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Designers, researchers, and developers are already using virtual environments in many ways and in many domains. The technology has matured enough so that now VEs are beginning to be used to certify the systems they simulate.

Using Immersive Virtual Environments for Certification

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D uring the last few years immersive virtual environment technology has matured to the point where industry researchers have begun using it for the design and evaluation of new systems. Immersive virtual environments have already been applied to a wide variety of domains, including automobile design, flight simulation, emergency rescue, and remote surgical training.

As VEs move from research laboratories to commercial use, there is a need to define the appropriate role of VEs in certifying the systems they simulate. In this article we describe the unique features of this developing technology, as well some key issues to consider when using VEs for certification.

VEs defined

A virtual environment is a computer-generated environment that creates an immersive, multi-sensory, viewer-centered interactive experience.[1] VEs integrate users with the virtual world by drawing on advanced human–computer interfaces, such as visual displays, tracking systems, and specialized input and output devices.

VE technology places operators within a three-dimensional world, providing a natural way to interact with a simulated reality built from the user's data. The data can be anything represented in a computer: an architectural environment, a model of a human heart, the result of an airflow simulation, an engineering design, an artistic environment, a geographical region, or even an imaginary world. Users can interact with these environments in a number of ways, including manipulating virtual objects, approaching interesting features for closer inspection, or flying over scenes for a bird's-eye view.

Historically, VEs have relied on head-mounted displays.[2] However, today's VEs use a variety of displays, ranging from enhanced desktop systems to surround-screen systems. Iowa State University has developed a surround-screen system called the C2 (see Figure 1). Much like the CAVE virtual reality system, the C2 is a 12′×9′×12′ room where three of the walls and the floor are projection screens.[3] The system projects stereoscopic computer images on the walls based on the position and orientation of the main user's head. Interaction devices, such as data gloves, wands, and control panels, enable users to interact with and manipulate virtual objects and their properties. A localized sound system provides 3D audio capabilities.

One advantage of surround-screen systems is that they allow multiple users to simultaneously share the virtual experience. One user controls the view and interaction, while the others look on passively. Surround-screen systems also allow researchers to incorporate and blend real objects into the virtual environment (see Figure 2).

VEs in the Real World

Recent uses of VEs indicate the range of possibilities and some of the challenges involved in using VEs for certification. Certification is a process whereby a certification authority determines if an applicant provides sufficient evidence concerning the means
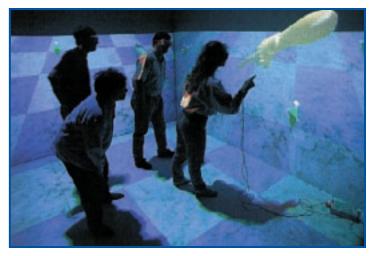

Figure 1. C2 surround-screen virtual reality display.

Figure 2. Real and virtual objects blended in the C2.

of production of a candidate product and the characteristics of the candidate product so that the requirements of the certifying authority are fulfilled.[4,5]

Certification and VEs for safety-critical systems can be examined at two levels. First, immersive environments require certification as a design tool acceptable in the development of critical systems. This involves demonstrating that the VE can simulate the system's domain-specific features and constraints. For example, a VE for vehicle dynamics simulation needs to be validated to ensure the calculations yield appropriate vehicle behavior.[6] In this regard, VE certification can be guided by the tool qualification and certification processes applied to other design tools for critical applications.[7,8]

The second and more intriguing use of VEs is in certifying systems with embedded software. In much the same way that researchers have used piloted simulation to certify aircraft systems, VEs are

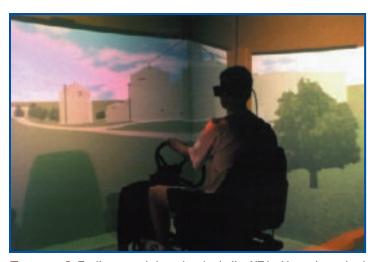**FIGURE 3.** A VE being used to test the safety of a new car design.

FIGURE 4. Testing a prototype tractor in the VE led to an important design change.

beginning to be used in areas such as virtual training and operator qualification.[9]

Figure 3 shows a VE being used to test critical new vehicle features. One important use of VEs is that they can reduce the need to expose users to dangerous environments. For example, one application used a VE to train firefighters for shipboard fires.[10] VEs can also function as cost-saving design tools. The automobile manufacturer BMW, for example, has used VEs extensively to test system behavior of automobiles during crashes. To reduce the costs associated with using dummies and real cars, BMW recently carried out 91 virtual crashes and only two physical crashes while testing a new model.[11]

Researchers at Iowa State University and Deere & Co. used a VE to assist with the design of a new tractor model (see Figure 4). When testing the prototype in the VE, the users noticed that one of the head lamps interfered with the driver's line of sight. Unobstructed driver visibility both in front of and behind the tractor is an essential performance feature. This user feedback led to a change in the design that was then successfully tested in the VE.

The aeronautics industry has used VEs to design and evaluate new panel displays in airplane cockpits. Currently, engineers build physical prototype cockpits when testing different designs; this costly requirement limits the number of designs that can be tested, since each prototype increases overall development costs. Thus, in addition to reducing the time and cost of prototype evaluation, VEs give engineers the flexibility to create and test a greater variety of designs under different conditions, including emergency situations.

VEs have also been used to validate network protocols. Today's networks are becoming more and more complex. Complicated algorithms control network traffic through available routers to ensure proper packet delivery. Developers have used VEs to play "what if" scenarios—to evaluate network behavior by disabling some of the routers, overloading network traffic, opening and closing routes, and changing other parameters. Given that networks support today's information infrastructure, including air traffic controllers, manufacturing processes, and a variety of other mission-critical applications, network fault tolerance has become a critical public-safety issue.

As the preceding examples suggest, researchers can use VEs to gather a wide variety of domain-specific information. Even given the diversity of potential applications, VEs can provide data in several, generally applicable ways:

♦ helping to narrow the range of tests required on an actual system for certification,
♦ demonstrating a system's compliance with some safety requirements,
♦ demonstrating that a system responds properly in preventing or controlling hazards, and
♦ helping to certify the limits of safe operation.

Yet despite the increasing maturity of VEs, technological limitations continue to prevent these environments from providing an exact match with the physical characteristics of the real world. The discrepancies between the two worlds can have significant effects upon human perception and performance during an immersive experience.[12] These effects, which can detract from the usefulness of VEs as a certification tool, can range from eye strain, dizziness, and nausea to more severe conditions such as disorientation, loss of balance, and loss of consciousness.

Here is a case in point. Disney conducted a safety study on DisneyQuest, the first virtual reality amusement park, before opening it to the public. Disney's developers collected data from over 45,000 subjects on the physical effects of an entertainment ride that uses a head-mounted display. The goal of this ride is to fly a magic carpet in the context of the animated Disney film, *Aladdin*. One safety-related finding was that most users had difficulty driving the magic carpet. The developers discovered that the users had too many degrees of freedom in the carpet control software, thus making it hard to maintain the navigational direction and orientation.[13] In these circumstances, users could feel like they were upside-down, backwards, or sideways. This could cause such psychophysical effects as dizziness, nausea, or fainting.

VE Requirements

To determine whether a VE will meet your certification needs, you should consider such factors as

♦ the kind of application you are testing (for example, safety-critical, data exploration, or entertainment);

♦ the participants' experience level (since an experienced user will have a different learning curve from a novice);

♦ the level of immersion that the VE provides, which is determined by the system's visual display;

♦ the length of time the user will spend in the VE;

♦ the system's interaction devices;

♦ the range of tolerance levels for system latencies, noise, and other technology dependent factors;

♦ the independent authority that has evaluated the VE.

In order to use a VE to certify a system, you must first validate that the VE accurately represents the real world that it is modeling. For example, if the model specifies that turning the vehicle's wheel clockwise will cause a certain shift in what the driver sees, then the VE user must experience the same shift. Developers validate the VE through model analysis and testing. Neil Storey identified four key considerations for measuring the quality of simulators that offer useful guidelines for VE model analysis:[14]

♦ Identify which environmental variables the system must include and which it can ignore.

♦ Confirm the accuracy of the representation of environmental factors.

♦ Confirm the accuracy and resolution of the system's calculations for each environmental variable.

♦ Confirm the adequacy of the timing considerations.

Developers will need to test the accuracy of the VE solution against the real-world prototype's performance. Test cases can be used to separate the effects of the VE, such as delays, from the effects of the system being studied. In the aerospace industry, for example, researchers often compare the pilots' performance in a simulated craft with their performance in the actual system being developed.[9]

Similarly, when measuring the fidelity of human factors in VEs, developers need to specify criteria regarding the user's tolerance limits to technological flaws, such as system latencies, response lags, and device calibration. Beyond this, tests also validate the users' performance in the VE against their performance in the actual systems to be certified. In these tests, developers compare the users' interactions with the VE—such as applying a brake—and the users' re-

> **Virtual environments can reduce the need to expose users to dangerous environments.**

sponses to sensory cues—for example, visual and auditory input—to the designers' expectations.

The VE developers must also ensure that the system's design model specifies enough information to verify that the as-built system complies with established safety requirements.[15] In cases where the VE interfaces with actual hardware or software from the system being tested, certification must include evidence that the VE configuration is using the same versions of the hardware and software that will be used in the actual system.

Although certification requires the validation of VE results by tests on the actual system, VEs can significantly narrow the range of tests required for system certification. For example, in complex systems there are often many failure modes. VE tests on a system can demonstrate to certification authorities how a system responds to a wide range of failure modes. The VE can also provide data that is useful in analyzing the effects of these failures and the likelihood of their occurrence. With this information, the system developers can choose to reproduce the most likely or most severe failure modes on the actual system.

Finally, users must also ensure that their VE meets the certification requirements of the system's particular industry and country, which may vary greatly. For example, in the US, the process of using a VE to

certify a flight display will follow FAA rules, and the process of using a VE to certify a medical application will follow FDA rules.

Among the advantages of using VEs for certification are the possibility of more complete testing and their dual-use as design tools and as certification tools. These factors will contribute to increased use of VEs in the certification of safety-critical systems, especially in analyses of system responses to failure conditions and in testing of hazardous physical conditions.

Yet a great deal of work lies ahead before VEs become commonplace design, test, and simulation tools in industry. VEs must mature further and develop a more extensive history of successful applications before most users will feel confident using them.

VE developers must also begin establishing benchmarks and test case suites so that researchers can compare results among different VEs. Developers need to determine how best to measure the subjective experiences of VE participants, and how to separate the effects of VEs from the effects of the systems being tested. ❖

ACKNOWLEDGMENTS

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