of a foam, E^*, relative to that of the solid from which it is made, E_s, plotted against the density of the foam, ρ^*, relative to that of the solid, ρ_s. (b) The plastic collapse stress of a foam, σ^*, relative to the yield strength of the solid from which it is made, σ_{ys}, plotted against the density of the foam, ρ^*, relative to that of the solid, ρ_s. Source: Gibson and Ashby, 1988.

equivalent regular honeycomb. Removal of cell walls has a dramatic effect on strength: removal of 10 percent of the cell walls results in a reduction of 70 percent in compressive strength (Silva and Gibson, in press; Silva et al., 1996). Finite element analysis of three-dimensional foams allows the effect of cell geometry to be determined as well as allows irregularities in the cell geometry or defects in the structure to be examined (Warren and Kraynik, in press).

Although there has been considerable progress in understanding the uniaxial behavior of cellular materials, further research is required to study multiaxial postyield behavior, fatigue, creep, and fracture.

APPLICATIONS

Structural members with two stiff, strong faces or skins separated by a lightweight core are known as sandwich panels. Separation of the skins by the core increases the moment of inertia of the panel with little increase in weight, thus producing an efficient structure for resisting bending and buckling loads. Because of this, sandwich panels often are used in applications where weight-saving is critical: in aircraft, in portable structures, and in sports equipment.

Consider the design of a downhill ski for instance. There is a particular value of bending stiffness for which the ski is designed; a ski that is too flexible or too rigid obviously is undesirable. The length and width of the ski are given. And let us assume that the designer has chosen the materials for the skin and foam core of the ski. The designer then wishes to find the values of the face and core thicknesses and the density of the foam core that minimize the weight of the ski for the required stiffness. The weight of the ski is the objective function; this depends on the densities of the face and foam core material as well as the length, width, and face and the core thicknesses of the ski. The required bending stiffness is the constraint; it depends on both the flexural rigidity of the faces as well as the shear rigidity of the foam core, which can be written in terms of the core density using the models described above. The bending stiffness constraint equation is then solved in terms of the core density, and this is substituted into the weight equation. Setting the partial derivatives of the weight equation with respect to the face and core thicknesses equal to zero then gives the minimum weight design for the ski. This same procedure can be applied to other, more complex loading geometries.

Foams are also widely used as packaging and protective padding. The goal here is to select a foam that will absorb the energy of the impact while keeping the peak force on the object to be protected below the limit that will cause damage or injury. The capacity of foams to undergo large deformations at almost constant load makes them especially good at this. The impact

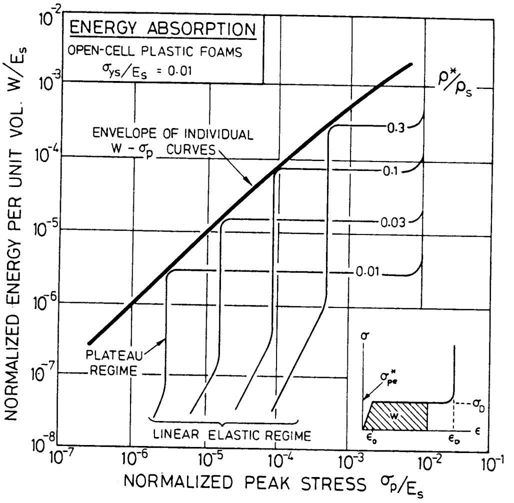

FIGURE 6 Energy absorbed up to a given peak stress plotted against the peak stress. Both axes are normalized by the Young's modulus of the solid from which the foam is made, E_s. Source: Gibson and Ashby, 1988.

performance of foams can be summarized in energy absorption diagrams (Figure 6), which can be made either from experimental stress-strain curves or from the results of the models described above. The diagrams allow the designer to select the thickness and density of a foam required for a given packaging application.

NEW DIRECTIONS

Recently, several new processes for producing cellular metals have been developed, offering several advantages over conventional cores in structural sandwich panels. Current honeycomb-core sandwich panels have three limitations: (1) they require adhesive bonding, (2) they are subject to penetration by moisture, leading to damage difficult to detect, and (3) they cannot be formed into complex shapes. The foamed metal processes allow the production of panels with integral skins, eliminating the need for adhesive bonding and reducing the risk of delamination. The use of closed-cell metal foams reduces moisture penetration and any resulting damage. The belief now is that current processes can be modified to produce more-complex shaped components. Current foam core panels usually use either expanded polystyrene or rigid polyurethane foam cores; their structural application is limited by the low creep and fire resistance of the polymer foam cores. Metal foam core panels, however, have improved performance in both creep and fire resistance. Together with a number of collaborators, we plan to evaluate the potential of metal foam use in lightweight structural components.

Novel biocompatible cellular materials are being developed in the new field of tissue engineering, which aims at growing new, healthy tissue within the body to replace defective tissue. The general principle is to provide a porous scaffold onto which cells will grow. One of the first examples of such a porous scaffold was an open-celled, foam-like collagen material used to regenerate skin cells on burn victims (Yannas, 1995). Over time, as the skin cells grow, the collagen scaffold resorbs into the body, leaving only the healthy new tissue behind. In a further development, the scaffold can be designed to carry bioactive drugs, such as epidermal growth factor, which act to increase tissue growth. Porous scaffolds for peripheral nerves, cartilage, bone and bone marrow currently are being studied by a number of researchers (Ellis and Yannas, 1996; Paige et al., 1996).

ACKNOWLEDGMENTS

This paper briefly summarizes work done over a number of years. I would like to acknowledge the contributions of my graduate students and my collaborators. In particular, I thank Professor Michael F. Ashby of Cambridge University's Engineering Department for his contribution to my work on cellular materials. Financial support has been provided by the National Science Foundation, the National Institutes of Health, the U.S. Army, the Office of Naval Research, and the Department of Energy.

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Silicon Satellites

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Silicon, the most abundant solid element in the Earth's lithosphere, is a material useful for spacecraft construction. It is used already as the structural material for microelectromechanical systems (MEMS) because of its high strength (Petersen, 1982), and should be considered for use in spacecraft structures as well. Single crystal silicon, which costs roughly $185 per kg, is stronger than aluminum, stainless steel, or titanium but is less dense. Materials with intrinsically high strength-to-density ratios are particularly valuable for spacecraft owing to launch costs of approximately $10,000 per kg to low Earth orbit (LEO) and approximately $50,000 per kg to geosynchronous Earth orbit (GEO). Single crystal silicon also is a common semiconductor substrate having a thermal conductivity about half that of aluminum, and it is transparent to much of the infrared radiation spectrum. These unique properties, along with its high strength-to-weight ratio, enable silicon to become most of the mass of a satellite; it can function *simultaneously* as structure, heat transfer system, radiation shield, optic, and semiconductor substrate. The benefits of this approach are as follows:

- Reduced parts count owing to integrated electronics, sensors, and actuators on a single substrate.
- Ability to add redundancy and integrated diagnostics without significantly impacting production cost.
- Decreased material variability and increased reliability because of rigid process control.
- Rapid prototype production capability using electronic circuit, sensor, and MEMS design libraries with existing (and future) CAD/CAM tools and semiconductor foundries.

- Elimination of labor-intensive assembly steps (welding, wiring cable harnesses, and so on).
- Automated testing of systems and subsystems.
- Paperless documentation of designs, fabrication processes, and testing.

Semiconductor batch-fabrication techniques enable us to produce low-power digital circuits, low-power analog circuits, silicon-based radio frequency circuits, and MEMS, such as thrusters and acceleration sensors, on silicon substrates. By exploiting these fabrication techniques, as well as by developing laser-based techniques, we will be able to mass produce highly integrated satellites for a number of applications. These silicon satellites are an assembly of thick single-crystal silicon wafers that are monolithic elements (i.e., wafer-scale integrated systems) or "circuit boards" that function as multichip modules (MCMs). The MCM approach is better for near-term, low-volume applications, whereas wafer-scale integration is better for longer-term, high-volume (thousands of units per production run) applications. Silicon satellites can range in mass from picosatellites (1 mg to 1 g mass), through nanosatellites (1 gm to 1 kg mass), to highly capable microsatellites (1 kg to 100 kg mass) that perform various missions with lifetimes ranging from a few days to longer than a decade.

Most spacecraft systems and subsystems can be manufactured on silicon substrates. The Command and Data Handling (C&DH) system, the "brain" of any satellite, is composed already of standard silicon-based digital electronics. The challenge now for silicon satellite design is to provide on-orbit radiation tolerance for silicon shielding thicknesses from 1 mm through 1 cm. This can be achieved by limiting orbit altitudes and inclinations, modifying transistor cell layouts (i.e., edgeless transistors), or incorporating radiation-hard process technologies, such as silicon-on-sapphire.

Silicon satellites will need radio frequency output power levels of between 1 mW and several watts at frequencies of between 500 MHz and tens of GHz. Today's silicon communications circuit technology, driven by the explosive growth in wireless personal communications systems, can be adapted readily for satellite communications from very high frequency (VHF; approximately 100 MHz at the bottom end) through S-band (up to 2.7 GHz). Higher frequencies will require gallium-arsenide substrates, but recent advances in high-resistivity silicon and silicon-germanium (SiGe) technology may allow all-silicon design for operation of up to 40 GHz.

MEMS technology is another enabling technology for silicon satellites. MEMS adds "muscle" and new sensing capability, allowing silicon satellites to perform the functions of larger traditional satellites. Guidance, navigation, and control (GN&C) functions will require micromachined sun sensors, Earth sensors, star sensors, accelerometers, gyros, thrusters, and/or magnetic torque rods. Accelerometers and gyros have been demonstrated already in the laboratory; the challenge is to improve their accuracy and/or performance to match more stringent spacecraft requirements. The Charles Stark Draper Laboratory has demonstrated a 1° per hour drift rate in a micromachined gyro, which is acceptable for some navigational requirements. Micropropulsion systems are being developed at a number of locations, including the Aerospace Corporation and NASA's Jet Propulsion Laboratory. The main impediment to development of these systems has been the leaky nature of MEMS valves. For very small spacecraft, such as picosatellites, the additional challenges of low-power operation and limited angular resolution for optical sensors must be addressed as well.

Silicon satellites offer a revolution not only in spacecraft design but in space system architecture as well. Batch-fabrication techniques will drive system architects to utilize thousands of identical spacecraft or spacecraft systems and to consider short spacecraft lifetimes with periodic or continual replacements. Dense (greater than 500 satellites) LEO nanosatellite constellations could be used for communications and Earth observation. These communications constellations will offer shorter user-to-satellite ranges than conventional space systems, which will allow low-power communications on both the ground and at the satellite. The Earth observation mission allows complete mapping of planetary cloud cover at 1 km resolution every 3 minutes.

In the future, more advanced silicon microsatellites will be composed of physically interconnected modules with distributed intelligence and payload functions. A phased-array communications microsatellite concept for the post 2015 A.D. era, based on intelligent silicon wafer stacks, will be presented. The major challenges will be to fabricate wafer-scale circuitry with high yield, to bond the wafers together reliably, and to provide reliable interconnections for both in-surface and surface-normal data paths that can survive launch loads (acceleration and shock) and thermal cycling on-orbit.

Mass-produced silicon satellites also can be deployed as free-flying elements in local clusters to form a large distributed satellite. Local cluster configuration can be maintained by using active thrusting or by appropriate choice of individual spacecraft orbital elements. Local clusters with effective diameters of greater than 10 km can be created by using several thousand silicon nanosatellites. Accurate knowledge of local position for each spacecraft, as well as management of data flow across this large network, will be required for distributed satellite operation. Possible applications of this technology include space-based radar and radio interferometry.

Silicon satellites can revolutionize the way spacecraft are designed, constructed, and used. Batch-fabrication techniques of semiconductor devices have fueled the "smaller, faster, and cheaper" paradigm in the electronics industry for over 30 years. It is now time to let the same techniques propel the space industry into the next century.

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Novel Ceramic Ferroelectric Composites

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Electronic scanning antennas will be functionally important parts of future commercial and military communications and radar systems. Most current radar scanning is mechanical, owing to the high cost of currently available phased-array antennas, and it relies on a gimbal arrangement to physically rotate/elevate the radar antenna. Therefore, scanning is slow and subject to mechanical failure.

Present phased-array antennas are constructed from ferrite elements. These elements are ferromagnetic and current driven, where the phase shift is caused by a change in the permeability (related to the magnetism) of the material. Although the performance of this type of phase shifter is very good, the material cost alone for each element is roughly \$3,000. Each element then must be hand wired, which further increases the cost by approximately \$2,000 to \$3,000 per element. Thus, in total each element costs almost \$5,000 to \$6,000. An array with roughly 1,000 elements, therefore, is approximately \$5,000,000. This factor has exclusively limited the use of phased-array antennas to strategically dependent military applications.

Ferroelectric materials, however, require a voltage-driven circuit, where the phase shift is caused by a change in the dielectric constant (permittivity, related to the energy storage—that is, capacitance). These types of circuits can be electroded and processed using standard circuit board technology. The materials perform at least as well as the ferrite phase shifters and cost only \$100 per element. The final packaging (including electroding and encapsulation) increases the cost per element by \$100. Therefore, the same array (of 1,000 elements) will cost \$200,000, which is only one-twenty-fifth the cost of the ferrite phased-array antenna.

Other savings realized with the ferroelectric phase shifter concern size and weight. The size is reduced by 50 to 75 percent for the materials alone. Reduction also occurs for the wiring and control circuits, which are reduced in size by another 50 percent. The total electro-optic antenna may be less than one-tenth of the size of the large ferrite array. The weight of the actual materials used is probably similar for the two. However, the amount of ferroelectric material required for any particular application is substantially less. Multiple phase shifters can be produced on a single piece of ferroelectric material. Also, thin films of the ferroelectric material can be used in many of the antenna systems, further reducing size and weight. Circuit board technology can be used to fabricate the antennas, which, again as seen in the semiconductor industry, produces very small, lightweight components and systems.

The problem until now has been that the ferroelectric materials that have produced substantial phase shift have too much loss (~20 dB) and, therefore, are not usable in phased-array antennas. However, the materials being investigated at our laboratory are low loss (~1 dB) yet highly tunable, thus offering excellent properties for use in phased-array antennas. These patented composites combine $Ba_{1-x}Sr_xTiO_3$ (BSTO) with other nonelectrically active oxide ceramics producing break-through electronic properties never previously attained (Sengupta et al., 1995).

As shown in Table 1, the bulk ceramic composites have reduced real

TABLE 1 Electronic Properties of $Ba_{0.6}Sr_{0.4}TiO_3$, $Ba_{0.55}Sr_{0.45}TiO_3$, $Ba_{0.50}Sr_{0.50}TiO_3$, and $Ba_{0.45}Sr_{0.55}TiO_3$/Oxide III Composite Bulk Ceramics, Measured at 1 kHz

Barium Content	Oxide Content (wt%)	Dielectric Constant	Loss Tangent	Tunability	Curie Temp (°C)
Ba = 0.45	0	1,280.83	0.01184	15.20	–45
	10	768.06	0.00068	3.90	–75
	20	418.98	0.00064	2.47	–70
	60	78.81	0.00049	3.67	–95
Ba = 0.50	0	1,907.99	0.05538	25.55	–25
	10	928.01	0.00076	5.48	–55
	20	592.20	0.00073	6.44	–55
	60	77.52	0.00096	3.66	–95
Ba = 0.55	0	2,771.73	0.03904	33.40	–15
	10	1,114.02	0.00094	8.88	–40
	20	742.29	0.00085	8.77	–40
	60	94.59	0.00034	6.46	–50
Ba = 0.60	0	5,160.64	0.00961	56.30	10
	10	1,527.34	0.00162	16.60	–30
	20	1,068.43	0.00194	15.80	–35
	60	116.86	0.00148	9.99	–55

Source: Materials Directorate, U.S. Army Research Laboratory.

dielectric constants, ε′, where ε = ε′ − iε″, and loss tangents, tan δ, which reduce the overall impedance mismatch and insertion loss of the device. These composites include a variety of oxide additives, and they have been developed to include an entire family of materials having electronic properties that can be tailored to any given application. In addition, tunability—the change in the dielectric constant with applied voltage—is maintained at a relatively high level for the dielectric constants of interest (Sengupta et al., 1995).

The temperature dependence of the electronic properties, such as aging and fatigue, also have been investigated. Microwave data were obtained at 10 GHz, as shown in Table 2, using a cylindrical TE_{01} mode-filtered X-band cavity. The minimum thickness limitation of the bulk materials is around 3 mils, which limits their usage to approximately 15 GHz. Initial results concerning the effect of ceramic processing, including the particle size and grain size of the ceramic, on the electronic properties will be presented in terms of additionally refining the ferroelectric/oxide compositions.

To increase the operating frequencies of these phase shifters, we fabricated and electrically characterized films of these novel composites.. Initially, we developed single-layer composites via nonaqueous tape-casting. We then screen-printed the electrode patterns onto the tapes using a cofired ink. The processing parameters for the tape cast and electrode materials were optimized for structural integrity. Finally, we characterized the electrical properties and compared them to bulk ceramics.

As shown in Table 3, the dielectric constants and loss tangents of the tape-cast specimens are similar to the bulk composites but decrease with an increase in oxide content and vary less than 2 percent with change in frequency (from 1 kHz to 1 MHz). The magnitudes of the dielectric constants and loss tangents are very similar to those of the bulk ceramics. Tunability is maintained at 12 percent (with a bias field of 2.00 V/μm), with up to 60 weight percent additive content. This trend was explained previously in the bulk ceramics by the position of the Curie temperatures and the size of the additive (O'Day et al., 1994). Also, laminated stacks with alternating layers of high and low dielectric constant were fabricated for use in a multilayer

TABLE 2 Microwave Properties of $Ba_{0.60}Sr_{0.40}TiO_3$/Oxide III Composites

Oxide III Content (wt%)	Frequency (GHz)	Dielectric Constant	Loss Tangent
30	2.139	646	0.0040
40	1.815	404	0.0042
	3.304	401	0.0051
60	4.581	113	0.0065
	10.02	106	0.012

Source: Materials Directorate, U.S. Army Research Laboratory.

TABLE 3 Electronic Properties of BSTO (Ba = 0.60)/Oxide III Composite Single-Layer Tapes Measured at 1 kHz

Oxide III Content	Dielectric Constant	Loss Tangent	Tunability (%)	Electric Field
0.0	3,192.2	0.0056	43.52	2.00
10.0	1,390.2	0.0015	15.03	2.00
20.0	616.44	0.0012	15.45	2.00
40.0	357.30	0.0041	14.00	2.00
60.0	91.16	0.0008	10.41	2.00

Source: Materials Directorate, U.S. Army Research Laboratory.

ferroelectric composite waveguide. The microwave properties of these waveguide structures have been fully calculated at the 10 GHz frequency region. The thickness limitation of the tape cast specimens is approximately 0.5 mils, which limits their usage to approximately 35 Ghz.

In order to further increase the operating frequency of these devices, we fabricated thin films using the pulsed-laser-deposition (PLD) method. The thin films were deposited on metallized single-crystal substrates, and the top electrodes then were deposited by a sputtering process to form the vertical capacitor structure. Electronic measurements of these structures have shown that the thin films follow similar trends in the electrical properties when compared to the bulk counterparts (Sengupta et al., 1994). It must be emphasized that high tunabilities were achieved in these thin films with much lower applied voltages than those applied to the bulk. It appears that certain specific additives can influence the lowering of the dielectric constant more than others even at a 1 weight percent level.

To produce larger area films of these composites, we utilized the direct-liquid-injection Metallo-Organic Chemical Vapor Deposition (MOCVD) method. We then characterized the electrical properties of the MOCVD films and compared them to those of the bulk thick films and PLD films.

A rigorous investigation of the material characteristics has been performed on all of the specimens included in this study. We have examined the microstructures, including grain size and phase analysis, using SEM and X-ray diffraction (glancing-angle X-ray diffraction was obtained for the thin-film materials), and we have investigated compositional topography using Raman and Fourier transform infrared microprobe spectroscopy, which identifies the reaction zones and provides a compositional topography of the specimens. The analysis of the phase formation and compositional variations has been related to connectivities and to the electronic properties of the materials.

This paper has presented a complete evaluation of the processing, materials characteristics, and breakthrough performance levels of these novel ceramic composites for use in Army electronic devices.

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Co-Continuous Composite Materials from Net-Shape Displacement Reactions

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Despite sizable and sustained federal and corporate investment in the science and technology of inorganic composites, there are few important commercial applications of these materials. The reasons for the sustained investments in research are clear. Appropriate composites may provide a mix of properties unavailable in monolithic materials. Also, many engineering devices or structures can benefit from the tailored properties composites may provide. Composites in which both phases are continuous, or interpenetrate, have received special interest (Clarke, 1992), because in these cases the composite may have some of the approximate macroscopic properties of each phase. For example, one phase may provide strength while the other contributes transport properties, such as thermal or electrical conductivity.

But the reasons for limited commercial application of advanced inorganic composites are less clear. Many of the impediments to application have to do with the cost of creating composites and then processing them to meet the dimensional and functional requirements of the component. Also, it simply takes time for any new material to gain commercial acceptance. This work demonstrates a novel method for producing co-continuous composite components that, in principle, should be inexpensive in large-quantity production. The method (Breslin, 1993) is illustrated for alumina-aluminum composites, but this scheme might be applied as well to many other chemical systems.

PROCESSING

The system we have the most experience with is based on immersing shaped and formed silica bodies into liquid aluminum at a temperature near

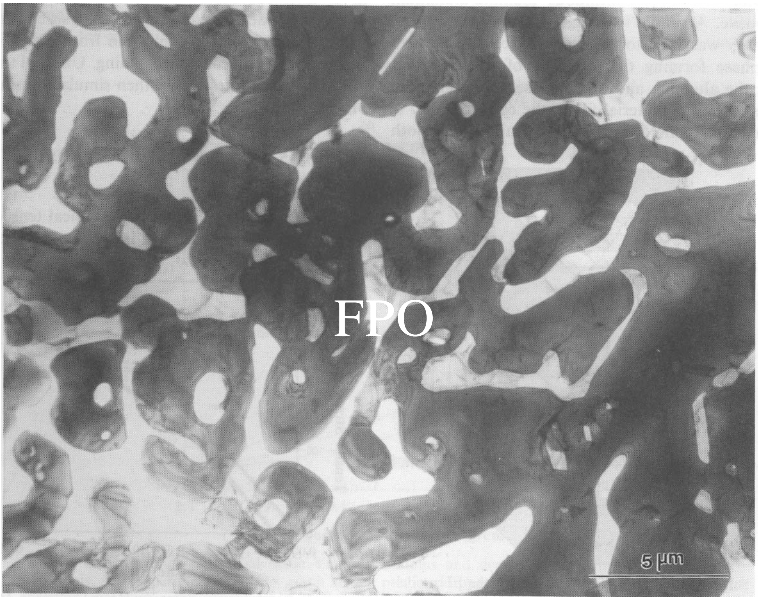

FIGURE 1 Transmission electron micrograph of a co-continuous alumina-aluminum composite produced by the immersion of glassy silica in liquid aluminum. The darker phase is alumina. Source: Reprinted with permission from Elsevier Science Ltd. (Daehn et al., 1996).

1100°C. The coupling of silica in aluminum is unstable, so a reaction takes place:

$$3SiO_2 + 4Al \rightarrow 2Al_2O_3 + \underline{Si}_{\text{(in solution)}}$$

When transforming three units of silica to two of alumina, there is a nearly 25 percent reduction in volume of the solid oxide phase. This opens up fine channels in the microstructure, which then are filled with the aluminum alloy surrounding the transforming sample. The typical material microstructure is show in Figure 1. The reaction generally penetrates at a rate of 1–3 mm/hour at 1100°C. Because the remainder of the precursor supports the transforming material, the transformed composite has virtually the same size and shape as the precursor. Since production techniques for shaped silica precursors based on traditional ceramic processing are widely practiced, procedures for fabricating net-shape bodies from advanced composites are widely available and may be quite inexpensive.

Although experiments have given many hints at how the microstructure evolves, we do not fully understand it and cannot yet truly control it. Despite this, it appears that similar reactions can be used with other chemical systems, provided the following criteria are met: (1) the produced compound is more compact and thermodynamically favored relative to the precursor and (2) the bath wets both materials. Application of these simple criteria could lead to a new class of co-continuous materials based on other chemical systems, including carbides, nitrides, or other compounds.

PROPERTIES

Since this material is a co-continuous mixture of a metal and a ceramic, it does have an unusual macroscopic mixture of properties. For example, the metal phase gives electrical conductivity and high fracture toughness to a material that is otherwise ceramic-like (i.e., very hard with a high specific stiffness).

Quantitative prediction of properties in these co-continuous materials presents significant difficulties. The process of simply characterizing, describing, and visualizing the geometry of the microstructure represents a significant problem. Usually, such descriptions are taken for granted as a starting point for models that correlate a material's structure and properties. Despite this, very simple descriptions of the microstructure have been shown to give good predictions of the magnitudes and trends in the elastic and plastic deformation of these co-continuous materials (Daehn et al., 1996). It is significant that even though the ceramic phase (which makes up 75 percent of the material) is incapable of plastic deformation, the composite will still exhibit plastic deformation under load. This basic elastic and plastic behavior forms the basis for determining higher-order properties, such as fracture toughness and wear resistance. The relatively small fraction of interconnected metal in the composite dramatically increases its damage tolerance and toughness.

APPLICATIONS

The obvious applications for these materials are those requiring some of the usual properties of ceramic materials (high specific strength and stiffness, high temperature strength, wear resistance, and high hardness), along with some of the properties found in metals (high thermal or electrical conductivity, high toughness, and damage tolerance). Such applications include the following:

- *automotive combustion cylinder liners*—where high wear resistance is required and improved thermal conductivity and a lower-density, smaller engine mass are desired;
- *automotive brake rotors*—where wear resistance, low density, and high thermal conductivity are all benefits; and

- *electronic packaging*—which could benefit from a low coefficient of thermal expansion, high thermal conductivity, and high specific strength.

In other classes of applications, the ability to easily produce net-shape components may be an important attribute. For example, methods of rapidly producing dies for polymer injection molding have been considered. Here, high thermal conductivity and wear resistance would benefit the component in service.

In each of the applications mentioned, there appear to be good technical reasons to use co-continuous composites processed as discussed above. However, at our present stage of developing this idea, it becomes clear that technical merit is only one important aspect of commercializing a new material or technique.

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DINNER SPEECH

Institutional Cultures and Individual Careers

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It is a privilege for me to have been asked to participate in this second Frontiers of Engineering meeting and to have been asked to speak to you. The NAE believes, and I hope you will find, that meeting colleagues from different fields and hearing about work in areas you do not normally visit will be intellectually stimulating, and may even lead to new directions for your work. I hope it will have other benefits as well, and I will talk about those in due course.

One can not read *IEEE Spectrum* or any engineering monthly, *Science* magazine, or *The Chronicle of Higher Education* without finding a discussion of corporate research, development, and engineering (RD&E) downsizing, of funding cuts threatened for many fields of academic science and engineering, and of pressure of many kinds on the federally supported national laboratory structure. Our institutions are living through troubling times.

But it is not only in quantitative and financial terms that our institutions are beset. The very cultures of our institutions are being stressed as never before, and defects are showing up that have been glossed over for decades. By "institutional culture" I mean the partly explicit, partly implicit set of goals and rules that determine how we interact with our colleagues, what we expect of them, and what we expect of ourselves in our institutional settings. I have learned over the years that these institutional cultures are very important, very different, and very hard to change. I have also learned that they can be very confining.

Most of our RD&E institutions had, until 5 or 6 years ago, enjoyed four decades of almost uninterrupted growth. However, no institution can enjoy decades of success and constantly increasing budgets, expanding programs, and increasing staff without developing a lot of bad habits and without sweeping a lot of problems under the rug of ever-expanding resources.

A consequence of this has been, I believe, that most if not all of our RD&E institutions have become clinically addicted to growth and are now suffering severe withdrawal symptoms. I mean for that analogy to be taken literally. It is very helpful in clarifying otherwise mystifying behavior.

If I am even partly right about this aspect of our current situation, then there is an additional benefit that may come from this gathering. For, just as you represent many fields, so you also represent different institutions and cultures within the academic, industrial, and public engineering sectors. There is an opportunity for you to learn from and influence each other with respect to institutional change.

I am not suggesting that our institutional cultures are mostly dysfunctional or that radical change is needed. I am suggesting instead that the troubles of the RD&E enterprise come partly from within and are not entirely due to external causes.

Indeed, each of us is nurtured and empowered by our institution to do our work; few of the achievements of the RD&E enterprise over the past five decades could have been made by engineers and scientists working in isolation. Our RD&E institutions are the most successful the world has ever seen; they are a crucial part of the technical infrastructure of our country.

My first major point this evening is that to the extent our institutions are troubled, each of us has a personal ethical responsibility to try to understand how to help. The current stress on our RD&E infrastructure poses individual as well as national issues. It is important to keep in mind that institutional cultures not only support us, they also constrain the choices we feel free to make. These constraints are, in my view, part of the problem now to be faced and overcome. And my second major point is that much of what needs to be done to strengthen our institutions will also improve opportunities for personal career growth and success. I hope you will indulge me while I illustrate these points with a few incidents from my own career in research and development.

I had the good fortune to graduate from college in 1956, right at the start of the golden age of postwar science and technology. I applied for and received an NSF graduate fellowship to start graduate school that fall. But just before graduation, my housemaster asked if I would like to apply for an all-expenses-paid year abroad, on what is known as a traveling fellowship. No formal study would be allowed, I would be expected to move every 6 weeks or so, and I would have to stay away until the money was gone. (At that point in my life, I had never been outside the country.)

Naturally, I talked to my senior advisor. He said, “Don’t do it; it will ruin your career.” That was easily the worst advice I have ever received, but I don’t blame him so much as the institutional culture. That culture felt, and still feels, that if you are serious about a professional career, you don't fool around. You get on with it. Understandable, but narrow-minded, to say the least.

To finish the anecdote: I had the good sense to listen to the institution at its best (offering me the chance of a lifetime to benefit from complete freedom and to spend a year relying entirely on my own initiative) rather than listen to the institutional culture at its narrowest. It was one of the best things that ever was done to and for me; it changed my life, and I guess many observers would conclude it did not ruin my career.

Something similar happened to me later at IBM Research. After 18 years of doing research, and then managing successively larger groups of researchers until I was reporting directly to the Director of Research, I decided to leave research and transfer to one of our product development labs, where I would manage about 650 engineers doing advanced bipolar process and circuit development. My colleagues in research could not believe that this was a voluntary act; they concluded that I had somehow offended my boss and was being banished. But I went, and it was one of the best periods of my whole technical career. Here again, the institution in the larger sense offered me a wonderful chance (including, of course, the chance to fail), but the local professional research culture was strongly discouraging. The moral of this tale is that the expectations of one's colleagues can be very stifling.

During the 2 years that I was in advanced technology development, I would occasionally visit the research labs and run into former colleagues; they were simply incapable of understanding why I was both enthusiastic about my new post and, as far as they could tell, happy. It was beyond them. Their attitude was an example of the insidious intellectual pecking order that most of us pick up from the air and water in graduate school.

I refer here to the view that "research is better than development," "science is better than engineering," "physics is better than chemistry," and so on down the line. In those days, manufacturing was so far beyond the experience of top-flight science and engineering schools, it was not even at the bottom of the pecking order. This pervasive but foolish set of intellectual prejudices is one of the most dysfunctional parts of the university culture. Things have improved some in the last 10 to 15 years, but not enough. You academic engineers should work to help stamp out this nonsense, although you will get scant help from your colleagues in the sciences.

A footnote to that story of industry culture is that, during my time in product development, I saw enough of the manufacturing culture to realize that the engineers there subscribed to a compensatory, but equally perverse, pecking order. For them, the engineers who worked in manufacturing, who were actually responsible for producing products that customers paid for, were the true heroes—the top of the pecking order. All the others involved, even the engineers who had, for example, invented the processes being used in manufacturing, were way, way down in the manufacturing engineers' hierarchy of contribution and worth.

These two anecdotes featured choices made in the face of those prevailing local prejudices that suggested rejecting choices offered by the institution as a whole. I have risked boring you with personal history because, during the course of my 35 years in the RD&E enterprise, I have seen more careers stifled and made mediocre by conventional choices than I have seen careers hurt by unconventional choices. This is one of the principal thoughts I would like to leave with you as individuals this evening. Think carefully, look before you leap, but try to free yourself from the conventional wisdom of your institutional culture. It is worth the risk, and it will set a valuable example for your less adventurous colleagues.

I have said that our institutional cultures suffer from weaknesses derived, at least in part, from decade after decade of growth and success, so it is appropriate for me to be more specific. I will start with industrial RD&E, which I know best, and then discuss the weaknesses of academic culture as I see them.

It is my hope that these remarks will stimulate or perhaps even aggravate you into discussion among yourselves of these issues of institutional culture and their impacts on your own careers.

Despite all the articles and the public handwringing about the decline in recent years in industrial R&D, and despite the fact that there certainly have been downsizings, I hold a contrary view that industrial RD&E organizations are, in general, at the moment, in better shape as institutions than their academic and national laboratory counterparts. (I am not claiming they are necessarily happier places.)

The industrial labs are in better shape precisely because they have already had to engage in a thorough and ongoing reexamination of their past effectiveness and their present relevance to corporate goals, and they have faced the task of reassessing the portfolio of those research and engineering fields that are good bets to give the corporation an advantage in the future (which is, after all, why companies do research and advanced engineering in the first place). These reappraisals have been agonizing, but they are now largely in the past, and the industrial labs I know best are looking forward to new successes—not bemoaning past glories.

The academic sector is not as far along in this agonizing reappraisal. And though it will be unpopular for me to say so, I firmly believe that the academic RD&E sector could learn a lot from a detailed and sympathetic examination of our recent industrial R&D experience. It is hard, indeed, to shrink across the board. But shrinking across the board, although seemingly "fair," is mindless; the opportunity must be taken to correct some of the mistakes of the past good times. Examples might include mistaken toleration of mediocrity and outdated resource allocations, such as departments that are no longer competitive or those that are in fields no longer seen to be either scientifically exciting or at the engineering forefront.

Back to industry. The two examples provided by AT&T Bell Laboratories and IBM Research often are in mind when observers deplore recent changes in industrial research. (And the observers always deplore; they never understand that management is doing what it is supposed to do.) In the not-too-distant past, there have been substantial changes in the research arms of Xerox, GE, and RCA. As the RCA case shows, not all industrial labs go through these hard times and emerge as vigorous laboratories. However, most have weathered these storms well and have emerged better prepared to serve their sponsors effectively.

Research, as understood in the university system and in the popular press, has always been a small part of total industrial RD&E investment, and the part of research that was ever basic research was always very small indeed. At IBM, for example, despite the outstanding achievements and Nobel prizes in basic research, it never amounted to more than 0.2 percent of the total R&D effort. Moreover, as a numerical fraction of the nation's total effort in basic research, the industrial component was always very small.

Nevertheless, recent changes in corporate basic research get a wildly disproportionate share of public attention and worrying. These are the views of outsiders; insiders know that since basic research is such a small part of the whole, the most significant weaknesses in industrial RD&E will be found elsewhere. For example, in the late 1980s IBM had about 60,000 technical workers in hardware, software, and systems development and engineering. Many of us felt that this was tens of thousands too many of some types of engineers and many hundreds too few of other kinds.

How could such a perverse allocation come about? It is a wise saying that "your success is also a potential source of weakness." One can pay too much attention to enhancing the highly successful products of the past and be too ready to react to the inexhaustible demands of customers for enhancements to those products. And since the amounts of money and personnel involved are large, owing to past success on a large scale, these parts of the RD&E agenda tend to monopolize management energy, attention, and political capital within the organization. Success brings many problems and gives rise to aspects of the corporate culture that are eventually counterproductive.

Another defect of large, successful RD&E organizations is that they become too inward looking, too wrapped up in their own world, and too little inclined to reach out and interact with the worlds of academic engineering and small rival firms. Big firms, in general, pay too much attention to their big competitors and not enough to their small ones.

I remember sitting in an R&D planning meeting at IBM headquarters in the late 1980s, during which the appropriate size of our R&D budget—overall—was under review. Someone showed a chart giving the total of all the

R&D expenditures of the 12 next-largest computer companies in the world. IBM's budget was comfortably larger than that sum.

I don't know what moral you draw from that story, but one of the morals I have drawn is that it is possible to spend too much money on RD&E: too much because the money is being spent on the wrong things, or too much because the money is producing results in the forms of processes, new product designs, and new capabilities faster than the rest of the corporation can absorb and exploit them. (By the way, you may want to ask yourself, as I have, whether or not a country can make the same mistake—that is, can be spending too much on R&D because it is spending it on the wrong things or is unable to appropriate a sufficiently large share of the fruits of its RD&E enterprise for its own benefit.)

There are two paths that can be taken in dealing with an RD&E budget that is believed to be too large. One is to try to remove the deficiencies impeding full exploitation of the bountiful fruits of R&D. The other is to readjust the portfolio of R&D projects to create a better match with the needs of the organization supporting the work. Both approaches are probably required in most cases.

Large, complex industrial organizations also suffer from the universal tendency of people to identify too closely with their local unit and to view other parts of the same company as rivals. The wonderful book, written by the just-retired Chairman of the NAE, Norm Augustine, CEO of Lockheed Martin, called *Augustine's Laws* has several chapters on this destructive form of internal rivalry.

These are some of the weaknesses of industrial RD&E culture. What are some of the remedies? There are no miracle cures for these weaknesses, but what might be called "internal travel" or "internal cultural exploration" is very good medicine for most of them. By "internal travel" I mean individuals experiencing working in different parts of the company.

It is usual for candidates for future executive management to be expected to move around as part of their company education. But, in my experience, it is very helpful for any organization to have a larger fraction of all of its engineers and scientists acquire personal experience of the cultures, the problems, and the satisfactions of other parts of the organization.

The reason is as profound as it is simple. There are crucial things to know about how one's firm works that can *only* be learned by experience. Prejudice and ignorance about the rest of the organization are source of a lot of the weakness of any large industrial firm—as they are of any large, complex organization (including, I fear, many universities).

So, I very much commend to you young engineers who work in industry that you seek out opportunities to enlarge your personal experience of the organization. There is every likelihood that you will find it challenging and enlightening, and I think it is probable you will find the experience fun as well. Furthermore, it will improve your effectiveness as an engineer, even if you have no interest in higher management.

During my years of working with scientists and engineers, I never met any who were not very proud of the contributions they had made to the company's products. In fact, the chief source of dissatisfaction among my engineer colleagues was the difficulty many of them felt in having such an impact. If more of them had had personal experience working with other parts of the company, they might have had an easier time achieving their principal source of satisfaction—namely, visible impact. This is a good example of my claim that what is required to improve the institutional culture will also be a source of improvement for individual careers.

Now, I turn my attention to the university cultures of science and engineering. The first thing to say about university culture is that it is a wonderful, supportive, and effective context for research, scholarship, and teaching. But a closer look shows that it suffers from the following problems, among others. First, the disappearance of mandatory retirement for tenured professors is a major challenge for the long-term health and vitality of universities. Different universities have had very different degrees of success in dealing with this challenge. What has been created is a situation in which de facto age discrimination—against the young—will be a feature of academic life for a generation.

My own counsel to senior faculty has been that they have a moral responsibility to their institutions to make room for the appointment of younger tenured colleagues. Acting in this morally responsible way need not mean being shut off from one's department or one's research, for there are many types of emeritus status allowing one to continue, although perhaps in less grand space, with more sharing of support. The key thing is that senior faculty have the moral responsibility to draw their remuneration from funds in the retirement pool, thus freeing up endowment funds for young people.

Large, complex organizations, including research universities, require effective management. But the academic culture is scornful of management, which is seen, at best, as a necessary evil; if it is your turn to be department chair, do it with as little attention as you can get away with, and get back to "real work" as soon as possible. I apologize for the caricature, for I realize that some of you probably have risen above these limitations of your surroundings. But let me remind you that I am discussing these issues both because they are impediments to your own careers and because you each have a responsibility to the future health of your institution. It is not enough to say that "If I do the best work I can, that is the best, and only, contribution I need to make to my university."

It is useful to think carefully about the issue of rotating department chairs—the notion that everyone must take a turn—that characterizes some of our universities. This is nonsensical from the point of view of effective management. Management skills are at least as thinly distributed in the population as is the ability to become a tenured professor. There is a very small set of the general population having the ability to become leading-edge contributors to science or engineering, and there is at least as small a set of the population having the talent and the psychological maturity to be effective managers. The overlap of these two sets is distressingly small, yet it is from this overlap that all healthy research organizations should recruit their leaders. This constitutes a serious dilemma for every organization with which I am familiar.

But understanding that not everyone should be expected to take a turn does not justify the scorn and abhorrence of management that are part of the warp and woof of the academic culture. One of the career options each of you has to explore, in one way or another, is whether you have both sets of talent and therefore fall into the very small set whose duty to your institution is to spend part of your career in a leadership, management position. By the way, mature, successful organizations try to make it possible for their members to explore management and, if they are not suited to it, to return without stigma to a purely professional role.

Whether or not you personally should be in management, as academics you should each try to help stamp out the scorn, or at least the low esteem, with which your culture views management. The point is not that you all have a duty to become deans but that you have a duty to create an atmosphere in which they can do their work effectively, and you and your colleagues should understand and support that atmosphere. This is vital if your university is to deal successfully with hard times ahead.

Ironically, just as corporations are finding it advantageous to flatten management structures and to have, in general, less management, universities are finding that they need more management and better-shared understanding of what management means. It has always struck me as evidence of institutional weakness that most academics do not distinguish between the functions of "administration" and of "management."

Parenthetically, I must add as an experienced senior manager that one must always be on guard against "volunteers" for management responsibility. Often, they are interested more in the title and supposed power that go with a managerial position than they are in the responsibilities of such a position. The best managers in any organization often have had to be coaxed and cajoled into testing their talents in this area; it is only after a successful "test run" that they appreciate what it is that they can contribute to the institution and what the personal satisfactions are.

The general low esteem for management in academia is part of what I call the "culture of irresponsibility," which is a rather confrontational shorthand phrase for "the lack of a feeling of personal responsibility toward the larger interests of the institution." All large RD&E enterprises suffer from this to some degree. The culture of irresponsibility in academia has been aggravated by pervasive dependence on outside agencies for research funds. Since one's funds come from DARPA, NSF, or DOD, for example, one does not need to care about the health of the university generally. This is doubly the case where all or part of salaries depend on "soft money."

The final aspect of the academic institutional culture I will touch on is the excessive reverence for disciplinary boundaries that is built into the departmental structure of our universities. Much attention has been given to this issue over the past 5 or so years; indeed, this meeting is an attempt by the NAE to counter the ills of overspecialization and to promote interdisciplinary thinking and collaboration.

As a former vice-president of an R&D organization, my principal complaint about overspecialization is that it produces graduates with a very narrow set of career expectations, low intellectual self-confidence, and a reluctance to strike out themselves in ways that are intellectually adventurous. Our companies need highly trained engineers, of course, but they also need engineers who are confident in their ability to master new areas and to strike out on their own across traditional boundaries. The university culture they bring with them usually is a decided hindrance to them in any attempt to be intellectually and professionally adventurous.

The traditional disciplines are useful for teaching and for some aspects of research, but we should never lose sight of the fact that these disciplinary boundaries have almost nothing to do with nature. Nature is not organized like the wall of mailboxes at your local post office, with physics in one box, electrical engineering in another, biology in a third, and so on. God did not make the world that way. Nature is much more like a mass of cooked spaghetti; each strand touches and is wound up with many others. You young professors of engineering owe it to your students to allow them, and encourage them, to move across traditional boundaries. You are leaders; you will lead best by example.

I wish you well in your individual careers. I hope you will think seriously about taking more risks and will be cautious when trying to fulfill the expectations of your peers. From my all-too-brief stay with you today, I am encouraged to find that many of you are, yourselves, adventurous.

I wish you well in your individual institutions; I hope that with your help they will emerge stronger from dealing with the formidable challenges of the next decade. I suggest that the kind of boundary-breaking and expectation-shattering careers that I have been endorsing will be a large part of the solution to the problems of your institutions.

Finally, I wish you well for the rest of this meeting. I am sure you will influence each other's understanding of engineering, and I hope you may even affect each other's careers.

APPENDIXES

Contributors

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JOHN A. ARMSTRONG is retired Vice President for Science and Technology at IBM. He received an A.B. in physics from Harvard College in 1956 and a Ph.D. from Harvard in 1961. He remained at Harvard as a research fellow until 1963, when he joined IBM as a research staff member. During his career at IBM, Dr. Armstrong held numerous positions, including manager of the physical sciences programs at the T. J. Watson Research Center, manager of materials and technology development at the IBM East Fishkill Development Laboratory, director of research, and vice president. From 1989 to 1993 he was Vice President of Science and Technology at IBM. Since his retirement from IBM, Dr. Armstrong has held visiting lectureships at MIT and the University of Virginia. Currently, he is a Visiting Professor of Physics at

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Dr. Armstrong's distinguished career includes service on numerous advisory boards and committees. He is a member and a Councilor of the National Academy of Engineering, a foreign member of the Royal Swedish Academy of Engineering Sciences, and a trustee of Associated Universities, Inc. He is also a director of Advanced Technology Materials, Inc., of Danbury, Connecticut. In 1996 President Clinton nominated Dr. Armstrong for a 6-year term on the National Science Board.

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STEVE BRYSON is a research scientist with MRJ Inc., working under contract for the Data Analysis Branch of the Numerical Aerodynamic Simulation Systems Division at NASA Ames Research Center. He does research in the application of virtual reality techniques for scientific visualization, of which the virtual windtunnel is the main focus. Mr. Bryson started in the virtual reality field in 1984 at VPL Research, working on a graphics-based programming environment using the prototype Dataglove for input. Later, he was involved in work on the Dataglove Model II. Mr. Bryson then joined Scott Fisher's VIEW lab at NASA Ames Research Center in 1987, where he was involved in integrating the various I/O and graphics systems into a virtual environment. This included research in software architectures for virtual reality systems and human factors.

GLENN S. DAEHN is the Mars G. Fontana Professor of Metallurgical Engineering at Ohio State University. He received his B.S. in materials science and engineering at Northwestern University and his M.S. and Ph.D. at Stanford University. At Stanford his research was focused primarily on the processing of and high-temperature deformation of laminated superplastic composites based on high carbon steels. His current research is in three areas: production and characterization of ceramic-metal composites via displacement reactions, hyperplasticity (i.e., the extended ductility seen in high-velocity deformation), and the deformation of composites.

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MARC LEVOY is an associate professor of computer science and electrical engineering at Stanford University. His principal publications focus on computer animation, volume visualization, and machine vision, and his current research interests include volume rendering and morphing, digitizing the shape and appearance of physical objects using multiple sensing technologies, geometry and image compression, image-based rendering, and the design of languages and user interfaces for data visualization. Dr. Levoy was the architect of the Hanna-Barbera Computer Animation System and served as Director of Hanna-Barbera's Computer Animation Laboratory from 1980 through 1983. He received his bachelor's in architecture and M.S. degree from Cornell University and a Ph.D. in computer science in 1989 from the University of North Carolina at Chapel Hill. Dr. Levoy received the NSF Presidential Young Investigators Award in 1991 and the SIGGRAPH Computer Graphics Achievement Award in 1996 for his work in volume rendering.

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Program

National Academy of Engineering

SECOND ANNUAL SYMPOSIUM ON FRONTIERS OF ENGINEERING

September 19–21, 1996

DESIGN RESEARCH

Organizers: David Ashley, Deborah Thurston, Robert Wagoner

Designing Vehicles in Changing Times
Connie L. Gutowski, Ford Motor Company

Development of Performance Based Seismic Design Procedures
Sharon L. Wood, University of Texas at Austin

Information in the Design Process
Alice M. Agogino, University of California at Berkeley

Product Modularity: A Key Concept in Life-Cycle Design
Kosuke Ishii, Stanford University

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VISUALIZATION FOR DESIGN AND DISPLAY

Organizers: Shira Broschat, Sheri Sheppard

Visualizing Aircraft Aerodynamic Design
Steve Bryson, NASA Ames Research Center

Virtual Reality and Augmented Reality in Aircraft Design and Manufacturing
David W. Mizell, The Boeing Company

Discussant: Scott Minneman, Xerox Corporation

The Frontiers of Virtual Reality Applied to High Performance Computing and Communications
Maxine D. Brown, University of Illinois-Chicago

Digitizing the Shape and Appearance of Three-Dimensional Objects
Marc Levoy, Stanford University

Discussant: Paul Nielan, Sandia National Laboratories

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MICROELECTROMECHANICAL SYSTEMS (MEMS)

Organizers: Stephen Drew, William Kaiser, Sophie Verdonckt-Vandebroek

Microelectromechanical Systems (MEMS)
Kaigham J. Gabriel, Defense Advanced Research Projects Agency

Fabrication Technology and the Challenges of Large-Scale Production
Karen W. Markus, MCNC

Frontiers in MEMS Design
Kristofer S. J. Pister, University of California at Los Angeles

Large-Market Applications of MEMS
Eric Peeters, Xerox Corporation

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INNOVATIONS IN MATERIALS AND PROCESSES

Organizers: Charlotte Chen-Tsai, Daniel Hastings, Shawn Walsh

Cellular Materials: Structure, Properties, and Applications
Lorna J. Gibson, Massachusetts Institute of Technology

Silicon Satellites
Siegfried W. Janson, The Aerospace Corporation

Novel Ceramic Ferroelectric Composites
Louise C. Sengupta, U.S. Army Research Laboratory

Co-Continuous Composite Materials from Net-Shape Displacement Reactions
Glenn S. Daehn, Ohio State University

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