JOHN SADOWSKY and ROBERT W. MASSOF

SENSORY ENGINEERING: THE SCIENCE OF SYNTHETIC ENVIRONMENTS

Over the past several months, The Johns Hopkins University Applied Physics Laboratory and the Schools of Medicine, Engineering, and Arts and Sciences have been developing an Interdivisional Sensory Engineering Program. Sensory engineering, an exciting and emerging discipline, incorporates such technologies as virtual environments and virtual reality, data visualization, human sensory system modeling, human–machine interface, and perception, cognition, and performance characterization. In this article, we define sensory engineering and its diverse applied fields: virtual reality, robotic telepresence, teleoperations, visualization, environmental overlays, and sensory enhancement. These fields are illustrated with current projects at the Laboratory and in the Schools of Medicine, Engineering, and Arts and Sciences. The Interdivisional Sensory Engineering Program is introduced, and plans for developing and implementing the program are presented.

INTRODUCTION

The computer has changed dramatically over the fifty years since it was developed as a labor-saving device for computational tasks. Today, computers are primary controlling modules in a wide variety of systems and appliances, from automobiles, washing machines, home entertainment sets, and answering machines to entire transportation control systems and weapons systems. In publishing, advertising, and communications, the computer may be the most important technological advance since the invention of the printing press. Innovations that early computer pioneers could not have imagined have followed from the idea that words and physical phenomena can be converted to numbers, transformed by mathematical algorithms, and either translated back to words and symbols or used to drive servomechanisms.

One exciting and challenging new application for computers is the synthesis of virtual environments.[1] Various applications of virtual environments—for example, to virtual reality, robotic telepresence, teleoperations, and human sensory enhancements—captured public enthusiasm long before any true implementations were available. The combination of high-speed computers with input and output devices for human sensation, especially vision and audition, has produced a seemingly infinite potential for creating new "worlds" of realities for humans to experience. Indeed, it seems that anything imaginable can be realized and experienced at some level.

The basis for the idea is that a computer can synthesize a three-dimensional (3D) graphical environment from numerical data. The data can be the output of a mathematical model of a physical situation, such as the dynamics of an aircraft flying over some terrain, or solid geometric objects arranged in a region of space, or even a geometric realization of some abstract multidimensional data set, such as a time series of ten dimensional vectors measuring the state of the economy over a fixed period. Using visual and auditory output devices, the human operator can experience the environment as if it were a part of the world. Further, because input devices sense the operator's reactions and motions, the operator can modify the synthetic environment, creating the illusion of interacting with and thus being immersed within the environment.

At the University of North Carolina's Department of Computer Science, we recently experienced several sample synthetic environments created by computer from data. In one such system, the world comprises a set of floating molecules that the human operator can fly through or grab and carry. Valence forces and geometric orientations of atoms and bonds that form the molecules limit the degree to which molecules can be fitted together, allowing the operator to study molecular docking through hands-on experience at a visible scale. In another example system, the input data from a scanning tunneling microscope (STM) are used to create a world. The operator virtually flies over the surface of a complex organic molecule. With the STM's stylus in hand, the operator feels the induced forces of the currents that define the atomic image of the surface. A third example system allows the human operator to walk through a simulation of a kitchen's architectural design. Before the kitchen is built, a home improvement customer can explore the look and feel of the design, even pick up the odd pot or pan, and decide if the cabinets are convenient, or the space is too confining, or the lighting is sufficient for meal preparation. We also experienced a classical museum's atrium, viewed through a state-of-the-art, high-resolution head-mounted display, and a system that lets an obstetrician "see" into a patient to a sonographic image of her fetus.

Although the feeling of immersion in the sample synthetic environments was far from compelling—we always felt as though we were standing too close to a television screen, not moving through a real world—the demonstrations convincingly showed the technology's potential. The technology has been slow to advance, however. The literature has described these same examples for nearly ten years, at almost the same level of sophistication and quality. After a rapid and promising start, the technology development for synthetic environments has hit a solid wall. We must scale the wall if we are to make significant progress. Part of the problem is high cost; as enabling technologies are developed and made affordable, new levels of progress are expected. More significant, however, are the gaps in our understanding of the fundamental concepts and sciences of human sensation, perception, and experiential knowledge.

A science of synthetic environments is needed to fill the gaps and create the enabling technologies. Kenneth Johnson of the JHU Department of Neuroscience coined the term "sensory engineering" for the collection of disciplines that contribute to our basic understanding of what makes a compelling and immersive synthetic environment. Preliminary investigations of research interests within the Hopkins community showed that the University has all the components needed to define and establish this branch of science. The difficulty, however, is that the discipline is diverse and unwieldy. A program is needed to facilitate the collaborations and multidisciplinary approaches necessary for significant advances.

Over the past eighteen months, a committee organized by the Provost's office at JHU has defined a plan for such a program. This article summarizes the plan. In the first section, we define the discipline of sensory engineering and describe a simple model of its components, tailored to several synthetic environment applications. Also in this section, we discuss the various sciences that sensory engineering encompasses. In the next section we define the enabling technologies whose development will significantly advance both the basic science and the applied products of the field. In the third section we present the plan for a program of sensory engineering at Hopkins. This plan involves both education and development of applied technologies. We conclude with a view of sensory engineering's future at the University and the Applied Physics Laboratory.

WHAT IS SENSORY ENGINEERING?

Sensory engineering is defined as the science of synthetic environments. A synthetic environment, in turn, is defined as a 3D world constructed on a computer from real and mathematically modeled data and presented to a human computer operator so that the operator experiences some degree of immersion in the environment. The immersion could be total, in which all of the user's senses are deceived into perceiving the synthesized world as the real world. For total immersion, all sensory inputs to the user must be realistic, even though created by the computer; also, the computer must detect all behavioral outputs from the user and convert them into modifications of the synthetic environment. The operator must interact solely with the computer and its synthesized world. Significantly lower degrees of immersion also fall within the definition of sensory engineering. Data visualization, for example, geometrically presents sets of data, such as time series measurements of various parameters, as curves, surfaces, or solid objects. The user can investigate and manipulate the objects to obtain a keener sense of patterns and structures within the data. Data visualization creates no illusion of total immersion in a synthetic world—the graphics are often viewed on the computer monitor, as if through a window—although the ability to interact with, modify, and reorient the graphics provides the operator a partially immersive experience.

Figure 1 represents a human observer immersed in the real world. The figure presents a simple model of the technologies and devices required for a human operator to experience and interact with a synthetic environment as though it were real. Without entering into the philosophic concerns about what constitutes reality, we have simply defined reality as that which human biological sensors can sense and human behavioral responses can consistently alter. The human biological sensory system processes environmental data in the form of light, sound, heat, mechanical forces, and chemical signals, producing usable measurements of phenomena in the environment. Our biological neural networks somehow transform these measurements into internal perceptions of the environment. The perceptions are then processed into information that permits us to make decisions. Some of the decisions affect behavior: actions or reactions to alter the

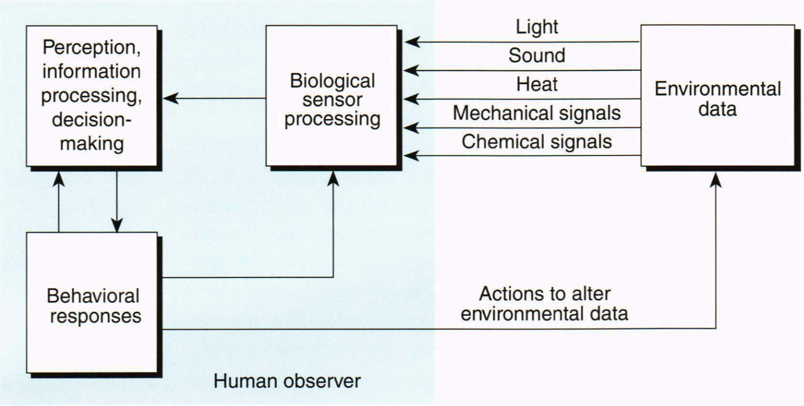

Figure 1. A simple model of a human observer interacting with the environment in the real world.

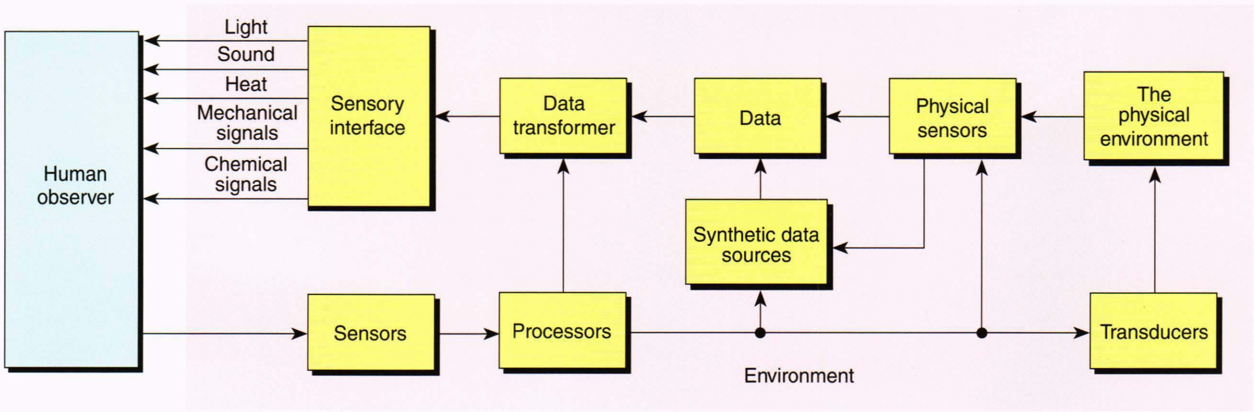

Figure 2. Enhancement of the simple model of a human observer interacting with the environment in the real world, extending it to include the virtual environment. Computer-controlled interfaces replace direct interactions with the real world.

environment, changes to the biological sensory system (e.g., a glance in a new direction), or internal modifications to the perception or information processing systems.

This simple model can be altered by placing computational devices between the human observer and the environmental data. The computer intercedes in every interaction between the human and the environment. Thus, in Figure 2, a sensory interface produces the same signals for the biological sensors that the natural environment of Figure 1 produced. Sensors such as head- and eyeball-tracking devices, position and orientation detectors, and data gloves read the human observer's actions to alter the environment. The synthetic environment is constructed from physical measurements of the real environment and from models that synthesize artificial or mathematical data about a geometric environment. The data are transformed into information that can be used to create biologically sensed signals. Similarly, the behavioral data sensed from the human observer can be either transformed into instructions to modify the synthesized environment or transduced into signals to drive servomechanisms that alter the real environment. Figure 2 does not show the internal components of the human observer. The model treats these components as a black box, although scientific investigation into cognitive processing of biologically sensed data is also a critical part of sensory engineering.

By modifying appropriate components and data flows, we can model various types of synthetic environments. First, assume that the interfaces between the human observer and the synthetic environment in Figure 2 are perfect: the observer cannot distinguish between the real world of Figure 1 and the synthetic environment of Figure 2. Under this assumption, component technology has advanced to a state where the synthetic environment has passed a sort of Turing test.* Many applications will require such realism. Simplifying the data flows (by limiting the sensory output to light and sound, for example) limits the realism. Limited realism is adequate for some applications and can be achieved with current or near-term technology.

Figure 3 shows modifications to the model for several applications. True virtual reality is shown in Figure 3A, sensory enhancement in Figure 3B, and environmental overlays in Figure 3C, and the virtual workstation model is shown in Figure 3D. Figure 2 serves as the model for robotic telepresence. Each of these applications is discussed in the following paragraphs; other applications could be similarly modeled.

Virtual Reality

Virtual reality removes the physical environment from the system; the computer generates the entire environment. Figure 3A illustrates this lack of contact with physical reality. In this model, the human observer has no contact with the physical environment modules, the physical sensors, or the transducers that permit interaction with the physical environment. True virtual reality is totally immersive. In such a perfect system, the human observer could not distinguish the virtual reality experience from a real-world experience. Confusion could arise if, for example, the virtual environment specifically violated perceived laws of nature. Data visualization applications are based on this version of the model, but they provide lesser degrees of immersion.

The popular culture often misuses the term virtual reality by applying it to interactive graphics systems having little illusion of immersion, such as multimedia systems and video games. Current technology has yet to produce a true virtual reality system.

Sensory Enhancement

Sensory enhancement applies signal conditioning algorithms to sensory data from the real environment. The system injects no synthetic data, nor does it use observer

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*Alan Turing proposed a test to determine whether a computer program has achieved true intelligence. If interrogators asking questions of hidden agents, some of whom may be computers, cannot distinguish whether computers or people are responding, then the computer program has passed a Turing test. Creating programs that can consistently pass the Turing test has been the great quest of artificial intelligence research.

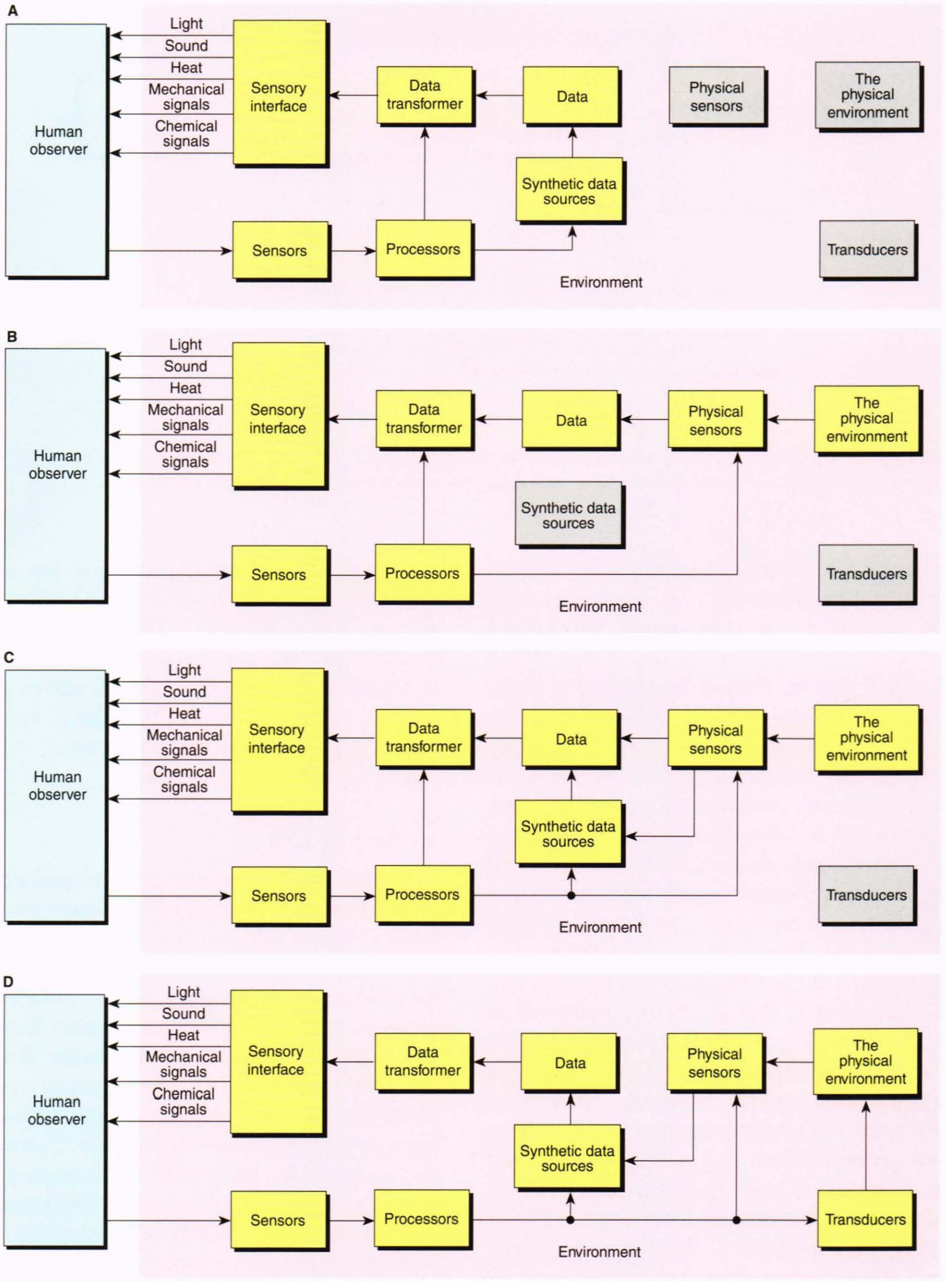

Figure 3. The virtual environment model, modified to illustrate components and data flows appropriate to various applications of sensory engineering. **A.** Virtual reality. **B.** Sensory enhancement. **C.** Environmental overlays. **D.** A virtual workstation.

behavior to modify the physical environment. Signal processors filter, enhance, or otherwise modify the signals from the physical sensors. Thus, Figure 3B shows synthetic data sources and transducer modules removed from the model. An example of sensory enhancement is the low vision enhancement system, described by Massof, Rickman, and Lalle in this issue of the *Technical Digest*. A visually impaired human observer wears a device that senses visible light through the lenses of television cameras. Image processing modifies the camera image, by edge detection, contrast enhancement, or more sophisticated processing, effectively computing an inverse transform of the visual degradation. The poor vision of the human observer then essentially undoes the transform. He or she experiences improved vision.

A second example of sensory enhancement is the research in polarization vision conducted by Larry Wolff of the JHU Department of Computer Science. Here, a polarization sensor is introduced into the physical sensors module, and polarization information is converted into a form that human biological signal processors can detect, such as color and intensity of visible light. The observer can experience the polarization of reflected or refracted light, an aspect of the environment not normally available to human sensation. This application suggests other potential uses, such as a device to convert visible light into audible information, which could help the blind to see virtually. Although sensory enhancement does not alter the physical environment in any computer-assisted fashion, the system must sense user behavior (head and eye motion, for example) so that the input signals can be appropriately adjusted.

Environmental Overlays

Environmental overlays are a natural extension of sensory enhancement. Besides conditioning signals from the physical environment, the computer synthesizes additional data to inject into the environmental database. (Figure 3C thus shows data flow from the synthetic data sources module. However, because this application does not use observer behavior to modify the physical environment, the transducer module is omitted.) An example of such an application is the head-mounted airplane maintenance display system currently under development at the Boeing Computer Corporation. Maintenance workers will wear special goggles onto which are displayed circuit diagrams or blueprints of electronics or other subsystems beneath the surface of the airplane. The information is extracted from a database and overlaid onto the transparent goggles; head tracking is used to keep the diagrams superimposed on the appropriate part of the airplane skin. Thus, the maintenance workers will be able to "see" through the skin of the airplane. Instead of head tracking, a camera could be used to sense the worker's visual field. Digital image processing techniques would then create an image of the field for display with the underlying diagrams. The University of North Carolina is developing a similar system to overlay sonographic images of a fetus onto images of a patient. Also, the 3D blackboard described in the boxed insert is a potential application of environmental overlays.

Robotic Telepresence

Sensory engineering also includes robotic telepresence. Because Figure 2 includes all modules except one for synthesizing data, it can serve as a model for robotic telepresence. The environment is remote from the human observer, however, so the data flows from the physical to the virtual environment are over longer distances. Applications include remote teleconferencing, in which the observer is present in all but body, or the use of robotic agents in dangerous situations, such as nuclear power plant maintenance, fire fighting, planetary probes, or unmanned weapons systems.

Virtual Workstation

The virtual workstation, modeled in Figure 3D, is similar to the complete synthesis model of Figure 2, except that data cannot flow directly from the behavioral sensors or the physical environment sensors to the data transformers. The human observer interacts with the environment through the workstation only, and the computer uses data from physical sensors to generate new data for presentation to the user. The environment can include both physical and synthesized data. The high-fidelity simulators that are nodes for a distributed interactive simulation (DIS) are an example application. The DIS concept originated with a system called SIMNET, sponsored and built by the Defense Advanced Research Projects Agency to simulate a battlefield over a network. Individual virtual workstations connected to the network simulate various military systems, such as tanks and helicopters. The SIMNET system has evolved into a more sophisticated and standardized virtual battlefield—the battlefield distributed simulation—and the APL submarine command bridge simulation has been enhanced to meet the DIS standards for participation in network exercises. Because the computer must sense only direct interaction with the workstation, the human operator's head and eye motions need not be tracked and used to modify the processors.

A THREE-DIMENSIONAL BLACKBOARD

A proposed prototype project for the Interdivisional Sensory Engineering Program's Technologies Applications Center is a 3D blackboard for use in teaching mathematics. We are collaborating with Edward Scheinerman of the JHU Department of Mathematical Sciences to develop the project. The idea was Scheinerman's; one day, while trying to explain a difficult concept in graph theory, he exclaimed, "If I only had a 3D blackboard!"

Using a 3D blackboard, a teacher could present abstract ideas in intuitively appealing ways, so that most students could grasp more of mathematics. Moreover, for the mathematically and scientifically talented student, the 3D blackboard might become a natural laboratory for investigating more difficult concepts not usually introduced in an undergraduate curriculum.

A typical use would be to investigate some geometrically realized mathematical object. Using the system we envision, the instructor and students wear head-mounted displays, which show images of the actual classroom but superimpose computer-generated solid graphic objects that appear to float in space. The instructor holds a spatial-tracking input stylus with which to mark, modify, and manipulate the floating object. If the object is a polyhedron, for example, the instructor can add vertices and connect them with edges to the polyhedron. By selecting from a palette (or some other means) the instructor can fill the faces of the polyhedron, make them transparent, or modify the object. The stylus can be used to grab and rotate the object, mark areas of interest, compress or expand the object in specific directions, or otherwise manipulate it.

The 3D blackboard could improve the quality and flexibility of mathematics and science education. Also, as a laboratory tool, it could help researchers investigate the basic science of how people learn and understand complex concepts. In particular, we could study the extent to which geometric representations of objects and their manipulation can increase the rate of learning, broaden the scope of material a student can learn, and improve intuition (e.g., by improving the ability to generalize and hypothesize new properties of a concept). Until the tool is available, however, all potential uses cannot be anticipated.

The Sciences of Synthetic Environments

The models of synthetic environments presented in the previous paragraphs reveal the scientific and technical disciplines that will be involved in the study of sensory engineering. These disciplines include not only the expected fields of engineering, science, and mathematics, but also medicine, physiology, psychology, and the cognitive sciences. Table 1 lists the scientific disciplines that sensory engineering includes.

Synthetic environment systems require the modular components of Figure 2 to be physically realized. Thus, sensory engineering includes the disciplines of computer science and electrical and mechanical engineering. Advanced algorithms and software architectures must be developed to process the massive amounts of geometric data in real time. For example, the human visual system can sense a field of view of approximately 120 degrees at a resolution of about 1 second of arc. Thus, a digital display for a head-mounted output device should be able to accommodate roughly 7200 pixels square, or 52 million pixels. At a video rate, this device should present 30 images per second, for a rate of 1.5 billion pixels per second. With two displays (left and right eye images), the display device requires a software architecture and driving computer capable of producing 3 gigapixels per second just to maintain realistic imagery. Further, to produce animated complex geometric objects for display in real time will require significant advances in computational geometry algorithms and data structures.

The components of a synthetic environment system must generate signals for the human observer's biological sensory system, detect the observer's behavioral responses, and process the responses. Fundamental scientific advances are needed in our understanding of how human sensory systems receive and process data. Although the virtual reality model of Figure 2 lists all five basic sensory systems, the visual, auditory, and haptic systems have occupied most of the research and development effort. Reproducing what one can see, hear, and touch, although not adequate for a feeling of total immersion, often gives enough of a sense of interaction with reality to meet the goals of a particular application.

In addition to these primary senses, humans have more subtle sensory systems that are important to a compelling feeling of immersion in an environment. The vestibular system, for example, provides a sense of balance (or lack of balance) and a sense of motion. Simulator sickness is a form of nausea that can occur with prolonged use of a head-mounted display system, or in a wide-screen movie, such as IMAX technology produces, in which camera motion is sustained. A principal component of simulator sickness results from a conflict between visual input, which implies that the observer is moving, and vestibular system input, which implies that the observer is still. The somesthetic system has a proprioceptive subsystem that senses the body's internal state, such as the position of limbs and joints and the tension of the muscles and tendons. Mismatches between the signals from the proprioceptive system and the external signals of a synthetic environment can cause discomfort or simulator sickness. Moreover, inconsistencies between expected proprioceptive responses to physically fatiguing behavior, such as marching uphill carrying a full backpack, and the actual feelings experienced in a virtual environment can limit the effectiveness of virtual reality for training. This limited effectiveness may pose a problem in providing realistic battlefield exercises for individual soldier workstations in the battlefield distributed simulation.

The sciences of characterizing biological sensor processing and performance are certainly essential for the design of effective synthetic environments. Even more important, perhaps, is how the human operator perceives reality—the internal perception, information, and decision-making processes that the model treats as a black box. How the observer converts outputs from the biological sensors into perceptions determines the functional requirements of the interfaces. A further complication arises from the context-sensitive nature of the conversion process. An example of context sensitivity can be found in the current technology for virtual-reality-type games in arcades. The technology is primitive: graphics are cartoonlike, head tracking has limited resolution and an uncomfortable delay, display resolution is coarse, individual pixels are clearly visible, colors are unnatural, and tactile feedback and audio directionality are limited. Even so, most players accept the "reality" posed with a feeling of immersion. Game players willfully suspend disbelief.

Table 1. The sciences involved in sensory engineering of synthetic environments.

Sensory psychophysics and physiology	Cognitive science	Human factors	Applied mathematics	Computer engineering
Physical properties and limitations of biological sensory systems Intra-sensory interactions Physiology of behavior	Characteristics, requirements, and limitations of perception Properties and limitations of attention and interest Decision making Learning Visualization	Behavior Task analysis Morphometry Human interface design Training Performance measures	Data reduction and data fusion Computational geometry Signal and image processing Real-time algorithms	Graphics engineering Displays and interfaces Advanced computer architectures Software architectures Optical computing Operating systems Systems engineering

Significant interest in the application affects the perception of reality.

The science of sensory engineering is highly interdisciplinary. Success requires the interaction of a diverse set of interests and knowledge, from biology and physiology, through psychology and cognitive science, to electrical engineering, computer science, and mathematics. The scientific issues for the disciplines of sensory engineering can be summarized as follows:

1. Characteristics and performance of biological sensors
2. Psychology of human perception and sensory information processing
3. Physics, physiology, and psychophysics of sensory interfaces and behavioral responses
4. Sciences of sensing and interpreting observer behavior
5. Mathematics of data synthesis and fusion
6. Cognitive and mathematical theories of data transformation for sensory information vectors, feedback and control, and data visualization
7. Advanced algorithms for computational geometry and real-time signal processing
8. Human–machine systems analysis and engineering

The University's plan for a sensory engineering program grew out of the need to establish a truly interdisciplinary approach to developing the sciences and solving the basic research problems involved. The approach coordinates and focuses the relevant research within the many divisions of the University and facilitates productive collaboration among APL and the Schools of Medicine, Arts and Sciences, and Engineering.

ENABLING TECHNOLOGIES

Just as important as the sciences and the basic research problems are the specific technologies that will enable researchers and developers to build effective synthetic environment systems. Without the specific components for building and testing systems, the entire field of sensory engineering will remain primarily speculative. Moreover, the enabling technologies and the basic scientific research are synergistic. We must understand the physiology and psychophysics of biological sensors and the mechanisms of human perception before we can build high-fidelity components. These new components must then become the instruments we use in experiments to investigate and verify the scientific models of human sensation, perception, and concepts of reality.

Historically, the field of synthetic environments has been defined by the software and devices for generating, presenting, and interacting with computer graphics. The primary purpose of the field was to develop new human-computer interfaces. The enabling technologies are thus defined by the components for computer interfaces and components for the computationally intensive processing required for immersive interaction with a 3D world constructed from data.

Technology development in sensory engineering is being driven by the following primary components:

1. Displays (chiefly head-mounted and boom-mounted)
2. Position and orientation trackers
3. Spatial-coordinate input devices (data glove, wand, and bat or 3D mouse)
4. Directional, high-fidelity audio output devices
5. High-performance, high-speed computing and accelerator boards
6. High-resolution graphics
7. Physical-environment sensors

The enabling technologies are organized into five categories: sensory interfaces; user behavior and movement sensors; adaptive processors; data synthesis, transduction, and transformation processors; and computer architectures. The following paragraphs briefly define each category.

Sensory Interfaces

An essential component of most synthetic environment systems is the sensory input. This component must convert information from the environment into signals a biological sensor system can receive, that is, visual, auditory, and haptic (e.g., tactile and force-feedback responses), as well as temperature, chemical information (e.g., olfactory and sapidity responses), and other features that can be sensed by the somesthetic system.

Interfaces should satisfy performance requirements based on characteristics of the human sensory system and on the application. Thus, for example, human vision resolution and field of view determine display characteristics. Depending on the application, however, the performance requirements may be a less-than-perfect match with human sensory characteristics. Game playing, for example, can afford a visual display resolution of between 256 × 256 pixels and 512 × 512 pixels in an array, and training and architectural walkthrough displays appear to be effective with 1000 to 2000 pixels on a side. In contrast, truly immersive virtual reality requires display resolution of 8000 pixels on a side. Similar statements can be made about sound localization, tactile discrimination, and other sensory perceptions. The state of the art is presently at the phase of early demonstration of potential. Currently available representations of reality are far from accurate.

Research in sound localization indicates that directionality uses cues based not only on differences in time of arrival at the ears (stereo), but also on the characteristics of the transfer function derived from the geometry of the ear's pinna. Azimuthal direction is determined by the time delay difference, and elevation is determined by local reflections from pinna surfaces. Stereo earphones, therefore, limit the extent of sound localization. More realistic audio systems will need more sophisticated methods of sound presentation, possibly from a signal conditioner that approximates the pinna transfer function, estimated from calibration of an individual human user's ears.

At present, most advances in sensory engineering technology have been in the area of head-mounted and other types of displays (for example, boom-mounted displays). Such displays present visual and, sometimes, auditory information. To a lesser extent, force-feedback arms have been used to create haptic sensation. (The stylus used for the STM prototype at the University of North Carolina provides haptic feedback.) Cost limits the development of output devices. At present, a 2000- × 2000-pixel, head-mounted monochrome display with some head tracking costs more than $75,000. Products created for the entertainment industry are rapidly decreasing the cost, however. (Sega has been promising a somewhat less capable head-mounted display for around $200.) Nevertheless, only further basic science will produce truly significant advances in realism of output devices.

User Behavior and Movement Sensors

The human operator's head and body movements and other physical reactions are a principal means for interacting with the synthetic environment. The computer must sense and then compensate for these movements. Head- and eyeball-tracking information is used to adjust the visual and auditory signals, translating the apparent position to maintain the illusion of a stationary environment. Sensors are needed to track head movements, eyeball movements, and gross and fine motor movements, as well as to detect and characterize changes in the observer's physiology that can affect the environment. Currently, coarse but adequate devices are available for sensing behavior and motions, such as data gloves, head- and body-motion trackers, eyeball trackers, force-feedback arms, and various input devices that the user holds, such as the bat (flying, 3D-space-oriented mouse) and the wand.

Adaptive Processors

The relationships between the head- and eyeball-tracking devices and the visual and auditory display devices motivate the need for adaptive processors. Feedback and feedforward systems translate the effects of operator behavior into modifications to the data transformers and data sources. To establish realistic requirements for adaptive systems, basic research will be needed to determine such performance issues as the acceptable length of delay between a head movement and the response within the visual field. Current methods for predicting head-movement trajectories and updating the resulting imagery have an annoying effect: the visual scene continues to move for a few milliseconds after the observer's head stops or slows down. The environment appears to jitter in synchronization with head movements, creating a kind of ringing that causes a disorienting illness in the user.

Data Synthesis, Transduction, and Transformation Processors

Data synthesis, transduction, and transformation processors are required to synthesize interactive environments and interfaces and to construct overlays of synthesized and real imagery. The technology involves various sciences and engineering, such as accurate numerical modeling of terrain dynamics (How does surface dirt fall as tanks pass through it?); real-time, high-fidelity, 3D graphics; and real-time signal and image processing for signal conditioning and sensory enhancement. Data transduction requires advances in environmental sensors and in devices to transduce sensed operator behaviors into appropriate signals. Data transformations comprise multimode sensory coordination and data fusion, multiresolution decomposition of vision and audition data, data compression, and the real-time, custom transformation of environmental data to accommodate individual differences in operators. (The low vision enhancement system will require custom transformations to mitigate vision degradation caused by scotoma, for example, as will a solution to the problem of elevation in sound directionality.)

Computer Architectures

Synthetic environment systems and visualization workstations must have the capacity for high computational loads and rapid throughput. Significant advances in hardware and software architectures will be needed to achieve these capabilities, eventually at reasonable cost. The enabling technologies will encompass developments in highly parallel digital processing; optical and analog computing; and new, computational, and smart materials.

PROGRAM OF SENSORY ENGINEERING AT THE JOHNS HOPKINS UNIVERSITY

Over the past several months, APL and the Schools of Medicine, Engineering, and Arts and Sciences have been developing an Interdivisional Sensory Engineering Program (ISEP). A committee of representatives from the divisions developed a plan for the University to assume leadership in establishing sensory engineering as a major discipline for technical and economic development into the next century. The program's success will build a new industry in the Washington–Baltimore area, with The Johns Hopkins University as the nucleus and the central training and education facility. The program was announced at the annual Technology Month meeting of the Greater Baltimore Committee in October 1993.

To investigate the interest in such a program within the Hopkins community and to encourage informal dialog among faculty and professional staff, a Sensory Engineering Day was held at the University on 28 June 1993. The boxed insert lists the talks given at the conference. The participation indicated that the program will attract a large segment of the Hopkins community. The scientific research that defines the program is active in all University divisions; however, it is not focused toward applications to synthetic environments. The ISEP will therefore be organized around existing activities and

ISEP MISSION STATEMENT

The Mission of The Johns Hopkins University Interdivisional Sensory Engineering Program is to facilitate the development and growth of a synthetic environments industry through basic and applied research; development of enabling technologies; education of scientists, engineers, and business people; creation and support of communication channels; and fostering partnerships between academia, government, and industry.

TALKS PRESENTED AT SENSORY ENGINEERING DAY

THE JOHNS HOPKINS UNIVERSITY, 28 JUNE 1993

Introduction to Sensory Engineering
  T. Poehler, Vice Provost for Research

Overview of the Interdivisional Sensory Engineering Program
  Robert Massof, School of Medicine

The Submarine Combat Information Laboratory and Virtual Reality
  Michael Dykton and Don Allison, APL

Tactile Information Processing
  Ken Johnson, Arts and Sciences

Perception and Attention
  Howard Egeth, Arts and Sciences

Applied Mathematics for Virtual Environments
  John Sadowsky, APL

The CIC [Combat Information Center] as a Synthetic Environment
  John Gersh, APL

Heart Model
  Rai Winslow, Whiting School of Engineering

Sound Localization
  Eric Young, Whiting School of Engineering

Blood Flow Visualization
  Will Geckle, APL

Geometric Pattern Matching
  Mike Goodrich, Whiting School of Engineering

Human Performance in Virtual Environments
  Bruce Hamill, APL

The Virtual Museum at JHU
  Robert Kargon, Arts and Sciences

Low Vision Enhancement System
  Robert Massof, School of Medicine

Motion Perception
  Michael Rudd, Arts and Sciences

Solid Modeling and Computer-Aided Geometric Design
  John Johnstone, Whiting School of Engineering

Real-Time Three-Dimensional Graphics Display of Command and Control
  Roger Sumey, APL

Polarization Imaging and Vision
  Larry Wolff, Whiting School of Engineering

Engineering a Telepresence System
  Andrew Goldfinger, APL

Optic Flow
  Kathleen Turano, School of Medicine

Mechanism of Human Visual Attention
  Steven Yantis, Arts and Sciences

The Graduate Program in Sensory Engineering
  Gerry Masson, Whiting School of Engineering

resources and will evolve by supplementing and augmenting existing programs. The goals of the program are as follows:

1. *Develop the infrastructure and organization.* Organize resources and establish a central office to coordinate, implement, and maintain the ISEP, including physical facilities, laboratories, supplies, a high-data-rate network, network support, and administrative staff.

2. *Establish a multidisciplinary graduate program.* Organize the steering committee, design a curriculum, develop additional courses, and identify and obtain funding to recruit and support students for a multidisciplinary academic program in sensory engineering.

3. *Seek funding for basic research.* Identify and pursue contacts and sources of funding within the government and private foundations to support basic research and collaborations.

4. *Seek funding for applied research.* Identify and pursue projects and funding sources within government and industry to support the building of systems and virtual environment products.

5. *Establish relationships with industry.* Formulate a plan to involve corporations and industries as partners in technology development and mutually beneficial collaborations.

6. *Develop professional and public relations.* Prepare literature, demonstrations, and other activities to publicize the program and the University as a center of research in sensory engineering.

The program consists of two parts, a sensory engineering graduate education program and a sensory engineering Technology Applications Center. These two parts serve the complementary goals of education and research and development to define the field of sensory engineering and set its agenda.

Graduate Program

The graduate education program involves the JHU Departments of Neuroscience, Psychology, Computer Science, Electrical and Computer Engineering, Biomedical Engineering, and the Part-Time Programs in Engineering and Applied Science. The program will consist of a doctoral degree in the academic departments and, eventually, a master's degree in the part-time program. Depending on recommendations of the steering committee, the program may be implemented as early as the 1994–95 academic year, with a group of four or five interested students who have been accepted into the participating departments. It will evolve into a full interdepartmental program over the next two or three years.

An essential component of the doctoral education will be a rotation through the various participating laboratories, not only within the academic departments, but also in the nonacademic participating divisions, such as the research laboratories at APL, the Center for Biomedical Visualization, the Lions Vision Research and Rehabilitation Center, and the Mind–Brain Institute. Thus, for example, a student in computer science with specific research interests in algorithms or architectures can spend six-month intervals as a researcher in laboratories in psychology, investigating human perception, and in the Medical School, studying biological sensors. In the first few years, the laboratory rotations will be organized informally within the participating divisions. They will become more formal as the program crystallizes.

Technology Applications Center

The sensory engineering Technology Applications Center will manage the program and coordinate funding and information. The Center will serve as a bridge between the ISEP and government and industry. It will drive development of the enabling technology for the sensory engineering industry; facilitate technology transfer from the University to start-up research and development and sensory engineering manufacturing companies; and collect and manage information on sensory engineering science, component technology, and applications within the industries served. The components of the Technology Applications Center include the central ISEP management, (offices to broker research and development contracts and grants and to incubate programs), high-data-rate network management, information management, and a Corporate Council.

The Corporate Council will be the vehicle for industry partnership with the University ISEP. It will foster formal collaboration between the University ISEP and business and industry. The Council will be modeled after similar centers, such as the Center for Non-Destructive Evaluation at Hopkins and the various National Science Foundation Centers for Excellence around the country. Members will pay an annual fee to support graduate students, cover the administrative costs of the program, and furnish seed money for research not otherwise funded. In exchange, they will have access to technology for potential licensing agreements and can influence the direction of enabling technology development, help select problems for basic research, and receive realistic information about the state of the field.

To become a reality, the Technology Applications Center needs specific prototype projects to motivate research and development in sensory engineering. Such projects should be important, but their goals must be simple enough to be achievable in a realistic time, as well as broad enough to encompass wide areas of enabling technology and applications for synthetic environments. To succeed, a prototype project should require research in sensory engineering, and it should produce a laboratory instrument and test bed for further basic research and innovation. One possible prototype project, a 3D blackboard for use in teaching mathematics, was discussed in a boxed insert earlier in this article.

FUTURE OF SENSORY ENGINEERING

Sensory engineering has often been compared to artificial intelligence: it promises much but so far has produced little that lives up to the promise. According to Jaron Lanier, a founding developer of the field, the promise is real but the technology is still at the fledgling stage. Even so, the industry has grown, mostly by redefining what qualifies as a synthetic environment. Judging from vendor demonstrations at the 1993 Meckler conference (a major exposition of new products and developments), any software and hardware that includes interactive interfaces and graphics now qualifies as virtual reality. Virtual reality and multimedia are commonly confused as well.

This watering down of definitions is unfortunate, because a true technological revolution is waiting to occur as the science and the enabling technologies are studied, developed, and made available at reasonable cost. Table 2 lists some of the many areas that will benefit from technological advances in sensory engineering. The promise will be realized, however, only with major programs of education, research, and development such as the one planned at Hopkins.

Many new initiatives are under way at APL to organize and strengthen sensory engineering expertise. Distributed interactive simulation is significant technology, not only for training but also for doctrine formation, systems engineering and analysis, systems and components testing, and other uses that will be devised as the technology matures. Although DIS systems clearly benefit military applications, as the earlier example of the distributed battlefield network showed, applications can easily be imagined in such areas as transportation, biomedical systems, and multipurpose communications systems.

Another major application for sensory engineering being investigated at APL is virtual prototyping. Sometimes called building "ships on a chip," the idea was pioneered in the Maritime Systems Technology Office of the Department of Defense's Advanced Research Projects Agency. Design tools and workstations are being developed to permit designers, developers, and users to build and experience an ocean-going ship virtually, without building anything physical. The time and cost savings of such a workstation would be tremendous—design flaws

Table 2. Commercial and industrial areas that will benefit from applications of the enabling technologies of sensory engineering.

Sensor engineering application	Areas that will benefit
Virtual reality	Entertainment, defense, medicine, energy, finance, communications, scientific research, space
Sensory enhancement	Medicine, defense, transportation, scientific research, space, safety
Environmental overlays	Manufacturing, defense, medicine, energy, transportation, safety, scientific research
Robotic telepresence	Safety, defense, medicine, energy, space, scientific research, communications, transportation
Virtual workstation	Defense, energy, finance, communications, scientific research, space, safety

could be identified and corrected early. Such virtual prototyping systems require, in addition to the advances in sensory engineering already discussed, significant advances in numerical modeling of the environment. For example, more needs to be known about the fluid dynamics of the ocean and a ship's passage through it.

These projects and others, such as data visualization workstations, high-resolution graphics software, and human-computer interface designs, have established APL as a major developer in the field of sensory engineering.

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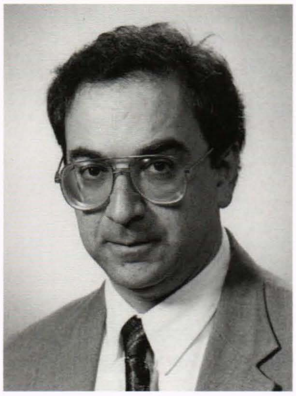

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