A GUIDE TO THE TECHNOLOGIES, APPLICATIONS,
AND HUMAN FACTORS FOR AR AND VR

Practical AUGMENTED REALITY

Steve **AUKSTAKALNIS**

Praise for *Practical Augmented Reality*

“A valuable addition to the library of anyone setting out on their virtual journey.”

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Head of VR, Nuclear AMRC

“A well-presented introduction to advanced visualization technologies, which will provide readers with an informed overview of this fast-paced, high-tech industry.”

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“Mixed or augmented reality is a grand frontier not only for computation, but for how people experience their world and each other. This book sets a frame around that which isn’t framed. Read it in order to understand our new world.”

—Jaron Lanier
Author of *Who Owns the Future* and *You Are Not A Gadget*

Practical Augmented Reality

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A Guide to the Technologies, Applications, and Human Factors for AR and VR

Steve Aukstakalnis

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In memory of my mother and elder brother,
both of whom passed away in the course of writing this book.
You left us way too early and are deeply missed.

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FOREWORD

After months of electrical, mechanical, Zero-G, underwater, and network certification, we had finally launched two Microsoft HoloLens mixed-reality devices to the International Space Station (ISS). On the morning of February 20th, 2016, our team, stationed at NASA Johnson Space Center's Mission Control, successfully made the first holographic call to space. Astronaut Scott Kelly picked up and proceeded to take us on a tour of his home for the past year. At one point, he guided us to the cupola (observation module), slowly lowered the solar shields, and showed us the curvature of the Earth as it floated into our view. As if that was not enough, Scott then drew annotations on top of the various ISS modules and talked about their importance in the discovery of science and the maintenance of life-support for the crew. This unforgettable moment was my affirmation in the future of virtual and augmented reality.

Back on Earth, we are using similar technologies at NASA to bring our scientists to Mars, provide CAD-level design visualizations to our spacecraft engineers, and enhance the capabilities of our robot operators. By providing better contextual awareness of the distant environments, we are dissolving the physical barriers between the operators and the robots they are expected to operate. By resolving issues earlier in the design, we can reduce the cost of building our spacecraft, which ultimately allows us to build more spacecraft.

Our fascination with this industry started many years ago as we investigated various hardware and software platforms. We have used many of the technologies that are discussed in this book and are excited for the many yet to come. Developing for this platform is unique and we often run into unforeseen challenges. Let this be a guidebook for understanding the expanding field of virtual and augmented reality as this technology becomes ubiquitous like the television and the internet. Start with an open mind and a clean slate and you can avoid some of the common misconceptions for new users.

At NASA, building spacecraft requires the right set of materials and resources, just as building an application in the world of VR/AR. As a developer, use this book as an index of equipment in your tool belt and make sure to pick the right tool for the right job, even if that means not using VR or AR at all.

Every spacecraft we build has various scientific instruments installed inside. To maximize science and reduce risk, we must be extremely selective in what payloads to ship. As a content creator, use the anecdotes in this book to help you choose the right experience for your target audience.

One of NASA's core missions is to inspire the next generation of explorers: the astronauts that will take humanity to the asteroids, Mars, and beyond. When the first representatives of Earth step foot on Mars, we will all be virtually present. We will welcome their arrival and explore alongside them. Together, we will make discoveries that will forever change our reality.

—Victor Luo
Senior Technical Lead, Software Systems Engineering
NASA Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
July 2016

PREFACE

Despite the public fascination with augmented reality (AR) and virtual reality (VR), few within the broader audience understand how these systems actually function. AR and VR are seen as cool technologies for better gaming and entertainment experiences, but beyond that point, the general understanding of the topic is vague. Since the initial wave of interest in the early 1990s, a new generation of tech-savvy youth, college aged individuals, and professionals has emerged with the same interest and fascination as two decades prior, but with relatively few up-to-date resources clearly explaining the enabling technologies, how they are intended to harness the strengths of the human perceptual system, or which show the variety of existing, problem-solving applications outside of gaming. This book attempts to fill that void.

Readers should recognize that, although the latest generation of products at the heart of this field come from highly talented individuals, the true pioneers of augmented and virtual reality can be found in the scientific literature, tech briefs, conference proceedings, and patents filings of the 1980s and 1990s. Those like Tom Furness, Mark Bolas, Stephen R. Ellis, Scott Fisher, Warren Robinett, Nathaniel Durlach, Ian McDowall, Fred Brooks, Henry Fuchs, Elizabeth Wenzel, Scott Foster, Jaron Lanier, and Tom DeFanti quietly worked in their labs solving the big problems, developing innovative hardware and software solutions, exploring the relevant human perception and performance issues, and in general, laying the groundwork for the current reemergence of this field.

It is upon their shoulders that I stand.

Who Should Read This Book

This book is intended as a supplementary text for undergraduate and graduate courses in computer science, engineering, architecture, and other fields that make use of standard computer visualization techniques as well as AR and VR systems.

If you are in business, engineering, or science, this book will detail a host of applications where these technologies are having a strong impact on design quality, cost control, more efficient collaboration and manufacturing workflows, and increased data understanding.

If you are a gamer or general AR/VR enthusiast, this book is ideal for providing a solid grounding in perceptual mechanics and the underlying enabling technologies of head-mounted displays, spatial sound solutions, sensors, and a range of tactile and force feedback devices.

Although there are no specific prerequisites, the author presumes an understanding of basic computing principles and human biology.

How This Book Is Organized

This book is organized in a manner that explains augmented and virtual reality systems from the inside out. As opposed to diving right into the various enabling technologies, it first looks at the mechanics of sight, hearing, and touch, each of which is immediately followed with respective explanations of wearable displays, 3D audio systems, and tactile/force feedback devices. The objective is helping you, the reader, gain an understanding and appreciation of how our extraordinary perceptual mechanisms directly dictate the design and application of relevant enabling technologies and the ranges of performance they attempt to achieve.

This book is separated into four parts:

- Part I, composed of two chapters, introduces basic concepts such as a clear delineation between augmenting and immersive displays and their respective histories, explanations of visual space and content, position and orientation in three dimensions, commonly used coordinate systems, and general navigation approaches.
- Part II, composed of ten chapters, explores the mechanics of our senses of sight, hearing, and touch, each followed by explanations of the key respective enabling technologies of visual, audio, and tactile displays, as well as sensors and input devices.
- Part III, composed of eight chapters, provides case studies and descriptions of a wide range of existing applications for these technologies in areas such as entertainment, architecture and construction, science and engineering, healthcare and medicine, education and training, telerobotics, and more.
- Part IV, composed of three chapters, explains the key human factors issues associated with the use of augmenting and immersive displays, legal and social considerations, as well as an outlook on what the future holds for key enabling hardware and software technologies.

The following is a detailed description of each chapter:

Part I, "Introduction to Augmented and Virtual Reality," spans Chapters 1 and 2.

- Chapter 1, "Computer-Generated Worlds," gives a general introduction to augmenting and immersive display systems, including optical and video see-through variants as well as a history of each.
- Chapter 2, "Understanding Virtual Space," provides a basic overview of the concept of virtual space, including the similarities and differences with physical space, the conventions used to define, characterize, and organize space, as well as approaches for navigation.

Part II, “Understanding the Human Senses and Their Relationship to Output / Input Devices,” spans Chapters 3 through 12.

- Chapter 3, “The Mechanics of Sight,” explores the physiological processes enabling us to visually perceive real and virtual worlds, including a review of the visual pathway, spatial vision, and monocular and stereo depth cues.
- Chapter 4, “Component Technologies of Head-Mounted Displays,” examines ocularity, display types, imaging and display technologies, and optical architectures.
- Chapter 5, “Augmenting Displays,” explores numerous monocular and binocular augmenting displays currently available on the market, highlighting their key functional and design differences as well as the initial uses for which they are intended.
- Chapter 6, “Fully Immersive Displays,” presents the details of the latest generation of commercially available, fully immersive head-mounted displays across several classes ranging from PC and console-driven devices to lower end systems based on modern smartphones.
- Chapter 7, “The Mechanics of Hearing,” explains how our ears convert rapid variations in the average density of air molecules into what we perceive as sound, how our brain localizes and separates sound sources, and how sound cues contribute to an overall sense of immersion within virtual environments.
- Chapter 8, “Audio Displays,” details the various types of audio displays and spatial sound solutions used in augmented and virtual reality systems, examining their functional differences and the types of application settings within which each is most beneficial.
- Chapter 9, “The Mechanics of Feeling,” explores the mechanisms enabling our sense of touch, including the anatomy of the skin, the functionality and range of capabilities of the various mechanoceptors and proprioceptors, and how tactile and kinesthetic cues can supplement visual and audio displays.
- Chapter 10, “Tactile and Force Feedback Devices,” examines a number of technologies and product solutions used to produce tactile and kinesthetic cues, as well as the challenges in leveraging the power of our sense of touch.
- Chapter 11, “Sensors for Tracking Position, Orientation, and Motion,” covers a variety of key sensor technologies used to track position, orientation, and motion of users, head-mounted displays, and input devices.
- Chapter 12, “Devices to Enable Navigation and Interaction,” covers a number of the current and emerging technology solutions enabling navigation through and interaction with virtual environments and the objects contained therein.

Part III, “Applications of Augmented and Virtual Reality,” spans Chapters 13 to 20.

- Chapter 13, “Gaming and Entertainment,” digs in to some of the unique applications for augmenting and immersive systems in the areas of art and entertainment, including multiplayer first-person games (MFPG), location-based entertainment, and cinematic virtual reality. The chapter also highlights strengths and challenges posed in harnessing these new technologies within this application area.

- Chapter 14, "Architecture and Construction," presents case studies that illustrate the widely varying ways in which augmenting and immersive displays are being used to solve design visualization, communication, and project management challenges.
- Chapter 15, "Science and Engineering," explores actual ongoing application of these technologies in such widely varying areas as space systems, naval architecture, and automotive, marine, and nuclear engineering.
- Chapter 16, "Health and Medicine," looks at the application of augmenting and immersive displays in such areas as the training of physicians, treatment of post traumatic stress disorder (PTSD) and phobias, vascular imaging, and healthcare informatics, highlighting the strengths and benefits of the solutions compared to methods traditionally employed.
- Chapter 17, "Aerospace and Defense," presents case studies within which augmenting and immersive displays, spatial audio, and tactile and force feedback systems are used to leverage strengths of the human perceptual system in the control of complex machines such as jet aircraft to train astronauts and help refine skill sets and situational awareness of soldiers on the battlefield.
- Chapter 18, "Education," explores some of the existing, high-impact applications for augmenting and immersive systems in tangible skills training, aiding students in learning abstract concepts in complex fields such as architecture, and experiential learning for children.
- Chapter 19, "Information Control and Big Data Visualization," looks at the applications of immersive displays in the visualization, manipulation, and interrogation of massive data sets that are now generated by many scientific studies and business operations.
- Chapter 20, "Telerobotics and Telepresence," explores several examples of the application of these advanced visualization and control technologies in the operation of semi-autonomous robotic systems at a distance.

Part IV, "Human Factors, Legal, and Social Considerations," spans Chapters 21 through 23.

- Chapter 21, "Human Factors Considerations" looks at some of the more pressing complications and physical side effects resulting from the use of these advanced visualization tools, including such problems as visually induced motion sickness and vergence–accommodation conflicts. It also highlights steps that can be taken to minimize their impact.
- Chapter 22, "Legal and Social Considerations," examines some of the profound legal, social, and ethical issues resulting from the rise of commercially available augmenting and immersive display technologies, including product safety, potential courtroom applications and the presentation of evidence, the increasing violence and realism of first-person games, and more.

- Chapter 23, "The Future," explores some of the next major advances for key enabling component technologies, highlighting the short- and long-term outlook and the benefits that the changes will enable.

In addition, this book includes two appendixes:

- Appendix A, "Bibliography," contains bibliographic citations for the parenthetical references found in the text of each chapter.
- Appendix B, "Resources," provides a consolidated list of dozens of visual displays, spatial audio solutions, tactile and force feedback devices, position/orientation sensors, and the web addresses for each of their manufacturers. Also included is a listing of a variety of DIY resources for those inclined to develop or tinker with their own system, and a list of product trademarks.

Conventions Used in This Book

The following typographical conventions are used in this book:

- *Italicized text* indicates emphasis on a word or phrase.
- **Bold** *text* indicates an important term or phrase.
- Parenthetical citations in the form (Doucet et al., 2012) are used extensively in this book and denote references to other works. In each instance, the full bibliographic citation can be found within Appendix A.

> note
>
> A note highlights useful or interesting information and facts.

Companion Website

The companion website to the book can be found at **PracticalAR.com**. This site provides regular updates on new products, sensors and applications, hyperlinks to important papers and presentations, an author blog, and more.

Register your copy of *Practical Augmented Reality: A Guide to the Technologies, Applications, and Human Factors for AR and VR* at informit.com for convenient access to downloads, updates, and corrections as they become available. To start the registration process, go to informit.com/register and log in or create an account. Enter the product ISBN (9780134094236) and click Submit.

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Writing a book of any type takes time, research, and assistance from a variety of sources. From those who support and encourage you in the effort to those who beat you like a rented mule when the gears are not turning, each plays a critical role in arriving at a finished product. To this end, initial thanks go to God Almighty for the grace and wisdom provided over the course of the project. Next, my deepest thanks go to Laura Lewin, executive editor with Pearson Technology Group and Addison-Wesley Professional, who provided the opportunity and oversight. Laura pushed me hard to keep the effort on track and at a high standard. Heartfelt thanks also go to the editorial and production teams. Songlin Qiu was the detail-oriented development editor, and Olivia Basegio, editorial assistant, provided crucial support across all activities leading to publication.

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To my friends and colaborers, including Steven "1234" Harris, Peter and Sonya, John and Stacy, Bernie and Naomi, as well as the rest of my friends at HCBC, thank you for your encouragement and prayers.

And to my family: it has been said that gratitude is when memory is stored in the heart and not the mind. Know that you have filled both.

ABOUT THE AUTHOR

Steven Aukstakalnis (Awk-sta-call-niss) is the former Director of the Virtual Environment and Interactive Systems Program at the National Science Foundation Engineering Research Center for Computational Field Simulation. He has served on the professional research staff at the University of Washington and the faculty of Mississippi State University. He is the author of two previous books about virtual reality and interactive systems. The second, *Silicon Mirage*, was published in six languages and adopted as a text in schools around the world. He is an invited lecturer and researcher for a host of universities, corporations, and government agencies. Steven lives in South Florida and is an avid kayaker and sailor.

CHAPTER 17

AEROSPACE AND DEFENSE

Applications for immersive and augmenting display technologies are widespread within the aerospace and defense communities of the United States and most other industrialized nations. From leveraging strengths of the human perceptual system in the control of complex machines such as jet aircraft, to training astronauts and helping refine skill sets and situational awareness of soldiers, virtual and augmented reality systems are having a solid impact on performance and cost efficiency. In this chapter we explore a number of such applications, detailing the benefits gained and some of the challenges still faced.

Flight Simulation and Training

Safely piloting an aircraft is an acquired talent. At the most basic level, it requires dozens of hours of actual flight time, plus classroom study, to develop, demonstrate, and test out on the legally recognized skill set and proficiency level necessary to become a licensed pilot. The more complex the aircraft, the greater the number of hours and specialized training necessary to learn how to safely and effectively handle the increasingly complicated systems.

This training methodology works sufficiently well up until the point that advanced skills are needed, such as flying in formation or aerial refueling. At that point, the training challenges and expense are magnified significantly to include the need for additional aircraft and crews, high-end simulators, and more.

Fused Reality

Systems Technology, Inc. of Hawthorne, California, asked this question: Can we use an actual aircraft as a simulator and get the best of both worlds? The answer is yes. In collaboration with NASA's Armstrong Flight Research Center at Edwards, California, and the National Test Pilot School in Mojave, California, engineers have developed an innovative combination virtual/augmented reality system known as Fused Reality that enables any aircraft to be used as a flying simulator.

As shown in Figure 17.1, the heart of the system is a fully immersive stereoscopic head-mounted display customized to include a centrally mounted video camera. Video signals from this camera are sent to a high-performance notebook computer, which itself is connected to the aircraft avionics data bus. Specialized software algorithms analyze the video signal and determine, quite literally, where the cockpit ends and the windscreen and windows begin. It is into these spaces (the windshield and windows) that computer-generated imagery is placed within the video signal returned to the display and presented to the user.

The orientation of the user's head (roll, pitch, and yaw) is monitored using IMUs built into the display unit. That information, as well as data from the avionics bus such as movement of aircraft controls, airspeed, and heading, is combined to generate and precisely register the computer-generated imagery.

The Fused Reality system provides two primary operating modes. The first, shown in Figure 17.2, provides a real-world view of the interior of the cockpit, but everything seen outside of the windscreen and windows is completely computer generated. Such a capability provides infinite flexibility in the creation of training scenarios. The user could actually be flying high above a barren desert but be presented with a detailed mountain scene within the display. Complicated approaches and precision runway or carrier landings can be practiced thousands of feet in the air. Or, as is depicted in Figure 17.2, complex aerial refueling operations and other formation flying scenarios can be practiced although there are no other aircraft for miles in any direction. It goes without saying that in this operating mode, having a safety pilot in the cockpit is highly recommended.

Figure 17.1 The Fused Reality head-mounted display shown in this image provides the user a combined view of the actual cockpit interior and instruments as well as computer-generated imagery beginning at the windows.
Credit: Image courtesy of NASA

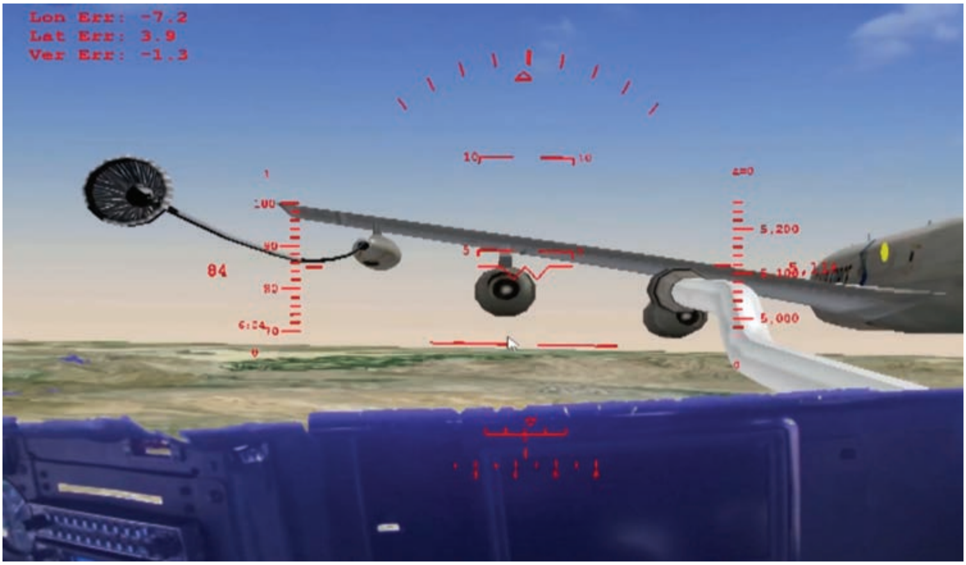

Figure 17.2 One operating mode of the Fused Reality system displays a completely computer-generated virtual environment beyond the edge of the pilot's view of the physical control panel. In this snapshot of an aerial refueling simulation, the pilot attempts to connect a virtual receiver probe into a drogue receptacle extending from the wing of a computer-generated tanker.
Credit: Image courtesy of NASA

The second operating configuration, shown in Figure 17.3, is referred to as “stencil mode.” This configuration gives the user a real-world view of both the cockpit interior as well as the scene outside of the aircraft, but with computer-generated objects such as aircraft added into that outside view. Here again, the breadth of potential application scenarios is limitless. Pilots can practice and hone skills at a fraction of the cost, and without the danger, of traditional real-world training missions involving other aircraft and crews. If you collide with a virtual aircraft in these simulations, you simply reset the training application and start again (Merlin, 2015).

In addition, the Fused Reality system holds several other distinct advantages over traditional ground-based simulators used to develop and hone advanced flight skills. Even the most cutting-edge, state-of-the-art, full-motion flight simulators are unable to re-create the internal sensations of g-loading and its subtle vestibular effects, airframe buffet cues, or the feel of energy bleed. By taking the simulator aloft, these important perceptual cues are preserved.

Figure 17.3 This image shows the Fused Reality system operating in stencil mode, within which a computer-generated virtual tanker is displayed over the real scene of the outside world.
Credit: Image courtesy of NASA

Mission Planning and Rehearsal

Simulators and training systems play a critical role in every branch of the U.S. military, as well as the defense forces of most other industrialized nations. These simulators range from large physical systems such as the U.S. Navy’s USS Trayer (BST 21), a 210-foot-long Arleigh Burke-class destroyer simulator where recruits are taught to respond to 17 different ship board emergency scenarios, to state-of-the-art, high-fidelity, full-motion flight simulators used by fighter pilots. Every U.S. soldier who deploys to combat zones overseas uses simulators in some aspect of their preparation, with an increasingly heavy reliance on immersive virtual training. As with all simulator methodologies, these systems provide the opportunities to hone skills, rehearse missions, and make mistakes without actual life or death consequence in a safe and cost-effective manner. The next few sections offer an overview of some of these solutions.

Dismounted Soldier Training System

The Dismounted Soldier Training System (DSTS) is a fully immersive virtual reality infantry team training solution specifically designed for the U.S. military. In its basic configuration, the DSTS is a robust, self-contained training system supporting up to nine soldiers, the current size of a standard U.S. Army rifle squad. As shown in Figure 17.4, each soldier is outfitted with a stereoscopic head-mounted display with integrated sensors to track position and orientation of the head, stereo speakers, and microphone for simulation of voice and radio communications, a small backpack containing graphics hardware for generation of display imagery, additional sensors that track movement of the user's body, and an instrumented weapon.

Figure 17.4 This image shows a U.S. Army soldier geared up and participating in a training scenario utilizing the Dismounted Soldier Training System (DSTS).
Credit: Image courtesy of DoD

Each soldier stands on a four-foot diameter rubber pad placed in the center of a 10-foot by 10-foot training area. The feel of the pad beneath the soldier's feet serves to keep each participant in a specific area within the training location. Instead of physically walking, soldiers maneuver their position through a virtual model using simple controls on their weapon. This specific aspect of the systems allows for training to be held in small, multiuse facilities at a fraction of the cost of live exercises.

Specifically designed to enhance squad and team tactics such as movement formations and room-clearing exercises (as opposed to marksmanship skills), the DSTS system provides infinite flexibility in developing training scenarios. The nine-person system is completely portable and can be used anywhere you can find electricity and about 1,600 square feet of space. Hundreds of these systems are in use around the world and are capable of unlimited networking for larger, geographically distributed training exercises (Koester, 2013).

PARASIM Virtual Reality Parachute Simulator

The very idea of humankind being able to step off into space from a great height and descend safely to the ground has been traced as far back as 9th century Chinese civilization. The first recorded design for a parachute by a known individual came from Leonardo da Vinci in 1495. That design consisted of a pyramid-shaped linen canopy held open by a square wooden frame. The first practical parachute and the generally accepted predecessor to modern parachute systems came in 1783 from French physicist Louis-Sebastien Lenormand. His work ultimately led to the first military use of the parachute by artillery observers in tethered observation balloons during World War I. Because the balloons were dangerously idle targets for enemy aircraft, the observers would bail out of the basket as soon as the threat was spotted.

Fast forwarding to the present, the parachute has become an essential tool for most modern armies. Parachutes enable the rapid delivery of large numbers of soldiers, equipment, and supplies into a warzone, and they facilitate the silent, nighttime arrival of small groups of special operations forces directly into the backyard of an enemy. But with all the advances to the science of parachute design and utilization, the activity, by its very nature, remains highly dangerous given the large number of variables and potential fault points. Those whose profession makes regular use of parachutes are in a constant search for new technologies and methodologies that can help mitigate risk.

One of those advances is the PARASIM Virtual Reality Parachute Simulator shown in Figure 17.5, from Systems Technology, Inc. of Hawthorne, California. Initially developed for the U.S. Forest Service to help train smokejumpers (wilderness firefighters) in identifying emergencies in their chutes, the system has gone on to become a vital training tool for all branches of the U.S. military, Special Operations Command, USDA Forest Service, the Bureau of Land Management, and similar organizations worldwide.

The PARASIM system is available in multiple configurations with the selection based on end user needs. For instance, in premeditated static-line and freefall operations, jumpers exit an aircraft and either immediately assume a horizontal orientation until a chute is deployed, or in the case of a static line jump, are relatively quickly moved into a vertical orientation. To support training for these operations, one version of the product includes powered winches, which will automatically transition a user from a horizontal to a vertical orientation once a virtual chute is deployed within a simulation.

Figure 17.5 The PARASIM Virtual Reality Parachute Simulator is used by all branches of the U.S. military as well as other departments and agencies to train personnel in critical airborne operations.
Credit: Image courtesy of Systems Technology, Inc

Another version of the product is specifically designed to facilitate training in aircrew emergency ejections and bailouts. In most real-world training scenarios, these situations result in immediate canopy deployment, thus eliminating the need for extra rigging in the simulator.

As shown in Figure 17.6, the general configuration of both versions of the system include a stereoscopic head-mounted display (a variable component based on customer specifications), IMU sensors to track orientation of the user's head, and control lines/steering toggles. In the version of the simulator used for premeditated jumps and delayed openings, a Microsoft Kinect sensor (see Chapter 11, "Sensors for Tracking Position, Orientation, and Motion") is used to track hand and arm motions to enable control of the fall through virtual space, just as in an actual jump.

The real magic of this simulator is in the software. PARASIM is a high-fidelity, physics-based jump simulator that includes more than 50 different chute designs, the detailed performance characteristics for which are accurately reproduced within the simulations. This enables high precision training using any chute, under any atmospheric conditions. Designed for training both novice as well as experienced jumpers, the system allows for simulation of malfunctions and emergency procedures, canopy control, development of proper situational awareness, variable landing techniques, and more. The software suite also includes a variety of simulation environments based on real-world locations (STI, 2013a).

Another highly useful feature of PARASIM is the ability to network an unlimited number of systems. In such simulations, all jumpers can see representations of one another, providing an ideal means through which to plan and rehearse group operations.

Figure 17.6 The PARASIM Virtual Reality Parachute Simulator includes a stereoscopic wide field of view (FOV) head-mounted display and sensors to track the orientation of the user's head.
Credit: Image courtesy of DoD

As shown in Figure 17.7, a third variation on the system is available for training jump masters. Using the Fused Reality technology described in the previous section, the system is a mixed-reality application intended to develop and refine the skills necessary to oversee and manage a combat-equipped jump and can be used in combination with groups of PARASIM users (STI, 2013b).

Figure 17.7 The Jump Master variant for the PARASIM system is a mixed reality application enabling in-depth training of jump masters in the management and oversight of airborne operations.
Credit: Image courtesy of Systems Technology, Inc

Dismounted Soldier Situational Awareness

Historically, battlefields have been places of great confusion and uncertainty in situational awareness, making information one of the most valuable commodities to a soldier. Indeed, even the classic guide to combat strategy, Sun Tzu's *Art of War* written in the 6th century B.C., carries the underlying theme that victory on the battlefield comes from a commander's ability to acquire, control, and manipulate information. In modern terms, this means information about enemy location and force strength, information about your own squad members and their locations, as well as information from remote-sensing platforms such as UAVs and other aircraft and satellites. In an ideal situation, and one the armed forces of the United States have been working on for decades, every soldier would act as both a consumer and a producer of information as part of a larger network. Over the past several years, the foundational elements of such a system have begun being deployed.

Nett Warrior

Nett Warrior is an integrated dismounted soldier situational awareness system for use during U.S. Army combat operations. As shown in Figure 17.8, the current implementation of the system utilizes an Android-based smartphone-like handheld/chest-worn device that connects to the soldier's Rifleman Radio for the sharing of position information, text messages, photos, maps, and other data. This secure radio-based connectivity is referred to as the On-The-Move self-forming network.

Figure 17.8 This image shows U.S. Army soldiers using their Android-based Nett Warrior integrated and dismounted situational awareness and mission command systems.

Credit: Image courtesy of DoD

The next phase of the program under active development will add a head-mounted augmented reality display component to the system intended for both day and night tactical applications. This phase of the program is intended to provide networked heads-up situational awareness to further reduce fratricide, as well as increase lethality, survivability, and maneuverability.

An example of tactical information to be displayed within such a device is shown in Figure 17.9. The baseline software for the system, known as ARC4, was developed by Applied Research Associates of Albuquerque, New Mexico, during a six-year collaboration with the Defense Advanced Research Projects Agency (DARPA). The display-agnostic ARC4 software gives users accurate geo-registered icons overlaid on their real-world view. The precision placement of the iconic information will be enabled via a helmet-mounted head tracking/video processing unit. The military version of the interface is intended to provide a common operating picture (COP) for commanders and small-unit teams, including heads-up blue (friendly force) tracking, navigation, target handoff, and nonverbal, non-line-of-sight communication between a team leader and individual warfighters (Applied Research Associates, 2015).

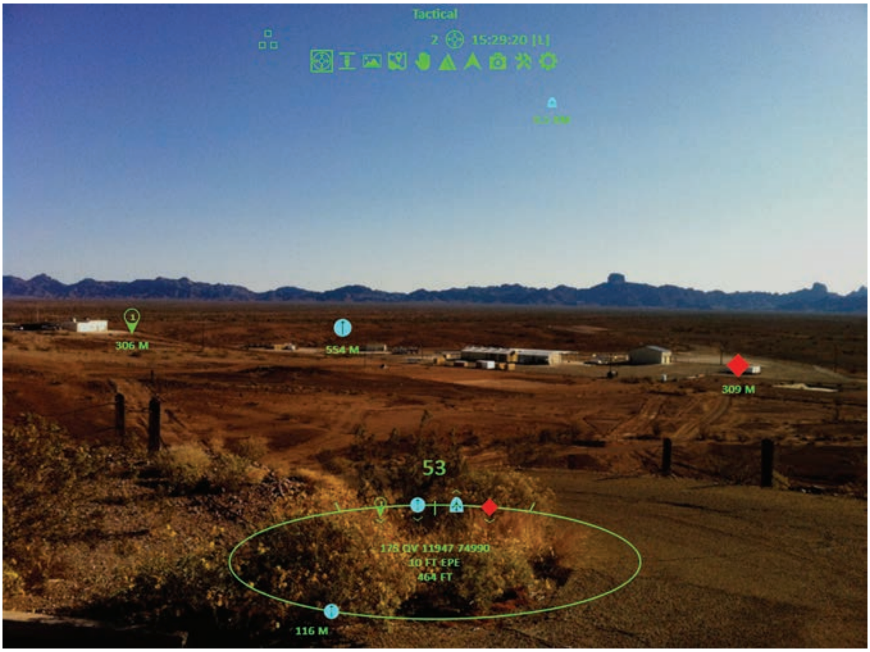

Figure 17.9 This image depicts an example of a dismounted soldier tactical information display enabled using the ARC4 augmented reality software solution developed by Applied Research Associates of Albuquerque, New Mexico.

Credit: Image courtesy of Applied Research Associates, Inc

Advanced Cockpit Avionics

Aircraft have evolved to become some of the most complex and consequential machines created by man. As their size and capability have steadily increased over the years, so too have the challenges involved in their safe operation and effective utilization. In the following sections we look at some of these challenges and the solutions found through the application of virtual and augmented reality-enabling technologies.

Military

The cockpit designs of military aircraft, and in particular fighter jets, have changed significantly over the past several decades. Previously, cockpits were filled with dozens of switches, buttons, and other manual controls, in addition to numerous highly coded dials and gauges providing information on aircraft systems, navigation, weapons status, sensors, and more. Often this information was presented in alphanumeric form (a combination of alphabetic and numeric characters), the totality of which was intended to communicate critical information and help a pilot form a mental image about what was happening outside of the aircraft. This complex mental processing task was over and above the actual job of operating the aircraft and solving problems related to the geometry of flight, aerial combat maneuvering, and tactical engagement. The great challenge with these early designs was that the pilot was forced to spend a significant amount of time with his attention focused inside the cockpit reading dials and gauges or interpreting grainy sensor images instead of looking outside the aircraft where targets and threats were located. The net result was a frequent sense of information overload, high stress, and a loss of situational awareness.

Movement to multifunction displays (small screens surrounded by buttons) within which this same information about aircraft systems, navigation, weapons status, sensors, and so on is logically organized into multiple pages, rather than everything always being visible, helped the information processing task immensely. Similarly, the widespread adoption of HUDs, or heads-up displays—a transparent screen, or combiner, typically mounted on the cockpit dash at eye level—and the conversion of some cockpit avionics information from letters and numbers to a symbolic representation further eased this burden. But here, the major limiting factor is that the pilot must be looking straight ahead to see this information.

At this point, the next logical step in cockpit design was the movement of the information display from the HUD unit to optical elements mounted within, or directly onto the visor of, the pilot's helmet. Such systems allow critical information to be displayed to a pilot regardless of where his head is pointing, further maximizing the amount of time a pilot spends looking outside of the aircraft instead of inside of the cockpit. In many regards, helmet-mounted displays can be considered the first widely deployed augmented reality systems.

To date, dozens of different helmet-mounted displays have been developed for fixed- and rotary-wing aircraft around the world, each of which has served at least one of the following purposes:

- Display targeting, navigation, and aircraft performance data to the pilot.
- Direct high off-boresight (HOBS) air-to-air and air-to-ground weapons.
- Slave onboard sensors such as radar and FLIR.
- Display sensor video.

Figure 17.10 shows two modern, currently deployed helmet-mounted displays in use within fixed- and rotary-wing aircraft.

Figure 17.10 This image shows two head-mounted displays currently in use within U.S military aircraft. On the left is the GENTEX Scorpion Helmet-Mounted Cueing System in use within the A-10 Thunderbolt and the Air National Guard/Air Force Reserve F-16 Block 30/32 Viper aircraft. On the right is the Thales TopOwl Helmet-Mounted Sight and Display that is operational in five major helicopter programs across 16 countries, including the Cobra AH-1Z and Huey UH-1Y.

Credit: Photos courtesy of Thales—a global technology leader for aerospace, transport, defense and security markets. www.thalesgroup.com

It is important to point out that within this application setting, extremely wide FOV displays are actually considered a hindrance and potentially dangerous. The goal is to provide the pilot with essential information from airborne weapons and sensor targeting suites without cluttering the visual field, which could have disastrous consequences.

F-35 Joint Strike Fighter Helmet-Mounted Display System

The most advanced helmet-mounted display system (HMDS) currently in use and representative of the absolute state-of-the-art in capabilities is that which is deployed with the Lockheed Martin F-35 Lightning II Joint Strike Fighter.

Built into the lightweight helmet shown in Figure 17.11 is a 30° × 40° binocular FOV, high-brightness, high-resolution display with integrated digital night vision. A fully integrated day and night flight weapons and sensor data visualization solution, pilots in aircraft equipped with the system have immense capabilities, not the least of which is to aim weapons simply by looking at a target. For night missions, in addition to the cueing of sensors and weapons, the system projects the night vision scene directly onto the interior of the visor, eliminating the need for separate night-vision goggles.

Figure 17.11 This image shows an oblique view of the F-35A Lightning II helmet-mounted display, which provides pilots unparalleled situational awareness, with real-time imagery from six sensor packages mounted around the exterior of the aircraft.
Credit: Image courtesy of DoD

One of the most innovative features of this system is the ability to display a spherical 360° degree view of the world outside of the cockpit as if the airframe were not present, including below and to the sides of the aircraft. Sometimes referred to as a "glass cockpit," this capability is enabled via an electro-optical Distributed Aperture System, which consists of six high-resolution infrared sensors mounted around the F-35 airframe. The overlapping FOV of the six sensors are blended to provide unobstructed spherical (4π steradian) imagery as well as missile and aircraft detection and countermeasure cueing. Figure 17.12 provides an example of the view a pilot would receive within the HMD by combining the infrared scene along with avionics and sensor data.

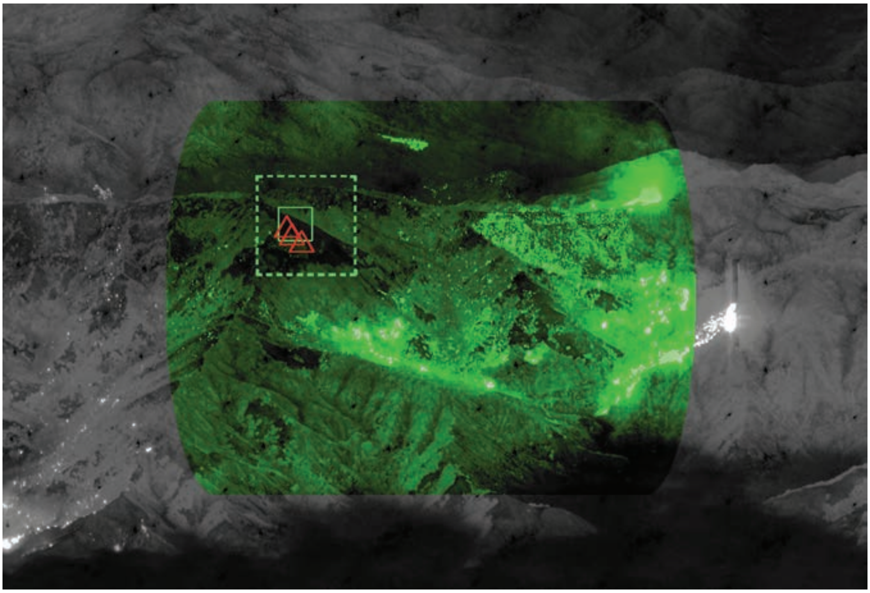

Figure 17.12 The F-35's Distributed Aperture System (DAS) fuses real-time imagery from externally mounted sensors with data provided by onboard avionics systems.

Credit: Image courtesy of S. Aukstakalnis

Commercial Aviation

Pilots within the commercial aviation sector face many of the same information availability and cognitive processing challenges as their military counterparts, but without the added burden of combat maneuvering, weapons targeting and deployment, and so on. In particular, challenges for the commercial aviation sector come in the form of takeoffs and landings in low-visibility conditions such as heavy fog and storms, to potential runway incursions when taxiing under the same conditions. These problems are obviously not new, and although aircraft manufacturers and avionics suppliers have integrated heads-up display technologies into a variety of aircraft, the challenge of the pilot only being able to see the information while facing forward remains. As such, several manufacturers are now introducing head-mounted displays for commercial aircraft as an option to their cockpit avionics suites. One such company is Elbit Systems, Ltd of Haifa, Israel.

Skylens Display

Skylens is the wearable display component of the Elbit Clearvision Enhanced Flight Vision System (EFVS). Clearvision uses multispectral sensors mounted outside of the aircraft to capture terrain and airport lights in darkness and reduced visibility. This data is fused with topology from a global terrain database as well as conformal flight guidance symbology and, typically, projected onto a fold-down HUD providing a high-fidelity view of the outside world even when actual visibility is limited or zero.

The Skylens component provides the pilot with the same information that would normally be displayed in the HUD, but in a head-mounted device. By tracking the pilot's head movements, critical information and symbology can be stabilized and correlated to the real world as the pilot scans the scene, improving the operator's ability to execute precision and nonprecision approaches and reducing the risks of Controlled Flight into Terrain (CFIT) accidents.

The Skylens system itself is a monocular, off-the-visor display, the image source for which is a 1280 × 1024 monochromatic (green) microdisplay with an effective area of 1024 × 1024 in a circular area. The system uses triple redundant optical sensors for head tracking.

Civilian

The general aviation sector also faces the same information availability and mental processing challenges as their commercial and military counterparts. Although cockpit avionics in general aviation aircraft have made significant advances over the past decade in enabling the visualization of terrain, navigational aids, hazards, weather, and traffic awareness information on state-of-the-art multifunction displays, here again, accessing the information still requires the pilot to focus attention inside of the cockpit and off the skies. Further, current display technologies still require pilots to mentally convert this complex assortment of 2D information into a 3D mental image of the environment surrounding the aircraft, dramatically increasing the workload and stress levels.

But unlike the military and commercial sectors, general aviation enthusiasts have, until recently, not had viable (or affordable) solutions on the horizon. Fortunately, the confluence of advances in augmented reality software and display hardware, as well as seemingly unrelated initiatives with U.S. and international aviation authorities, is resulting in the development of some amazing alternative information display possibilities for general aviation participants.

In a nutshell, if you want to operate an aircraft in designated U.S. airspaces (Class A, B, C, and parts of D and E) after January 1st, 2020, federal regulations require that your aircraft be equipped with what is known as an ADS-B (Automatic Dependent Surveillance-Broadcast) transponder. This small piece of electronics gear, simply referred to as ADS-B OUT, transmits information about your plane's altitude, airspeed, and GPS-derived location to ground stations, as well as to other aircraft in your vicinity equipped with ADS-B IN receivers. Air traffic controllers and properly equipped aircraft use this information to "see" participating aircraft in real time, with the ultimate goal of improving air traffic management and safety. Typically, the ADS data is shown on a 2D multifunction display within the cockpit.

Aero Glass

Aero Glass, Inc. of San Diego, California, and Budapest, Hungary, is one of several companies developing a means through which to display ADS-B and other instrument data within augmenting head-mounted displays such as the Epson Moverio and Osterhut Design Group (ODG) R-7 (both of which are detailed in Chapter 5, "Augmenting Displays").

As shown in Figure 17.13, the visual effect is the overlay of this information in graphics and symbolic form onto the user's real-world view regardless of the position and orientation of the pilot's head or the aircraft.

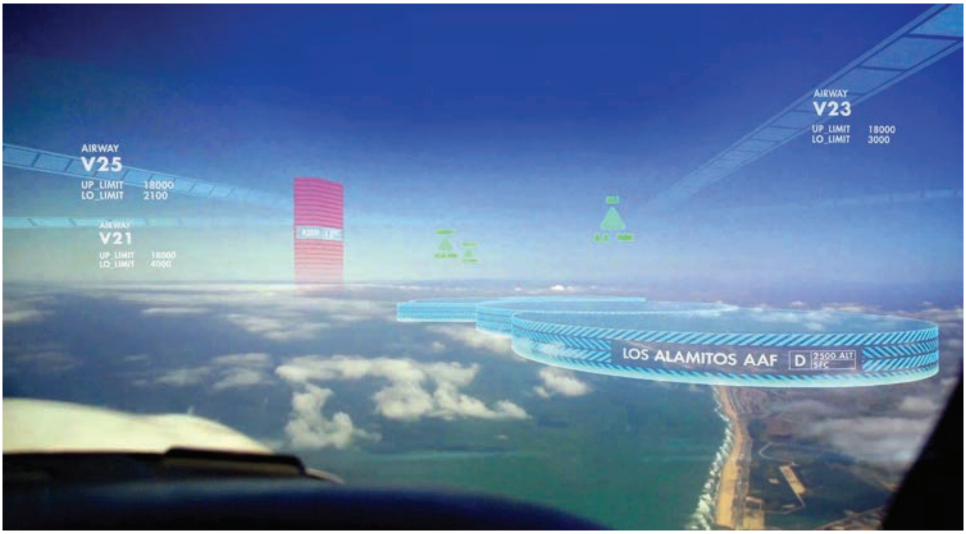

Figure 17.13 This image depicts a sample of the aeronautical information that can be displayed using Aero Glass software, an augmented reality head-mounted display and sensor to track position and orientation of the pilot's head.
Credit: Image courtesy of Aero Glass Corporation

As depicted in this image, several of the raw data types shown that would normally be represented in 2D on a multifunction display or map/chart in the pilot's lap actually represent static as well as time-varying 3D phenomena, such as controlled or restricted *volumes* of airspace, multiple airways, and the position and movement of nearby aircraft. By displaying information in a manner that depicts the actual spatial characteristics of the data, as well as its precise position, the pilot is given a greatly increased level of situational awareness and visual understanding about the real environment through which one is flying.

The Aero Glass system consists of a software suite that combines ADS-B and other avionics data, information from sensors measuring the pilot's head position and orientation, and the actual display device.

Space Operations

Some of the most advanced virtual and augmented reality systems and applications found anywhere in the world are located in NASA laboratories spread across the United States in support of manned and unmanned space operations. Significant time, effort, and expense have been put toward developing a host of facilities and tools that are now used to train every U.S. astronaut who travels to space. Most of that training takes place in the Virtual Reality Laboratory (VRL) at NASA's Johnson Space Center in Houston, Texas, a snapshot from which is shown in Figure 17.14.

Figure 17.14 This image shows NASA astronaut Michael Fincke using virtual reality hardware in the Space Vehicle Mock-up Facility at NASA's Johnson Space Center.
Credit: Image courtesy of NASA

In addition to years of traditional training and preparation, NASA makes extensive use of immersive virtual reality systems and related technologies to train the astronauts in four primary areas:

- **Extra-Vehicular Activity** (**EVA**) **Training**, which prepares the astronauts for space walks and the tasks they will be performing while outside of the International Space Station (ISS).
- **Simplified Aid for EVA Rescue** (**SAFER**) **Training**, which teaches the astronauts how to use a small, self-contained propulsive backpack system worn during spacewalks. In the event that an astronaut becomes detached from the ISS or a spacecraft and floats out of reach, SAFER provides a means of self rescue.
- **Robotics Operations**, which teaches astronauts the use of robotic systems such as the Canadarm2.
- **Zero-G Mass Handling**, which simulates zero-g mass characteristics of objects in a microgravity environment. (Remember that while objects in space may be *weightless*, an object's *mass* still presents formidable handling and maneuvering challenges if large enough.)

Project Sidekick

Despite upward of two years of training astronauts undergo prior to space travel, it is impossible to carry out missions without extensive assistance from team members and subject matter experts on the ground. From solving engineering problems to proper operation of onboard experiments, significant effort is put into assisting astronauts in being able to safely and effectively carry out their mission objectives. To this end, NASA is constantly investigating methods with which to render this support beyond standard radio, video, and textual communications. One such investigation underway at the time this book was written is known as Project Sidekick.

Leveraging advances in augmenting display technologies such as those provided by Microsoft's HoloLens (see Chapter 5), the goal of this project is to explore the use of an immersive procedural reference (that is, a manual or guidebook) and remote assistance system developed to provide the crew information and task support whenever it is needed. Based on the concept of a mixed reality setting (combining the physical environment and virtual objects), high-definition holograms displayed within the HoloLens device can be integrated into the astronaut's real-world view within the Space Station, enabling new ways to access and exchange key information and guidance between personnel on orbit and individuals on the ground. Figure 17.15 shows the HoloLens device in pre-deployment testing.

Figure 17.15 This image shows NASA and Microsoft engineers testing Project Sidekick on NASA's Weightless Wonder C9 jet. Project Sidekick will use Microsoft HoloLens to provide virtual aid and ground-based assistance to astronauts working on the International Space Station.
Credit: Image courtesy of NASA

At the time of this writing, the Sidekick system had two basic operating modes: Standalone (a procedural reference system) and Remote Expert:

- **Standalone Mode** gives the astronaut access to an extensive preloaded manual with instructions, procedures, and checklists displayed as holograms that can be placed anywhere the astronaut finds it most convenient.
- **Remote Expert Mode** is a video teleconference capability enabling real-time first person assistance with ground personnel. In operation, the crew member opens a holographic video screen where he can see the flight control team, system expert, or payload developer. Using the HoloLens' built-in camera, the ground crew is able to see the astronaut's work area and offer direct assistance in support of the task objectives.

The Sidekick project is only one of multiple applications for the HoloLens and other head-mounted augmenting displays within various manned and unmanned space programs. Another project referred to as OnSight currently places Earth-based scientists and engineers within a virtual re-creation of the operational environment of the Curiosity Rover on Mars. Using data sent back from the rover, 3D models are generated and displayed within the HoloLens device, enabling scientists to freely explore the area from a first-person perspective, plan new rover operations, and preview the results of past system tasking.

Conclusion

This chapter has only lightly touched on the large number of solid, existing applications for virtual and augmented reality technologies within the aerospace and defense sectors. This advance stage of adoption and utilization in comparison to other areas is due to a variety of reasons, including well-defined, mission-critical needs (which ultimately drives a focused development agenda), budgets that support intensive multiyear research, development and problem-solving efforts, as well as the technology showing demonstrable results.

To this end, it is impossible to quantify the immense breadth and depth of the contributions of the Department of Defense and NASA to the current state of the art in virtual and augmented reality systems. From the start of their separate research and development efforts with these technologies in the 1960s and 1980s respectively and continuing to the present, their support of small businesses and university researchers in this field through product acquisition and grants, collaboration, and the sharing of subject matter knowledge and experts has been, and continues to be, absolutely vital to the field's development. Some of the areas where their contributions are most notable include sensor technologies, user interface design, binaural audio, optical systems, and core research on human perception and performance.

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