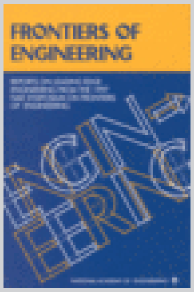

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Preface

This book is the third publication highlighting the presentations of the National Academy of Engineering's (NAE) symposium series, Frontiers of Engineering. The Third Annual NAE Symposium on Frontiers of Engineering was held September 18-20, 1997, at the Beckman Center in Irvine, California. The 101 emerging engineering leaders from industry, academia, and federal laboratories who attended the meeting heard presentations and discussed pioneering research and technical work in a variety of engineering fields. Symposium speakers were asked to prepare extended abstracts of their presentations, and it is those papers that are contained here.

GOALS OF FRONTIERS OF ENGINEERING

In 1994, the NAE Council initiated Frontiers of Engineering, and the first symposium was held in September 1995. Motivating the activity is the idea that the changing nature of engineering compels researchers and practitioners alike to be aware of developments and challenges in areas other than their own. Providing an opportunity for outstanding younger engineers to hear from their peers about these frontiers will, it is anticipated, lead to collaborative work, the transfer of new techniques and approaches across fields, and the establishment of contacts among the next generation of leaders in engineering, among other benefits.

Symposium participants represent the full range of engineering fields in the industrial, academic, and government sectors. They are invited to attend after a competitive nomination and selection process. The number of participants is kept relatively low, about 100, to maximize the opportunity for interaction and exchange among the attendees. The selection of topics and speakers for each year's meeting is carried out by an organizing committee composed of engineers in the same 30- to 45-year-old cohort as the target participants.

CONTENT OF THE THIRD ANNUAL SYMPOSIUM

Presentations at the symposium covered leading-edge research and technical work in five areas: biomechanics; sensors and control for manufacturing processes; safety and security issues; decision-making tools for design and manufacturing; and intelligent transportation systems. Talks focused on such topics as implant design and technology, design and application of optical fiber sensors, quadrupole resonance explosive detection systems, multicriteria evaluation of manufacturing performance, and automated highway systems. (See Appendixes for complete program.) Speakers were asked to tailor their talks to a technically sophisticated but nonspecialist audience and to address such questions as: 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?

As in past years, the varied backgrounds of the participants set the stage for lively question-and-answer periods and discussions both during and after the formal sessions. The 1997 program included a wrap-up session intended to focus on some of the broader, more policy-oriented issues that emerged from the sessions and a field trip to the Beckman Laser Institute.

Philip M. Condit, chairman and CEO of The Boeing Company, gave the after-dinner address on the first evening of the symposium. His presentation, which is also included in this volume, focused on today's rapid pace of change. He urged symposium participants to keep an open mind about learning from others, including those from dissimilar industries and disciplines.

As with past symposia, feedback from participants confirmed the value of Frontiers of Engineering. Attendees found the opportunity to interact with engineers from other sectors and disciplines a broadening experience that, if nothing else, exposed them to ideas and people that they would not have encountered in any other forum. Moreover, many mentioned how useful the presentations and discussion were to particular aspects of their work. Comments such as these indicate that the groundwork is being laid for achieving the goals set out by this activity.

Funding for the Third Annual Symposium on Frontiers of Engineering was provided by the National Science Foundation, the U.S. Department of Defense, the U.S. Department of Energy, and the National Institute of Standards and Technology. The National Academy of Engineering would like to express its appreciation to these groups for sponsoring the symposium as well as to the members of the Symposium Organizing Committee (see p. *iii*) for their work in planning and organizing this event.

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BIOMECHANICS

Overview

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Photographs surfaced recently of a creature that can serve as an emblem of the paradigm we are about to enter in biomechanics. It was a mouse, about 4 inches long, and on his back was what appeared to be a surgically implanted human ear. The ear was at least 75 percent as large as the mouse himself.

That alone is remarkable—a huge appendage on the back of a mouse. What is even more remarkable is that this implanted tissue was viable by every known measure. Our colleagues at the Massachusetts Institute of Technology and the University of Massachusetts had built a human ear from human cartilage cells. They grew it in the laboratory and implanted it surgically in the back of a mouse.

This is an emblem of where medical science and engineering may take us in the new millennium. We call this field tissue engineering, and it is nurtured by, founded on, and supported by biomechanics. The field did not exist 15 years ago.

Many biological materials can be coaxed to grow in a culture dish—skin, bone, and cartilage are being generated artificially, constructed, and tested in clinical settings right now. Skin is already on the market; one can buy artificially constructed skin. Certainly many problems remain, including issues associated with growing three-dimensional rather than two-dimensional structures and issues associated with vascularization and innervation. Nonetheless, the progress has been exciting.

The focus of these papers from the Biomechanics session of the Third Annual Symposium on Frontiers of Engineering is on bone and cartilage and their mechanical properties. It is important to realize that implanted cells do not function in isolation. For them to be biologically active, they have to coalesce and respond as normal tissues do in many respects. That is, not only are they driven by and able to drive mechanical events, but they also interact with their chemical and physical environments. Biological consequences result from and can trigger the mechanical activity discussed in the papers in this volume.

The role of biomechanics in biological systems is not surprising if one thinks about it on a macrolevel. One of the earliest-known mechanoreceptors in the human body is the baroreceptor—tiny structures that exist near the carotid artery, which supplies blood to the brain. They are exquisitely sensitive to pressure. In fact, they are the mechanical sensor in the mechanical feedback loop controlling blood pressure. A familiar scene on certain TV shows and movies is that of someone coming up behind a character and applying a sudden pressure to his neck, triggering an abrupt change in blood pressure and blood flow to the brain, which causes the person to pass out. This is the baroreceptor response, which is a mechanoreceptor in the body.

There are other places where mechanoreceptors play important roles. There is a lot of evidence to indicate that the cells that line the arteries are mechanosensitive—in other words, sensitive to shear, stress, and strain. As a consequence, through mechanisms that are not yet well understood, lipids are deposited. Thus, there is a relationship between the mechanical response of the cell on the artery and the development of atherosclerosis.

The first paper in this section, “Biomechanics of Cells and Cell-Matrix Interactions,” discusses mechanosensing properties of cells and the ability of cells to generate mechanical responses. It focuses on cartilage and, to some extent, bone, and reminds us that changes in the mechanical environment alter the homeostatic set point. All mechanisms in our bodies strive toward a stasis, a balance. One example is the balance between bone creation and bone resorption. When bone is stressed and consequently the cells are stressed, regrowth occurs. In the absence of that we get deterioration.

More examples of this type are described in the second paper, “Mechanical Influences on Bone Development and Adaptation.” That paper focuses on the mechanical environment in which bone thrives and in which the adaptive responses elicited by physiochemical factors amplify and supplement the responses to mechanical loading. Genetic factors play into this; however, the interplay between the physicochemical biological milieu and the mechanical milieu is critically important.

The third paper, “Implant Design and Technology,” covers the design of structures to work with, supplement, and in some instances, replace bones and joints. There have been spectacular successes in the past 20 years with artificially implanted mechanical structures. There have also been spectacular failures. For instance, if 15 years ago we had known about the role of mechanical events in building bone, we probably never would have designed an artificial implant that removes the load from the bone. This is because once the load is removed, the bone deteriorates, creating a hostile environment for the implant.

The papers in this section, which cover cellular, tissue, and constructed environments for bone structures, have some common themes. One is the interplay between the biochemical and the mechanical environments and how one feeds and triggers the other. Another theme is that the advances discussed could not have occurred without major developments in technology, in particular the ability to measure exquisitely tiny forces. Technological developments such as new imaging modalities, microscopic modalities, adaptively analytical finite element models, large-scale numerical modeling ability, and computational power have been critical factors in the intellectual advances in physiology and biomechanics discussed herein.

Biomechanics of Cells and Cell-Matrix Interactions

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Cells are the fundamental structural and functional entities that form the basis of life. The physiological activity of a cell is a tightly controlled process that is regulated by the genetic programming of the cell in combination with signals derived from the chemical and physical environments. In the human body the interaction of living cells with physical forces, such as mechanical stress, is critical to the normal health and function of most organ systems. Cells not only have extraordinary capabilities to generate mechanical forces but also can possess exquisite abilities to detect and respond to mechanical signals in their environment. In many cases the sensitivity and efficiency of living cells in interconverting chemical and mechanical energy surpass those of the best man-made systems.

However, the mechanisms through which mechanical forces interact with cells are not fully understood. The study of the biomechanics of living cells is a rapidly growing, multidisciplinary field that brings together expertise from several different areas to study problems in medicine and biology. The field of cell mechanics utilizes concepts of engineering, medicine, biology, chemistry, and physics to further our understanding of the biological and biophysical mechanisms involved in bone and joint disease, cardiovascular disease, wound healing, reproduction, and cancer. Recent advances in engineering technology have had a significant impact on this field by introducing new experimental and theoretical techniques for the study of cellular biomechanics (Mow et al., 1994).

MECHANICAL SIGNAL TRANSDUCTION

Many cells of the body are specialized in their ability to detect mechanical signals for sensory purposes such as touch and hearing (Hudspeth, 1992).

However, most nonsensory cells also have the ability to perceive mechanical signals in their environment and to transduce them into an intracellular chemical signal. Cells of the musculoskeletal, cardiovascular, and respiratory systems are particularly sensitive to their mechanical environment and depend on mechanical signals to properly regulate their activity. This capability of mechanical signal transduction is necessary due to the large metabolic demand required to maintain and regenerate living tissues of the body; tissues that are not adequately utilized are not regenerated. For example, bone is normally in a balanced physiological state such that the rate of tissue resorption equals the rate of new tissue formation. Changes in the mechanical environment of the cells can shift the balance of synthesis and degradation to adapt to increased or decreased mechanical requirements by producing or resorbing surrounding tissue (Rubin et al., 1994; van der Meulen, 1998). Similarly, muscle cells rapidly grow in response to the physical demands of exercise and atrophy with lack of use (Costill et al., 1979). In many cases, mechanical loads are required for the maintenance of healthy tissue, and insufficient loading can lead to a pathological condition of tissue loss (e.g., osteoporosis).

The mechanisms by which single cells or ensembles of cells are able to transduce relatively small forces and deformations involve a complex cascade of biophysical and biochemical events that are not fully understood. Many recent advances in this field have been made through the application of new theoretical and experimental engineering technologies in combination with techniques in cell biology. In particular, new microscopy and imaging techniques coupled with large-scale numerical modeling have been very useful in providing new information on the micromechanical environment of single cells.

One paradigm system that will be reviewed is the process of mechanical signaling in articular cartilage, the tissue that serves as the bearing surface for the joints of the body. Cartilage cells (chondrocytes) perceive and respond to the cyclic mechanical loads generated by the activities of daily living such as walking and running. Under normal conditions, the chondrocytes are able to maintain the integrity of this tissue over decades of cyclic loading at peak stresses of up to 18 megapascals (~2600 psi) with little wear or degeneration. However, under abnormal circumstances, mechanical loading can lead to progressive joint degeneration with such diseases as osteoarthritis. Therefore, knowledge of the specific mechanisms of signal transduction would provide new insight into the causes of osteoarthritis and may lead to the development of new techniques for the prevention or treatment of the disease.

Large-scale numerical computing has been utilized to theoretically model the mechanical and biological behavior of living cells and their interaction with the extracellular matrix. These models require a detailed knowledge of the mechanical properties of cells and their various components, as well as information on the constitutive laws governing their behavior. New techniques using micropipette manipulation as shown in Figure 1 (Guilak et al.,

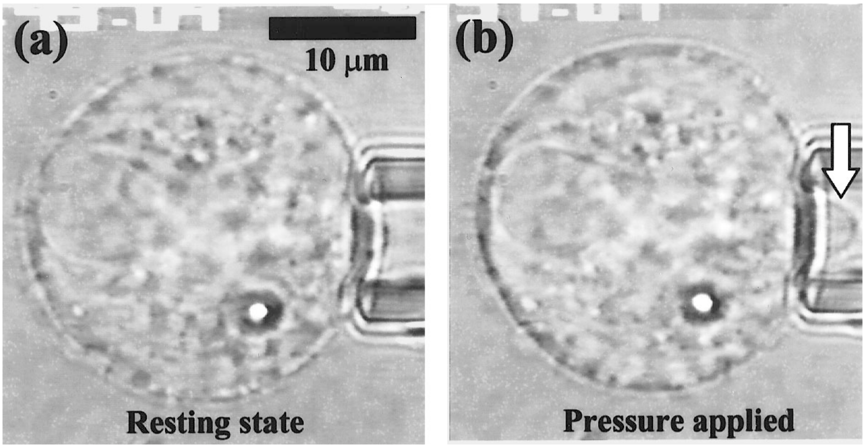

FIGURE 1 The micropipette aspiration test for determining the elastic and viscoelastic properties of living cells. A glass micropipette (inner diameter ~5 µm) is used to apply pressure to a single cell, and the resulting deformation of cell is recorded using video microscopy (arrow). A theoretical analysis is combined with these experimental measurements to determine the properties of the cell.

1996; Hochmuth, 1993) and atomic force microscopy (Shroff et al., 1995) have been successful in quantifying the mechanical properties of individual cells and their components. The major engineering contribution of these techniques has been the ability to measure forces on the order of piconewtons and displacements on the order of nanometers. These measurements, in conjunction with a continuum viscoelastic model of the cell in its extracellular matrix (Guilak and Mow, 1992), have provided new information on the spatial and temporal distributions of stress and strain around a single cell under both normal and disease conditions. Validation of these theoretical predictions has been made using three-dimensional confocal scanning laser microscopy to quantify the changes in shape and volume that living chondrocytes undergo as articular cartilage is subjected to physiological levels of compression (Guilak, 1995). Confocal scanning laser microscopy has also been used to elucidate the earliest intracellular events that occur in response to mechanical stimuli. With this technique, it has been shown that cells can respond to mechanical stress within milliseconds by rapidly altering the concentration of intracellular ions such as calcium (Guilak et al., 1994).

MECHANICAL FORCE GENERATION

The ability of cells to generate force is clearly a necessity for bodily functions such as locomotion, respiration, and blood circulation. On a smaller scale, however, many important cellular and subcellular activities require the generation of force by "molecular motors" within the cell. For example, contractile forces and controlled intermolecular motion drive the locomotion of single cells, which is involved in numerous physiological processes such as wound healing, reproduction, and cellular invasion (e.g., metastasis of cancer cells). The generation of internal forces is also necessary for critical cellular processes such as cell division and intracellular transport of various molecules.

Cellular force generation in these cases is a series of reactions by which chemical energy is used to translocate one molecule relative to another (e.g., actin and myosin in the case of skeletal muscle). The magnitude of the forces involved in the mechanics of single cells are on the order of nano- to piconewtons. These forces often represent the interactions between individual molecules and are at the limit of detection using current technologies. New advances in engineering technology have enabled measurement and application of extremely low forces in this range using such techniques as atomic force microscopy, optical gradient traps, micropipette manipulation, and microelectromechanical systems.

For example, most cells migrate by extending the leading edge of their plasma membrane as a pseudopod ("false foot"), which is then attached to the underlying substrate and used to pull the cell forward. These gross cellular motions are driven by forces generated by mechanochemical enzymes such as the molecule kinesin. Recent studies have been able to quantify the force generated by a single molecular motor. These forces were measured with a laser-induced, single-beam optical gradient trap, also known as optical tweezers. This device can be used to generate forces of a few piconewtons using a gradient in laser light that traps a latex microsphere. In this experiment it was found that the motion of kinesin could be stopped by exerting a force of approximately 2 piconewtons (Kuo and Sheetz, 1993). The ability to measure forces generated by single macromolecules now permits determination of the fundamental thermodynamic mechanisms of mechanochemical force transduction by living cells.

CELL-MATRIX INTERACTIONS AND CELL ADHESION

The transmission of force between a cell and its extracellular matrix occurs through adhesion molecules on the cell membrane that bind to specific matrix proteins. Thus, an understanding of the processes involved in the formation and dissociation of these bonds is an important aspect of the interaction of cells with mechanical forces. Several recent studies have sought to measure the force of a single molecular bond between a cell membrane receptor and an extracellular protein using novel transducers with piconewton force resolution.

Development of the atomic force microscope has revolutionized the quantification of intermolecular forces by allowing accurate and precise measurement of extremely low forces (10 to 1,000 piconewtons) at frequencies of up to 20 kiloherz (Chilkoti et al., 1995; Engel, 1997). Several other novel techniques based on micropipette manipulation have been developed for quantifying the force of adhesion of a single molecular bond. These techniques are based on fluid pressures being applied through a glass micropipette with a diameter of 1 to 5 microns. One technique has involved using a blood cell that has been pressurized by micropipette suction as an ultrasensitive force transducer. Deformation of the cell can be measured with nanometer resolution using interference microscopy. By altering the tension, the sensitivity of the transducer can be tuned through a range of forces from 0.01 to approximately 1,000 piconewtons (Evans et al., 1995). By coating the transducer and the target region with specific molecules, the kinetics and strength of individual bonds can be studied.

FUTURE DIRECTIONS

With the development of such techniques as atomic force microscopy, optical gradient traps, and micropipette manipulation, it is now possible to measure the extremely low forces and displacements generated by molecular interactions in living cells. Simultaneously, rapid advances in computational speed and power have made it possible to develop large-scale continuum and structural models of the interactions between tissues and cells. With improved imaging and microscopy techniques, recent studies have been able to decrease the geometric scale of these models while increasing the level of molecular detail that is modeled. As this trend continues, we approach the fundamental limits of continuum mechanics, and new approaches are incorporating structural models of cells and tissues at the molecular level. It is now becoming necessary to acquire information on the intrinsic mechanical properties and behavior of single molecules and the interactions between individual molecules.

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Mechanical Influences on Bone Development and Adaptation

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The vertebrate skeleton is a wonderfully adaptive structure whose form is determined in part by its structural function. The bone tissue of the skeleton consists of a hard mineralized matrix that has living cells embedded in it. These cells produce the extracellular matrix around themselves and enable the skeleton to respond to its environment by altering their matrix production. Many biophysical factors influence bone cell function, including mechanical loading, hormones, growth factors, and intrinsic genetic composition. For centuries the ability of the skeleton to adapt its structural form has fascinated scientists, including Galileo and Darwin.

Mechanical regulation of skeletal biology begins during embryogenesis and continues throughout postnatal life. Most skeletal elements form initially as cartilage prepatterns in the embryo. In the human embryo, involuntary muscle contractions begin 6 weeks postconception, coinciding with the initiation of ossification in the cartilage rudiments. These muscle contractions result in joint motions and tissue strains that guide the ongoing skeletal development. After birth, continued skeletal growth is strongly influenced by mechanical forces that affect both bone size and density. Mechanical loading-based influences are particularly evident in the diametrical growth of the dense cortical bone found at the midshaft and in the structure and anisotropy of the porous trabecular bone at the epiphyses of the long slender bones of the appendicular skeleton (Carter et al., 1996).

Because normal growth is mechanically regulated, alterations in mechanical loading due to physical activity, injury, or implants induce an adaptive skeletal response. Experimental studies examining bone functional adaptation to mechanical loading have been performed for over a century. In the adult, increased mechanical loading results in increased bone formation; decreases in loading result in bone loss, or resorption (Biewener and Bertram, 1993). Analytical engineering-based approaches are becoming more common and need to be combined with experimental data. In the past decade, adaptive analytical and finite element models have been developed to simulate the functional adaptation of both the continuum and microstructural features of bone (Beaupré et al., 1990; Mullender et al., 1994; van der Meulen et al., 1993).

Whereas the overall nature of the adaptive response of bone has been well documented, the mechanisms that transduce a mechanical stimulus to a biological signal to increase or decrease bone mass are not understood, including the stimulus, signal transduction pathway, and response process (Duncan and Turner, 1995). Without this knowledge, our ability to quantitatively predict adaptation is very limited. Important questions that need to be addressed include possible physical stimuli associated with mechanical loading, including cell deformation, fluid flow, streaming potentials, and fatigue damage. We also need to understand how bone cells sense these stimuli and respond to their environment, such as the research described in the previous paper, *Biomechanics of Cells and Cell-Matrix Interactions*. However, the results of such in vitro cell culture studies must be applied to understanding the in vivo behavior of cells, tissues, and organs.

Technological advances in imaging, computing, and molecular biology have started to impact our understanding of the skeleton, and these techniques not only need to be implemented but, more importantly, integrated. Emerging techniques for imaging are allowing us to observe and ask questions about structures and phenomena never before visualized. The architecture of trabecular bone has traditionally been evaluated by reconstructing two-dimensional serial sections. In the rat, trabecular widths and separations are around 50 and 150 μm, respectively. Micro-computed tomography (micro-CT) is a noninvasive method for assessing three-dimensional trabecular bone structure. Micro-CT scans of bone samples can nominally obtain resolutions of 14 μm (Müller and Rüeggsegger, 1997). Current limitations include high radiation doses and sample size restrictions. These systems are slowly becoming widely available and are considered the standard for trabecular morphometry. Further improved resolution can be obtained using monochromatic synchrotron radiation (Kinney et al., 1993). Synchrotron-based x-ray tomography provides spatial resolutions of 2 to 8 μm and can be performed in vivo but is clearly not widely available. In addition to detailed structural data, the tomographic intensities also provide the bone mineral density locally at the same resolution.

Increased computational speed and availability have led to more complex models and algorithms. Both continuum and cellular-level models of bone have been used, but each level of analysis has traditionally been examined independently. Enhanced computational power coupled with improved imaging resolution has led to the development of models incorporating continuum, tissue, and cellular details. Using micro-CT imaging, very detailed models of trabecular microstructure have been developed (van Rietbergen et al., 1997). These models convert the micro-CT voxels directly to cubic finite elements, producing finite element models with 10^5-10^6 elements. Comparisons between continuum apparent behavior can be made with tissue-level predictions.

Genetic factors underlie the development of bone and cartilage, but external physicochemical factors, such as mechanical loading, control and modulate gene expression. Improved molecular biology techniques allow us to essentially map cells, genes, and proteins throughout tissues. Specific questions about protein expression during bone adaptation can now be addressed, particularly in embryological experiments. In experiments on bone growth and development, the presence and patterns of expression of proteins believed to play a role in skeletal tissue formation can be followed. In addition, the ability to deactivate, or knock out, genes has enabled us to begin to examine the contributions of individual genes (Mikic´ et al., 1996). To date, these studies have primarily been used to map normal gene expression, and we are beginning to address the interaction between gene expression and epigenetic factors (van der Meulen and Allen, 1997).

The difficulty in combining these technologies arises from the interdisciplinary nature of this research. Measurements made in the laboratory need to be related to the inputs required for engineering models. Validation of analytical models is critical to their success and can only be achieved by better integration with experimental technology. Experiments need to be designed with measurements that can be incorporated into models. Observations made on cells in culture need to be translated to in vivo organ responses. Communication and interaction between engineers, biologists, clinicians, and others is critical and will determine future advances.

The potential impact of understanding bone adaptation to biophysical stimuli is significant: mechanical factors are implicated in many orthopedic and endocrine skeletal disorders, including total joint replacements, fracture healing, arthritis, and osteoporosis. Osteoporosis is a severe worldwide health problem. In the United States, 9.4 million (30 percent) postmenopausal Caucasian women are estimated to have osteoporosis when the condition is defined by low bone mass; half of these women are estimated to have severe osteoporosis, based on experiencing one or more fractures. For 1986 the economic cost of osteoporosis and associated fractures in the United States was estimated to be $7 billion to $10 billion (U.S. Department of Health and Human Services, 1991). Fractures experienced by osteoporotic individuals are the direct consequence of bone loss, which compromises skeletal ability to withstand loads. Therapies for increasing bone mass include exercise and pharmacological agents; therefore, an understanding of the relationship between mechanical loading and bone mass changes during bone adaptation is important. Osteoarthritis is the endstage of cartilage degeneration and is associated with many factors, including mechanical loading. Osteoarthritic cartilage damage affects nearly half of all individuals over age 65 and often requires costly total joint replacements, as discussed in more depth in the following paper, *Implant Design and Technology*. As the elderly population worldwide increases in the coming decades, the incidence and cost to society of load-related skeletal conditions also will increase, motivating the need to better understand skeletal functional adaptation.

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Implant Design and Technology

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Mechanical replacement of diseased or traumatized joints with engineered structures is one of the great medical triumphs of the past 30 years. Over time the indications for joint replacement surgery have broadened faster, and to include even younger patients, than has science's ability to engineer longer-lived devices. Society's reliance on increasingly more technological solutions to the challenges of aging has cast into the field of implant design the holy grail of a lifetime prosthesis coupled with a minimum alteration of the patient's lifestyle. To this end the engineer, scientist, and clinician must synthesize their ideas and experiences with an eye to understanding that hypothesis testing can take many years, if not decades.

Until about 1960 the normal degradation of joint function with increasing age, or due to systemic disease such as rheumatoid arthritis, was considered a regrettable but essentially nontreatable chronic condition. In about 1960 Sir John Charnley of the United Kingdom developed the idea of replacing the articulating mechanism of the hip with an artificial construct consisting of a stainless steel ball affixed to an implantable stem articulating with a plastic (polyethylene) bearing. In addition, he pioneered the idea of using a polymer grout (methylmethacrylate) to fix the stem within the femoral canal. The true breakthrough, however, was in the choice of a bearing that was substantially smaller than the natural head in order to reduce the torque generated by the mechanism. Thus, the kinematics of the hip joint were restored using a design that varied from the apparent optimum design provided by biology.

In subsequent years, as the artificial hip became an accepted treatment for natural joint degradation, attention turned to the other large weight-bearing joint in the body—the knee. In France a group of designers developed what became known as the Guepar knee, which took its design cues from the natural knee's suggestion that a hinge coupling the femur and tibia would best replace a damaged knee. While moderately successful in patients with limited physical activity, the design neglected to permit the rotatory motion about the natural knee, and the torque thus generated in the artificial construct tended to tear the components out of their bone bed. Once again, it took a sideways path away from the natural biology to develop a kinematically successful knee replacement. Eventually designs that mimicked the bearing surfaces of the natural knee while permitting the still-intact ligaments to dictate the kinematics were developed and used successfully beginning in the early to mid-1970s.

While other joints in the body, including the shoulder, elbow, and wrist to name a few, can be replaced with man-made constructs, hip and knee replacements dominate the field, and much research today is focused on improving the longevity and, to a lesser degree, the function of these two joint replacements. If one momentarily assumes that the kinematics of the designs are roughly optimized, the research questions that arise tend to be almost exclusively in the domains of material and interface improvements.

Early hip and knee prostheses were fixed to the bone using an in situ polymerizing polymer. Within about a decade following widespread acceptance of hip replacement in the medical community, patients began to present with lesions about the stemmed portion of the implant in the femoral canal, caused by localized osteolysis. Thin lesions, while not destroying the bone per se, had the effect of decoupling the bone-implant construct, which led to pain and necessitated reimplantation of a second stem after cleaning out the femoral canal. Larger lesions increased the risk of fracture of the femur itself due to thinning of the femoral tube's walls and thus posed an ongoing problem even if the original stem was exchanged. In time these osteolytic changes were attributed to the release of microscopic amounts of methylmethacrylate in particulate form, leading to a localized macrophage response. Design focus then shifted to development of femoral stems that could be implanted without the polymer grout and thus development of a direct interface between the living bone tissue and the (almost always) metal stem. These implant designs, known as cementless implants, came into clinical use in the early 1980s.

Early cementless implants were made of a cobalt-chromium alloy surfaced with tiny beads to create pores into which the living bone would grow and thus form a mechanical bond and load transferring interface between the femur and the implant. Strategies for placement of the beads varied by design, but it became apparent that in order to achieve bony integration with the implant the relative motion between the implant and the bone had to be reduced to below about 100 μm. For a time research efforts focused on optimizing the stem design to make it as motionless within the femoral canal as possible, a constraint that had previously been nulled out by the use of the polymer grout. In time one old and one new problem arose with the use of these cementless stems: osteolysis in the femoral canal and loss of bone density about the implant. The first problem was the one supposedly solved by the use of a cementless construct, and the second was a problem already understood to be caused by a transfer of load from the relatively low stiffness bone to the very stiff implant, thus bypassing or shielding the bone from load and causing an adaptive response leading to lowered bone density.

Further development that continues today in femoral stem design has chiefly been oriented toward reducing the structural stiffness of the implantable stem, thus increasing the bone's share of the joint loads and reducing the adaptive response leading to bone resorption. Titanium alloy stems were developed that had the chief advantage of being twice as flexible on a size-for-size basis as an equivalent cobalt-chromium stem. They had a second advantage of naturally passivating to a coating of titanium dioxide, which biological studies had shown was more biointegrable than the cobalt-chromium surface of the previous generation of implants. Unfortunately, because of the notch sensitivity of the material, the beads used previously to encourage bonding of the bone to the stem could not be used without risk of fatigue fracture of the stem itself. Attempts to implant the stems directly without any mechanically roughened interface were generally unsuccessful. Attempts to encourage bone ingrowth into pads of fibrous titanium affixed to the stem were more successful, but results were still much more varied than the uniformly good record of cemented implants in the early to midterm.

If the interface was the problem, the solution lay in finding a material that would be both biologically compatible and mechanically feasible. Hydroxylapatite, a calcium phosphate that is the naturally occurring mineral phase of bone, was chosen as a natural biologically compatible material. However, since it is a ceramic with very low bulk strength, attempts to apply the material to stems in large amounts led to delamination. Application of a very thin layer using a plasma spray process was much more successful in maintaining a bond between the metal and the ceramic while still presenting a biologically compatible surface to the host bone. Hydroxylapatite-coated stems came onto the U.S. market in the late 1980s and to date have shown a significantly lowered propensity toward bone resorption, presumably because of the enhanced load transfer to the bone as a function of the reduced structural stiffness of the stem coupled with an enhanced interface between the living bone and the calcium phosphate layer.

The second failure mode, osteolysis, is now known to be caused by small particles of almost any material, be it titanium, cobalt-chromium, or more especially polyethylene. As younger and more active patients are fitted with prostheses because of their overwhelming clinical success, more wear of the plastic bearing is seen. Research since the early 1990s has focused extensively on both characterizing polyethylene as it exists today and on ways of increasing its resistance to abrasive wear while reducing the polymer's natural tendency to degrade through oxidation. Development of inert gas packages and enhanced cross-linking through high-energy irradiation are some of the techniques being developed to reduce the level of particulates generated in the artificial joint. Alternative bearing couples, such as ceramic-ceramic bearings that wear almost imperceptibly, also are being developed in the United States, although earlier designs somewhat more prone to fracture because of larger grain sizes have been used in Europe for over a decade.

The kinematics of implant function have come under scrutiny as newer methods of in vivo visualization, such as full-motion cinefluoroscopy, have permitted scientists to compare the functions of natural and replaced joints, especially knees. Recently, nearly 100-year-old ideas regarding how the femur bends and rotates about the tibia have been challenged as a result of data emanating from fluoroscopy studies, and devices incorporating some of these findings are now entering the market. Recognition that the plastic bearing in knee devices is subject to very different loads than that in hip devices has led to a bifurcation in studies on how to improve this material. Specifically, while polyethylene destined for hip bearings may need to be designed to resist abrasive wear, the same material used in a knee bearing may need to resist microcracking arising from high cyclic contact stresses.

The overall goal of research into the design and fabrication of implants today is to produce man-made devices that last the natural life of the recipient. While in many areas people no longer believe that technology will rescue them from whatever challenge befalls, in medicine the same people place a trust on the engineer, scientist, and physician that all ailments can be cured or at least substantially mitigated—hence, the continued study of artificial prostheses, their material composition, and their interaction with the living body.

SENSORS AND CONTROL FOR MANUFACTURING PROCESSES

Emerging Control Structures

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The method by which engineering materials are processed into usable components, structures, devices, or systems is a critical factor in determining the success of industries as diverse as aerospace, automotive, and construction (Wen, 1991). Competence, quality, and reproducibility in manufacturing are essential for the processing of new materials into viable products and for the continued improvement of components made from conventional materials (National Research Council, 1989). Technologically advanced industries manufacture components and systems requiring tight constraints in terms of material properties and parts configuration, yet it is not cost effective to perform quality control after a part is completed.

Additionally, flexible manufacturing practices to produce a number of similar parts utilizing the same equipment would be advantageous so that large inventories need not be maintained nor long lead times required to fabricate modified components. On-line process monitoring with in situ sensors and reactive control systems is required to improve parts quality and product yield and to allow for flexible processing methods. A program to implement real-time sensing and control of spray-formed preform conditions was completed by the U.S. Navy. The objective of the program was to develop sensor and control technology to monitor the critical process conditions and to modify parameters during the spray metal-forming process to produce components with repeatable microstructural quality.

High-deposition-rate spray forming is a new technology under development to reduce the cost and improve the workability and mechanical properties of a spectrum of engineering alloys. In the spray deposition process, a stream of molten metal is atomized by an inert gas, producing a spray of liquid droplets that are cooled by the gas and accelerated toward a substrate where they consolidate to form a fully dense deposit. Results of prior research indicated that fully dense preforms could be sprayed and roll extruded into nickel alloy piping with properties equivalent to conventionally made piping at substantially reduced costs (Moran and White, 1990). The technology is alloy nonspecific and therefore applicable to a wide range of metallic systems. Currently, however, spray-forming technology is limited to symmetrical shapes and requires trial runs to establish processing parameters. Development of in-process controls to minimize the trial-and-error method for establishing processing parameters would further reduce costs and make spray forming more commercially attractive. More importantly, it would provide a cost-effective means of producing a variety of quality near-net-shaped (requiring little machining to meet final dimensional tolerances) products not now possible with spray forming. Such components could be substituted for higher-priced forgings or lower-performance castings.

The objective of intelligent control is to establish relationships between the primary process parameters and indicators of final parts quality that can be sensed and controlled in real time. These relationships are represented by mathematical models and neural networks. In the intelligent spray-forming system, a fuzzy logic controller monitors the critical process conditions and modifies parameters during the process to produce components with repeatable microstructural quality. The first step in developing the controller was to construct sensors and controls to monitor the effects of several independent process parameters such as melt superheat, metal flow rate, gas pressure, spray motion, spray height, and substrate motion. In the second phase the selected sensors and controls were combined with actuators for integration with the spray-forming equipment, as shown in Figure 1. Laser striping and infrared cameras are used to evaluate preform surface quality during deposition.

The control system is divided into subsystems, including a spray planner, spray modeler, motion planner, run simulator, and run manager. The spray planner and spray modeler use a database of past run experiences and an expert system shell to develop the process recipe for each new run. The run recipe contains the process set points as a function of time. Part motion is defined by the motion planner, which uses information from previous runs to generate a path for the manipulator. The run is simulated by the simulator subsystem so that preform growth and shape can be evaluated before actual execution. Expected values for shape, surface condition, and temperature are utilized by the run manager to guide the process during the actual spray-forming run. Sensor data are used by a fuzzy logic-based intelligent controller to make adjustments to primary process parameters such as atomization gas pressure, droplet flight distance, and melt flow rate. These adjustments are made in small increments, and sensor feedback determines whether appropriate responses are obtained in the process. The goal is to maintain a quasi-

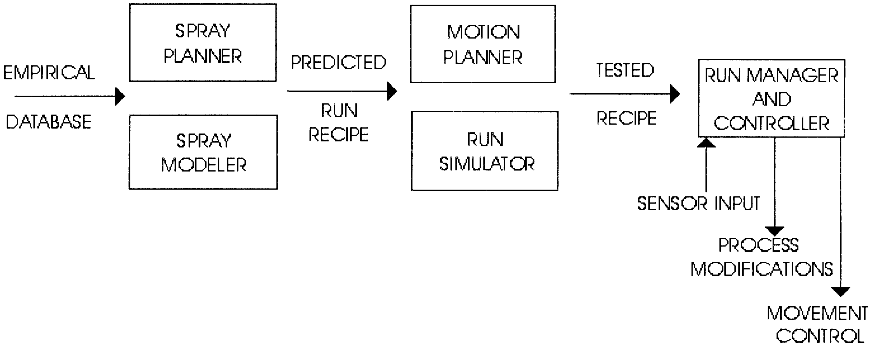

FIGURE 1 Schematic of the intelligent spray-forming control system.

static process state in which appropriate deposition-layer thickness and temperature result in a fully dense preform with a fine equiaxed grain structure.

The spray collector uses hydraulic actuators and has five axes of motion, including withdrawal, spray height, wrist roll, wrist pitch, and tool roll. Asymmetric components such as hemispheres and tapered tubes can now be produced via spray forming. In addition, a detailed empirical process database has been developed that includes all monitorable process conditions such as alloy type, microstructural quality, and preform soundness.

To optimize spray forming in terms of the microstructure and properties of a product, it was necessary to model the process. This was done by dividing the complete sequence of events into six discrete steps or submodels (Mathur et al., 1989, 1991) that address atomization, the spray, droplet consolidation, preform shape, solidification in the preform, and development of the microstructure. Collectively, the submodels constitute an integral model of the process since the output from one stage is used as the input to another stage down the line. The atomization model is used to predict droplet size distribution in the spray as a function of the spray-forming process parameters. The spray model is a mathematical model that describes the metal spray and predicts the condition of the spray upon impact with the substrate.

The modeling results suggest that, under normal operating conditions, approximately 50 to 70 percent of the spray is solidified during flight in the form of fully solid and partially solid droplets. This mode of solidification occurs at high cooling rates ($>10^4$°C/sec) and results in a fine-scale microstructure in the solidified and partially solidified droplets that arrive at the deposition surface. Droplet consolidation occurs when a mixture of solid, mushy, and liquid droplets from the spray impact the deposition surface. Only a portion of the droplets stick to the surface and contribute to the growth of the deposit; this proportion is termed the sticking efficiency, which exerts a major influence on the yield, shape, and microstructure of spray-formed deposits. The droplet consolidation model predicts the sticking efficiency as a function of the spray condition at impact and the preform surface condition. The optimal strategy to maximize yield is to raise the fraction of liquid on the preform surface close to 50 percent as soon as possible in the run and then maintain it at this value throughout the process. The shape model dynamically predicts the evolution of the shape of the part for various substrates and spray configurations, while the solidification model utilizes heat transfer analyses to anticipate the preform liquid fraction as a function of temperature change. The size of the grains in the microstructure in spray cast deposits is computed from the microstructure model (Moran et al., 1994).

To produce high-quality spray-formed parts consistently, correlations were made between the input process parameters and the final part quality. Emphasis was placed on an empirical form of modeling to fully understand the spray-forming process. This effort was accomplished through advanced sensing techniques such as laser striping and infrared photography as well as neural networks, which are used as a tool to help define the relationship between spray-forming process parameters and quality. Specifically, an artificial neural network was trained with actual operating data and designed to mimic the problem-solving process exhibited by the human operator and later tested with hypothetical data. Neural networks accurately predict trends in spray-forming process outputs based on variations in process inputs. Like the biological neuron in human thought processes, processing elements (PEs) in a neural network receive inputs from many other PEs and send outputs to many others. These inputs are usually weighted, combined by simple summation, and then analyzed by a transfer function in the PE (Webster, 1991). The neural networks are used to define the spray-forming process parametric limits utilized by the fuzzy logic controller to monitor and adjust the process in real time, thus assuring optimal parts quality (Payne et al., 1993). Graphs generated by the neural network prediction help define the optimal operating region for the spray-forming process and indicate the effect of changing input process parameters on final parts quality.

In summary, intelligent control techniques have been applied to the spray-forming process, which has significant metallurgical and economic benefits but requires sophisticated control technology to achieve the level of reliability and reproducibility required for widespread commercialization. Process models and artificial neural networks suitable for such control have been developed. Critical process parameters can be sensed and controlled via a fuzzy logic controller that identifies and implements parametric actions based on process conditions to assure parts quality.

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Design and Applications of Optical Fiber Sensors

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Fiber sensors have found numerous industrial, military, and civil applications in the past decade, including transportation systems, such as aircraft, spacecraft, and automobiles; power generation and distribution systems; and civil structures, such as bridges, buildings, and dams. These sensors possess small size and high sensitivity, are immune to electromagnetic interference, and can be easily embedded or attached to structures to provide online monitoring of strain, temperature, and other parameters. For example, typical communication-grade silica optical fiber will survive up to 900ºC when coated with gold, and sapphire optical fiber will survive up to 2000ºC. F&S has demonstrated measurements of strain and temperature up to 1750ºC with sapphire fiber extrinsic Fabry-Perot interferometers. These sensors also enable measurements in very harsh environments not previously accessible with existing technology. For example, F&S has measured strain on the magnets in large accelerators that produce 4-tesla magnetic fields in liquid helium, as well as inside magnetic resonance imaging systems.

While fiber optic sensor research has been going on for a long time, turning these sensors into commercial products still remains the largest challenge. There are many very complicated fiber optic sensors that are great research tools but are not likely to be viable commercial products. The challenge we face at F&S is in moving these interesting research projects into more developed products and then to commercially off-the-shelf systems.

F&S's initial product was a fiber optic strain sensor called the extrinsic Fabry-Perot interferometer (EFPI), which has been shown to be an excellent choice for both surface-attached and embedded strain measurement applications. It possesses all of the advantages of fiber optic sensors and has the added advantage of being sensitive only to axial displacements, as opposed to intrinsic fiber optic strain gauges, which exhibit sensitivities to all six states of strain. The EFPI is a displacement measurement platform capable of quantitative measurements of displacements. These displacements can be produced by a structure under load, in which case the attached or embedded EFPI is a strain gauge. If the EFPI is surrounded by a tube that changes its properties as a function of temperature, the EFPI becomes a temperature sensor. If an EFPI is coated with palladium, it makes a very sensitive hydrogen sensor because palladium changes its length as a function of hydrogen. Coating the EFPI with magnetostrictive material makes it possible to measure magnetic fields since it changes its length as a function of the field strength. A magnetostrictive material-coated EFPI has been embedded into an uncured polymer material for the purpose of measuring cure state. An external magnetic field is applied to the EFPI to modulate the sensor length internally. The stress-strain relationship of the EFPI sensor inside the polymer material can be used to determine the cure state. It is also possible to get a very accurate viscosity measurement with this type of sensor, for example in oils in large heavy equipment, where it is important to measure the viscosity of the oil as it is being used. The optics and the electronics that support each of these types of EFPI sensors are very similar.

Commercializing a product requires consideration of the tradeoffs, such as great resolution versus high speed. In meetings on how to improve a particular system, the engineers in the room all want to make it faster, make it do more, and add more knobs to the front. The critical question, however, is "Isn't it a better system if it sells more?"

It is also important to think about the end user. If you want to sell a lot of sensors, you have to sell them to people who use them every day. For example, conventional strain gauges are on a small polyimide patch. Initially, F&S's fiber optic strain gauge looked like a thin strand of glass, and the user had no idea what to do with it. As a result, we had to go back and package the tiny little sensor in a very large patch that looks just like a conventional strain gauge, and now it is starting to sell more.

CURRENT RESEARCH AND APPLICATIONS

Some of F&S's current research is in the following areas:

- *Chemical and biological sensors.* Such sensors are useful for measuring different chemicals that are produced during certain processes. They also are useful for identification purposes, such as measuring very quickly the content of blood in an emergency room setting (from 4 hours to parts per trillion sensitivities in less than 2 minutes), or for detecting and identifying chemical and biological weapons.

- *Microelectromechanical systems (MEMS) and ionic self-assembled monolayer systems.* The MEMS device consists of a pump about the size of a pencil eraser that moves fluids around for a chemical and biological sensor. The self-assembled monolayer coatings allow for the build up of specific types of coatings, one molecular layer at a time. It is possible to modify the internal workings of one of these pumps and change the wall parameters as a function of space and get some very effective coatings on those particular devices.
- *Measuring displacements on works of art.* In the Sistine Chapel, for example, cracks in the frescoes open during the day and close at night due to temperature and humidity changes. Because the sensors are the size of a human hair, they are virtually invisible.
- *Evaluating different bridge structures.* One concept being tried is replacing bridge deckings with aluminum or polymer matrix composite structures instead of using very heavy, labor-intensive steel reinforcement rods. Sensors are used to take measurements of these structures during their lifetimes.

In conclusion, fiber optic sensors offer the opportunity to measure many different things, from physical parameters such as strain, temperature, and pressure to chemical and biological materials. These sensors are being used to 1) improve the fabrication process of materials and structures, 2) perform some type of nondestructive evaluation of the finished product, 3) become part of a sophisticated in-situ health monitoring system, and 4) perform as the nervous system of future smart structures.

Process Control for Chemical Production: An Industrial Success Story

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The chemical process—a single processing unit or combinations thereof used to convert raw materials and energy into finished product—is operated on the basis of the following three broad objectives: (1) process and operator safety must be assured, (2) specified production rates must be maintained, and (3) product quality specifications must be met. Chemical processes are, by nature, dynamic, meaning that their variables are always changing with time. To achieve these objectives, there is a need to monitor and be able to induce change in those key process variables that are related to safety, production rate, and product quality. This dual task of monitoring process condition indicator variables and inducing change in the appropriate process variables in order to alter process conditions favorably is the job of the process control system. Process control is that aspect of engineering concerned with the analysis, design, and implementation of control systems that facilitate the achievement of the stated objectives of safety, production rate, and product quality.

The chemical process industry as a whole is a very broad and diverse industry with various major segments such as oil/gas/petrochemicals, specialty/commodity chemicals, and food/pharmaceuticals/agrochemicals, among others. Furthermore, the processes typically encountered in each segment have distinct characteristics. Within the petrochemicals segment of the industry, the most significant distinguishing characteristics are: (1) similarities between corresponding processing units (i.e., a catalytic cracking unit at an Exxon refinery will be similar to one at a Shell refinery); (2) large-volume, mostly continuous operations, with infrequent startups and shutdowns; (3) strict environmental regulations and constraints; and (4) relatively slim profit margins.

Within the specialty chemicals segment, the distinguishing characteristics are (1) significant diversity in the overall process types and processing units (for example, unlike catalytic cracking units, there is no typical polymerization reactor: there are simply too many different polymerization mechanisms and reactor options); (2) medium-volume, continuous, batch, or semi-batch operations with frequent startups and shutdowns; (3) very strict environmental regulations and product demands; and (4) average profit margins. The food/pharmaceuticals/agrochemicals segment is mostly characterized by: (1) an even greater amount of diversity in processes and processing units; (2) relatively low-volume, almost exclusively batch operations; (3) the strictest government regulations; and (4) much higher profit margins although typically accompanied by generally higher research and development costs.

This breadth and diversity inherent in the chemical process industry affects how process control is practiced, distinguishing chemical process control from control as practiced, for example, in the aerospace industry. In the latter, the control system designed for a prototype of the Boeing 777 can essentially be replicated for future productions; such replication of a successful specific control system design is rendered virtually impossible in the chemical industry by virtue of its breadth and diversity.

Across virtually all sectors of the chemical process industry, however, the current state-of-affairs is dictated by a universal drive for more consistent attainment of high product quality, more efficient use of energy, and an increasing awareness of environmental responsibilities (Miller, 1994). These factors have all combined to impose far stricter demands on control systems than can be routinely and consistently met by traditional techniques alone. A historical perspective on the evolution of chemical process control theory and practice is essential for a proper appreciation of this current state of affairs.

A HISTORICAL PERSPECTIVE

Prior to the 1940's, most industrial chemical processes were controlled manually by skilled operators. This is because the product and process demands were not too strict, the processes themselves were not too complex, and hence, the task required of the control system was easy enough to accomplish by manual control. By the early 1950's, production volume demands had increased; process operation mode had shifted more towards continuous as opposed to batch at the same time that the process interconnections were becoming more complex, hence, there was a more compelling need for automation. This need was met by the introduction of basic feedback control. From the early 1960's onward, with increased process and product demands (increased production volume demands coupled with tighter product quality specifications, increased stringency in environmental regulations, etc.) and even more complex process interconnections with energy integration, novel designs, and operation strategies, the tasks required of the control system became more challenging, creating the need for more sophisticated techniques. Fortunately, the 1960's also brought the advent of the digital computer, without which none of the sophisticated techniques developed during this period could have been implemented.

MODEL PREDICTIVE CONTROL

In the 50-year period since the end of World War II, the success story of process control practice in the chemical industry is, arguably, model predictive control (MPC)—a computer control scheme that utilizes an explicit model of process dynamics in conjunction with optimization techniques for the effective control of multivariable, poorly understood, difficult-to-model industrial processes that are subject to multiple constraints (Garcia et al., 1989). Originally developed entirely in industry, MPC as a class of control schemes has enjoyed such remarkable success and popularity that it is currently the most widely utilized of all the so-called advanced control methodologies in industrial applications (Ogunnaike and Ray, 1994). Yet, nearly 20 years after its development and its first application in industry was made public (Cutler and Ramaker, 1979), a rigorous theoretical basis for the technique is only now beginning to emerge (Rawlings and Muske, 1993; Morari and Lee, 1997).

Even though the various specific versions of MPC techniques differ in implementation details, they all share the same main structural elements. At the current time k (see Figure 1), a process model is used in conjunction with available process measurements to predict the future process output behavior over a prespecified (prediction) horizon of length p, in response to a sequence of m moves in the manipulated inputs. An optimizer is employed to find the particular sequence of manipulated input moves $\{u(k), u(k+1), \ldots, u(k+m-1)\}$ that will cause the predicted process outputs to follow the desired behavior as closely as possible, subject to constraints in the inputs and outputs. Only $u(k)$, the first control move in the computed sequence, is implemented on the real process at the current time instant k. At the subsequent time instant $(k + 1)$, the time horizons are shifted forward by one step and the entire procedure repeated in what is typically referred to as a moving horizon (or receding horizon) formulation. Commercial software packages are now widely available from control system software vendors for implementing MPC on host computers. Since the late 1980's it has become possible to implement these schemes on various distributed control systems that are now routinely available in most modern plants.

In addition to the applications reported in the pioneering publication by Cutler and Ramaker, many other applications of MPC to industrial processes have been reported in the open literature. A recent review of a representative sample of these applications is available in Richalet (1993). A specific ex-

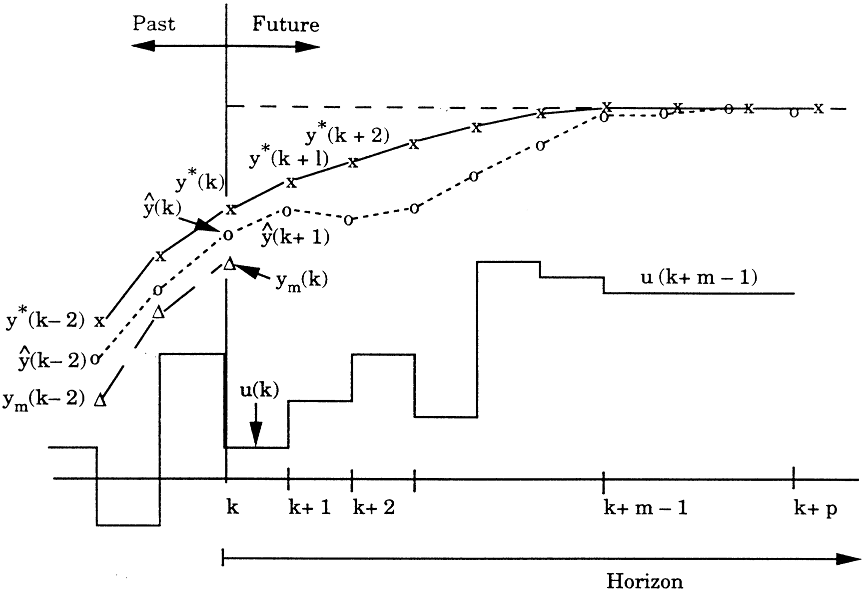

FIGURE 1 Example of elements in model predictive control: x——x: reference trajectory, y^*; o- - - -o: predicted output, $\hat{y}$; Δ— —Δ: measured output, y_m; ——: control action, u. Source: Reprinted with permission from Oxford University Press (Ogunnaike and Ray, 1994).

ample of an application to the control of an industrial terpolymerization reactor (taken from the author's own personal experience) is available in Ogunnaike (1994). In this example, by employing the MPC technique, the overall quality of the terpolymer product manufactured in an evaporatively cooled, continuous stirred tank reactor, was significantly improved.

Despite (or perhaps because of) its remarkable industrial success, MPC remains an active area of research. Initially, the somewhat unconventional form of the original MPC formulation made theoretical analyses almost impossible. With the subsequent state-space reformulation, many advances have been made since in MPC theory and implementation, particularly with respect to such critical issues as feasibility, stability, robustness, and nonlinear extensions.

FRONTIERS IN PROCESS CONTROL

The ever increasing stringency of the demands in the global marketplace, the trend towards more efficient utilization of existing assets rather than capital expenditure, the emergence of new manufacturing sectors creating novel process operation challenges that are difficult to meet with currently available control technology—these are some of the factors motivating current process control research along many fronts, ranging from control theory on one extreme to control systems implementation technology on the other. Some of the most important frontiers of these research efforts include:

- Instrumentation
- Integrated process and control system design
- Process modeling, simulation, and optimization
- Controller design (theory and implementation technology)
- Process and controller performance monitoring and diagnosis.

Some recent breakthroughs and other works-in-progress in these selected frontier areas are summarized below.

Instrumentation

- *"Soft" sensors.* Software-based systems (typically neural networks) for on-line inference of critical process properties available only off-line, or not at all; "virtual" analyzers developed to replace (or augment) laboratory analyzers.
- *"Smart" sensors.* Hardware devices with installed (microprocessor-based) computing power that can execute simple maintenance and diagnostic functions.
- *Fieldbus technology.* A bi-directional digital communication link between control systems and attached "smart" digital field devices; can communicate large volumes of complex process and device data; can certify and correct measurement errors, etc; allows control procedures to be performed at field device level; makes possible vendor-independent interoperability among devices; set to replace centralized control networks with truly distributed ones. Current status: First test carried out in 1993 (BP Research, Sunbury site); multivendor field trial completed in July 1997 on a combustion plant in Nagoya, Japan.

Integrated process and control system design

- *Design for operability.* Mathematical programming approaches for assessing dynamic operability—the ability of a process plant to guarantee high product quality (low variability); quantifying trade-offs between economics and dynamic operability, providing an objective systematic procedure for discriminating between competing designs.
- *Taguchi methods.* Statistical design techniques for selecting free design parameters to make a process intrinsically robust to the propagation of disturbances such as variabilities in the raw material characteristics or ambient operating conditions.

Process modeling, simulation, and optimization

- *Integrated modeling environment.* Novel modeling language and paradigm for ensuring model consistency across various applications; novel equation solving techniques.
- *Process visualization.* Software systems for visual representation of process operation from various perspectives.
- *Production planning and scheduling.* Novel (global) optimization techniques for coordinating activities across multiple production, storage, and distribution facilities.

Controller design (theory and implementation technology)

- *Model predictive control.* Theoretical foundations and extensions; development of effective techniques for simultaneous model identification and control.
- *Intelligent control.* Knowledge-based controllers with higher degrees of autonomous operation; control systems emulating human mental faculties of adaptation, learning, decision-making under significant uncertainty, etc.
- *Novel man/machine interfaces.* Application of techniques from computational and cognitive sciences, neurophysiology, and information theory for the design of interfaces connecting the human operator with increasingly complex processes and associated sophisticated instrumentation.

Process and controller performance monitoring and diagnosis

- *Fault detection and diagnosis.* Statistical techniques for plant-wide process performance monitoring; control loop performance monitoring; diagnosis and recommendations for improvement.
- *Abnormal situation management.* Knowledge-based techniques for "smart" alarming and providing guidance to the human operator for timely and effective decision-making under abnormal process operating conditions.
- *Data-based modeling and analysis.* Information theory-based approaches for on-line process behavior analysis and adaptive modeling.

SUMMARY AND CONCLUSIONS

The chemical process industry is broad, diverse, and continuously evolving. The processes are becoming more complicated, the operating requirements are more stringent, and to meet all the objectives of safety production rate and product quality in such an environment requires control systems that are far more effective than ever before. Model predictive control has been one of the most influential advances of the past 50 years; other advances currently in use or under development will also have significant impact on the future success of the chemical industry.

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SAFETY AND SECURITY ISSUES

Air Traffic Control Modeling

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ABSTRACT

This paper describes how the U.S. national airspace system (NAS) operates today and discusses anticipated changes. Examples are given of recent modeling efforts. Models help NAS stakeholders make better-informed decisions about how to safely implement agreed-upon goals for the next generation of air traffic control equipment and procedures. The models sometimes suggest to decision makers what the goals ought to be. Six fundamental modeling concepts that lie on the modeling frontier and will influence its future directions are discussed. These concepts are suggestions for future research and areas where interdisciplinary contributions would expedite advances at the frontier.

INTRODUCTION

The term *modeling* spans the spectrum from simple relationships to highly complicated, parallel, fast-time, constructive, “human-in-the-loop,” and discrete-event computer simulations. This presentation emphasizes the frontier in modeling. Toward that end, the most exciting work in modeling and simulation is in the development of fundamental modeling concepts. This paper begins with a summary of how the national airspace system (NAS) operates today and then covers anticipated changes and gives examples of models. Then, concepts at the modeling frontier that will guide its future directions and opportunities for interdisciplinary research are discussed.

U.S. NATIONAL AIRSPACE SYSTEM OPERATIONS

Both analytical and computer models are critical tools for researchers of the NAS. The reason is that if we wish to conduct tests or deploy new equipment or procedures, we cannot simply halt NAS operations. The NAS operates continuously. Nor can we simply plug in advanced prototype systems for testing during NAS operations because human lives would be at stake should anything go wrong. So we use models.

NAS airspace spans all U.S. territories and beyond the continental shelf. The NAS includes all air traffic control (ATC) and traffic management facilities and personnel as well as equipment used for communication, navigation, and surveillance, such as VHF/UHF voice transmitters and receivers, navigation beacons, weather and windshear radars, and instrument landing equipment. The Federal Aviation Administration (FAA) procures, operates, and maintains this equipment. Besides the FAA there are the system users who generate flights, including scheduled passenger and cargo carriers, business jets, the military, and general aviation (recreational and experimental aircraft). The NAS is the largest command, control, and computer system in the world.

On a typical day in the United States, over 1.5 million people fly safely aboard some 130,000 flights (Federal Aviation Administration, 1996). The United States maintains a sterling aviation safety record. In economic terms the U.S. civil aviation industry contributes about 5 percent of the annual U.S. gross domestic product, so there are also economic incentives to maintaining a safe and healthy civil aviation industry (Wilbur Smith Associates, 1995).

The FAA assures safety via certification of the people, procedures, and equipment that operates and is maintained in the civilian ATC system, and by regulation of the aviation industry. For example, the FAA inspects and certifies equipment airworthiness and skill levels of flight and maintenance crews. Regulations require that while flying under visual flight rules pilots must "see and avoid" to ensure safe separation. Safe separation means ensuring three-dimensional distance separation between all aircraft at all times.

FAA regulations similarly require that, while flying under instrument flight rules (e.g., passenger flights), pilots must adhere to an FAA-cleared flight plan. Air carrier dispatchers must maintain positive operational control of flights. Positive operational control means uninterrupted origin-to-destination surveillance, communication, and navigation services for every flight. Meanwhile, an FAA ATC specialist ensures safe separation under instrument flight rules.

Starting from gate pushback, the phases of flight include (see Figure 1) taxi, departure, en route transit, approach, land, taxi, and at gate (Nolan, 1994). Correspondingly, ATC control of a flight is passed through a series of controllers: ground, terminal, departure, en route, approach, terminal, and ground. While en route, a flight passes through imaginary chunks of airspace

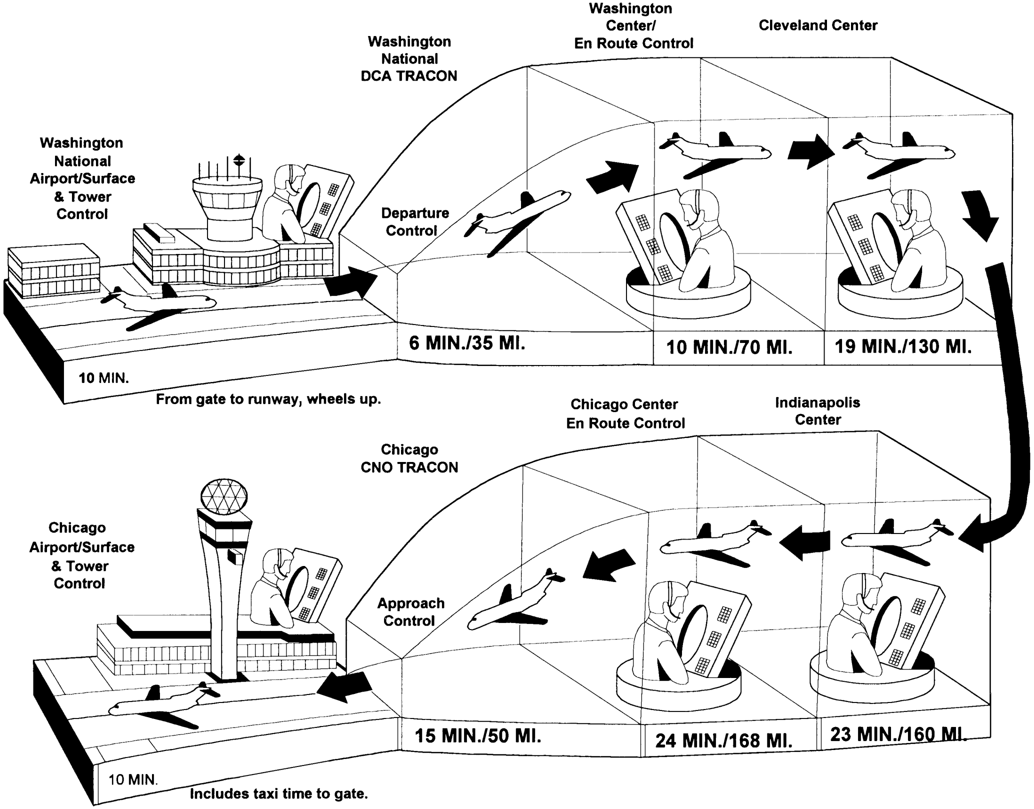

FIGURE 1 Phases of flight. Source: The MITRE Corporation.

and is monitored and controlled by facilities called Air En Route Traffic Control Centers or simply "centers."

One additional control facility is the ATC System Command Center. There, traffic management specialists monitor and manipulate traffic flows nationwide so that traffic demand does not overwhelm system capacity. The command center coordinates among FAA centers and air carrier dispatchers to reroute traffic around pockets of bad weather or disrupted airports. In times of extreme congestion or service disruption, specialists are authorized to impose traffic flow initiatives such as ground delay, ground stop, or miles-in-trail (instructing pilots to maintain a particular distance between leading and trailing aircraft).

The system that has been described is how the NAS currently operates. However, economic and safety factors are driving change. Essentially, the anticipated changes are contained in the "Free Flight" concept (see Figure 2). Under Free Flight, today's system is expected to evolve toward one with distributed decisionmaking, increased information flows, and shared responsibility. Free Flight's greater planning and trajectory flexibility is expected to reap economic benefits. To illustrate, consider that scheduled air carriers' collective profits were about $2.5 billion in 1996 (Air Transport Association, 1997). Under Free Flight, preliminary research conducted by MITRE and others indicates that scheduled air carriers may reap cost savings on the order of $1 billion annually from known, near-term communication, navigation, surveillance, and air traffic management enhancements.

Concern for safety is also driving change. The highest levels of the federal government have articulated a goal to improve safety. The reason why can be shown mathematically. U.S. passenger traffic is forecast to grow by 4 percent per year well into the next millennium (Federal Aviation Administration, 1995; Boeing Commercial Airplane Group Marketing, 1996). In addition, the scheduled air carrier accident rate has averaged 42 accidents per year over the past five years, including both fatal and non-fatal accidents (Federal Aviation Administration, 1997). Compounding the 4 percent annual traffic growth rate and applying the annual accident rate yields a doubling of the annual number of accidents by the year 2014. The only recourse to that unacceptable safety level is to decrease the accident rate by changing the NAS.

MODELING

Since we cannot simply halt NAS operations, analytical and computer models are critical in developing, testing, and evaluating equipment and procedures that show promise for bringing future NAS goals to fruition. For example, security improvements will come from better weapons detection (Makky, 1997) and passenger screening (National Materials Advisory Board,

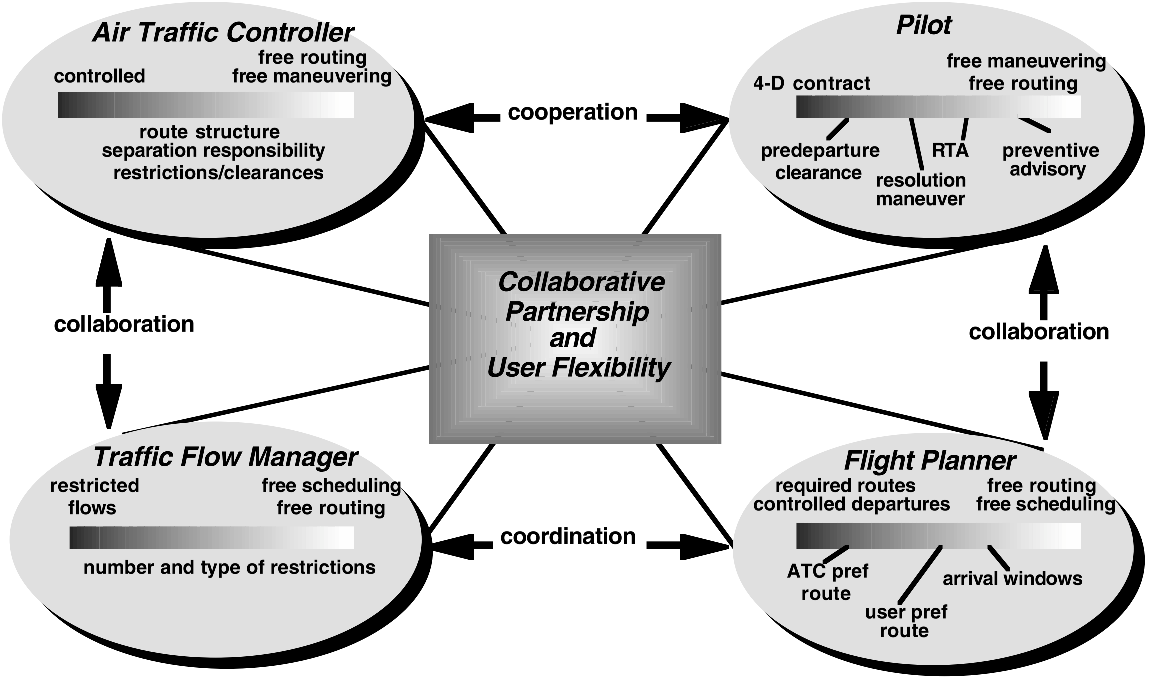

FIGURE 2 Free flight. Source: The MITRE Corporation.

1996). Equipment, materials, and procedures to accomplish this are often modeled by Monte Carlo and discrete-event computer simulations. Experimental designs implemented using these models reveal, for example, ways to improve detection error rates.

MITRE has in-house, human-in-the-loop, real-time cockpit and ATC console simulators that can even simulate weather conditions. Field operational conditions are set up, and air traffic controllers and/or certificated pilots are asked to participate. Sometimes simulations run under controlled experimental conditions, but they often run under exploratory research conditions.

One very well recognized large-scale model developed at MITRE is the Detailed Policy Assessment Tool (DPAT) (MITRE, 1997). DPAT is a constructive, discrete-event, fast-time computer simulation distributed over four Sun Microsystems processors with simulation time synchronized using the Georgia Tech Time Warp product. In about 4 minutes, DPAT can simulate more than 60,000 flights among more than 500 U.S. or international airports. DPAT simulates each flight, computing trajectory, itinerary, and route, as well as runway utilization, system delay and throughput, and other statistics.

Our modeling work has spanned a spectrum of logical paradigms, including deterministic and stochastic rules, fuzzy logic, genetic algorithms, simulated annealing, and mathematical programming. The remainder of this section details those efforts.

In one case we designed algorithms to model stakeholder responses to NAS traffic flow disruptions (Heimerman, 1996). Disruptions could be caused by severe weather, unanticipated airport closure, or other reasons. Responses are decisions to delay, divert, or reroute flights. The algorithms more realistically simulate runway arrival and departure queues as NAS users and command center specialists manage traffic demand. The model also illuminates critical information flows on which decisions are based.

We also constructed a fast-time Monte Carlo model called the Simultaneous Instrument Approach Model. It simulates simultaneous approaches to parallel runways, where there is some probability that a blunder event could occur (see Figure 3). If the blunderer deviates enough, ATC will instruct the evader aircraft to perform a breakout maneuver and go around for a second approach. We designed and verified fuzzy logic algorithms representing the controllers' selection of one of several possible breakout maneuvers.

Current modeling effort explores how air carrier dispatchers might respond if given access to information as envisioned under Free Flight. A secure digital data exchange computer network will allow near-real-time exchange of data that have not been shared before. Such a system ought to enable decision makers to shift their attention from mere information exchange to collaborative decision making.

We have developed two prototype models to explore the implications of such a hypothesis. One is a linear program that shows the economic value of

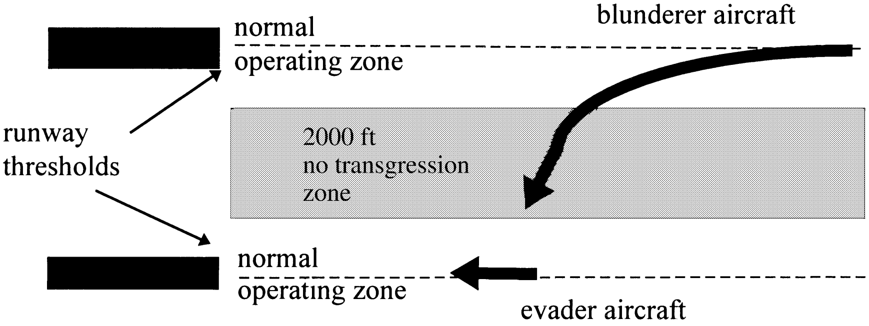

FIGURE 3 Blunder event during simultaneous approaches. Source: The MITRE Corporation.

information sharing. It shows that, if dispatchers are given an accurate, timely report of reduced arrival capacity at an airport, they can dispatch more economically prudent arrival streams. A second model is a set of coupled difference equations that represent an iterative competitive marketing game among air carriers. We used it to identify conditions under which one competitor dominates. A controller entity assumes strategic roles such as arbiter, referee, enforcer, or negotiator. The model exploits principles from complex adaptive systems theory and nonlinear dynamics.

To support these "data greedy" models, parameter estimates are obtained by conducting field tests. One such field test had as its purpose to examine whether datalinks that passed real-time arrival sequence information from the FAA to scheduled air carriers would improve dispatcher situational awareness, operational cost effectiveness, or collaborative problem resolution and decision making. Versions of this field test are currently under way.

FRONTIER AND INTERDISCIPLINARY OPPORTUNITIES

Six fundamental modeling concepts are driving the modeling frontier. These concepts are shaped in aviation applications by an uncompromising regard for safety. The safety constraint translates into a requirement for model credibility, which arises from the processes of verification (assuring that computer programs encode a model's conceptual design) and validation (assuring that the model reflects the real system). As one learns in graduate school, (1) a model is a simplified abstraction of the most salient features of a system and (2) the modeling process invokes a blend of mathematical relationships and art (Banks and Carson, 1984).

- *Concept 1*: The first fundamental concept driving the frontier is that statements (1) and (2) are coupled to the extent that the art of modeling manifests itself in the ways that different people perceive and define the terms *salient features* and *real system*. This fact wreaks havoc on the model validation process, a research area where more work should be done.

The difficulty occurs when two experienced and knowledgeable individuals cannot agree on a single description of the system to be modeled. As a consequence, there is difficulty determining not only when the modeling effort is finished, but also which of the inconsistent perceptions of reality to use for comparison during the validation process. Heated arguments can ensue, particularly where safety is involved. These matters are exacerbated by the fact that the English words modelers use to try to resolve their differences are vague relative to the absolute requirement for unambiguous computer instructions.

- *Concept 2*: Model validation may be additionally confounded when the system of interest is not a real system. For example, we might build a model intended to alert us to never-before-imagined system states, behaviors, processes, or boundaries. So if the model is not supposed to reflect reality, can we know when we have achieved success in modeling? Model validation is not well understood. To those interested, see Oreskes et al. (1994).

- *Concept 3*: Though not required by statements (1) and (2), most students are taught a host of modeling techniques that first decompose a problem into component parts, solve those parts, and then aggregate the solutions as a solution to the larger problem. This approach is called "reductionism" and results in a pyramid of component models. This "pyramid scheme" approach is popular because it is the only one known to many modelers and because object structures in modern object-oriented programming correlate well with a system's component parts.

In fact, however, reductionism is not a productive approach to modeling those systems that are not simply the sum of their parts. The reason is that examining the components does not recognize their dependencies or interactions over time. For example, in a hierarchy of descriptive variables pertinent to some system, the measurement scales at the top and bottom of the hierarchy are often quite different. Such systems are said to exhibit a nonhomogeneous resolution scale throughout its components. As a consequence, reductionist approaches do not apply. More research to supplement reductionist techniques would be helpful.

- *Concept 4*: Another modeling approach that needs to be examined arises from the fact that throughout the history of mathematical modeling we have proactively conserved computational time in order to generate results in a timely manner. For example, we use look-up tables of formula values or estimate functional values by a truncated Taylor's series expansion. We code techniques like these into our models. However, where beneficial and in light of today's high computer speeds and memory capacities, we should reappraise previously abandoned techniques such as exhaustive searches of variable spaces and response surfaces.

- *Concept 5*: Modelers, as a group, are very good at writing computer code that describes physical phenomena such as six-degree-of-freedom projectile trajectories. Increasingly important, however, are models of cognitive, social, and behavioral phenomena and ways that individual behaviors cause flux in trends and paths traversed by humans collectively. Examples include dynamics such as the public good, group performance, economic influences on decision making, and consequences of political struggles.

- *Concept 6*: Related to the preceding point is the concept of modeling how individual people think, process information, and identify the need to reevaluate options or change behavior. Even with results from artificial intelligence, little is known about the links between a decision and the information on which a decision was based. For example, we do not understand "selective attention" in which decisionmakers turn their attention at points in time to the data that they wish to focus on and discard the remaining data. Social scientists could help us understand human reasoning, but that would not be enough. The question of how to encode these processes in computer programs is an additional matter that needs investigation.

SUMMARY

Research providing a richer theory about these six modeling concepts would expedite advances at the frontier. Clearly, contributions could come from other disciplines. Meanwhile, the newest ATC models help NAS stakeholders make better informed decisions about how to safely implement agreed-upon goals for the next generation of air traffic control equipment and procedures. The models are even helping us frame what the goals ought to be. This is an exciting and dynamic time for the modeling and simulation community and for civil aviation.

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Quadrupole Resonance Explosive Detection Systems

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Quadrupole resonance (QR) has been demonstrated to be an effective technique for detecting the presence of energetic materials hidden in baggage and cargo. Quantum Magnetics has developed a series of explosive detection devices (EDDs) based on QR technology. The QSCAN1000 can detect the presence of two main high-explosive molecules, RDX and PETN. These two materials are the main explosive constituents of many military plastic explosives. C4 and Semtex H contain RDX; Detasheet and Semtex A and H contain PETN.

QUADRUPOLE RESONANCE ANALYSIS: BACKGROUND

QR is a magnetic resonance technology that occurs as a result of the inherent electromagnetic properties of the atomic nuclei in crystalline and amorphous solids. Nuclei with nonspherical electric charge distributions possess electric quadrupole moments. QR originates from the interaction of this inherent electric quadrupole moment with the gradient of the electric field in the vicinity.

In classical terms, when an atomic quadrupolar nucleus experiences an electric field gradient from the surrounding atomic environment, different parts of the nucleus experience different electric fields. Therefore, the electric quadrupole experiences a torque that causes it to precess about the electric field gradient. This precessional motion carries with it the nuclear magnetic moment, so that a rotating magnetic field in phase with the precession can change the orientation of the nucleus with respect to the electric field gradient. After such a radio frequency magnetic field pulse, the precessing magnetization produces a detectable oscillating magnetic signal. For explosives and drug detection applications, there are three significant quadrupolar nuclear isotopes: nitrogen-14 (^{14}N), chlorine-35 (^{35}C1), and chlorine-37 (^{37}Cl).

The most significant distinguishing characteristics of a QR response are the precessional (or transition frequencies) and the relaxation times. Relaxation times are measures of the rates at which nuclei return to equilibrium after being disturbed by a radio frequency (RF) field. The types of RF pulse sequences that are appropriate for detecting QR signals are determined by the values of these relaxation times.

SYSTEM DESCRIPTION

The QR scanner described here is referred to as the QSCAN1000, an EDD suitable for inspecting items up to 0.8 m (height) x 1.0 m (width) x 1.0 m (length) in size. The scanner is a conveyorized open-ended system with no encumbrances to impede the flow of baggage and is centered around a number of key components:

- A detection head that consists of a large RF coil that can be tuned over a frequency range containing the QR frequencies of plastic, sheet, and military-grade explosive compounds. RF coil tuning is completely automatic and adjusts for any baggage situation.
- An electro-magnetic interference (EMI) shield to protect the RF coil from external interference. Open access to the coil is afforded by shield tunnels that allow the scanner to operate without any door or cover while affording adequate EMI shielding.
- An electronics package containing an IBM-compatible PC chassis with four plug-in cards (the RF pulse programmer, the RF card, the analog-to-digital conversion card, and a general controller card) that responds to changes caused by different items in the detector head, an RF driver amplifier, control hardware, and system control software.

For explosive detection applications, a pulse train is applied at or near the QR frequency. The response to this train of RF pulses is captured and analyzed for the presence of the characteristic QR signal from an explosive. Two different scans are applied at different QR frequencies for two different explosives, RDX and PETN. The total scan takes less than 8 seconds to perform, equating to a throughput rate of 450 bags per hour. The scanner is shown in Figure 1.

SYSTEM PERFORMANCE

At present, the QSCAN1000 scans for the presence of RDX and PETN. The major factor that dictates detection performance is the signal-to-noise

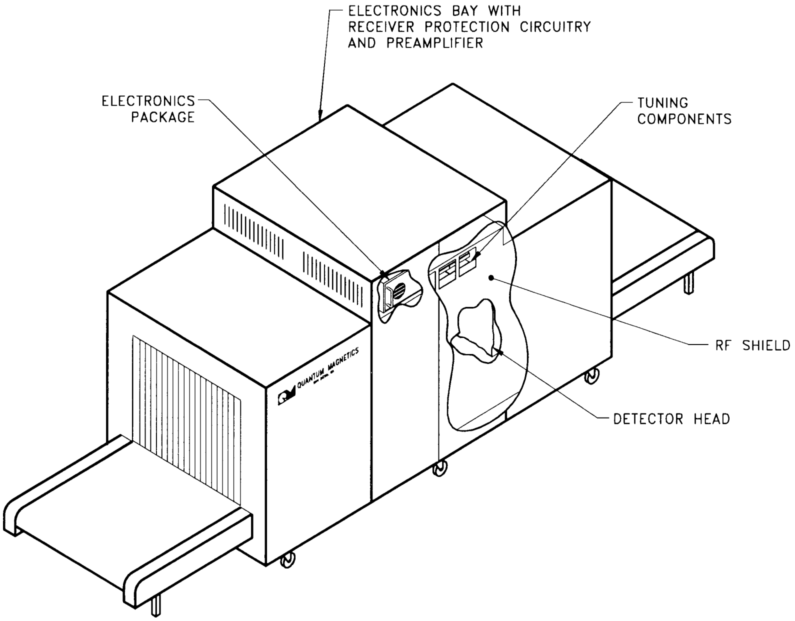

FIGURE 1 The QSCAN1000 EDD, showing the system's key components. Source: Quantum Magnetics.

ratio (SNR) and the false alarm rate. SNR is related to a number of factors, including the efficiency of generating a QR signal and spurious noise in the system. As an example, Figure 2 shows histograms of signal amplitudes from a series of scans, with the QSCAN1000 containing explosives and not containing explosives. The figure clearly shows how the signal amplitude increases as explosives are added. Detection is based on the signal amplitude exceeding a predetermined threshold amplitude (shown as the dark line).

The scan results also can be displayed as a receiver operating characteristic (ROC) curve. The ROC curve is a convenient way to display the tradeoff between the probability of false alarm, P(FA), and the probability of detection, P(D). Figure 3 presents the same data shown in Figure 2, this time in the form of an ROC curve.

The dominating factor that affects the false alarm rate for the QSCAN1000 EDD is the phenomenon of magnetostrictive ringing. Certain types of metallic items when scanned can generate a QR-like signal.

FIELD TRIALS

The QSCAN1000 has been field tested at a number of locations. The first test was at Los Angeles International Airport's Terminal 7, replacing a stan-

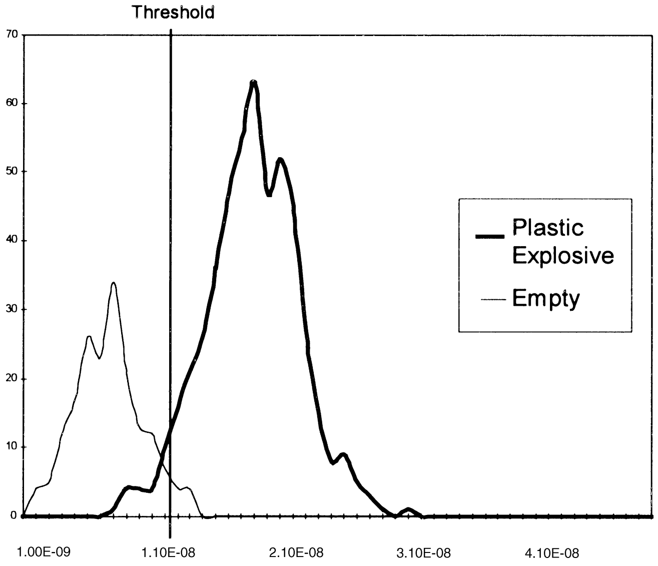

FIGURE 2 This spike voltage histogram shows the distribution of test results on an empty bag and on a bag containing plastic explosive. Source: Quantum Magnetics.

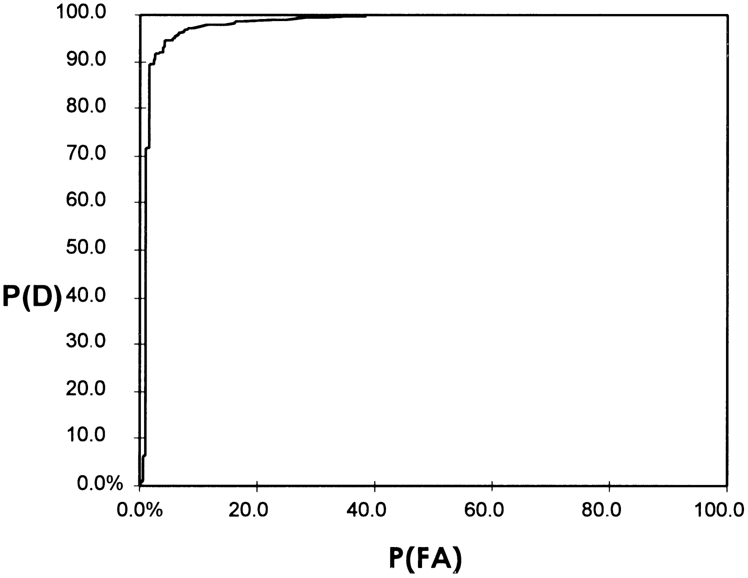

FIGURE 3 Plastic explosive data from Figure 2 presented in the form of an ROC curve. Source: Quantum Magnetics.

dard in-line x-ray system in United Airlines' international baggage-handling line. This trial was the first test ever of a QR explosives screening system in an actual airport environment. During the 1-week trial, a total of 4,000 bags was scanned, at a throughput rate of approximately 600 bags per hour. Further tests were done in the United Kingdom at Manchester and Heathrow international airports. In those tests, over 6,000 bags were scanned, at a throughput rate of approximately 300 bags per hour.

In April 1996 the QSCAN1000 was tested at the Federal Aviation Administration's William J. Hughes Technical Center in Atlantic City. The QSCAN1000 was tested for detection of live explosives of various kinds and in different configurations. The tests were very successful in showing QR to be an effective screening system.

FUTURE WORK

As the development of QR technology has continued, Quantum Magnetics has embarked on a very wide ranging development schedule. The schedule includes both the technical development of QR and its introduction to different areas of airline security, such as the screening of cabin baggage.

Quantum Magnetics is currently engaged in a number of key areas of development with respect to improving the performance of QR-based explosive detection devices for aviation security applications. The detection of plastic explosives will be increased by (1) optimizing the pulse sequences used to detect the signal; (2) utilizing novel multiple frequency detection schemes to increase detection in the presence of magnetostrictive ringing; (3) investigating complex pulse shaping to increase detection bandwidth in order to mitigate deficiencies in detection caused by temperature shifts encountered in airline baggage; and (4) improving throughput with the implementation of an inductive tuning method. The program also will investigate the detection of two additional explosive materials—TNT and ammonium nitrate—and will study other related issues concerned with EMI shielding and the detection of shielded volumes.

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The Role of Nondestructive Evaluation in Life-Cycle Management

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INTRODUCTION

Nondestructive evaluation (NDE) is a suite of techniques that allows visualization of the external and internal structures of an object without damaging it. For example, a very common NDE technique that most people have experienced is the use of dental x-rays for cavity detection. NDE plays an even larger role in nonmedical applications. It is being integrated into the entire product life cycle (Figure 1).

Traditionally, NDE has been viewed only as an end-product inspection tool. The traditional view does not take advantage of the full economic benefit that NDE provides. NDE can ensure/improve safety, shorten the time between product conception and production, and help reduce waste. Examples include new material and process development; raw materials acceptance; process monitoring and control; finished product and in-service inspection; and retirement for cause, disposal, and reuse (Goebbels, 1994). Therefore, NDE is increasingly being used throughout the life-cycle management of products (Cordell, 1997).[1,2,3] Presented here is an overview of some NDE methods and life-cycle applications of NDE.

OVERVIEW OF NDE METHODS

NDE draws on the expertise of a multidisciplinary team and a broad range of technologies. The Lawrence Livermore National Laboratory's (LLNL) NDE organization is an example of such a multidisciplinary team. LLNL has a team that consists of mechanical and electrical engineers, material and com-

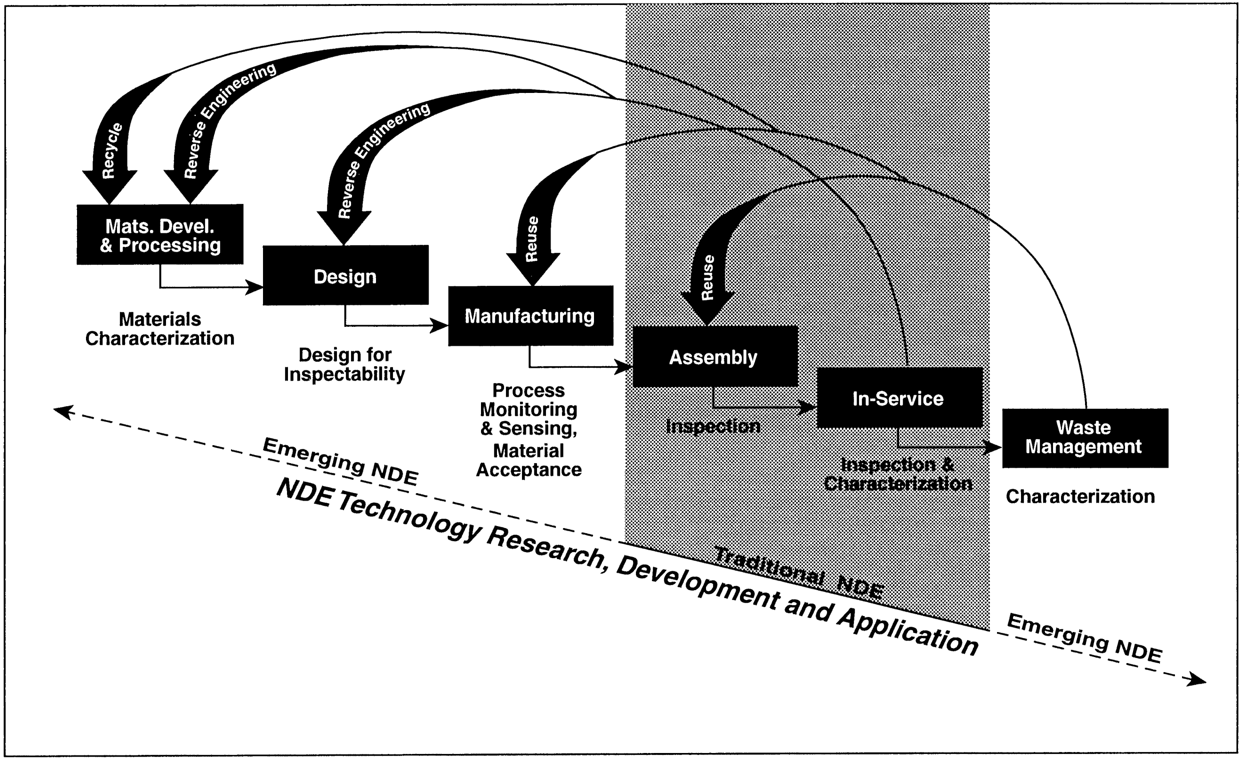


FIGURE 1 Nondestructive evaluation's role in the life cycle of a product.

puter scientists, physicists, and chemists. The broad range of technologies used at LLNL includes electromagnetic (e.g., visual, x-ray radiation, infrared, microwave) and acoustic (e.g., ultrasonics and acoustic emission) measurements.[4] The research, development, and application of these technologies require experimental, theoretical, modeling, and signal and image processing capabilities. NDE is successful when all of these technologies and disciplines are integrated while working closely with the customer to determine the most appropriate technique(s).

NDE techniques have a core of common components: a source (radiant energy); a detector to acquire transmitted or scatter radiation from the object; a manipulator/stage to translate, elevate, and/or rotate the object or source/detector synchronously; and a computer for control, data acquisition, processing, and analysis (Figure 2). A broad range of sources, detectors, manipulators, and computers have been used in NDE. Figure 3 provides some examples of the different electromagnetic sources used in NDE at LLNL. The next section briefly describes some NDE technologies under research and development at LLNL (see note 4).

Visual Inspection

Visual inspection is probably the oldest NDE technique. However, coupling cameras with computers and image processing greatly enhances the NDE application of visual inspection. Innovative lighting schemes provide high-contrast images allowing inspections never before possible with simple camera systems.[5,6] Techniques range from common high-speed and time-lapse photography streak cameras to miniature cameras and fiber-optic-based systems for access to restrictive or hazardous environments (McGarry, 1997). Surface finish, cleanliness verification, presence or absence of specific features, and dimensional measurements are typical NDE tasks performed by visible light systems (Mascio et al., 1997). Traditionally, these measurements required careful orientation of the object to avoid perspective effects. Recent stereo image processing techniques have removed the necessity of having precise part alignment (Nurre, 1996). In addition, stereo techniques are leading to reverse engineering and art-to-part applications where computer-aided design drawings can be realized directly from a scanned image of a part (Levoy, 1997). In this report I do not provide any visible light NDE examples but refer the reader to the above and other references[7] (see also notes 5 and 6).

X- and Gamma-Ray Imaging

X- and gamma-ray imaging techniques in NDE and nondestructive assay (NDA) have seen increasing use in an array of industrial, environmental, military, and medical applications[8] (see also notes 1, 2, and 3). Much of this

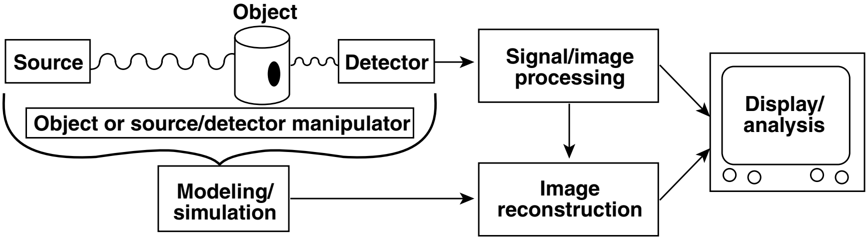


FIGURE 2 Schematic of a typical NDE system configuration.

growth in recent years is attributed to the rapid development of computed tomography (CT). First used in the 1970s as a medical diagnostic tool, CT was adapted to industrial and other nonmedical purposes in the mid-1980s. Single-view (or angle) radiography hides crucial information—that is, the overlapping of object features obscures parts of an object's features and the depth of those features is unknown. CT was developed to retrieve three-dimensional (3D) information of an obscured object's features. To make a CT measurement, several radiographic images (or projections) of an object are acquired at different angles, and the information collected by the detector is

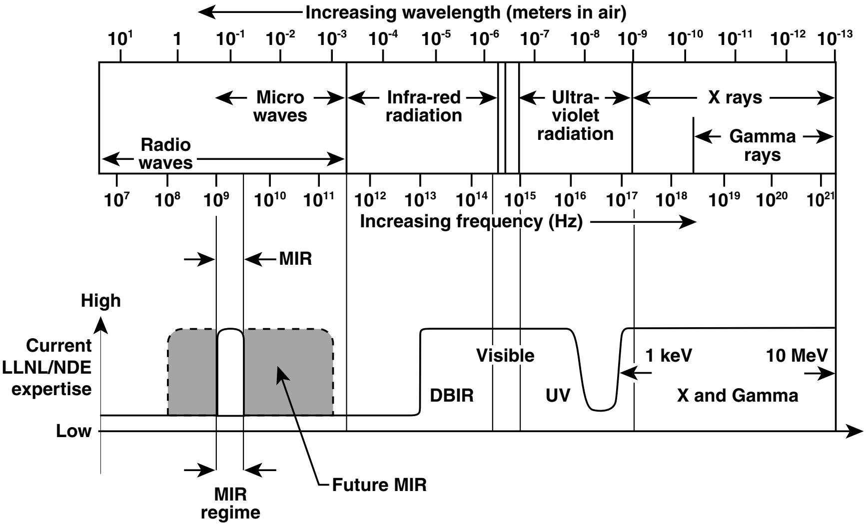


FIGURE 3 Electromagnetic spectrum showing the range of frequencies used in nondestructive evaluation at the Lawrence Livermore National Laboratory. MIR is micropower impulse radar. Source: Reprinted with permission from Lawrence Livermore National Laboratory (Mast and Azevedo, 1996).

processed in a computer (Azevedo, 1991; Barrett and Swindel, 1981; Herman, 1980; Kak and Slaney, 1987). The final 3D image, generated by mathematically combining the radiographic images, provides the exact locations and dimensions of external and internal features of the object. Two examples of CT are presented here; one is for improved implant design, the other for radioactive waste management.

Ultrasonic Testing

Ultrasonic NDE interrogates components with acoustic energy and can be used to determine material properties, wall thickness, and internal defects (Krautkrämer and Krautkrämer, 1990). High-frequency (~1 MHz) pulses of ultrasonic energy are radiated into the material and subsequently detected using specially designed transducers. The sound pulses are altered as they travel into and through the material as a result of attenuation, reflection, and scattering. The output pulse—the detected signal—is displayed, processed, and interpreted in terms of the internal structure of the object under investigation and based on its relation to the input pulse. Most often, ultrasonics is applied to detect thickness and to search for flaws in metals—namely, cracks and voids (see notes 1 and 2). However, ultrasonics can also be used to ascertain grain size, measure residual stress and elastic moduli, evaluate bond quality (e.g., solid-state, adhesive), and analyze surface characteristics (Krautkrämer and Krautkrämer, 1990; see also notes 1 and 2). Whenever the configuration of the object under test permits, a 2-D or 3-D image of the interior of the object can be made with reflections of the sound. An example of the use of ultrasonic testing for understanding material properties in the aging of composites is presented below.

Infrared Imaging

Infrared (IR) imaging is a global area inspection technique used for thermal NDE. IR imaging measures temperature and temperature differences to detect debonding, delamination, cracks, residual stress, metal thickness loss from corrosion, and other conditions that impact heat flow (see notes 1 and 2). Damaged materials heat and cool differently than do undamaged ones. Infrared images of flash-heated materials and structures produce temperature maps at video frame rates. Time-sequenced temperature maps are processed with computer codes developed at LLNL to reveal 3D images of flaw location, size, shape, thickness, relative depth, and percentage of metal loss for corrosion-damaged materials (Del Grande, 1996).

The dual-band infrared (DBIR) technique, developed at LLNL, is used for high-sensitivity temperature mapping to evaluate the quality of subsurface materials and structures. Concurrent use of two thermal IR bands allows separation of thermal and nonthermal IR signal components. Spatially dependent surface emissivity noise is subtracted from IR images, thereby decoupling temperature from emissivity effects. The DBIR method has been highly successful in isolating the effects of corrosion damage from those of clutter produced by IR reflectance anomalies, corrosion inhibitors, ripples, and interior insulation (Del Grande, 1996; Del Grande et al., 1997). An example for in-service inspection of aging aircraft is presented below.

Signal and Image Processing

Imaging technology and image analysis are integral parts of NDE (Russ, 1995). In the past several years the NDE organization at LLNL has assembled and developed tools that couple image processing with computational NDE algorithms (see note 4). LLNL uses MatLab, Explorer, IDL, VIEW, and VISU (the latter two are LLNL-developed image processing codes) as tools for connecting state-of-the-art computational NDE with a wide variety of signal and image processing functions. The focus areas include edge detection and image enhancement for digitized radiographs; noise reduction from electronic and radiation sources; focused wave mode calculations for ultrasonic inspections; in-depth examinations of image reconstruction techniques including modeling of radiographic imaging (Martz et al., 1997b); novel applications of image processing to IR imaging (Del Grande et al., 1995); and statistical studies of different NDE algorithms (Azevedo, 1991).

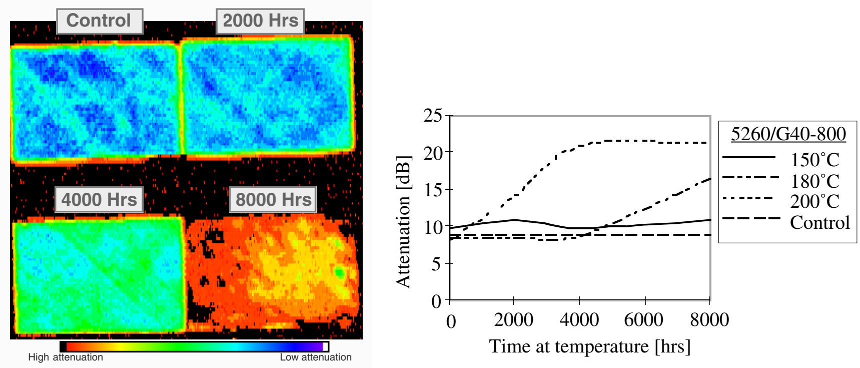
LIFE-CYCLE APPLICATIONS OF NDE

This section provides several examples of how different NDE technologies are applied throughout the life cycle of different products.

Material Development for Durability of Composite Materials

For many carbon composite materials, particularly in aerospace applications, durability is a critical design parameter. Development of composites for durability is facilitated by understanding aging mechanisms. With a design lifetime of 120,000 hours (13.7 years) and skin temperature at ~180°C, real-time durability studies of candidate materials for high-speed aircraft structures are time-consuming and very expensive. Test programs are being developed so that long-term aging can be accelerated and the design of composite materials can occur in a reasonable period of time and at lower costs. For example, two methods used to accelerate aging of composites are elevating temperatures and varying chemical compositions in test environments.

Ultrasonic NDE is currently being used to aid in the characterization of fiber composite materials for high-speed aircraft structures (Chinn et al., 1997). Using ultrasonic attenuation, LLNL has characterized a series of fiber poly-



(A) (B)

FIGURE 4 The 5260/G40–800 composite samples are aged to 8,000 hours. (A) C-scan images of samples aged at 180°C show postcuring up to 4,000 hours and extensive damage at 8,000 hours. (B) Ultrasonic attenuation of the sample increases with time and temperature. Source: Reprinted with permission from Plenum Press (Chinn et al., 1997).

mer composites aged under different temperatures, times, and chemical environments.[9] Figure 4 shows the results of one type of fiber composite aged under different temperatures. The ultrasonic images show the deterioration of the sample aged at 180°C and up to 8,000 hours. The data reveal that damage at 180°C begins after 4,000 hours. Aging at 200°C causes damage after only 2,000 hours. Chemical analysis of the same series of materials confirms the damage trend that ultrasonic attenuation measurements suggest.

A comparison of accelerated aging to real-time aging is shown in Figure 5. The attenuation history of a sample aged for 2,500 hours in argon at 220°C is very similar to that of a sample aged for 20,000 hours in air at 180°C. These results appear very promising for ultrasonic testing to be used as a tool in the further development of aircraft composite materials.

In future work, LLNL will determine and better understand the correlation of ultrasonic attenuation data and the mechanical properties of fiber composite materials. These studies, combined with destructive mechanical testing, and microstructural and chemical analyses, will improve our understanding of composite durability as a function of the aging process.

Improved Prosthetic Implant Design

Human joints are commonly replaced in cases of damage from traumatic injury, rheumatoid diseases, or osteoarthritis. Frequently, prosthetic joint im-

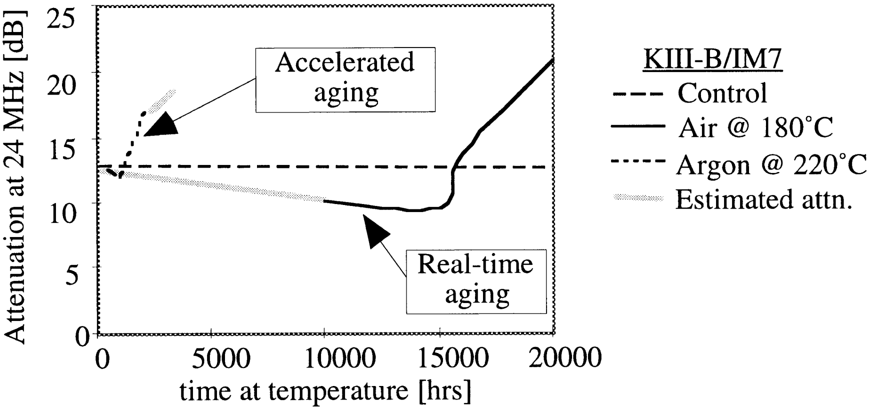


FIGURE 5 Real-time aged samples of KIII-B/IM7 composites exhibit ultrasonic attenuation characteristics over time as samples aged in an accelerated program. Shaded lines indicate estimated behavior of time periods where data are not yet available. Accelerated aging correctly predicts initial drop in attenuation caused by postcuring in the real-time aged sample. Source: Reprinted with permission from Plenum Press (Chinn et al., 1997).

plants fail and must be surgically replaced by a procedure that is far more costly and carries a higher mortality rate than the original surgery. Poor understanding of the loading applied to the implant leads to inadequate designs and ultimately to failure of the prosthetic.[10]

LLNL's approach to prosthetic joint design offers an opportunity to evaluate and improve joints before they are manufactured or surgically implanted. The modeling process begins with computed tomography data, which are used to develop human joint models (see Figure 6). An accurate surface description is critical to the validity of the model (Bossart and Martz, 1996). The marching cubes algorithm (Johansson and Bossart, 1997) is used to create polygonal surfaces that describe the 3D geometry of the structures identified in the scans. Each surface is converted into a 3D finite element mesh that captures its geometry (Figure 6). Boundary conditions determine initial joint angles and ligament tensions as well as joint loads. Finite element meshes are combined with boundary conditions and material models. The analysis consists of a series of computer simulations of human joint and prosthetic joint behavior. The simulations provide qualitative data in the form of scientific visualization and quantitative results such as kinematics and stress-level calculations. These calculations predict possible failure modes of the implant after it is inserted into the body.

Results from the finite element analysis are used to predict failure and to provide suggestions for improving the design. Multiple iterations of this pro-

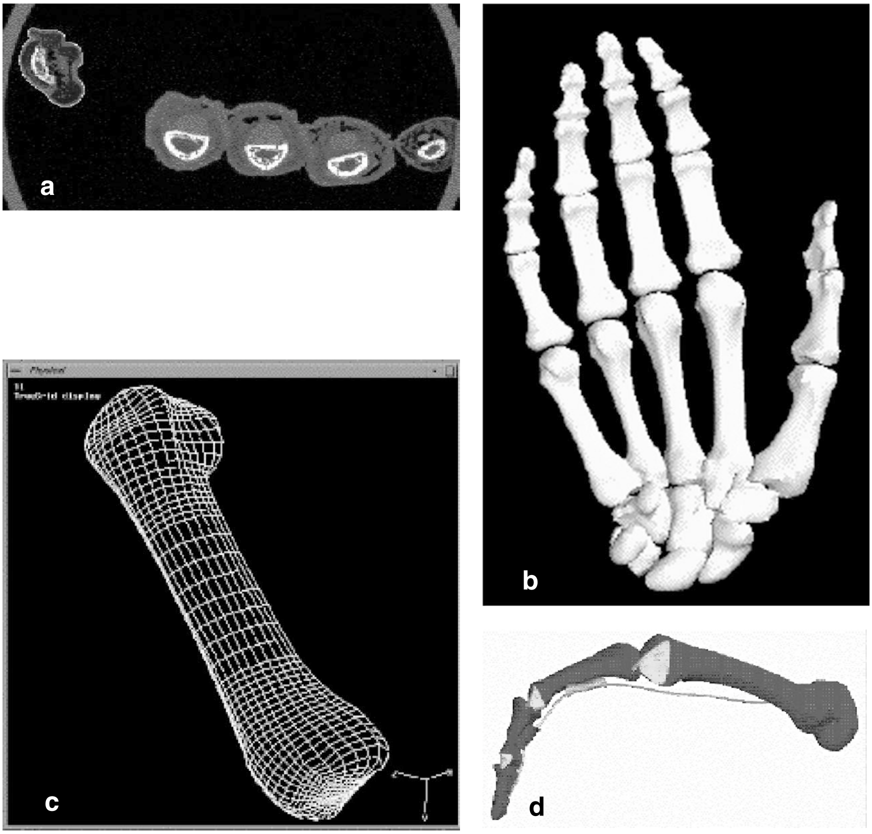


FIGURE 6 The process of biomechanical model development begins with a CT scan of human joints. Data are identified from the scan using a semiautomated segmentation process, shown here applied to the bones in the fingers (a), and three-dimensional surfaces are created for each identified tissue (b). The surfaces are prepared for finite element modeling in a volumetric meshing step (c). The finite element results show soft tissue deformations and stresses in the index finger ligaments and tendons (d).

cess allow the implant designer to use analysis results to incrementally refine the model and improve the overall design. Once an implant design is agreed on, a prototype is made using computer-aided manufacturing techniques. The resulting implant can then be laboratory tested and put into clinical trials (Hollerbach and Hollister, 1996).

Three failure modes are prevalent: kinematic, material, and bone-implant interface. Currently, LLNL is analyzing human joint models to determine the in vivo loading conditions of implants used in normal life and implant components as they interact with each other. Future research will combine the human and implant models into a single model to analyze bone-implant interface stresses, thereby addressing the third common implant failure mode.

In-Service Inspection of Aging Aircraft

Detection and quantitative evaluation of hidden corrosion have been of major importance to the Federal Aviation Administration (FAA) since the famous Aloha Air accident in which an older Boeing 737 lost a large portion of its fuselage skin in midair. Moreover, the U.S. Air Force (USAF) needs to extend the useful life of its existing military aircraft. Much of the problem associated with life extension is the destructive nature of undetected corrosion. Also, with reduced budgets, the USAF does not want to spend time or manpower repairing corrosion that has not reached a dangerous level or that in reality does not exist. A number of NDE methods have been tested on aircraft structures that contain hidden corrosion[11] (see also note 7). They all show promise but so far none has proved to solve this problem.

LLNL, sponsored by the FAA, developed and demonstrated a dual-band infrared (DBIR) imaging thermography technique for corrosion detection. This technique combines a commercial dual-band IR system[12] with LLNL-developed smart defect-recognition algorithms. The DBIR technique was used to demonstrate results for corrosion loss in aircraft.

At LLNL we have obtained results that agree qualitatively with eddy current measurements taken by Boeing scientists (Del Grande et al., 1997). We detected, imaged, and quantified 5 percent (0.003-inch) corrosion metal thickness loss in the outer skin of a Boeing 727 fuselage. The accuracy of these results will be verified after dismantlement of this section of the aircraft by Boeing.

We also measured less than 10 percent skin thickness loss in a United Airlines 747 lap-splice structure scheduled for repair. This was confirmed by destructive exploratory maintenance prior to the repair. In addition to the commercial aircraft inspection activities, we measured the relative metal volume losses due to corrosion under 13 wing fasteners in a Tinker Air Force Base KC-135 wing panel (see Figure 7). Application of the smart defect-recognition algorithms with the IR imager was highly successful in isolating the effects of corrosion damage from clutter to eliminate false positives (or alarms) (Del Grande, 1996).

Our current research focus is on improving the depth resolution of IR tomography down to 20 to 40 micrometers, two orders of magnitude better than existing systems. This would greatly facilitate interpretation of DBIR temperature, thermal inertia, and heat capacity maps that detect, image, and quantify aircraft corrosion with few or no false alarms.

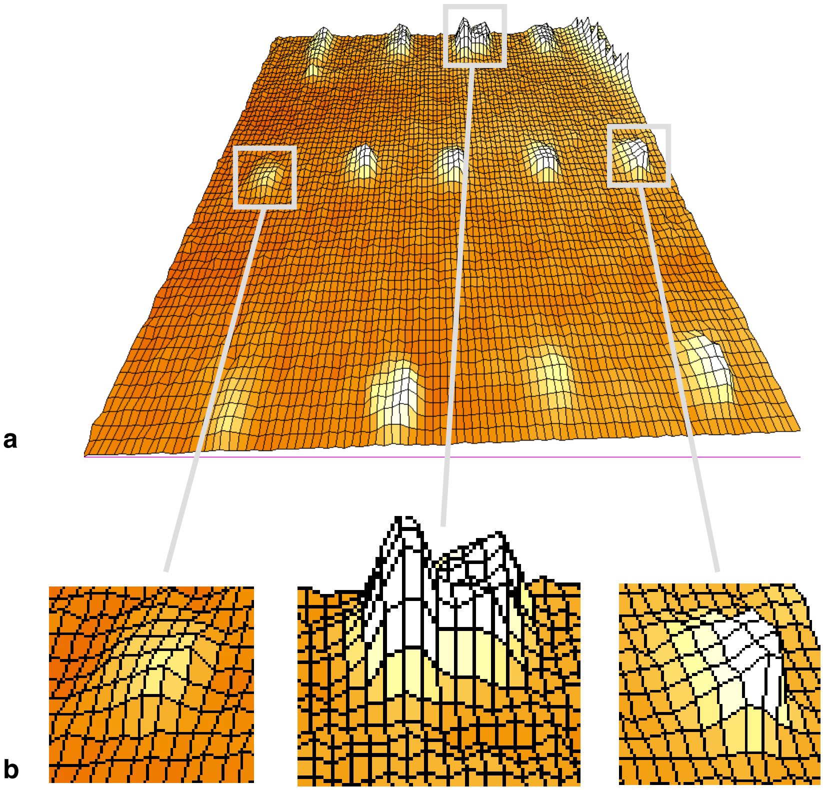


FIGURE 7 Results of infrared imaging of a military aircraft (KC-135) corroded wing fasteners. Contour maps of processed thermal data quantify the relative metal-loss volume from intergranular corrosion. In (a) damage varies under 13 wing-panel fasteners as shown. In (b) magnified views of 3 selected fasteners reveals, from left to right, slight, substantial, and moderate metal loss (corrosion) under the aircraft fasteners.

GAMMA-RAY NONDESTRUCTIVE ASSAY FOR WASTE MANAGEMENT

Before drums of radioactive or mixed (radioactive and hazardous) waste can be properly stored or disposed of, the contents must be known. Hazardous and “nonconforming” materials (such as free liquids and pressurized containers) must be identified, and radioactive sources and strengths must be determined. Opening drums for examination is expensive mainly because of the safety precautions that must be taken. Current nondestructive methods of characterizing waste in sealed drums are often inaccurate and cannot identify nonconforming materials.[13] Additional NDE and NDA techniques are being developed at LLNL (Decman et al., 1996; Roberson et al., 1995a) and elsewhere (see note 11) to analyze closed waste drums accurately and quantitatively.

At LLNL we have developed two systems to characterize waste drums. One system uses real-time radiography and CT to nondestructively inspect waste drums (Roberson et al., 1995a). The other uses active and passive computed tomography (A&PCT), a comprehensive and accurate gamma-ray NDA method that can identify all detectable radioisotopes present in a container and measure their activity (Decman et al., 1996). A&PCT may be the only technology that can certify when radioactive or mixed wastes are below the transuranic (TRU) waste threshold, determine if they meet regulations for low-level waste, and quantify TRU wastes for final disposal. Projected minimum-detectable concentrations are expected to be lower than those obtainable with a segmented gamma-ray scanner, one method currently used by the U.S. Department of Energy.

Several tests have been made of A&PCT technology on 55-gallon TRU waste drums at LLNL (see Figure 8), Rocky Flats Environmental Technology Site (RFETS), and Idaho National Engineering Laboratory (INEL).[14] These drums contained smaller containers with solidified chemical wastes and low-density combustible matrices at LLNL and RFETS, respectively. At INEL lead-lined drums were characterized with combustibles and a very dense sludge drum. In all cases the plutonium radioactivity of the drums ranged from 1 to 70 grams. At LLNL we are measuring the performance of the A&PCT system using controlled experiments of well-known mock-waste drums (Camp et al., 1994; Decman et al., 1996). Results show that the A&PCT technology can determine radioactivity with an accuracy, or closeness to the true value, of approximately 30 percent and a precision, or how reproducible the result is, to better than 5 percent (Martz et al., 1997a).

Perhaps the most important future development for this technology is to improve the system's throughput. The current throughput requires about 1 to 2 days per drum using a single detector-based scanner. At LLNL we have designs for upgrading this scanner to multiple detectors for throughputs estimated to be on the order of a few hours per drum (Roberson et al., 1997). Additional research and development efforts include improving the accuracy of the system and developing self-absorption correction methods.

SUMMARY

This paper provides an overview of some common NDE methods and several examples for the use of different NDE techniques throughout the life cycle of a product. NDE techniques are being used to help determine material properties, design new implants, extend the service life of aircraft, and help dispose of radioactive waste in a safe manner. It is the opinion of this author and

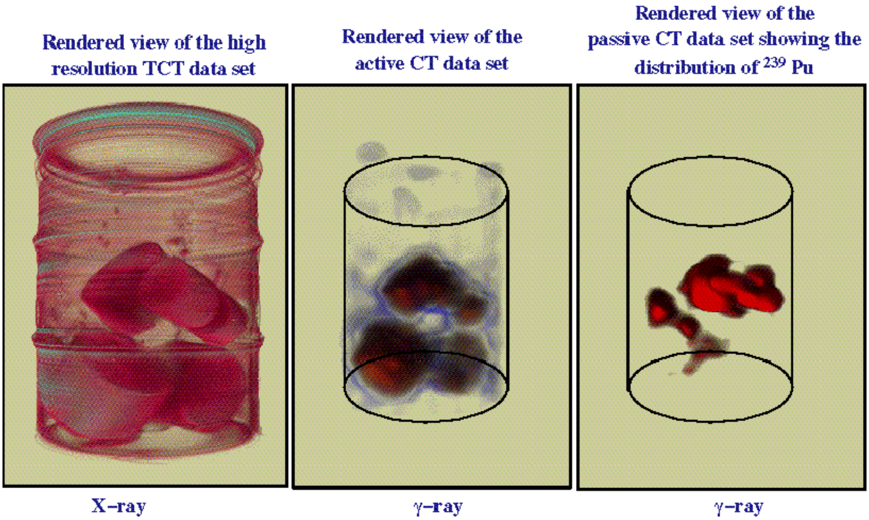


FIGURE 8 Representative three-dimensionally rendered CT images of an LLNL transuranic-waste drum. (left) High-spatial (2-mm voxels) with no energy resolution x-ray CT image at 4 MeV reveals the relative attenuation caused by the waste matrix. (middle) Low-spatial (50-mm voxels) with high-energy resolution active gamma-ray CT image at 411 keV of the same drum reveals the quantitative attenuation caused by the waste matrix. (right) Low spatial (50-mm voxels) with high-energy resolution passive CT image at 414 keV reveals the location and distribution of radioactive ^{239}Pu in the drum. A&PCT was used to determine that this drum contained 3 g of weapons-grade Pu. Source: Reprinted with permission from Lawrence Livermore National Laboratory (Roberson et al., 1995b).

others that the NDE community needs to work more closely with end users in the life cycle of a product to better incorporate NDE techniques. The NDE community needs to highlight the importance of NDE in the entire life-cycle process of a product by showing real costs savings to the manufacturing community.

FUTURE WORK

All NDE techniques have limitations. Some techniques are limited by physical constraints, while some can be overcome by developing new NDE system components. Examples include brighter sources, higher spatial and contrast resolution and more efficient detectors, higher-precision manipulators/stages, better image reconstruction, and signal and image processing algorithms with faster computers.

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9. This work is being performed under a cooperative research and development agreement with Boeing.

10. For further information, see papers by J. Fouke, F. Guilak, M. C. H. van der Meulen, and A. A. Edidin in the Biomechanics section of this book.

11. The First Joint DOD/FAA/NASA Conference on Aging Aircraft, July 8-10, 1997, Ogden, Utah.

12. A portion of this work is performed under a Cooperative Research and Development Agreement with Bales Scientific Inc. (BSI), Walnut Creek, CA, in which we adapted LLNL algorithms for their DBIR scanner and thermal image processor.

13. For further information, see papers in Proceedings of the 5th Nondestructive Assay and Nondestructive Examination Waste Characterization Conference, Salt Lake City, Utah, January 14-16, 1997; Proceedings of the 4th Nondestructive Assay and Nondestructive Examination Waste Characterization Conference, Salt Lake City, Utah, October 24-26, 1995.

14. Some of these tests were performed in collaboration with BioImaging Research Inc., of Lincolnshire, Illinois, under a Work for Others Agreement. A mobile waste inspection tomography (WIT) trailer was used to acquire this data. The WIT trailer is described in Bernardi and Martz, 1995.

Challenges of Probabilistic Risk Analysis

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The ever-increasing power of technology creates the potential for catastrophic accidents. Because such accidents are rare, though, the database on them is too small for conventional statistics to yield meaningful results. Therefore, sophisticated probabilistic risk analysis (PRA) techniques are critical in estimating the frequency of accidents in complex engineered systems such as nuclear power, aviation, aerospace, and chemical processing.

The approach used in PRA is to model a system in terms of its components, stopping where substantial amounts of data are available for most if not all of the key components. Using data to estimate component failure rates, the estimates can then be aggregated according to the PRA model to derive an estimate of accident frequency. The accuracy of the resulting estimate will depend on the accuracy of the PRA model itself, but there are good reasons to believe that the accuracy of PRA models has improved over time.

The failure rate estimates needed as input are generally obtained by using Bayesian statistics, owing to the sparsity of data even at the component level. Bayesian methods provide a rigorous way of combining prior knowledge (expressed in the form of “prior distributions”) with observed data to obtain “posterior distributions.” A posterior distribution expresses the remaining uncertainty about a failure rate after observing the data. The posteriors for component failure rates are then propagated through the PRA model to yield a distribution for accident frequency.

Two major challenges of PRA are (1) the reliance on subjective judgment and (2) the difficulty of accounting for human performance in PRA. These issues are discussed below.

SUBJECTIVITY

PRAs generally result in distributions for accident frequencies, and these distributions are based extensively on subjective judgment (i.e., expert opinion), both in structuring the PRA model itself and in quantifying prior distributions for component failure rates. It is now generally accepted that the uncertainties in PRA results are not an artifact of PRA but are characteristic of low-frequency, high-consequence events. Explicitly recognizing these uncertainties should lead to better decisions; however, the subjectivity of PRA results poses larger problems.

The use of subjective probability distributions in making individual decisions is theoretically well founded. However, the situation is more complex for societal decisions, which pose significant policy and technical questions.

Policy Questions

The subjectivity of PRA results has been partially responsible for delays in implementing risk-based approaches to regulation. Regulators recognize that PRA can make it possible to achieve lower risks than the current body of regulations at no greater cost. However, because of the complexity of the facilities being analyzed and of the resulting models, regulators are dependent on risk analyses performed by facility owners/operators, and even validating a PRA is a costly undertaking. Ignoring the possibility of deliberate misrepresentations, the different incentives of a regulator and a licensee (combined with the subjectivity of PRA models) create ample opportunity for results to be “shaded” favorably to licensees.

Taking advantage of the opportunity for risk reduction posed by PRA requires careful attention to regulatory incentives and disincentives. In particular, licensees must have incentives to openly disclose information that may support increased or unfavorable risk estimates. Otherwise, licensees whose PRAs reveal unfavorable results will be unlikely to share those results with regulators, and licensees may be discouraged from upgrading their existing PRAs. These issues are currently being addressed by the U.S. Nuclear Regulatory Commission (NRC), which recently formulated draft regulatory guides for risk-informed decision making.

Technical Questions

In addition to policy questions, reliance on subjective judgment also poses interesting technical questions. In particular, PRA practitioners have sometimes treated the subjectivity of their inputs somewhat cavalierly. Significant guidance exists regarding the elicitation of subjective prior distributions, but this guidance is costly to apply, especially when prior distributions are needed for dozens of uncertain quantities. Therefore, it would be desirable to develop less resource-intensive default methods for choosing prior distributions for use in PRA.

Similar work has been done in other fields, with attention focused on so-called robust or reference priors. The idea is to let the database speak for itself as much as possible and to avoid selecting priors that may have unduly large influences on the posteriors. While this approach may not work well in PRA because of data sparsity, it would at least seem worthwhile to identify families of priors that are likely to yield unreasonable posteriors. Such research could lead to improved guidance for PRA practitioners and improved credibility of PRA estimates.

HUMAN ERROR AND HUMAN PERFORMANCE

Another challenge to the accuracy of PRA is the difficulty of predicting human behavior. In this discussion I will distinguish between human error per se and the effects of organizational factors. Both topics are being addressed by the University of Wisconsin-Madison Center for Human Performance in Complex Systems, which is supported by several major high-technology companies and the NRC.

Human Error

Many large industrial accidents, including those at Three Mile Island and Chernobyl, were caused in part by human errors. Hence, it is natural to wonder whether such errors are adequately incorporated into PRA. Human errors are conventionally divided into errors of omission and those of commission. Errors of omission are relatively straightforward to model, since they can be explicitly enumerated based on the procedures to be performed.

Errors of commission have historically been considered extremely difficult to analyze, because of the infinite variety of possible human actions. More recently, it has been recognized that the vast majority of commission errors fall into a few simple categories. Barring sabotage or insanity, people are unlikely to undertake actions that seem unreasonable at the time. Therefore, most errors of commission reflect factors such as shortcuts, competing goals, or misdiagnoses. While these causes are harder to analyze than errors of omission, the recognition that most errors of commission have a rational basis makes them amenable to analysis, and there have been several pilot studies incorporating this approach.

After identifying relevant human errors, their probabilities must be estimated. Progress has been hindered both by the fact that psychologists do not yet know enough about the factors contributing to human error and by the tendency for PRA practitioners to prefer simple engineering-style models of human performance. While engineers are known for their willingness to make assumptions in order to get the job done, more empirical knowledge of human error would contribute to better assumptions.

Organizational Factors

Another issue of concern is the effect of organizational factors on risk. At least for U.S. commercial nuclear power plants, corporate culture has as much effect on risk as plant design. Some such influences are implicitly taken into account in current PRAs (e.g., in plant-specific data), but it is unclear how risk will change if practices change. Moreover, organizational factors may also have numerous unmodeled influences on risk.

These issues are difficult to analyze in part because we cannot as yet even reliably quantify corporate culture, let alone identify features conducive to good performance. Despite these difficulties, the PRA community has recently begun to address organizational factors, and the NRC is currently funding research in this area.

SUMMARY

The state of the art of PRA offers many promising research areas. Interestingly, the engineering basis of PRA seems better established than the input required from other fields. For example, although Bayesian statistical theory is well established, there is room for more work on the implications of alternative prior distributions.

More importantly, insights gained from PRA, and the necessity of safely managing complex hazardous systems, should inform the research agendas of social scientists. For example, in the real world errors need not reflect mistakes, but rather may represent people performing well under suboptimal conditions. Thus, broader definitions of "error" and greater attention to context would make some psychological research more relevant. Questions also remain in organizational behavior. For example, clearly both democratic/participatory and autocratic/hierarchical management styles can work well under the right circumstances, but the ingredients needed to make either style work effectively are not yet known. Such issues are often not prominent on the research agendas of social scientists, but I believe there is room for basic social science research with significant practical benefits.

Today, PRA is being productively applied to a variety of engineering technologies and is being used more extensively in the regulatory process. Since PRA is here to stay, it is time to develop closer ties with other fields. PRA practitioners stand to learn a lot from related areas of research. Moreover, the practical orientation of PRA can yield insights into the most important issues in high-hazard industries and can contribute to more relevant research agendas in other fields.

DECISION-MAKING TOOLS FOR DESIGN AND MANUFACTURING

Variation Risk Management in Product Development

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Product development industries are under pressure to decrease both cost and development cycles. In addition, customers are constantly demanding increased quality. As a result, industry is spending significant resources to improve product development processes (PDPs). PDP improvement initiatives have a variety of elements, including simultaneous engineering, variation reduction, quality methods, and integrated product teams. As a part of the Lean Aircraft Initiative and the National Science Foundation's Center for Product Innovation and Development at the Massachusetts Institute of Technology, I have focused on developing tools and methods to assist in the reduction of the effect and magnitude of product variations.

Reducing the effect of variations can have dramatic cost benefits. For example, in the aircraft industry, variability in airframe parts and assemblies influences both cost and quality. Shimming, rework, and repair are major contributors to the labor content of aircraft. In addition, once assembled, variability in wing location as well as steps and gaps between skin panels can increase drag. These problems have strong parallels in the automotive industry.

It is common knowledge that 80 percent of design costs are set in the first 20 percent of a product's definition stage. Early decisions about architecture, assembly processes, and product layout can set a limit on the quality and cost of the final product. In the case of airframes and automotive bodies, fixture design, product decomposition, and assembly methods all affect final product quality (Cunningham et al., 1996; Leyland, 1997). Ideally, early design stages should focus on making tradeoffs between the cost of the product and the ability to achieve the desired product quality.

Many authors have discussed this need and have suggested a variety of tools such as concurrent engineering and design for manufacturing (DFM) techniques (Clark and Fujimoto, 1991; Wheelwright and Clark, 1995). However, the expanded set of tasks is often in conflict with the need to reduce the product development time. I have observed several projects where, because of pressure to deliver a product, tasks such as variation analysis, DFM, and design for assembly (DFA) were jettisoned.

INDUSTRY NEEDS

Based on extended observations and discussions with a range of product development firms, I have identified the need for systematic and quantitative methods to predict yield and manufacturing costs early in the design process. By predicting yields and costs, analysis of alternatives can be made earlier in the design process. However, these methods must operate in an environment where the geometry is not finalized; process capability is uncertain; costs of tooling, rework, and repair are estimated; and the resources available for analysis are limited.

Although this may seem like an impossible goal, the task is simplified because early in the design process designers do not need precise information. What is needed is the ability to predict, with a level of certainty, that option A is more likely to be not as good as option B or that feature C will have the highest rework impact.

Comparing design alternatives involves evaluating multiple optimization criteria. One layout may have a higher labor content but also higher yield rates; another may have less expensive tooling but lower yield rates. The simplest way to make direct comparisons is to reduce the multiple criteria into a single function—cost. Quantitative evaluation of cost and yield is now feasible because cost and process capability databases are being generated within companies and by outside suppliers (Nagler, 1996).

METHODS

Current approaches to compare alternatives in the early stages of design have three major shortcomings. First, they predict yield and not total cost. By focusing only on magnitude of yield rather than the overall cost of a product, suboptimal products can be generated. Second, the models required to predict yield are time consuming to generate and often require detailed geometry definition. Third, tools such as Taguchi methods (Taguchi and Clausing, 1990) are limited in their ability to evaluate complex highly coupled systems.

To address these shortcomings, I have developed a set of tools that enable a designer to quickly build a model of a product. Using the model, the costs of labor, tooling, and yield can be evaluated. These tools are based on capturing the key characteristics (KCs) of a product.

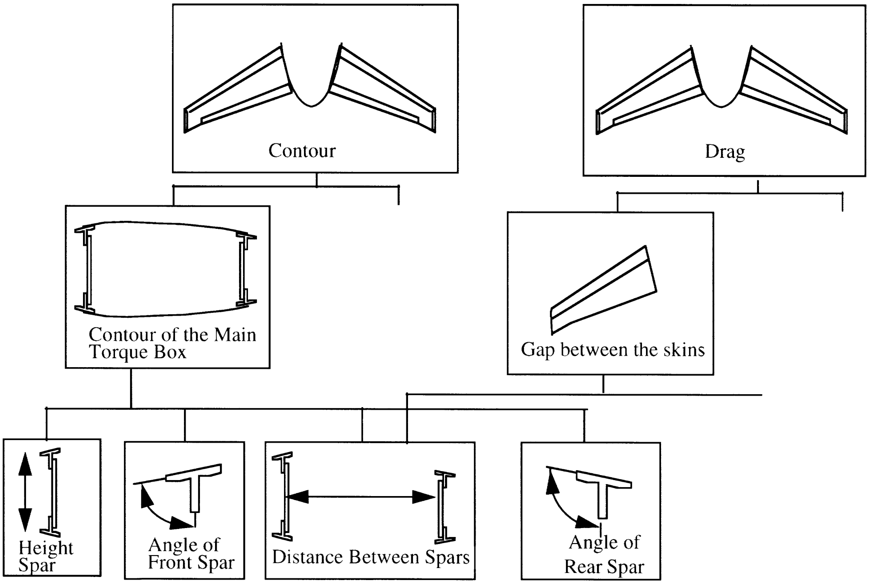

FIGURE 1 KC flowdown for an aircraft wing. Source: Reprinted with permission from the American Society of Mechanical Engineers (Lee and Thornton, 1996b).

Key Characteristics

KCs have been used by a variety of manufacturing organizations, including Boeing, GM, Ford, Chrysler, Xerox, Kodak, Northrop Grumman, McDonnell Douglas, and ITT. KCs are product features, manufacturing process parameters, and assembly features that significantly affect a product's performance, function, and form. KC implementation started in the 1980s and, although these practices are integrated into current design processes in industry, they have been written about predominantly in internal publications (Lee and Thornton, 1996a,b; Thornton, 1996a,b).

KCs can be described in a hierarchical tree structure such as the one in Figure 1. At the top of the tree are the system KCs—the product requirements set by the organization. At the bottom of the tree are the manufactured features. There are often many layers between the system and feature KCs.

I have expanded the typical KC flowdown used in industry to contain a constraint that defines how lower-level KCs combine to create the system-level KC (Lee and Thornton, 1996b). A first-order model of the process capability propagation is used to predict the end yield of the product characteristics by propagating the expected variation at the feature level to the system level (Thornton, 1996b). In addition, the cost of scrap, rework, and repair as well as other costs such as tooling, labor content, and materials can be

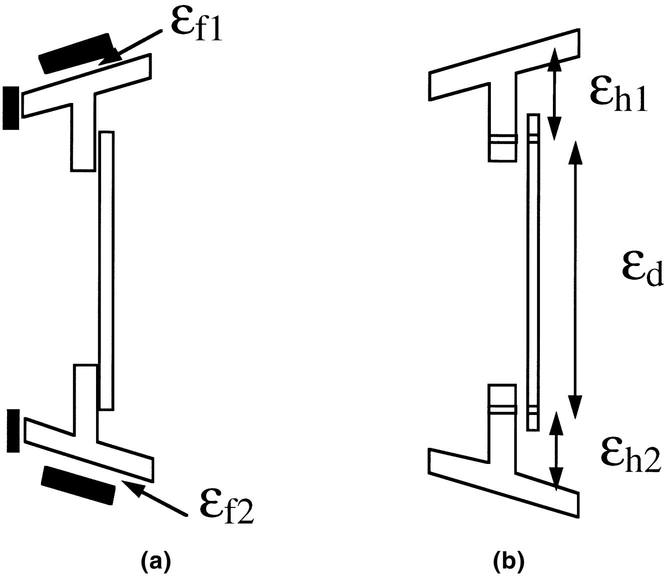

FIGURE 2 Standard method for assembling forward and aft wing spars. (a) Fixtured; (b) Precision. Source: Reprinted with permission from the American Society of Mechanical Engineers (Thornton, 1997).

attached to the general model to enable rapid evaluation of design alternatives. Because of modeling time restrictions and uncertainty in the data, secondary interactions and costs related to other features are not included.

A variety of tools using this representation have been successfully implemented and tested in industry. The following section provides a simple example of how the KC flowdown and related costs are used to make a direct comparison between two different assembly options in aircraft design. One approach is a traditional assembly requiring fixtures and the other is a newer approach that employs precision features to locate the parts.

Example

Figure 2a shows a simplified version of the standard method for assembling the forward and aft spars for a wing. The fixtured assembly method locates the two cords on hard fixtures by locating the back and upper surface of the cords with the fixtured surfaces. After the cords are located, the web is placed on the surface of the "T." The pieces are match drilled, separated, deburred, sealed, and assembled in the same fixture. Figure 2b shows the precision assembly process. During parts manufacture, holes are drilled in

TABLE 1 Example Cost Tradeoff Between Fixtured Assembly and Precision Assembly

		Fixtured Assembly			Precision Assembly	
		Min.	Max.		Min.	Max.
Dimensions (expected variation)	$f1$	0.01	0.020	$h1$	0.010	0.020
	$f2$	0.01	0.020	$h2$	0.010	0.020
				d	0.020	0.030
Height variation		0.005	0.009		0.008	0.014
Fixture cost		\$100K	\$120K		\$30K	\$40K
Process cost		\$100K	\$110K		\$110K	\$120K
Failures/1,000		3	138		87	309
Quality cost		\$3,600	\$165K		\$104K	\$370K
Total cost		\$204K	\$395K		\$244K	\$530K

Source: Reprinted with permission from the American Society of Mechanical Engineers (Thornton, 1997).

each of the cords and in the top and bottom of the web. The holes and surfaces are prepared before assembly. The spars are created by locating the parts using the fixture holes. Some form of nondimensional fixture will be required to support the weight of the parts during assembly.

The dominant key characteristic of the spar assembly is the final height. In the fixtured assembly the feature-level KCs are the errors in the location in the fixture, ε_{f1} and ε_{f2}. In the precision assembly the KCs feature-level are the distance from the top of the cord to the precision holes, ε_{h1} and ε_{h2}, and the distance between the holes in the web, ε_{d}. Table 1 shows cost comparisons of the two options using typical data available from the cost and process capability databases.[1]

CONCLUSION

In summary, a set of tools and methods are being developed by the author to predict and mitigate expensive rework, scrap, and repair while balancing other cost drivers in manufacturing processes. These tools use the KC flowdown of a product to focus calculations on those areas likely to have the most significant cost effect on a product. It has been found that first-order analyses are able, even with the uncertainty in process capability and layout, to accurately rank by order high-risk areas and provide a quantitative basis for decision making. The investment in collecting the data and performing the analysis is minimal, thus making use of the tools feasible in the early stages of a design process.

ACKNOWLEDGMENTS

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NOTE

1. The data and geometry do not reflect the actual costs or process capability of the assembly and are used for demonstration purposes only.

Multicriteria Evaluation of Manufacturing Performance

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Manufacturing systems comprise many interacting processes and material flows. Measuring the performance of these complex systems can be difficult. Often, performance is measured by monitoring the processes and materials and then gauging performance by the resulting end-product. In complex manufacturing systems the use of computer integrated manufacturing (CIM) systems permits an enormous amount of data to be gathered during production. Statistical methods have become an essential way to manage this data explosion, yet they may not provide the total solution to measurement of overall factory performance. Measurement methods that focus on processes or material flows alone may not provide an adequate metric for overall manufacturing performance. In addition, with processing times growing and multiple products in process at once, simply counting products as they exit the end of the line may distort factory performance for the products still in production. For these complex manufacturing systems, a more rigorous measurement procedure is needed to consider the individual performance measurements of process and product while providing an overall gauge of manufacturing performance.

Decision analytical methods have been used extensively for project evaluation (e.g., Keeney et al., 1986) and investment and economic decision making (e.g., Boucher and MacStravic, 1991). Some decision analysis applications consider uncertainty and risk in the individual decision criteria (Lavelle et al., 1997). These methods allow the decision maker to balance and trade off competing criteria analytically while representing decision subjectivity mathematically. More recently, decision analysis has been used to improve the process of design (e.g., Thurston, 1991) by modeling competing design goals and measuring tolerable tradeoffs toward achieving those goals. In this context, constructs such as the von Neumann utility function allow designers to evaluate a candidate design subject to multiple criteria. Just as multicriteria design benefits from decision analysis, a natural extension to other complex systems suggests that decision analysis may be used for multicriteria evaluation of manufacturing performance. Decision analytical methods provide a way of integrating the contributions of multiple performance criteria into a single measure of factory performance.

At Motorola, decision analysis has been used to model complex manufacturing systems and provide a single metric of factory performance. In semiconductor manufacturing facilities, for example, hundreds of processes and dozens of material flows are tracked simultaneously—making evaluation of factory performance a challenge. Several factors make a performance assessment difficult: (1) products are produced in batches that may require repeated passes at certain processes (reentrant flows); (2) billion-dollar facilities require large work in process to reduce unit costs; and (3) because of product variety and technology type, the total cycle time in the factory may vary from 20 to 40 days. Clearly, current methods that examine only the end-of-line output of a manufacturing system fail to provide an adequate measure of overall system performance. Sophisticated CIM systems monitor and schedule production, tracking hundreds of equipment and material parameters. Still, factory managers may have difficulties in determining how the factory is performing at any given time. By using information from the factory CIM systems, decision analysis allows simultaneous consideration of multiple criteria, such as number of turns, work in process, process yield, queue size, and cycle time at key processes. Preferences are modeled analytically and combined with tradeoff parameters assessed with the certainty equivalent method (Keeney and Raiffa, 1976). These individual criteria data are combined via a multiattribute utility function that permits a measure of total performance of the system. This utility function can be used to more closely monitor and improve factory performance. By deriving the total differential of the utility function, for example, the optimal direction for improvement in performance can be quickly determined. Further, the utility-based performance metric is normalized, which permits easy comparison of performance over different time periods.

Implemented in one Motorola wafer fabrication facility, engineers are using this system to decrease their reaction time to problems in the factory. Prior to installation of this system, problems in performance might have been determined only after several individual performance indicators signaled serious error. With this utility-based performance gauge, reaction time has decreased from days to hours. When the utility function gauge suggests that manufacturing performance is suffering, the tradeoff calculation shows the factory staff where to focus efforts for greatest improvement. Factory engineers report that the quality of manufacturing decision making is greatly improved now that all factory staff are using the same metric to measure performance, and indirect costs are expected to decrease because of better performance. By using multicriteria decision analysis to integrate traditional methods of measuring and monitoring data, total system performance is greatly improved.

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INTELLIGENT TRANSPORTATION SYSTEMS

Intelligent Information for Transportation Management

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Urban congestion continues to be a leading problem in cities across the country. The inability to move people and goods within the transportation systems causes delays, lost productivity, and increased product costs. The average cost of this congestion for each of the 50 largest urban areas is over \$1 billion per year (Lomax and Schrank, 1996). Future urban transportation systems will not focus on constructing new streets and highways but rather on improving the operation of existing ones. This will be accomplished, in part, with the application of advanced technologies to transportation—termed intelligent transportation systems (ITS).

How we operate today's transportation system is a function of institutional arrangements, jurisdictional boundaries, and funding procedures. Users of a transportation system, however, do not care who operates the facility or in whose city the facility is contained. The travelers on a system are concerned about getting to their destinations safely and quickly. The development of ITS has opened up new ways of managing and operating transportation systems, especially between agencies. The deployment of ITS technologies has also resulted in more devices within an infrastructure being capable of collecting more data. Many public-sector agencies find themselves overwhelmed by the amount of data. The key to improving transportation system management is turning the data into useful information.

A simple definition of intelligent information is providing the right information, at the right place, at the right time. The challenge is defining the right information from both an operator's and a user's perspective and delivering that information where it can be used in a timely fashion. In addition, intelligent information is information that can be used for multiple applications, reducing the need to collect data redundantly. Once collected, data should be used and reused for applications that can benefit from this information.

DEVELOPING AND DEPLOYING ITS

The federal government has been working with state and local governments, private industry, and academia to develop and deploy ITS. There exists a national ITS architecture to guide the development of ITS and several deployment initiatives around the country.

National ITS Architecture

The U.S. Department of Transportation sponsored the development of a national ITS architecture. The goal of the architecture is to establish a framework by which intelligent transportation systems can be designed for interoperability and connectivity between ITS components. The architecture defines the functions that must be performed, the physical entities where those functions reside, the interfaces/information flows between physical entities, and the requirements for actual physical communications channels over which the information flows travel (U.S. Department of Transportation, 1997). This level of detail helps transportation system operators determine how data can be used for additional applications.

The architecture also functionally divides ITS service options into 40 market packages grouped into the broad categories of advanced traffic management systems (ATMS), advanced public transportation systems (APTS), advanced traveler information systems (ATIS), advanced vehicle safety systems, commercial vehicle operations, emergency management, and planning.

Advanced Traffic Management and Information Systems

While the national ITS architecture identifies advanced traffic management systems and advanced traveler information systems, the California Department of Transportation has been promoting the idea of advanced traffic management and information systems (ATMIS). Recognizing these together reflects the true interrelationship of these subsystems. An ATMIS uses traffic monitoring, communications, and control devices to more efficiently allocate available capacity to traffic demand and to communicate traffic information to travelers. The current state of the practice is illustrated in Figure 1.

The ATMS includes both the freeway system and the surface street system with signalized intersections. Transportation agencies are typically installing inductive loop detectors (ILDs) and closed-circuit television (CCTV) cameras to collect traffic conditions. On freeways, individual lane control signs and ramp meters are used to control the flow of traffic onto and through

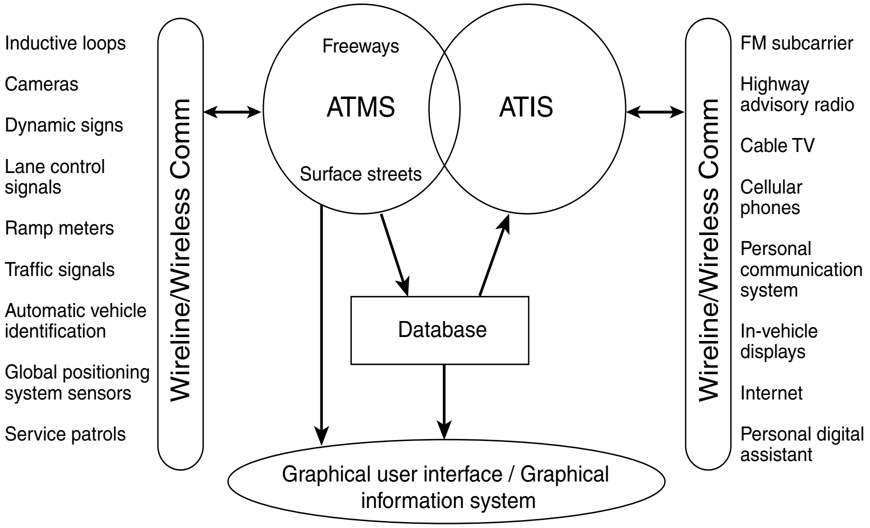

FIGURE 1 Advanced traffic management and information system. Source: Texas Transportation Institute.

the freeway system. On the surface street system, traffic signals are used at intersections to allocate capacity to the expected traffic flows. Some field devices, such as dynamic message signs and highway advisory radio, are used to communicate traffic information to aid managing traffic demand. Operators in a transportation management system interact with the ATMS software through a user interface that may be tied to a geographical information system. The storage of data, however, is less common and is highly variable between centers.

The ATIS uses a host of ITS technologies to communicate to travelers information derived from an ATMS. With advances in ITS technologies, both cost and convenience of receiving traveler information are improving.

ITS DATA MANAGEMENT SYSTEM

The deployment of ITS technologies in urban areas has resulted in the potential to generate considerable information on traffic conditions. The ability to collect, store, manage, and make available this information can be described as an ITS data management system. The concept of an ITS data management system is depicted in Figure 2.

The current functions being performed by transportation management centers, such as freeway control, incident management, and traveler information, are basically acting on real-time information. When an ATMS detects con-

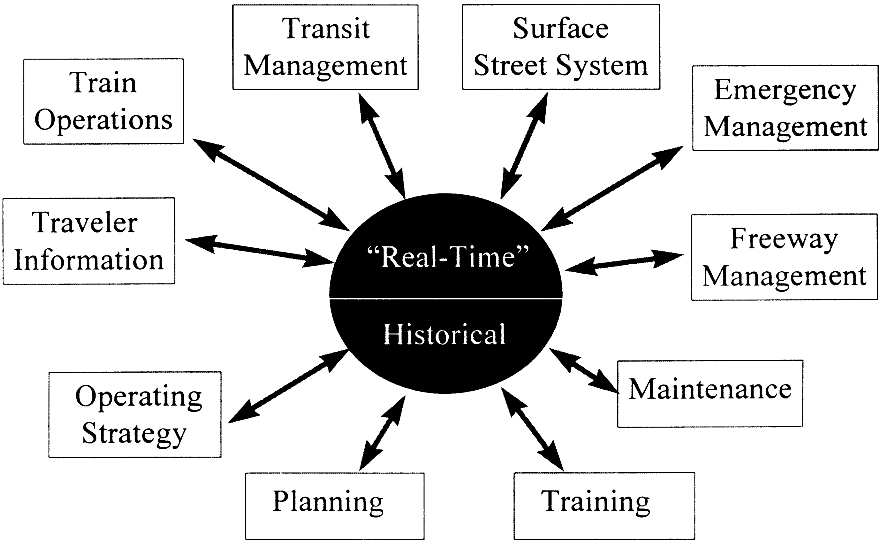

FIGURE 2 ITS data management system. Source: Texas Transportation Institute.

gestion that is due to demand exceeding capacity or an incident, operators can implement a new traffic control strategy and disseminate information to travelers. The objective behind an ITS data management system is to store these data for developing future operational strategies, performing maintenance activities, training operations personnel, and planning future improvements to the system.

Applications with Real-Time Data

Real-time information is primarily available through ILDs and probe vehicles in the traffic stream. ILDs typically obtain lane-by-lane speed, volume, and loop occupancy at a given point on a roadway. Loop placement is usually between one-third and one-half mile. While this is a fairly dense deployment, there is considerable variability in speed between sensors. Probe vehicle data can gather travel time along segments of roadways and help provide more reliable information about conditions over longer segments of roadway. Probe vehicle data can be gathered with toll collection systems by tracking toll tags or with automated vehicle location systems used on vehicle fleets such as transit buses.

At the same time, most transportation management centers have CCTV systems that provide high-quality video feeds from selected points on the system. ILDs and probe vehicles can detect when traffic conditions are degrading. The CCTV cameras are used primarily to verify incidents. The ability to detect, respond to, and clear incidents faster is already showing significant benefits in urban areas. For example, in Houston, Texas, the deployment of ITS technologies for the city's incident management system has resulted in shorter durations of incidents and less associated congestion and secondary accidents.

Another concept, highlighted in Figure 2, is broadening advanced traffic management beyond highways and streets to include public transit, railroad, and emergency service operations. By integrating these subsystems, real-time information can pass between agencies to improve the effectiveness of providing other services. For example, by blocking highway-railroad grade crossings, train activity in an urban area disrupts surface street operations. Information about these blocked crossings can be shared with emergency service providers in real time to dynamically reroute the vehicles to the fastest route, not necessarily the shortest route. The right place to receive this information is at the station before an emergency vehicle leaves for an incident because the greatest number of options are still available for route selection.

Applications with Historical Data

The ability to store real-time data from these data-gathering systems creates the potential for an information-rich environment. Currently, there is considerable variability in the format for storing data. The advantage of an ITS data management system is the ability to "mine" the data for specific information on the operation of the transportation system. Performance measures related to efficiency and quality of service provide valuable information for both operators and planners.

Performance measures can be divided into three types: point measures, link-based measures, and corridor or system measures. Point-based measures include spot speed and volume (either vehicle or, more appropriately, person). Link-based measures are usually only a piece of a longer trip along a transportation facility. These measures could be travel time, average speed, or delay. Corridor measures are the largest aggregate level of ITS data but are very important to start evaluating how the system is performing throughout the day and from day to day. These measures may be average person speed, person delay, person miles of travel, or person hours of travel.

CONCLUSION

ITS is a tool for better operating and managing of transportation systems. The deployment of ITS technologies has created a data-rich environment to assist transportation professionals in their daily activities. The challenge will be to efficiently use the data in intelligent ways to operate the system as a truly multimodal, seamless transportation system. In addition, the data from

ITS will allow for the calculation of system or corridor performance measures. These measures of effectiveness improve operational planning, future system planning, and the deployment of ITS technologies.

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Automated Highway Systems

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Forty thousand people are killed each year and 1.7 million are injured in automobile accidents on U.S. highways. The annual cost to the nation is estimated to be more than $150 billion.

Seventy percent of today's peak-hour traffic is in congestion. The number of vehicles caught in congested traffic will double by 2010 unless there is a major improvement in the transportation system. The annual loss of productivity due to traffic congestion is estimated to be more than $50 billion.

In 1991 Congress enacted the Intermodal Surface Transportation Efficiency Act to improve safety and reduce congestion on the nation's highways. In response to a provision of that act, the U.S. Department of Transportation solicited applications in 1993 for a research and development program leading to a prototype automated highway system (AHS). The National AHS Consortium (NAHSC), formed in 1994, prepared the winning proposal to develop the prototype AHS.

The NAHSC consists of nine core participants and over 120 associate participants. The core participants are Bechtel, the California Department of Transportation, Carnegie Mellon University, Delco Electronics, General Motors, Hughes Aircraft, Lockheed Martin, Parsons Brinckerhoff, and the University of California at Berkeley's California Partners for Advanced Transit and Highways (PATH) program. The associate participants represent nine stakeholder communities: (1) state and local government agencies, (2) transportation users, (3) transit authorities, (4) environmental interests, (5) highway designers, (6) the vehicle industry, (7) the electronics industry, (8) commercial trucking interests, and (9) the insurance industry.

Japan and Europe have initiated similar public-private partnership programs for AHS development. The Japanese Ministry of Construction launched a program with 24 private industry members with the goal of deploying the first AHS highway in Japan in 2010. This program consolidates and continues the ongoing Road/Automobile Communication Systems project, the Advanced Mobile Traffic Information and Communication System project, and the Vehicle Information and Communication Systems project. Activities in Europe include the Program for European Traffic with Highest Efficiency and Unprecedented Safety project, the Dedicated Road Infrastructure for Vehicle Safety in Europe project, the Promote-Chauffeur project, and the Praxitele project.

Research on automated highway systems predates formation of the NAHSC. Work between 1940 and 1970 focused on mechanical control systems such as underground cables and electrical relays. Arrival of microprocessors in the 1970s spurred the development of electronic control systems for the different vehicle functions. Integrated circuits and signal-processing technologies greatly expanded the availability and reliability of sensing and actuation devices used in vehicle control. From the late 1980s through the early 1990s, several research institutions, including California PATH and Carnegie Mellon University, and several automobile manufacturers demonstrated automatic lateral and longitudinal control of vehicles. Today's fully automated vehicles can operate at highway speeds under the control of a single personal computer.

AHS CONCEPTS

As part of the concept development effort, the NAHSC determined that AHS concepts can be characterized in terms of the following six attributes:

Distribution of intelligence. This attribute pertains to the allocation of information and control to the different parts of the transportation system. It has the following range of choices:

- *Autonomous*: all information is entirely within each vehicle.
- *Cooperative*: vehicles communicate their information to each other following well-defined protocols.
- *Infrastructure supported*: the highway infrastructure supports the AHS operation by gathering information using special sensors and communication devices and by providing information back to vehicles using special signage and communication devices.
- *Infrastructure managed*: the highway infrastructure provides not only information but also commands to control the aggregate behavior of the AHS.
- *Infrastructure controlled*: the highway infrastructure provides detailed commands to control the behavior of individual vehicles on the AHS.

Separation policy. This attribute pertains to the manner in which vehicles maintain spacing on the highway. It has the following choices:

- *Free agent*: each vehicle individually maintains a safe distance from any vehicles around it.
- *Platoon*: vehicles within a platoon cooperate in order to maintain close spacing between each other, while different platoons maintain safe distances between each other.
- *Slot*: each vehicle is assigned a moving space-time slot on the highway by the infrastructure.

Mixed traffic. This attribute pertains to the mixing of fully automated, partially automated, and manual vehicles in the same lane. It has the following choices:

- Dedicated lanes with continuous physical barriers.
- Dedicated lanes with some gaps in the physical barriers.
- Dedicated lanes with virtual barriers.
- Full mixing of traffic.

Mixed vehicle classes. This attribute pertains to the mixing of different vehicle classes such as light-duty passenger vehicles, trucks, buses, and articulated trucks in the same lane. Concepts may allow or disallow mixed vehicle classes.

Entry/exit design. This attribute pertains to the special characteristics of entries and exits of the AHS. It has the following choices:

- Dedicated ramps to dedicated lanes.
- Transition lanes next to dedicated lanes.
- Identical to today's entry and exit designs.

Obstacle handling. This attribute pertains to the manner in which the system detects obstacles and maneuvers to avoid them. It has the following choices:

- Manual sensing and avoidance.
- Automatic sensing and manual avoidance.
- Automatic sensing and automatic avoidance.

From about a thousand possible combinations of these concept attributes, the NAHSC chose 23 meaningful alternatives for further evaluation. These concepts were analyzed for safety, throughput, cost, flexibility, and acceptability. Three major concept architecture families emerged from this analysis for further study:

- *Autonomous vehicles*. This concept family focuses on vehicle-centered development to maximize system performance with minimal assistance from the infrastructure.
- *Cooperative vehicles*. This concept family adds vehicle-to-vehicle communication to autonomous vehicles, thereby providing shared control infor-

mation. Vehicle-to-vehicle communication is likely to require infrastructure assistance with respect to communication channel allocation and media access services.

- *Infrastructure-supported platoons.* This concept family adds infrastructure modification to cooperative vehicles to support tighter coordination and control for platooning operation. This concept family has the potential to address both safety and congestion in a radically significant manner.

These three concept families identified for further development also form a deployment timeline, with cooperative vehicles succeeding autonomous vehicles and platooned vehicles succeeding cooperative vehicles. Accordingly, in the short term we will see the commercial availability of vehicle-centered technologies such as adaptive cruise control, front collision warning, front collision avoidance, and lane keeping. Full automation is likely first to emerge in specialized transportation niches such as automation of port operations, truck fleets, and snow plows, before reaching the general consumer market.

Seven specific concepts from these three concept families were demonstrated by the NAHSC during a technical feasibility demonstration in August 1997. NAHSC's concept development, analysis, and demonstration activities were supported by specially developed simulation and analysis tools and specially designed sensor and actuator technologies. There was significant activity on the institutional and societal aspects through stakeholder relations.

PLATOON OPERATION

Of all the AHS concepts, platooning offers a radically different solution for improving safety and reducing congestion. This architecture proposes a strategy of grouping several vehicles as they travel along a highway. The separation of vehicles within a platoon is small (2 to 6 m), while separation of platoons from each other is large (40 to 60 m). The movement of vehicles is realized through simple maneuvers—joining two platoons to form a larger platoon, splitting one platoon into two smaller ones, single-vehicle lane change, AHS entry, and AHS exit.

The platooning concept uses fully automated vehicle operation in an infrastructure-supported context, without mixed traffic. It requires a modification to the entry and exit design of the highways. The automation strategy of the platooning architecture is organized in a control hierarchy with the following five layers:

- *Physical layer.* The physical layer consists of the automated vehicles themselves. The vehicle dynamical models are given in terms of nonlinear ordinary differential equations.
- *Regulation layer.* The regulation layer consists of the sensors, actuators, and control systems responsible for safe execution of simple maneuvers

such as joining two platoons, splitting a platoon, single-vehicle lane change, AHS entry, and AHS exit. Control laws are given as vehicle state or observation feedback policies for controlling vehicle dynamics.

- *Coordination layer.* The coordination layer consists of the communication protocols that vehicles and highway segments follow to coordinate their maneuvers to achieve high capacity in a safe manner. The protocols are given in terms of finite state transition systems.
- *Link layer.* The link layer consists of the control strategies that highway segments follow in order to maximize throughput. Control laws are given as traffic state and observation feedback policies for controlling highway traffic using activity flow models.
- *Network layer.* The network layer consists of end-to-end routing, so that vehicles reach their destinations without causing congestion. Control laws are given in terms of fluid flow and queuing models.

The physical, regulation, and coordination layers reside on each vehicle, and the link and network layers reside on the roadside. To avoid single-point failures and to provide maximum flexibility, the design proposes distributed multiagent control strategies. Each vehicle and each highway segment is responsible for its own control. However, these agents must coordinate with each other to produce the desired behavior of high throughput and safety.

Magnetic markers are buried 0.5 inches underneath the road surface along the center of each automated lane at intervals of 4 feet. These magnets are used as a reference for the lateral control of vehicles. The magnetic reference works under all weather conditions and can withstand nominal maintenance of the road surface. It is possible to embed a binary code along the lane by arranging the polarities of the magnets. Roadway geometry information such as curvature, grade, and banking can be encoded in the markers using such a code.

Vehicles are equipped with radar, six magnetometers, and radio communication transceivers. The radar measures the range and the range rate to the vehicle in front. The magnetometers, three in front and three in the rear, measure the deviation of the vehicle from the center of the lane. Their differential readings can be used to deduce road curvature and vehicle yaw rate. The radio transceivers are used to communicate the lead vehicle speed and acceleration to all the vehicles in the platoon. Radio communications are also used to communicate faults or other emergency situations. The accuracy of longitudinal control is within 20 cm, and the accuracy of lateral control is within 10 cm.

Platooning relieves congestion by increasing highway capacity two- to threefold. It enhances safety through improved communication, coordination, and control. Surprisingly, it is also intrinsically safe since collisions between different platoons can be avoided because of the large separations between them, and when there is a collision between vehicles within a platoon, it is likely to be a low-impact one because of the close spacing. Platooning has significant benefits with respect to fuel economy and emissions, reducing fuel consumption by almost one-half because of smooth traffic flow and reduced air resistance. Rider response has shown that platooning is comfortable for passengers because its tight control performance inspires confidence.

Other marker and sensor technologies for vehicle control have been developed and tested. These include vision-based lateral control, scanning laser- and radar-based range measurement and obstacle detection, and radar-reflective metallic stripes on roadways.

CONCLUSION

From an engineering perspective, the AHS program has several important and rare features. It has a profound impact on the day-to-day lives of virtually all individuals and on society as a whole. It brings together diverse engineering fields—civil, mechanical, electrical, and computer engineering. It involves diverse institutions representing a wide range of public and private concerns. It opens rewarding research and development areas in the context of a concrete application. It poses institutional challenges with respect to the deployment of AHS technologies.

The August 1997 NAHSC demonstration firmly established the technical feasibility of the different AHS technologies. Remaining institutional and technical challenges to AHS deployment will likely be resolved over the next decade.

DINNER SPEECH

Working Together in the Twenty-First Century

PHILIP M. CONDIT
The Boeing Company
Seattle, Washington

It is great to be with you, “the best of the best” of our young engineering community from industry, government, and academia. As an engineer and a member of the National Academy of Engineering (NAE), I am honored to be here. Let me, first, congratulate you on your selection from 270 nominees to participate in NAE’s Third Annual Frontiers of Engineering Symposium.

Second, I want to thank President Bill Wulf and the NAE for hosting this symposium, which allows you to find out about new research and pioneer thinking across many different fields. You are certainly working on exciting projects—from the biomechanics of cells and tissue engineering to distributed satellite systems, from instrumentation for the evaluation of the lungs to blended-wing-body aircraft concepts, and much more.

This symposium offers you great opportunity to learn and work together. I find that dialogue is the best way of learning. But before we start that dialogue, I would like to talk a little about change, the need to work together, and the ability to think differently about ourselves.

First, change. We live in rapidly changing times. In just the past few months, NATO signed a new partnership agreement with its former Cold War adversary Russia, and Hong Kong reverted back to China. The Internet and CNN link us daily to other cultures and continents—even to outer space. Today we send mail electronically to each other that is delivered in seconds, and we are eyewitnesses to natural disasters and onboard space shuttle conversations . . . all from our homes. We live in a time of phenomenal change, and we need to recognize this change.

I think it is important to understand that this is a new phenomenon. If you had lived in medieval times, you would have seen little change. You automatically did what your grandfather and father did, and your children followed. Skills and crafts passed from generation to generation. And in the 1700s, people traveled very slowly by horse and buggy—like Benjamin Franklin and Alexander Hamilton to their meeting to sign the U.S. Constitution, 219 years ago. Many of you traveled quickly by air to this meeting here in California. Airplanes were not even created 100 years ago, and the first artificial earth satellite, Sputnik, was launched into orbit only 40 years ago. Today, we watch a tiny vehicle chug around Mars on our TV or computer.

Technology and, as a result, the world are changing at an increasing rate. We have to keep up! So what are the implications of all this change for each of us? I think the implications are that either we must adapt to change or simply disappear. The Darwinian imperative says, "If we're unwilling to change, someone else will, and go forward with it."

Let me give you a couple of examples. At the turn of the century, the seventh-largest company in the United States (Boeing is number 10 today) made buggy whips, saddles, and carriage seats. Because that company failed to adapt when the motor car arrived, it does not exist today. On the other hand, the Warren Featherbone Company, founded in 1883 in Michigan, does. It first recognized the need to replace more expensive whalebone used for women's corset stays. It invented a new stay material made from turkey feathers discarded in making feather dusters and created a cheaper, more pliable stay material. Then fashion changed. The company had to adapt or go out of business, so it moved to rubber diaper covers. Then came disposable diapers. It learned to survive and thrive by reinventing and refocusing again. Today, the company is a successful baby clothing manufacturer in Georgia.

At Boeing I had to learn, too! When I first went to Boeing in 1965, the biggest computer in the world couldn't compare to what I carry in my briefcase today. In the 1960s, airplanes were designed in two dimensions using pen and ink on big sheets of mylar. Now our people create airplanes entirely electronically. They work and rotate colorful, solid, three-dimensional models to see all dimensions of their design. We need to recognize and adapt to change.

Second, working together. I happen to believe we control our own destinies and that we can accomplish great things by working together.

The Boeing Company was founded in 1916 by aviation pioneer Bill Boeing. He hired Tsu Wong as the company's first aeronautical engineer to replace Boeing's original business partner, Conrad Westerveldt. An engineering graduate from the Massachusetts Institute of Technology, Tsu Wong became the first chief engineer at Boeing. During those early days of the company, employees such as Tsu Wong sat together at the Red Barn, the company's first building in Seattle. Engineers upstairs; builders downstairs . . . working together side by side . . . solving problems. Boeing grew bigger as the years rolled by. Bureaucracy crept in. Groups became isolated. The process became serial. People did only their piece of the job and handed it over to the next without sharing knowledge or resources.

When the idea of a whole new airplane family—the Boeing 777—came along, we knew we had to do something different. The 777 has 3 million parts, including 2,885 pieces of tubing, 1,300 wire bundles, 14 tires, and 2 huge engines. To produce our new 777, it would take a new approach: a lot of people and a lot of people working together. We looked to those first days of the company and its rich heritage to create the 777. And we began by creating a mission. Our mission statement became working together to produce the preferred new airplane.

First, two key words: *working together*. As the 777 program started to develop, we said, "Let's invite our customers in; let's create teams to design and build our new airplane family; let's all work together." At first it was difficult. None of us likes someone watching us. We like to complete our work before showing it to someone. A teacher friend of mine gave me a button a few years ago that read, "None of us is as smart as all of us." I believe that statement is true. I also believe it works well with the two words *working together*. We can do magical things working together. In fact, our customers really helped us with the 777. They helped a lot, and they helped with literally thousands of things: reading lights that can be easily changed in flight and understanding that a latch, designed to be operated by a 99 percentile-sized human finger, didn't work with a glove on in minus 15 degrees at Chicago's O'Hare airport in January. We learned that it's worthwhile to listen closely to the customer. The 777 is an airplane of thousands of "working together" ideas.

Second, the next key word—*preferred*. Only the customer gets to decide what is "preferred." Preferred is a very strong reminder. When I was seen jumping up and down at the first flight of the 777 a few years ago, I was asked "Why? Didn't you think it would fly?" The answer was that I knew it would fly, and I was excited because it proved that the process of working together worked. Today at Boeing, working together is an integral part of how we design and build everything from the international space station to the joint strike fighter. Working together works. None of us is as smart as all of us.

Third, the ability to think differently about ourselves. I'm often asked, "What's the most important thing you've learned in the past 10 years?" And I have to answer, "I can never say airplanes are different." Learning to say that I'm not different, that my industry is not different, that my business is not different, is hard. Airplanes are amazing. They're big, they're complex, they fly. They're amazing machines. But saying "my airplanes are different" is the best excuse for not learning.

What you should want to do is learn from everyone. What you do isn't so special that you can't learn from anyone you meet. We learned that by standing on the production line at Toyota—a very dramatically efficient production system. If we had thought “interesting … but airplanes are different,” we would not be improving the Boeing production system today. During that visit to Toyota a few years ago, we learned that we could never again say “but we’re different.”

The ability to think differently about ourselves, to continuously learn allows us to change. And that brings me full circle. First, the world is changing rapidly. Our choice is to recognize that it is happening. Second, working together is a powerful concept. None of us is as smart as all of us. Third, we must be willing to think of ourselves differently. If we do that, I believe we can survive in the twenty-first century.

APPENDIXES

Contributors

VICKI M. BIER is an associate professor with a joint appointment in the Departments of Industrial Engineering and Engineering Physics at the University of Wisconsin, Madison. Dr. Bier has also spent a year as a visiting professor in the Chemical and Nuclear Engineering Department at the University of Maryland and has worked for more than 10 years as a consultant with PLG, Inc., and Arthur D. Little, Inc. She has participated in risk analyses of a wide variety of complex engineered systems in both the United States and Europe, including nuclear power plants, chemical and petrochemical facilities, and the space shuttle. She has a Ph.D. in operations research from the Massachusetts Institute of Technology.

PHILIP M. CONDIT is chairman and CEO of The Boeing Company, the largest aerospace business in the world. He leads more than 235,000 Boeing people who develop, manufacture and support a wide variety of commercial aircraft, space systems, military aircraft, information systems, missiles and defense-electronics products. Boeing, the world's largest NASA contractor and largest manufacturer of both commercial and military aircraft, has customers in 145 countries; operations and facilities in 27 U.S. states and in several other nations. Dr. Condit joined Boeing in 1965 as an aerodynamics engineer on the Supersonic Transport program, and worked on the 707, 727, 737, 747, 757, 767, and 777 in various engineering, sales, marketing, and management positions. He has served in several executive positions in the Commercial Airplane Group, including executive vice president and general manager of the Group's 777 Division. There he involved customers, employees, and suppliers in a precedent-setting "working together" process to design and produce Boeing's 777 airplane. Dr. Condit earned a B.S. in mechanical engineering from the University of California at Berkeley in 1963 and holds M.A. degrees in aeronautical engineering and management from Princeton University and the Massachusetts Institute of Technology, respectively. In May 1996, he was awarded an honorary doctorate from Rensselaer Polytechnic Institute. He received a doctorate in engineering from Science University in Tokyo in 1997. Dr. Condit is a member of the National Academy of Engineering, a fellow of the American Institute of Aeronautics and Astronautics, a fellow of the Royal Aeronautical Society, and a member of the Society of Automotive Engineers. He serves on numerous advisory bodies and boards of directors. In 1997, he was named Chief Executive Officer of the Year by his peers in an annual award given by *Financial World* magazine.

AKASH R. DESHPANDE is a research engineer with the California Partners for Advanced Transit and Highways (PATH) program of the University of California, Berkeley. At PATH, Dr. Deshpande's main work consists of research on analysis and design tools for automated highway systems. He is also the co-founder of Amravan Group, a consulting and product development company based in Berkeley. Previously, he worked as a project manager and senior engineer at TCSI Corp., Berkeley, and as a member of the technical staff at AT&T. Dr. Deshpande has a B. Tech. in electrical engineering from the Indian Institute of Technology, Bombay; an M.S. in electrical and computer engineering from the University of Florida, Gainesville; and a Ph.D. in electrical engineering and computer sciences from the University of California, Berkeley.

AVRAM ALLAN EDIDIN is staff scientist and advanced technology manager for new technology and business development at Osteonics Corp. in Allendale, New Jersey. Dr. Edidin joined Osteonics as a research analyst in 1991 and was manager of international scientific affairs and staff scientist before assuming his current position. He did his graduate studies in the Cornell Hospital for Special Surgery Program in Biomechanical Engineering in Ithaca and New York City, receiving a Ph.D. from Cornell University in 1991.

JANIE M. FOUKE is division director for bioengineering and environmental systems at the National Science Foundation (NSF). She is serving at NSF while on leave from Case Western Reserve University, where she has been on the faculty in the Department of Biomedical Engineering since 1981. Dr. Fouke's research interests are in respiratory mechanics and instrumentation for the evaluation of the lungs. Instrumentation that she has built has been critical to the understanding of the etiology of airway diseases such as asthma and the pulmonary effects of such things as environmental pollutants. Dr. Fouke has graduate degrees in biomedical mathematics and engineering from the University of North Carolina.

FARSHID GUILAK is an assistant professor at Duke University with joint appointments in the Departments of Surgery, Biomedical Engineering, and Mechanical Engineering and Materials Science. His current research is on the biomechanics of the musculoskeletal system, with an emphasis on the fields of cell mechanics and tissue engineering. Dr. Guilak received a B.S. in biomedical engineering from Rensselaer Polytechnic Institute (RPI) in 1985 and an M.S. in the same field, also from RPI, in 1987. He continued his graduate work in mechanical engineering at Columbia University, focusing on the biomechanics of articular cartilage. After earning a Ph.D. in 1992, Dr. Guilak took a faculty position at the State University of New York at Stony Brook, then moved to Duke University in 1994 to head the Orthopaedic Bioengineering Laboratory.

KATHRYN T. HEIMERMAN is a member of the senior research staff at The MITRE Corp., a non-profit, federally funded research and development center. Dr. Heimerman's research is sponsored by the Federal Aviation Administration and is focused on advanced aviation systems development as well as modeling and simulation of the national airspace system. Before joining MITRE, she published technical studies at the non-profit Center for Naval Analyses. Dr. Heimerman has worked at GTE, where she conducted advanced network planning for the US Sprint telecommunications network by evaluating the feasibility and impact of fiber-optic technology deployment strategies. She has an M.S. in operations research and statistics from Rensselaer Polytechnic Institute and a Ph.D. in industrial engineering and operations research from the University of Massachusetts.

ANGELA LOCASCIO is a senior staff engineer at Motorola's Corporate Manufacturing Research Center, where she develops methods to improve decision-making related to product design and manufacture. Dr. Locascio's research interests are focused on design economics, engineering decision-making, and multicriteria optimization. Prior to joining Motorola, she was a research assistant and fellow at the University of Illinois at Urbana-Champaign, where she earned an M.S. and Ph.D. in mechanical engineering.

HARRY E. MARTZ is the nondestructive evaluation (NDE) thrust area research leader in the Engineering Department at the Lawrence Livermore National Laboratory. Dr. Martz's current interests include the research, development, and application of noninvasive X- and gamma-ray computed tomography to better understand material properties and for assaying radioactive waste forms. He is responsible for leading the research and development efforts on different NDE methods, including X- and gamma-ray digital radiography and computed tomography, visual and infrared imaging, laser ultrasonics, micropower impulse radar imaging, and signal and image processing algorithm development. Dr. Martz has applied computed tomography to the inspection of automobile and aircraft components, reactor-fuel tubes, high explosives, shape charges, dinosaur eggs, concrete, composites, and waste-drum contents. He has master's and Ph.D. degrees in nuclear physics, both from Florida State University.

ANGELA L. MORAN is an associate professor in the Department of Mechanical Engineering at the United States Naval Academy. For 10 years prior to joining the Naval Academy in 1993, Dr. Moran was a materials engineer and the spray forming technology group leader in the physical metallurgy branch at the David Taylor Research Center in Annapolis, Maryland. She has master's and Ph.D. degrees in materials science and engineering, both from The Johns Hopkins University. In 1991, she was selected Most Outstanding Female Engineer in the Federal Government, and in 1994, she was selected as Maryland's Outstanding Young Engineer. In 1996, she was the recipient of a Ford Research Labs Recognition Grant for Manufacturing Excellence.

KENT A. MURPHY is president and co-founder of F&S, Inc. in Blacksburg, Virginia, and an associate professor in the Department of Electrical Engineering at Virginia Polytechnic Institute (VPI). F&S has grown during the last 2 years from 3 to 35 full-time employees and has over $15 million in development contracts and manufacturing orders. F&S has also sponsored research projects at VPI totaling more than $3 million. Dr. Murphy received a B.S. in engineering science and mechanics and M.S. and Ph.D. degrees in electrical engineering, all from VPI.

BABATUNDE A. OGUNNAIKE is a research fellow in the advanced control and optimization group of DuPont Central Science and Engineering and an adjunct professor in the Chemical Engineering Department at the University of Delaware. Before joining DuPont in 1989, Dr. Ogunnaike was a professor at the University of Lagos in Nigeria, holding joint appointments in the Chemical Engineering and Statistics Departments. Prior to that, he was a research engineer with the process control group of the Shell Development Corp. Dr. Ogunnaike is the co-author of a widely used textbook, *Process Dynamics, Modeling and Control* (Oxford University Press, 1994). His research interests include modeling and control of polymer reactors, identification and control of nonlinear systems, applied statistics, and reverse engineering biological control systems for process applications. Dr. Ogunnaike has an M.S. in statistics and a Ph.D. in chemical engineering, both from the University of Wisconsin, Madison.

CHRISTOPHER M. POE is an associate research engineer and director of the TransLink Research Center at the Texas Transportation Institute, College Station, Texas. TransLink is a national, multimodal, public-private partnership focused on the application of advanced technologies and operating strategies for next-generation transportation management. Mr. Poe is responsible for the administration and is technical director of the center's $13 million, 5-year research program TransLink, so named because it focuses on linking various elements of the transportation system to form one integrated, cooperative transportation management system. He is finishing his doctoral degree at Pennsylvania State University, where he has led research efforts to study the relationship between vehicle operating speeds and roadway geometric design in low-speed urban areas.

TIMOTHY RAYNER is the noninvasive quadrupole resonance group leader at Quantum Magnetics, where he leads several projects involving the development of large-scale quadrupole resonance (QR) based scanning instruments and other applications. Dr. Rayner is currently working on low-frequency QR detectors for contraband and explosive materials and is actively involved in defining the role of Quantum Magnetics in the development of noninvasive security devices. He has designed and built a low-inductance, high-homogeneity electromagnet for use in a fast-field cycling magnetic resonance (MR) spectrometer and the world's fastest mechanical sample shuttle double resonance MR spectrometer. Dr. Rayner has a Ph.D. from King's College in London.

ANNA C. THORNTON is an assistant professor in the Department of Mechanical Engineering at the Massachusetts Institute of Technology (MIT). After receiving a Ph.D. from Cambridge University, Dr. Thornton joined the mechanical engineering faculty at MIT as a half-time lecturer for 18 months. During that period, she gained practical experience at Polaroid Corp. as a design engineer and with Concentra Corp. in design software development. In 1995, Dr. Thornton was appointed to an assistant professor position. Her research includes work with the Fast and Flexible Manufacturing Project, Leaders for Manufacturing, Lean Aircraft Iniative, and the Center for Innovation in Product Development. The goal of her work is to develop computational tools and formalized methods to assist in the design process.

MARJOLEIN C. H. VAN DER MEULEN is an assistant professor in the Sibley School of Mechanical and Aerospace Engineering at Cornell University, a position she assumed in July 1996. She also has an appointment as an assistant scientist in the Department of Biomechanics and Biomaterials at the Hospital for Special Surgery of Cornell Medical Center in New York City. Prior to this, she was a biomedical engineer in the Rehabilitation R&D Center of the Department of Veterans Affairs Medical Center in Palo Alto, California. Dr. van der Meulen received an S.B. in mechanical engineering from the Massachusetts Institute of Technology and an M.S. and Ph.D. in mechanical engineering from Stanford University. Her research interests are in orthopaedic biomechanics, focusing on skeletal functional adaptation to mechanical loading and bone structural behavior.

Program

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Mechanical Influences on Bone Development and Adaptation
Marjolein C. H. van der Meulen, Cornell University

Implant Design and Technology
Avram Allan Edidin, Osteonics Corporation

* * *

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Angela Locascio, Motorola Corporate Manufacturing Research Center

* * *

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Christopher M. Poe, Texas Transportation Institute, Texas A&M University

Automated Highway Systems
Akash R. Deshpande, California Partners for
Advanced Transit and Highways
University of California, Berkeley

* * *

WRAP-UP SESSION

Organizers: Susan Corwin, Robert Wagoner, and Connie Gutowski

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DINNER SPEECH

Working Together in the Twenty-First Century
Philip M. Condit, The Boeing Company

Participants

National Academy of Engineering

THIRD ANNUAL SYMPOSIUM ON
FRONTIERS OF ENGINEERING
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