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**THE MATRIX REVISITED: A CRITICAL ASSESSMENT OF VIRTUAL REALITY
TECHNOLOGIES FOR MODELING, SIMULATION, AND TRAINING**

by

George Demetrius Lecakes, Jr.

A Dissertation

Submitted to the
Department of Electrical and Computer Engineering
Henry M. Rowan College of Engineering
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Dedication

I would like to dedicate this dissertation to my two sons, Georgie and Arthur.

Acknowledgements

The material within this dissertation took the better part of twenty years to complete, and there were many who helped along the way.

First, I would like to acknowledge my advisor, Dr. Shreekanth Mandayam for providing me countless opportunities to explore and grow since 2003 when he accepted a civil engineer into his laboratory. Both he and Dr. John Schmalzel put me on the path of my Master's research through the NASA Graduate Student Research Program (GSRP).

I would like to thank the countless members of the Rowan VR Laboratory, including my peers who developed VR applications with me, or students whom I advised during various projects.

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Finally, I am grateful for my wife of ten years, Jennifer Marie Curtis, without whom I would not be here today.

Abstract

George Demetrius Lecakes, Jr.

THE MATRIX REVISITED: A CRITICAL ASSESSMENT OF VIRTUAL REALITY
TECHNOLOGIES FOR MODELING, SIMULATION AND TRAINING

2020-2021

Shreekanth Mandayam, Ph.D.

Doctor of Philosophy

A convergence of affordable hardware, current events, and decades of research have advanced virtual reality (VR) from the research lab into the commercial marketplace. Since its inception in the 1960s, and over the next three decades, the technology was portrayed as a rarely used, high-end novelty for special applications. Despite the high cost, applications have expanded into defense, education, manufacturing, and medicine. The promise of VR for entertainment arose in the early 1990's and by 2016 several consumer VR platforms were released. With VR now accessible in the home and the isolationist lifestyle adopted due to the COVID-19 global pandemic, VR is now viewed as a potential tool to enhance remote education.

Drawing upon over 17 years of experience across numerous VR applications, this dissertation examines the optimal use of VR technologies in the areas of visualization, simulation, training, education, art, and entertainment. It will be demonstrated that VR is well suited for education and training applications, with modest advantages in simulation. Using this context, the case is made that VR can play a pivotal role in the future of education and training in a globally connected world.

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Chapter 1

Introduction

In the 1999 Hollywood blockbuster, *The Matrix*, the protagonist Neo, played by Keanu Reeves, realizes along with the audience that the world he inhabits, his entire life and the lives of everyone he has ever known is one of pure imagination, a simulation and not real. Less than three years later the box office hit, *Minority Report*, would portray law enforcement comfortably merging the world of imagination with reality in pursuit of justice – the first popularized instance of augmented reality (AR) in Hollywood. Ten years earlier, an aspiring PhD student at the University of Illinois in Chicago's Electronic Visualization Laboratory, had invented a walk-in audio-visual virtual reality (VR) experience, which she recursively named the CAVE® - CAVE Automatic Virtual Environment.

1.1 Virtual Reality Emerging

Robinson Crusoe, a book first published in 1719 and regarded as establishing the realistic fiction genre, represented one of the first alternate realities experiences. Transporting the reader into the eyes of the titular protagonist during his 28 years as a castaway on a tropical island [1] [2]. Public art exhibits with murals painted in 360 degrees on the walls depicted far off locales and would slowly rotate to create the sensation of motion [3]. Written words and flat images were surpassed with seemingly 3D imagery would appear from a set of images when using a binocular vision system built by an optician in 1832 [4]. The optician was tasked with the creation of a stereoscope that, when viewed with both eyes, allowed the wearer to feel the sensation of

depth from two side-by-side pictures. The stereoscope capitalized on binocular depth cues; a function of the human brain capable of determining depth from the amount of horizontal separation between two images referred to as parallax [5]. The device had a wooden divider running down the length acting as a separation between the set of images, which isolated what the wearer could see with each eye. In 1902, motion pictures captivated audiences by uniting recorded imagery with camera trickery to transport viewers to exotic locations as depicted in *A Trip to the Moon* [6]. *The Power of Love*, released in 1922 was the first confirmed film to utilize stereo imagery [7]. Unlike the stereoscope, which could only be viewed by one person at a time, 3D film utilized one or more projectors with separate film for the left and right eye. Some of the earliest 3D films used a process referred to as anaglyph where the left and right images were displayed using differing colors such as red and green or red and blue. The audience wore a pair of glasses that filtered based on the color of the film, blocking imagery that was not intended for that eye [7]. This technique worked well for black-and-white films where color was not recorded or displayed. Anaglyph was also utilized to allow the audience to decide their preferred outcome for the end of the movie by watching with one eye closed. Depending on the viewer's choice of left or right, they would see a happy or tragic conclusion, a limited but early form of audience participation [8]. In 1927, the first feature films emerged and were labeled "talkies." They incorporated the sense of hearing that was only commercially possible due to advancements in sound amplification and film synchronization [9]. Throughout the history of VR, development lulls would occur until new technologies were available that were capable of incorporating new senses and methods of interaction. Aldous Huxley imagined the future of sensory input in *Brave*

New World. He envisioned a future media referred to as “feelies,” movies capable of incorporating the sense of touch, down to the individual hairs on a bear-skinned rug [10].

While the term virtual reality may not have yet existed, it did not prevent researchers from engaging in thought experiments concerning the seemingly inevitable blending of human and machine. The term cybernetics was first described in 1948 by Norbert Wiener as “the scientific study of control and communication in the animal and the machine [11].” Rather than look at the user and machine as separate entities, Wiener saw communication as both physical and digital, existing in both the virtual and reality. A rift in the field, possibly due to dissatisfied colleagues, caused the term artificial intelligence (AI) to overtake cybernetics in the hard sciences [12]. Researchers under the umbrella of AI secured most of the national funding. Afterward, cybernetics was rebranded as belonging to social sciences and therapy [13].

In the early 1950’s, an inventor named Morton Heilig began to piece together an idea that would later give birth to the Sensorama. Heilig saw dozens of studios releasing self-proclaimed revolutionary technologies such as Cinerama, Cinemascope and Stereophonic Sound. He saw these are only the first step in the theater of the future [14]. In 1955, Heilig wrote that the future of cinema would engage all the senses, moving from a visual artform to an art of consciousness, providing the sensation of being physically present in the movie. In 1962, the first Sensorama prototype was created, attempting to unify visual, auditory, tactile, and olfactory senses in one experience [15] [2]. The device looked similar to an arcade machine but with a segment in the center to sit upon. The viewer sat on the device and leaned their face into an opening that isolated them from the

real world. Five short films were created that used color stereo film, audio, simulated wind, a vibrating seat with handlebars, and a selection of aromatics. Scenes included a ride through Brooklyn, driving over the sand dunes in California, and a motorcycle ride through New York and ended with a belly-dance show complete with the smell of perfume [16] [2].

Improvements in cinema were focused on incorporating additional senses. However, there were technological limitations that prevented further progress. One fundamental flaw in these systems was that they were all passive experiences with no input from the viewer. The Sensorama, even with all its complexity, was a purely analog system that only provided the user with one choice, what video to watch next. After making their decision, the viewer was stuck on a prerecorded path, referred to as being on-rails. To reach new heights, artists of cinema had to give up absolute control of the medium [14]. The viewer would have to become a participant in the experience. Ivan E. Sutherland proposed the ultimate display in 1965, which would not only override all the user's senses, but do so through an immersive computer simulation that would monitor the user's actions and create a feedback loop allowing for real-time interaction [17].

1.2 Virtual Reality Realized

It would not be until 1968 with the creation of the Sword of Damocles that the transition from passive viewer to active participant would occur [18]. The device's ominous name refers to a Roman parable of a court flatterer who spoke of the amazing feast spread before a king. The king told the person to sit at his table and eat while a sword was suspended overhead to demonstrate that the responsibilities of ruling eclipsed

any form of enjoyment. The name of the device did not refer to the display, but the mechanical tracking systems suspended above the wearer [19]. The large and heavy tracking system determined the position and orientation of the wearer's head, and while imposing, allowed for an interactive wireframe overlay to be superimposed over the real environment. The Sword of Damocles is often credited as the first augmented reality (AR) device. Luckily, the Sword of Damocles would never live up to its name, however, another similar head-mounted device (HMD) in the 1970s took a life when an unfortunate accident occurred during a military training exercise [20].

A concise and universally accepted term still did not exist for this developing technology. The closest was artificial reality, popularized in the mid-1970's by M.W. Kreuger, who created some of the earliest artforms that combined real-time participant interactivity with surreal imagery [21]. His work generated several walk-in experiences where user interaction would produce colored tubes of light, interactive mazes. In 1984, the term "cyberspace" was invented within the science fiction novel *Neuromancer*. It would come to mean a single shared virtual existence that thousands participated within at the same time [22].

Lanier in 1984 coined (or popularized) the term virtual reality. He started a company that produced some of the first commercial and affordable VR gloves [20]. The gloves utilized haptics, the stimulation of senses for touch and motion. A series of sensors captured joint orientations for use in the VR environment. Development of touch and haptic-based interaction dominated virtual reality research during this decade. Lanier

later served as a VR consultant for *Minority Report*, providing suggestions as to how humans would effortlessly interact with computers through gesture and finger tracking.

VR systems up until the late 1980s classified displays as being either cathode ray tube (CRT), head-mounted display, or binocular omni-oriented monitor (BOOM) [23]. A fourth display system was showcased at SIGGRAPH in 1992 called the CAVE®. It was described as “a room whose walls, ceiling and floor surround a viewer with projected images.” The name is a recursive acronym, CAVE Automatic Virtual Environment, and is commonly associated with the allegory of Plato’s *Cave*. Plato described a scene where prisoners were chained inside a cave with a bonfire at their backs. They were positioned facing away from the fire, only able to see the shadowy images produced on the wall. The dark and distorted shadows become their entire reality [24]. CAVEs would provide small audiences a non-intrusive, walk-in experience compared to OMNIMAX theaters and early flight simulators [23]. The original CAVE system utilized projector screens oriented on the sides of a cube to create a complete 360-degree field-of-view. Users wore a pair of stereo shutter glasses, which used liquid crystal lens that fluctuated between opaque and transparent. CAVEs excelled at reducing the intrusive nature of HMD and binocular displays. CAVEs allowed for multiple users to experience the same virtual environment while communicating naturally with their bodies, with no need for virtual avatars.

1.3 Virtual Reality for Researchers

Up until the early 1990s, VR was only accessible to researchers. This was partly due to the high costs of the hardware, exceeding hundreds of thousands of dollars per unit and requiring significant technical knowledge to integrate and operate successfully [25].

Nearly 75% of the 50 million spent on non-military VR went to research and development [26]. Considerable effort was focused on incorporating touch through haptic gloves and interactive tactile objects [27]. AT&T sought to use force feedback as a way to enhance voice telecommunications. Bell Labs considered methods for applying simulated pressure to the palm of a physician's hand for surgical practice. The first signs of VR as a commercial product available to the public began to appear through video game consoles such as Atari, Nintendo, and Sega and even the personal computer [28]. Atari utilized force feedback in the game *Hard Drivin'*, using a steering wheel that vibrated. Sega promoted an extension to the Sega Genesis home console that, had it been conceived, would have provided total immersion and 3-D stereoscopic vision [26]. LucasArts Entertainment co-developed a VR system based on the technology used in flight simulators as an attempt to transition the technology into the commercial market after Department of Defense (DOD) budget cuts [29]. At mall kiosks and back-corners of bars, fly-by-night VR pods were deployed, charging five dollars for a five-minute experience [26]. Spectators could watch external monitors that displayed the virtual environment their friends were experiencing behind HMDs [25]. The media began to take notice, and both researchers and entrepreneurs claimed that anywhere between tomorrow and five years, VR would be out of the laboratories and in our homes [26] [30]. Prudent researchers in the field answered back, stating technological gaps between the VR systems used by researchers and what was commercially feasible in 1994 were too large to provide realism [31]. At the time, the best HMDs used by the military cost nearly one-million dollars per device and had the resolution of a desktop computer, or roughly 640 pixels wide by 480 high. A study of the scientists behind VR research stated that

objectivity had been abandoned when it came to the present capabilities of VR. The industry itself was continually focused on realism as the measure of success for VR, citing that photorealistic imagery would require 80 million polygons to appear photorealistic. But this notion of a set number of polygons makes little sense with no context. Is this the quantity of polygons for a single object, the viewable portion of the scene, or an entire environment? In 2021, real-time processing of scenes containing 80 million viewable polygons is still unattainable. Instead, the notion of realism has less to do with the quantity of polygons and instead on the accuracy of simulating light and its movement through the virtual environment.

The idea of VR in the home captivated the imagination of the public, and both academics and marketers were at fault for overpromising. Article would routinely appear in newspapers and magazines about the future of entertainment through VR. This anticipation alerted entrepreneurs across automotive and special-effects industries, inspiring them to use robotics and other niche technologies to try and re-create their own custom systems while promising the most realistic, and intense experiences [29] [25]. Many of these systems were re-tooled robotic arms from automotive production lines meant to use small but sudden acceleration with the force of gravity to lurch the participants and cause the sensation of movement. However, the devices were heavy and cumbersome, causing reviewers to attack the participant's appearance. It was and still is common for VR devices to be referred to as embarrassing to be seen in. Worse than public perception was the sensation of cybersickness that would afflict more than half of participants, a form of nausea with some similarity to motion sickness but without the vomit [26] [32] [25]. The promises made by the industry and experts were never fulfilled,

and it would take decades until an industry outsider would usher in the first commercially successful VR system [33].

While the promise of VR never came to fruition for the commercial sector, researchers continued to find new applications. The concept of using VR for the treatment of mental health was suggested by Kreuger in the early 1990s [21] and led to clinical use for treating anxiety and phobias in 1993 [3]. VR was used to produce fictitious AI driven characters for the arts at Carnegie Mellon University [34]. The University of North Carolina created virtual x-ray vision by overlaying ultrasound imagery on live video in an HMD to view a pregnant mother's fetus in real-time [35]. At the University of Houston, researchers used VR for high school education to explain the concept of gravity and how the mass of each planet would alter the force felt depending on whether they were on a star, moon, or in deep space [30].

The Defense Advanced Research Project Agency (DARPA) channeled millions of dollars per year into research for developing telepresence surgery [36]. A display device would allow surgeons to see a 3D image of a patient's abdomen while at a different location. A console converted the surgeon's movements into digital signals that operated a robotic device, mirroring their movements but at a finer scale. Feedback from the device was translated into tactile vibrations and audio cues for the surgeon. In 1995, scientists from the University of Washington and the Fujitsu Research Institute of Tokyo explored the capabilities of telepresence by remotely meeting over four days through a 5,200-mile fiber-optic cable. The deep-sea cable provided the connection and bandwidth

to allow digitized versions of their faces to be transmitted as they discussed research and engaged in cooperative gaming [37].

A seven-year-long project to reconstruct historic ruins began in 1996 as a form of virtual forensic archaeology of the Die Frauenkirche cathedral in Eastern Germany [38]. Referred to as the Dresden Project, original architectural plans and photos were used to construct both the interior and exterior of the virtual church before real construction started. Visitors were able to take a virtual tour of the site while the reconstruction was underway.

In medical studies where scanning technology is required, VR has been difficult to implement due to the restrictive spacing and strong magnetic fields present. However, researchers from the University of Pennsylvania in Philadelphia merged brain imaging technologies with virtual reality to study the hippocampus and its role in memory and learning [39]. A mirror-based projection system was used to display immersive content to immobilized patients undergoing functional magnetic resonance imaging (fMRI) of their brain to better understand the effects of simple visual and auditory stimuli.

The Georgia Institute of Technology partnered with Zoo Atlanta to create an exhibit of virtual gorillas, a starting point for a future where wildlife parks could operate without the possibility of animal cruelty [40]. Visitors placed a binocular display on their head and used a joystick to interact with the virtual apes. The virtual gorillas were designed from video recordings and their behavior modeled after insights from the zoo personnel, capturing communal behaviors such as dominance. Participants were able to

make gestures that caused the virtual gorillas to respond with a series of scripted reactions.

Automotive engineers worked with VR technologies to refine vehicle concepts including both the aesthetic as well as ergonomic characteristics [41]. The Naval Research Laboratory in Washington D.C. used HMDs for firefighter testing in smoke-filled ships. Psychologists at Georgia Tech coupled therapy with VR for patients suffering from acrophobia by having them explore building roof-tops and fly inside of airplanes. At the University of Illinois at Chicago, architects walked their clients through virtual buildings in CAVE systems. The Sarnoff Corporation in New Jersey utilized CAVEs for emergency vehicle deployment across a 3D map.

In 1999, Stanford and IBM created a 3D scanning system for digitizing the Florentine Pieta sculpture by Michelangelo. Their goal was to generate highly accurate point clouds, millions of datapoints representing a surface, of Michelangelo's sculptures [42]. Researchers were interested in how Michelangelo distorted anatomy to refine the intent of his sculptures and VR allowed them to unravel the stone forms and determining the true dimensions of the figures when outstretched. The digital statue could be transported to different virtual recreations of locations around the world with different lighting conditions, giving present day viewers a chance to glimpse the statue where it was originally intended to reside. Whereas Boeing's Phantom Works division in Seattle sought to digitally assemble and disassemble complex machines in the hopes of cutting time and training costs for workers [43]. Every part of the machine could be virtually

handled, and force feedback hand-held devices provided the sensation of touch when virtual objects collided.

In 2001, the combination of artificial intelligence and computer graphics produced the first fully virtual celebrities that were designed for and controlled by corporations [44]. The world's first virtual newscaster named ANNOVA appeared on CBS and NBC. LILI, from MTV Asia, guest-starred during the Asian Television Awards. Aki Ross, the lead in the box office failure, *Final Fantasy: The Spirits Within* was featured on the cover of Maxim. The virtual supermodel, Weebie Tookay appeared in Nokia ads and commanded a price of \$60k per assignment. Hatsune Miku, whose name translates as "the first sound of the future", emerged as a voice synthesized software product called a vocaloid [45]. She emerged to become a digital Japanese pop-idol with real-life holographic concerts around the world.

At Yale University in 1991, David Gelernter had the idea of a mirror world, where data from the real world could be used to create a virtual reflection of reality. This reflection would incorporate all the of the known information about the location in one place. And in 2003, a glimpse of this idea began to appear as virtual cities and digital economies began to engage millions of people in online communities [46]. Virtual shopping experiences in the online world of *There* provided virtual fitting rooms and next day product delivery. The Canadian game *Neverending* allowed virtual meeting spaces for grassroot organizations to fringe cults. Virtual communities became increasingly complex and engaging, so much so that users would create their own virtual constitutions and laws. Penalties were unique to each virtual world, however they ranged from

banishment to an endless virtual farm field to complete account deletion. Edward Castronova likened the virtual governance model to “isolated moments of oppressive tyranny embedded in widespread anarchy [47].” *Second Life*’s real estate market sold virtual properties, with transactions exceeding hundreds of thousands of dollars each day for purely virtual goods. Virtual worlds became so compelling that Castronova, an economics professor from California State University, calculated the per capita gross national product of the online fantasy world of *Everquest* to be on par with Russia.

As a virtual existence continued to take hold, using these experiences for managing real-life took root at the University of Washington School of Medicine in 2004. VR therapies were developed to mitigate the pain experienced by burn victims during recovery [48]. The virtual environment of *SnowWorld* used an arctic, snow-covered theme designed to reduce the perceived pain levels associated with wound undressing and redressing in burn victims. The process could be so painful that even aggressive opioids such as morphine were unable to control the patient’s pain. In their tests, VR was directly compared against existing 3D, but non-stereo, console games created by Nintendo with output to a conventional 2D display. When compared to games, VR environments showed a substantial drop in perceived pain while the patient’s burns were being tended by medical staff. Examining the results of fMRI imaging showed that virtual reality caused decreased activity within the brain of the user when compared to console games. It was speculated that when presented with an immersive VR environment, the brains inability to multitask caused the reduction in perceived pain. The ultimate goal of the project was not to completely remove pain but reduce the need for high doses of pain medications during treatment that could later lead to addiction.

HIT-Lab and Jaume I University in Spain utilized a virtual environment referred to as *Spiderworld* that featured a virtual tarantula during exposure therapy sessions. The goal was to help control the obsessive-compulsive behaviors of a 20-year patient referred to as Miss Muffet. After ten one-hour sessions, Miss Muffet's obsessive compulsive behaviors disappeared, and she was able to handle a live tarantula for several minutes. The technology was then used by Cornell University to help treat a woman who experienced the September 11th attack on the World Trade Center in New York City. Within exposure therapy VR, virtual jets were shown flying over and then into the towers with animated explosions and audio. As the therapy progressed, visuals became ever more gruesome and realistic, showing virtual people jumping from burning buildings while the screams of jumpers were intermixed with emergency crew sirens.

At the University of Manchester, a double-blind protocol was developed for testing telepathy using VR. HMDs and gloves were worn by two subjects that were then placed within a virtual room filled with a variety of objects. The first subject concentrated on a specific object in the virtual space. Subject two attempted to identify the object chosen by subject one from an assortment of decoys [49].

At Western Macedonia Research Center in Greece, researchers created a virtual model of a local school to determine if 12 to 16-year-old children could be prepared for real-life earthquakes within a virtual environment [50]. Fifty students with Down syndrome and 90 without were recruited for the project. They were then exposed to a virtual earthquake in a virtual school. By coincidence, several months after initial exposure to the VR simulation, an actual earthquake occurred at the school. Researchers

were then able to assess the difference in coping and emotional security between those students who can experienced the virtual earthquake and those who had not. Those exposed to the VR earthquake were able to cope better when the real quake occurred. Those with Down syndrome were 45% better at following teacher instruction and 87% reported being panic-free.

Schizophrenia diagnosis using VR environments was conducted at the Hebrew University of Jerusalem in Israel. Subjects explored streets, shopping malls, and markets while being asked to spot color, position, and sound incoherencies within the virtual world. Those without schizophrenia would spot on average 87% of the inconsistencies, while those with schizophrenia spotted less. While it was not a clear diagnostic method for identifying the disorder, VR could be used to improve upon typical pen-and-paper diagnostic tests, allowing for multiple senses to be tested simultaneously. It was also revealed within the virtual environment that schizophrenics had difficulty completing daily routines that could result in treatment difficulties including failure to take the correct medication dose at the correct time [51].

In 2009, the US Navy began construction of a new Ford-class aircraft carrier. In prior decades, ships were designed using pen and ink and then iteratively improved through full-scale wooden models. At the shipyard site, a CAVE system was used to visualize the entire computer aided design (CAD) layout of the ship. Each piece of the ship was replicated down to the part number that could be used to linked directly with supplier information. Such detail allowed the Navy to explore the entire ship from any location with a VR system without the need to for costly and labor-intensive physical

mock-up. Alterations could be made in VR that updated the CAD documents and then be exported for use in the computer-controlled paths of plasma cutters that made the holes in the steel plating for pipes and wiring [52].

1.4 Virtual Reality for Consumers

From the 1990s to 2012, developments in complementary technologies would bring together the necessary pieces for high-quality, low-latency VR at a price the average consumer could afford. The popularity and widespread use of personal smart-devices and cellphones created the need for lightweight, high-resolution displays and computer hardware. The demand for increasing realism and graphics (referred by many as a computational black hole) in both computer games and visualization systems drove the need for dedicated hardware that would become known as the graphics processing unit (GPU) [53]. Widespread internet access allowed for data to be transferred between connected systems. The transition to an ‘always-on’ internet spurred a new level of customer support where devices would automatically connect, update, and install applications. This simplification significantly lowered the knowledge entry barrier that many early adopters had to endure. Massively multiplayer online games (MMOs) provided a form of escape from physical reality and generate a whole new society with virtual currency, laws, and property. People were willing to spend real-world currency for completely virtual commodities [54]. The development of the 2.5D, real-time, interactive PC games of ID Software started the never-ending need for evermore immersive gameplay that made ‘first-person-shooter’ a household phrase. The lead engine developer, John Carmack would later play a key role in VRs first commercial success.

Late in 2012, a Kickstarter campaign generated excitement through the promise of an affordable head-mounted virtual reality device built using existing high-resolution cellphone displays and a pair of Fresnel lens. Called the Oculus Rift, the creators promised solutions for HMDs biggest issues: affordability, high resolution, low-latency and 6 degree-of-freedom motion tracking that were all contained within an aesthetically pleasing and ergonomic enclosure [33].

The project lead used a Kickstarter campaign to generate initial funding, which required a target goal be met before withdrawals could be made from the backers. The initial Oculus Rift campaign asked for \$250,000, which barely covered the cost of hardware and assembly. However, it raised over \$2.4 million in crowdfunding from over 9000 backers (the author of this dissertation among them). The initial concept was a literal ‘hack’ of technologies, assembled by a self-taught teenager named Palmer Lucky. He frequented several niche online display forums as well as managed his own website on the topic. Over the course of his time working with the technology, Palmer acquired what he believed was the world’s largest collection of HMD devices, totaling over 40. His first prototypes had image distortion issues due to the Fresnel lenses that acted to ‘push back’ the screen and make it appear at a distance the human eye was capable of focusing upon. A chance conversation between Palmer and John Carmack of ID Software through Palmer’s online forum led to a revised version of the game *Doom 3*. Carmack altered the rendered output of the game to counteract the effects of the lenses, providing a distortion-free depiction of the first-person shooter [33]. Carmack would leave ID Software to join the newly formed Oculus company, which would be later bought by Mark Zuckerberg for \$2 billion dollars even before the first HMD shipped. Zuckerberg’s

deal put a spotlight once again on VR, with pundits forecasting the growth of a billion-dollar industry. Other companies rushed to develop their own VR HMD solutions including Sony, Samsung, Google, Microsoft, HTC & Valve [55]. After several years of competition, several tiers of VR HMDs emerged.

The lowest tier was composed of an inexpensive cardboard or plastic shell. A user would supply the display and computation device by inserting a cellphone behind a pair of low-cost Fresnel lenses. Some solutions were inexpensive enough that they were freely given away as pieces of perforated cardboard in magazines to be assembled at home. Other systems, particularly those using an injection molded plastic shell or featuring USB connections would cost upwards of \$100. The more expensive units featured additional hardware including a wand with orientation tracking. Nearly 91% of Americans in 2013 owned a cellphone, lowering the entry barrier for those unacquainted with VR [56]. However, these low-cost devices may have done a disservice to VR because of the poor quality of the lens and limited hardware support for head or wand tracking [57].

The second tier did not require the use of a separately sold cellphone for the display and compute system. The screens and hardware were built into the plastic enclosure and sold for between \$200 and \$400. On some systems, optional cellphone tethering could be deployed so that basic operations, account management, and live gameplay streaming could be performed from within the VR environment. The second tier offered a complete package in a price range comparable to low-end cellphones and game consoles. However, most lacked positional tracking and only supported a rotationally tracked wand or Bluetooth game console controller.

The third tier cost \$400 to \$1,000 and included a position and rotation tracking system. Different methodologies were used for the tracking system, initially all using an outside-in approach with sensors placed around the wearer. These sensors were usually cameras that would track a series of precisely placed infrared emitters on the HMD. Becoming more common, the inside-out approach uses cameras mounted on the HMD to locate registration and tracking points in the environment to determine position. Another form of inside-out tracking used a series of ‘lighthouses’ that were placed within line of sight of the HMD. The lighthouses emitted a sweeping beam of infrared light that would be detected by the HMD’s sensors and used to calculate position and orientation. This third tier, at first, required a direct cable connection to a high-end computer, costing at least \$1000. Typical requirements included a multi-core 3.0+ GHz central processing unit (CPU), a discreet GPU, 8 Gigabytes of memory, display port 2.0 or HDMI 1.3+ output, USB 2.0 and/or 3.0 connections and the Windows 10 or Linux operating system. There was limited support on some iOS systems [58]. In 2021, Apple released information on an iOS compatible device with 8k resolution but with the exceptionally high price of \$3,000.

As the technology continues to advance, the capabilities of the third tier are now being integrated into the lower tiers, with position and rotational tracking being handled by inside-out optical systems on the HMD, providing fully portable, untethered headsets. In addition, for those needing hardware that exceeds what is packaged in the devices, wireless transmission devices have been created. However, the high resolution and 90+ Hz update rates necessary for VR still create bandwidth issues, requiring temporal compression and other unique methods of transmitting the display data in real-time.

Steam is the world's largest distributor of PC games, with 75% of the global market share as of 2019. In April of that same year, Steam revealed that of its 90 million users, between 1.7 and 2 million users have used their VR device with Steam. In addition, Sony confirmed that 5 million PlayStation VR units were sold worldwide [59] [60]. While these numbers only account for a small percentage of the entire population of the world, it marks the first time VR has become accessible to such a large market.

1.5 Motivation and Scope of this Dissertation

The term 'VR' was coined in the late 1980s and its definition has been under constant contention. Lately, considering other emerging realities such as augmented reality and mixed reality, VR has been refined to mean the complete replacement of sensory inputs with simulated experiences [61]. With the recent resurgence of VR in the eyes of the public, many seek to apply the technology to problems that receive little to no benefit. Non-experts, enticed by a burgeoning industry, are misapplying VR and promising capabilities and insight that are not feasible. VR has had several false-starts over its lifetime, making its strategic application to specific problem domains more important than ever. Without a clear understanding of where to apply the technology for optimal benefit, another cycle of public disillusionment and regression is bound to occur.

Since early 2000, over 35 projects have utilized VR within the Rowan Virtual Reality Center. Through careful assessment of each project, we believe it is possible to determine whether VR is the correct tool for a given problem based on the project requirements and expected outcomes. Each project was categorized as belonging to either one or a combination of the following categories: visualization, simulation, education,

training, entertainment, or art. Given the problem statements for each project, and the final implementation in VR, we believe it is possible to determine how effectively VR was utilized based upon the four fundamental elements: immersion, interaction, navigation, and virtual environment. It is the intent of this dissertation to evaluate the past 17 years of VR applications across a variety of problem domains and evaluate how the elements of VR were utilized to solve the problem statement. Ultimately, this analysis will yield a series of usable methodologies for applying VR through a series of high-level flowcharts and an analysis of which project categories best utilized the elements.

The specific objectives of the research work presented in this dissertation are:

1. To critically evaluate the appropriate use of VR across problem domains using the elements of immersion, interaction, navigation, and virtual environment;
2. To review the success of VR in visualization, simulation, education, training, entertainment, and art;
3. To determine the effective application of immersion, interaction, navigation, and virtual environment to a problem domain.

The research work presented in this dissertation demonstrates the hypothesis that the greatest scientific value-add of VR technologies is in the area of training and education. This dissertation is organized as follows. Chapter 1 provides a historical overview of the emergence of VR in popular culture and consumer use. Chapter 2 contains a detailed survey of literature that provides the background for the research work presented in this dissertation. Chapter 3 describes the methods utilized to evaluate VR projects across various problem domains and illustrates the design process with

flowcharts. Chapter 4 presents application results supporting our hypothesis. Chapter 5 summarizes the research activity presented in this dissertation, makes conclusions, and offers recommendations for future work.

Chapter 2

Background

2.1 Virtual Reality Defined

In a perfect world, virtual reality would be defined in a few sentences. Textbooks introduce the term with a half-humorous mention that there have been as many definitions as there are professionals in the field [62]. Not only has a definition been a source of contention for nearly forty years, but usage of the name itself has been met with disagreement among researchers in the field [63] [64]. The blame has been squarely put on the mis- and over-use of the term by marketing departments, mass media, and entrepreneurs which led to unrealistic expectations from the public and the association of VR with HMDs and awkward-appearing gloves [65] [66]. The mere fact that the term virtual reality is singular and not plural has generated arguments since there is no ‘one’ virtual reality, but an infinite possibility of realities [32]. Others have labelled the name an oxymoron, a juxtaposition of two inherently conflicting terms [67]. Even Jaron Lanier, credited with coining the term virtual reality, provided over a dozen different definitions for VR depending on the subject being explored in his novel, Dawn of the New Everything [12].

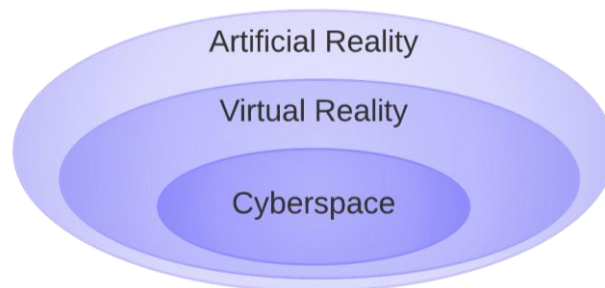
Early on, VR was defined by the tools used to create the synthetic sensory experience, which is why such a strong association between VR and HMDs and haptic gloves appeared in the late 1980s [68]. The tools of VR are always evolving and the means by which VR is experienced have changed drastically. A proper definition should

not be specific to the tools used or else the definition would have to be revised every decade [68].

Visual coupling was one of the first terms used to describe VR systems, focusing on head-mounted displays being updated with head tracking information in real time [62]. Alternative names have been proposed such as: high-fidelity simulations, artificial reality, virtual worlds, virtual realities, cyberspace, telepresence and more [62]. Some of the synonyms have been repurposed, resulting in one possible hierarchy of realities. Cyberspace refers to a single collective virtual existence that spans multiple computers, users, and datasets as imagined in the novel *Neuromancer* [67]. Artificial reality, as explained by Kreuger, is meant to encompass all possible realities including those that have no real antecedents in reality, reinforcing the general idea that virtual reality should be concerned with experiences that are similar to, but not the real world (Figure 1) [21] [69].

Figure 1

A Hierarchy of Realities



When forced into a clear definition, VR is typically associated with a computer generated, interactive, three-dimensional environment in which a person is immersed [69]. This definition firmly associates VR as the interaction between a computer and a participant.

However, one can imagine a future where VR is not restricted to the interface between humans and computers, but any entity requiring communication through available senses. Even the notion that VR must be 3D has more to do with the evolution of computer graphics from simplified 2D text to the common 3D generated imagery seen today. VR itself can represent any number of dimensions and even be used to gain knowledge of higher dimensions and how a three-dimensional being would experience them like the 2D beings presented in *Flatland: A Romance of Many Dimensions* by Edwin A. Abbott [69]. Examples of computer-generated environments already exists that bend or completely break the rules governing high-school geometry, referred to as non-Euclidean by game designers unfamiliar with its mathematical definition. Kreuger states that VR is constructed from human artifice, a system of clever devices meant to trick or deceive [21]. This definition hints at potential devious uses for VR including fooling the user's senses by acting as a second skin denying them user agency [54]. A situation explored in many works of fiction and examined in the movie *The Matrix*.

Taking each of the two words alone as 'virtual' and 'reality' does not solve the issue. Virtual refers to the essence or effect of something while not being fact, and reality is the state of something being real, existing, or happening [66] [69]. Delving further into the definition of reality invokes philosophical arguments. Some texts attempt to

differentiate the reality we perceive and seemingly share with everyone else from the virtual by using the term physical reality. Physical reality is then defined as the shared collective experience and imagined reality becomes the collection of experiences encountered in thoughts, dreams, novels, films and so forth [66]. Further exploration of this definition can lead to arguments about the concept of memory and whether the past truly even exists. Further complicating matters are altered or false memories as well as mass hallucinations. Following this idea down the rabbit hole can quickly lead to discussions on what is real, whether anything can truly be known, and discussions on quantum mechanics, observation, entanglement, and quantum decoherence. Philosophical implications that may have been best summarized by Richard Feynman [70], “I think I can safely say that nobody understands quantum mechanics.”

As humans, we perceive reality through the senses: sight, sound, touch, smell, and taste. Loomis [71] explained that our sense of reality is mediated, an elaborate construct that learns from and reacts to sensory input received through the nervous system. Our mental model is functional enough that we fail to recognize the distinction between the physical and the phenomenal. These senses utilize structures within the human body to transmit signals to the brain. And while the systems used to receive and transmit signals to the brain for interpretation are similar between individuals, how the impulses are interpreted by the brain is unique to each person [67]. Even the simple earlobe, a structure that is uniquely shaped for each person, is described as coloring sound waves before directing them into the ear canal to assist in sound localization. If you were to modify or swap lobes with another person, the brain would not be able to properly interpret the information. Luckily, areas of the human brain can be highly plastic, and in

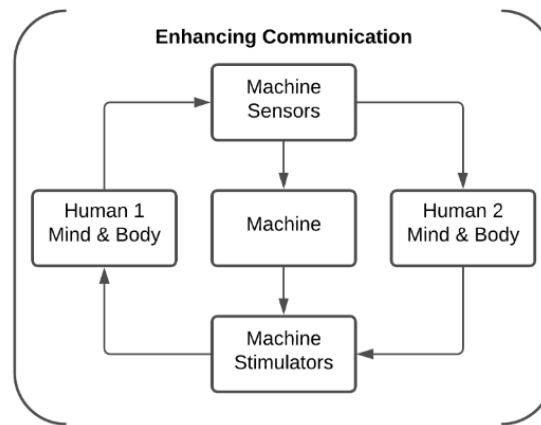
the case of trauma, sometimes reroute functionality to different areas. We will not explore the complicated matter of when the operational parts of the brain are altered, whether through physical or chemical means, to produce results contradictory to our expectations [67]. If reality is what we interpret through our senses, then humans must create a consensus as to what is real or not, and that requires communication. John Stuart Mill's famous quote [72] was discussing the concept of liberty, it is quite easy to apply to the concept of reality, "If all mankind minus one, were of one opinion, and only one person were of the contrary opinion, mankind would be no more justified in silencing that one person, than he, if he had the power, would be justified in silencing mankind."

Communication is the sharing of information from one mind to another. The process of communication initially appears rudimentary since we use it every day, however its ubiquity does not constitute simplicity. Communication requires translating ideas within the mind into signals that command the body to form words, gestures, and motions that form symbols. These forms must then be experienced by another, converted into sensory signals, and interpreted by another and understood [73]. For many, VR is about creating better ways to communicate, whether that is between humans and machines or enhancing inter-personal communication [67] [68] [64] [73]. A VR interface should reduce interruption, minimize information loss, and maximize the return on human effort expended [73]. It is a method to reduce the margin of error in interpretation between one user and another through the use of sensory vocabulary [73]. Virtual reality is a way to represent and communicate imagined thoughts without the need to convert them into abstract symbols and can be shared with other people [74] as

depicted in Figure 2. Communication requires the senses, and therefore is necessary in the definition of VR.

Figure 2

To Enhance Communication, VR Works Through the Senses



It is through the senses that a better understanding of VR is possible. As a human interface, VR requires enough computational processing power and speed to create a real-time feedback loop with the participant. A convergence of these technologies, with sufficient maturation, leads to the medium known as virtual reality and is perceived as authentic, intuitive, interactive, while facilitating collection, perception, and analysis of data [73].

While many of these technologies have matured, VR is still imperfect. What VR will achieve when fully realized has been stated as the following experience [74]: “when the screen disappears, and you see an imaginary scene, then you are in virtual reality” or, “as long as you can see the screen, you’re not in virtual reality.” These ideas allude to the

concept of *immersion* or *presence* within the VR environment, another fundamental component. The ultimate VR system creates an illusion by providing a complete range of sensory experiences while also allowing multiple users to experience the same virtual environment from their own perspectives [75].

We have explored a variety of definitions for VR, and in some ways, it may appear more nebulous than when we started. However, we have firmly realized that two pieces of VR are integral in its definition: communicating through the senses of the participant and immersing them in a virtual environment. Table 1 is a collection of definitions provided by different authors, both in the field of VR and from the general public.

Table 1

A Collection of Definitions for Virtual Reality

| Definitions of VR |
|--|
| A simulation in which computer graphics are used to create a realistic looking world that responds to user inputs, the key piece being real-time interactivity [68]. |
| A high-end user interface that involves real-time simulation and interactions through multiple sensorial channels [76]. |
| The use of computers, their software and hardware, to generate a simulation of an alternate world [77]. |
| An immersive, interactive experience generated by a computer [74]. |
| A way for humans to visualize, manipulate, and interact with computers and extremely complex data [67]. |
| A three-dimensional computer-generated world or environment where a human being can interfere with the environment through a variety of computer peripheral devices [3]. |
| The illusion of participation in a synthetic environment rather than external observation [63]. |
| Any electronic simulation or display that suggests the sense of involvement or interaction [78]. |

2.2 The Spectrum of Realities

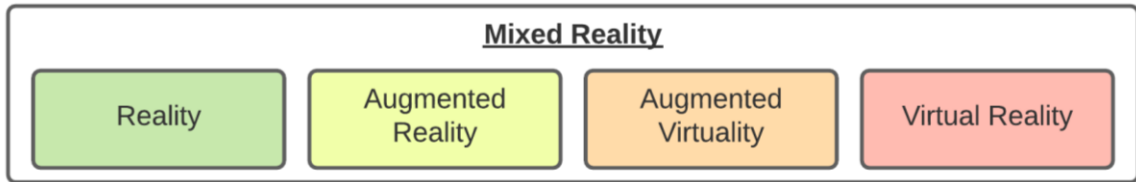
As new hardware technologies have developed, so has the VR. Virtual reality is now placed opposite to physical reality, defining a spectrum of realities (Figure 3).

Between the real and the virtual lie mixed realities. Some definitions attempt to put all realities under the umbrella of mixed reality. However, this usually causes confusion, so we will refer to mixed realities as anything between the completely virtual and the real.

Between the two reality extremes are augmented reality (AR) and the lesser-known augmented virtuality (AV).

Figure 3

Mixed Reality is the Spectrum of Possible Realities Between the Real and Virtual



Augmented reality refers to enhancing physical reality using virtual objects.

Physical reality is a term used to define the shared reality we all believe we experience collectively and can agree upon through our senses whereas imagined reality is the collection of experiences generated from thoughts, dreams, novels, films and so forth [66]. AR is not interested in replacing the senses but working alongside to enhance them. AR typically uses many graphical user interface overlays that would normally never be considered as VR.

Augmented virtuality (Figure 4) refers to real objects being integrated into the virtual world. More common is for the term mixed reality to be used in the place of augmented virtuality, referring to the mixing of real and virtual. Even so, the notion of separate definitions for AR and AV help to further refine our expectations of what VR should be: the complete and total replacement of real sensory input with artifice.

Figure 4

Augmented Virtuality Blends Real Objects into the Virtual World



2.3 The Elements of Virtual Reality

When defining VR, the senses are artificially stimulated to make the participant feel immersed within the virtual environment. To feel immersed, the user needs to believe they are present within the virtual environment and have some form of agency, acting independently and of their own free choice. The user's state, which can mean as little as the position and orientation of their head to the orientation of every joint within their entire body, must be monitored. The collected data is then interpreted by the computer system, evaluated by the rules governing the virtual environment, and used to update the environment in real-time. The term real-time is a broad term and used to mean the smallest increment of time necessary to make the participant believe their actions have immediate impact. The delay between responses can be over different durations

depending on the sense being monitored and stimulated. A feedback loop between the user and the virtual environment must be established and maintained (Figure 5).

Figure 5

VR Feedback Loop

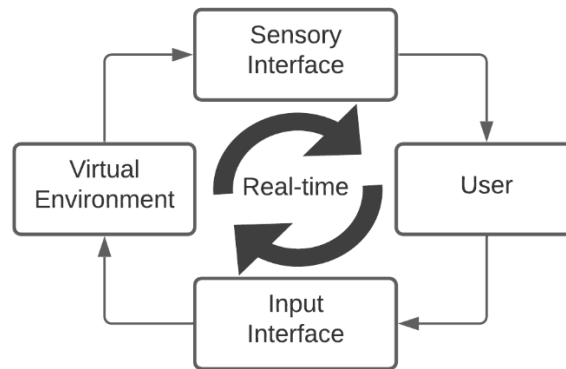


Table 2 is a survey of VR elements, the building blocks from which VR arises, as defined by various sources. While each presents their own vocabulary for the elements of VR, there is an underlying theme of immersion, interaction, and navigation. Distinctions are primarily due to nomenclature with a few exceptions. Sensory feedback relates to the monitoring and subsequent updating of the virtual environment and can be viewed as an aspect of interactivity. Imagination is mentioned to highlight that virtual reality requires a designer, who can be thought of as a modern god, defining the governing rules in the environment [76]. Witman and Singer include intuition when discussing immersion, which relates to how users communicate with their surroundings in a natural or intuitive way [3]. The viewpoint encapsulates the idea of a virtual camera within the environment that can be oriented and used to determine what visual information can be seen as well as

heard, properties of the virtual environment [64]. An element often neglected is the content used to create the sensory experience. All of the data and rules governing the interactive experience are consolidated into the element known as the virtual environment.

Table 2

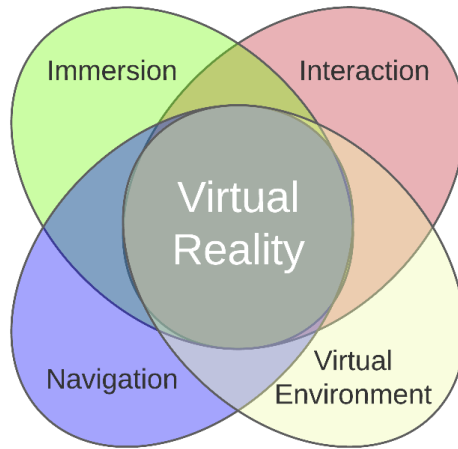
Proposed Elements of VR from Different Sources

| Elements of VR |
|--|
| Immersion, Interactivity, Sensory Feedback, Virtual World [66] |
| Immersion, Interaction, Imagination [76] |
| Immersion, Manipulation, Navigation, Viewpoint [64] |
| Immersion, Manipulation, Navigation [2] |
| Immersion, Manipulation, Navigation, Immersion [64] |
| Immersion, Interaction, Intuition [3] |

A virtual reality environment is composed of four elements: immersion, interaction, navigation, and the virtual environment (Figure 6).

Figure 6

The Elements of Virtual Reality



Combining these four elements, the definition of VR becomes a medium of interactive computer simulation that sense the participant’s position and actions, replacing / augmenting feedback to the participants senses, which allows for the feeling of being immersed within the environment [66].

2.3.1 Immersion

Immersion is being surrounded by something, being a participant in a medium, having the senses stimulated to invoke the experience of “being there” [67] [74]. We are immersed in physical reality since birth, but do not associate it with immersion because we have no other alternative. The environment stimulates the senses, enabling the mind to create and update a mental model. From experimentation and stimulation, a mental model is formed along with expectations. The model is continually adjusting based on the sensations produced by new experiences. If anticipations are not met, a feeling of presence within the environment is lost along with immersion [67]. Therefore, the

environment needs to provide stimuli that make sense and follow rules, whether they are real or not [67].

The usage of the term immersion in VR is likely due to the HMD, where a user places the display over their head, blocking reality and immersing themselves within another environment [54]. Some regard immersion as the faithfulness of the simulation to reality, the accuracy of the three-dimensional renderings, field-of-view, framerate, and tracking systems [67] [74]. The sensation of being immersed within a virtual environment would then be greatly influenced by the user's integration with the rendered imagery or other sense output [79]. The more senses engaged, then the more positive the immersion [79]. Therefore, these VR experiences seek to mimic our own reality as much as possible, presenting the world from a first-person perspective [79].

This idea that VR must be as realistic as possible has more to do with how computer graphics have been traditionally evaluated. Progress is judged by how closely the rendered imagery matches photographs [80]. However, the primary function of VR is in enhancing communication and there are many examples of where non-realistic rendering techniques are preferable to photorealism [81]. In fact, attempting to realistically depict humans can result in the opposite effect, known as the uncanny valley, where there a person viewing a humanoid will feel revulsion [82]. This phenomenon has been noted in the fields of robotics but was brought into the common vernacular through Hollywood computer generated films such as *The Matrix Reloaded*, *The Polar Express*, and *Final Fantasy: The Spirits Within* where fully computer-generated characters were seen as disturbing and unnatural [83].

Immersion can also refer to the isolation of a user's senses from the surrounding environment, being replaced by information coming from a computer [66] [74]. Stated with a more nefarious intent, VR can be referred to as a machine that takes control of your senses and cuts you off from true reality [2]. However, the goal of VR has never been to fool the user into thinking they are still in their physical reality, because the user is a willing participant that chooses to enter into the virtual world [54] [75]. We will not consider cases where VR is unwilling forced upon a user such as in an infant immersed since birth or a form of torture and mind control similar to imagery in Stanley Kubrick's interpretation of *A Clockwork Orange*.

Perception of the surroundings is controlled by five senses, which are used to build an internal world model [63]. Interactions with the environment produce sensory input that are used to interpret and define the world model, which is different for each person [63]. The overall components of the model are similar enough among most humans to allow for us to agree upon a common set of concepts [63]. Our model of the world depends on consistency and if sensory input is disrupted or the interpretation process change, discomfort and disorientation can occur [63]. If the sensory inputs can be interpreted into a coherent result, then that is the mental picture we have of the outside world [63]. When the sensory inputs are produced by a computer, it is referred to as virtual reality [63].

Immersion relates to a participant being able to perceive a medium other than what they would normally perceive without external influence, separating the concept of reality from virtual [66]. This idea can be extended to not only perceiving an alternate

world, but a different point-of-view [66]. VR has the ability to put a person in the shoes of another and perceive reality through societal biases of others. This makes VR possibly one of the greatest tools capable of eliciting empathy [66]. Immersion ties heavily into suspension of disbelief, whether when reading a book, watching a television show, or engaging in a computer game. What further distinguished VR from these other mediums is the possibility of physical immersion and not just mental.

The true purpose of immersion within the context of VR is to assist in the suspension of disbelief so that the participant ignores the VR interface and concentrates on the experience [54] [74] [75]. Immersion is the participant's belief that they are present in the virtual world and can navigate and function within the simulation [77]. Immersion is important because it ties into the ability to focus the participant's perceptual powers on a specific problem, amplifying knowledge extraction by turning data into experience [74].

While immersion is a core piece of VR, full immersion is not necessary, and without deceiving the participant, not always feasible [66]. Different approaches to harness the innate sensory capabilities of humans require different degrees of immersion [74]. Comparable to becoming absorbed within a book, it is acceptable to be immersed within a computer-generated world, even with its flaws. When a user interacts with virtual molecules or simulations of the solar system, the intent is not to deceive the user into believing they are manipulating real molecules or capable of influencing an entire solar system. The desired outcome is for the participant to make observations and gain useful insights.

While difficult to quantify directly, levels of immersion have been proposed as outlined in Table 3 [84].

Table 3

Levels of Immersion

| Levels of Immersion | |
|----------------------------|--|
| None | The experience is with the computer. |
| Minor | Virtual objects are perceived as part of the user's space, but the user does not regard themselves as part of the virtual environment. |
| Engaged | Focus is on the interactions with the virtual environment and not the real world, but the user can clearly distinguish between the real and virtual when questioned. |
| Full | The user feels completely part of the virtual environment, forgetting about the VR interface to the extent that they are startled when encountering the real world while experiencing the virtual. |

Immersion can also refer to the graphics and the all-encompassing displays that wrap around the participant with the intention of blurring the line that separates the real and illusionary [73]. Immersion has been used to differentiate VR systems, making a distinction between experiencing a virtual reality through HMD or CAVE systems as opposed to a computer monitor, commonly referred to as a window. This association insinuates that desktop VR experiences cannot be as fully immersive as HMD and CAVE systems [2].

VR systems have been classified based on their level of immersion as either immersive, non-immersive, or hybrid [79]. An immersive system blocks physical reality

and replaces it with a first-person perspective within the VR environment, adjusting to the position and orientation of the participant [85] [79]. A sub-category called through-the-window or window-on-world (WOW) VR systems were based around using workstation monitors. Hybrid VR systems combine the view of virtual worlds with the real-world (now referred to as augmented reality or mixed reality). Whether the real-world is viewed through a camera and displayed on a screen or virtual graphics are overlaid on a transparent surface does not matter.

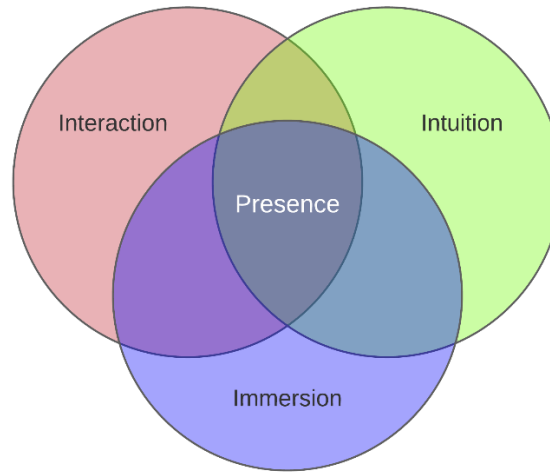
2.3.1.1 Presence. Immersion is often associated with the term presence, the idea of existing within or being surrounded by a space that is interactable [62] [75]. It is described loosely as the feeling of “being there” or the sense of being mentally immersed [66]. It has been used as a replacement for immersion, and may have origins in the term “telepresence,” allowing a person to operate equipment remotely while feeling as though they are at the location (with some suspension of belief) [75] [66]. Presence is a subjective sensation, a mental manifestation that is not amenable to measurement [86]. Presence has two alternative descriptions, the first is a matter of focus [Fontaine 1992], the direction of attention toward something, and depending on the activity or how well-practiced, can require little focus. Presence is also described in conjunction with selective attention, the focusing on meaningful information that is relevant and interesting to the individual. Triesman [87] has shown that the meaningfulness of the information guides attention. Presence within a virtual environment requires focusing on meaningful stimuli and excluding unrelated stimuli from the physical world [88]. Importantly, presence does not require the total displacement of attention from the physical to the virtual.

Presence is frequently mentioned when referring to VR is looked at as a method of mental health treatment. Goisman's study [89] showed that behavioral treatments were a valid method for treating disorders and in vivo exposure was more effective than relaxation or imaginal techniques. However, in vivo exposure can be inconvenient and expensive, requiring both the therapist and patient to create real world situations. In this case, VR offers the therapist a chance to simulate exposure within the safe confines of their office. This form of treatment is referred to as VR-enhanced psychotherapy or virtual reality graded exposure therapy (VRGET) [3].

In mental health treatment, presence becomes a measure of the effectiveness of a VR experience. At this time, little research has been performed on the psychological or emotional aspects of presence. Witmer and Singer [88] presented that immersion, interaction, and intuition form a triad for presence, with intuition being a novel element meant to describe how natural it is for the participant to interact with their surroundings. This is especially important for novice users of the technology.

Figure 7

Presence can be Regarded as the Triad of Immersion, Interaction, and Intuition



Frustratingly, presence can be influenced by a number of factors including the participant's mental state, their familiarity with VR, and the specific experience being simulated. For driving tasks, the visual representation was shown to be the least important factor while the sensation of motion the most important [90]. In this situation, low-fidelity visuals could be utilized so long as accurate motion systems were in place. For patients using VR as exposure therapy, individual differences in attention, kinesthetic perception, spatial recognition, and mental faculties can affect an individual's response to the environment [91].

Presence can be broken into subcategories [61]. Virtual presence refers to the feeling of being or existing within the virtual environment. Physical presence refers to the feeling of the user's body being within the virtual environment through the simulation of senses through synthetic stimuli. Mental presence refers to the level of engagement and the expectations of the user within the virtual world. Emotional presence attempts to

utilize well understood physiological state accompanying the sensation of presence through heart rate and skin conductance [3]. Telepresence is the feeling of being present in a location when separated by distance. Absence is the opposite of presence, the feeling of being removed from the environment such as when a person must detach themselves from the real world to focus on reading a book.

2.3.1.2 Points-of-View. One factor that can influence immersion is the perspective by which the virtual environment is perceived, called the point-of-view (POV) [66]. The most common POV in VR is the first-person perspective meant to be through the eyes of the virtual character [66].

Second person in VR refers to being able to see some representation of yourself within the virtual environment [66]. Similar in concept to how the second person in literature refers to the speaker's audience, since you are both the speaker and the audience in VR, second person refers to being able to see yourself within the environment. This does not mean you see the virtual version of your body from a first-person perspective, but instead that you see some form of your virtual body and are able to then react to your own presence within the environment. Another definition of second person is to have the camera tethered but at a distance to your virtual self, such as from behind a vehicle.

Third person is when the user is not part of the virtual environment and is used to represent the state most viewers take when watching a video or reading a novel [66]. The user is at a distance or even an omniscient vantage point [66]. What makes third person not part of VR is that the person's view is entirely unassociated with the participant's

location within the environment [66]. These definitions do not match those popularized by the gaming industry, describing games as either first or third person, with third person referring to any experience not from the eyes of the character being controlled.

2.3.2 Interaction

When immersed within a virtual environment, participants are naturally tempted to try and touch the virtual objects to see how far the experience can go [79]. Interactivity further leads to the feeling of immersion, making the user a part of the experience [68]. To interact, the VR system must track the user's body, referred to as their presence within the virtual environment [85].

Interaction refers to the ability to manipulate objects within the virtual environment, creating an interdependence between the user and system [2] [73] [77]. Interaction requires sensory feedback, responses that are processed at a sufficient rate to allow a user to make changes that appear immediate to the participant [66] [78] [92]. Some definitions include the concept of navigation as an element of interaction, expanding the definition to include being able to move within the virtual world [66] [74].

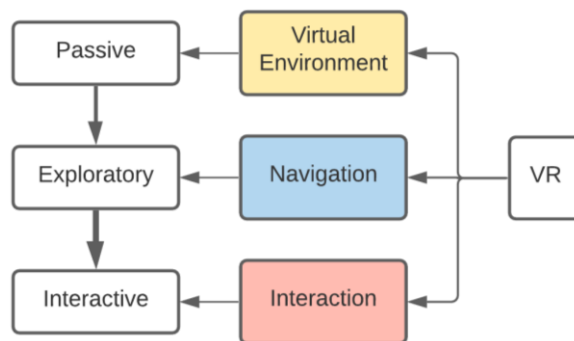
The rules of the environment and how the contents of the virtual environment react with one another is referred to as dynamics [74]. Rules can be modeled after the laws of motion or operate with no real-life equivalent.

The level of interactivity of a VR environment can be separated into passive, exploratory, and interactive, with each becoming increasingly difficult to successfully implement (Figure 8) [67] [92]. Passive refers to the participant receiving sensory input

but with no way of affecting the environment and excludes any form of navigation by the user [67]. This definition means that a VR environment can technically be different based on whether the viewer is a tracked participant or an observer, such as with large-scale multi-user CAVE systems. Exploratory refers to movement in the virtual environment and is often used for architectural walk-throughs, mechanical assemblies, or virtual art exhibits. Interactive requires the components of passive and exploratory but includes the ability to change the environment through a series of rules established by the designer.

Figure 8

Levels of Interactivity can be Expressed as Combinations of the Elements of VR



2.3.3 Navigation

Navigation is a means of locomotion, the ability of the VR system to change the position and orientation of the viewpoint within a computer-generated environment, moving from one location to another with the purpose of exploration [2] [64] [74] [78]. Navigation also refers to the ability of the participant to move through a virtual space without losing one's way and is the combination of travel and wayfinding [66] [75].

Travel is how the user moves while wayfinding is how the user knows where they currently are and where they are going.

Navigation is typically restricted to describe movement in three dimensions, however, the rules within a VR environment can allow movement through time, or through additional dimensions. Studies have shown that VR navigation as the combination of travel and wayfinding is typically not as easy as real-world navigation [75].

In some definitions, navigation is listed as a sub-element of interaction since the user must interact with a device or other interface to signal the desire to move. For now, navigation will be kept as a separate element. However, as systems evolve and interactions become more commonplace, navigation may become a sub-element of interaction.

2.3.4 *Virtual Environment*

The elements of VR often exclude what many consider the most important part of a virtual experience, the content itself. Without the virtual environment, navigation and interaction would be meaningless. Because it is a necessity, it is assumed to be part of the virtual experience and should be noted as a fundamental element. The term virtual environment is often interchanged with the term virtual world. In this dissertation, we will use the term environment as it specifically refers to the surroundings or conditions an entity is operating under. The term world already has numerous associations ranging from countries, societies, institutions, and has also been used to refer to a collective of virtual environments.

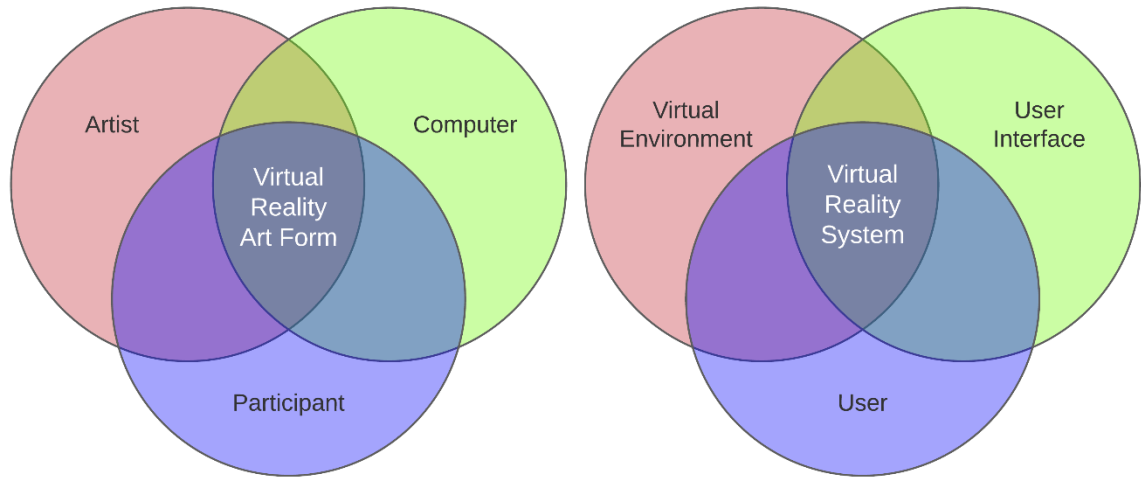
Virtual environments are synthetic sensory experiences that are communicated to a participant [62]. They exist within the memory of the computer and define what sensory information should be generated as well as the governing rules. It can consist of data describing 3D models, images, complex data, or procedural algorithms.

The virtual environment is said to exist even outside the VR interface [66]. As an analogy, a script for a theatrical performance exists even when it is not being performed. It is a document describing all the parts necessary to make the performance occur. It describes the actors, stage sets, music, and the interactions between all defined elements. A virtual environment is a blueprint that exists even without a participant, describing all the parts of the virtual world, rules, and relationships [66].

There are other noted elements of VR, however, they depend on the concept being discussed, how it is deployed, or where it is applied. Two notable distinctions are the elements of VR as an art form and the elements of a VR system shown in Figure 9 [21] [68].

Figure 9

The Elements of VR as an Artform and as a System



2.4 Senses

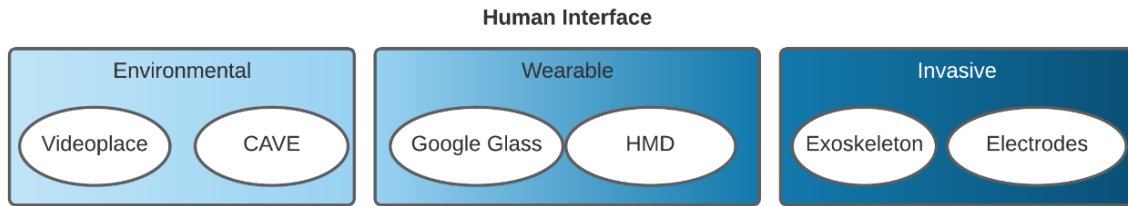
An understanding of the human senses and how they operate allows for better technology to synthetically generate sensations, creating more effective communication between the participant and the system [67]. Generating synthetic stimuli requires an understanding of the medium the senses operate within, their input and output, as well as a minimum threshold of time over which they operate over. Humans have five senses: sight, hearing, touch, smell, and taste. Devices have been developed to provide synthetic stimulation for each of the senses, however sight and hearing have dominated research and are present in nearly all VR devices. Generating tactile sensations has also been given considerable effort, however the sense of touch is actually a complex interaction of many different types of sensors non-uniformly distributed over the human body. The following subsections describe each sense with a focus on vision and hearing. Below the

challenges in generating artificial stimulation are explored including the requirements for excitation and the pathway the signals take through the human body.

Many technologies have been developed to stimulate the senses. One method of classification is not the technology, but rather, how invasive it is to the participant. Until technologies are developed that allow for direct communication with the areas of the brain responsible for sensory interpretation or techniques for directly stimulating pathways between the sense organs and the brain, all VR technologies must interface with the sensory organs to deliver information to the brain. The three categories are environmental, wearable, and invasive (Figure 10). The environmental approach does not encumber the participant with sensing equipment and instead distributes it in the surroundings such as with Krueger's interactive art displays or walk-in CAVE™ systems. Wearable devices are physically placed on the participant, which makes data collection easier, but can encumber the wearer with increased weight, reduced locomotion, and mental pressure. The mental pressure results from the participant being self-conscious about their appearance while wearing the equipment. Invasive techniques are that intrude the participant, whether physically being inserted into biological systems or creating the mental sensation of being violated. Figure 10 includes an exoskeleton in the invasive category and not wearable because these systems must exceed the strength of the wearer to inhibit motion, which can frighten the wearer and possibly injure them.

Figure 10

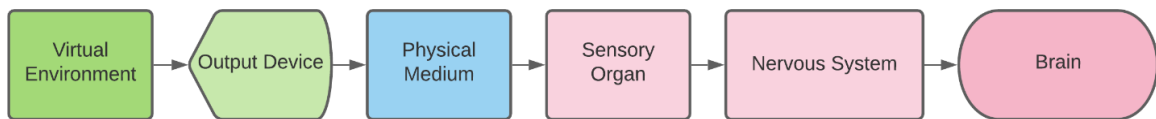
Approaches to Virtual Reality Include Unencumbered Setups to Invasive Surgery



Each of the following subsections are dedicated to a human sense. When discussing the senses, the format presented in Figure 11 will be used to explain the path of communication between the virtual environment and the participant.

Figure 11

Diagram of Output from Virtual World and Input to the Human Senses



2.4.1 Sense of Sight

The algorithms and techniques necessary for creating realistic synthetic visuals have dominated the research within computer graphics and VR, becoming the most mature area of development. This is in part due to the enormous impact vision has had on the evolution of the human brain, with estimates as high as 50 percent of it being dedicated to processing visual stimuli [67]. The eye is even regarded by some as a direct extension of the brain with a direct neural connection to the visual cortex. Several of the

tissues within the eye originate directly from brain matter. It therefore makes sense to utilize this existing, high bandwidth capability within the human brain by mapping information to visual stimuli. By converting data and information into visualizations, humans can gain insight and understanding with little conscious effort [74]. It is important to understand that VR visuals are not meant to allow a human to outperform computers in pattern identification or discovery, especially in higher-dimensional space.

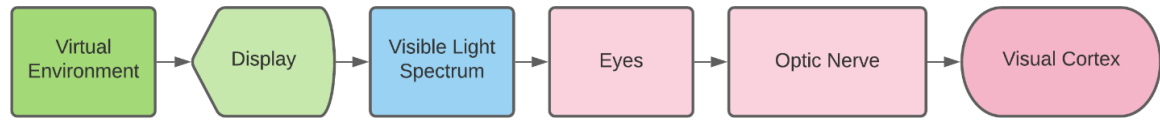
The human visual system is sensitive to a narrow band of electromagnetic radiation, referred to as the visible light spectrum, with peak sensitivity to wavelengths of 435, 535 and 565 nanometers, which correspond to what we perceive as blue, green, and red [67]. The human eye is most sensitive to green wavelengths followed by red and then blue. To stimulate the visual senses, light must enter the human eye through the protective cornea and pass through the iris, the black hole in the middle of the eye referred to as the pupil. A flexible lens redirects the light rays before entering the vitreous humor, a gelatinous fluid filling the interior of the eye. It then strikes the back wall of the eye called the retina and is concentrated at a point called the fovea. Two types of photoreceptors are non-uniformly distributed across the retina, referred to as rods and cones because of their shape. Rods are sensitive to changes in brightness while cones are able to discern color. The fovea has the greatest concentration of cones, while rods are more greatly distributed in the periphery. Within the rods and cones are light sensitive molecules that, in a process called isomerization, undergo a change in shape when struck by light. This change alters the electrical properties of the photoreceptor and releases chemical transmitters in one-thousandth of a second, starting the process for sending a neural impulse from the eye to the brain. The receptors transmit impulses along the optic

nerve to the optic chiasm, the lateral geniculate nucleus and into the occipital and visual cortex. An eye only has a field of view of about 156 degrees, and color can only be detected within 30 to 60 degrees along the direction of gaze. Shapes are discernable between 5 and 30 degrees, while text is between 5 and 10 degrees. In addition, age has a large impact on the perception of color as the lens can thicken by up to 400% by at the age of 90. The lens itself has a slight yellow tint, which absorbs some blue wavelengths and ultraviolet light. It is important to understand that most humans are unaware of the large limitations of their eyes. It is the job of the brain to stitch together the incoming information and create what appears to be a continuous and accurate account of the surroundings.

Once the signal has reached the brain, visual processing occurs. While the entire process is not completely understood, signals are processed by the visual cortex through a series of interconnected neurons with layers of ever more specialized functionality. Information is passed through these interconnected neurons and based on their specific function, either excite or suppress the incoming signal. As an example, one of the neural layers may be stimulated by a change in color between the cones, which would then be passed to another neuron that would detect changes in contrast, which would be passed to even more specialized neurons searching for vertical or horizontal edges to discern boundaries. As the layers of neurons continue, their focus can move from processing signals from individual rods and cones to interpreting macroscopic features such as objects and faces.

Figure 12

Process for Stimulating the Sense of Sight



2.4.1.1 Depth. To make sense of a three-dimensional world from the thin lattice of light-sensitive receptors inside the eye, the brain uses four basic types of depth-perception cues: static, motion, physiological and stereoscopic. Static cues refer to any visual cue that can be seen in a still-frame picture and includes interposition, shading, brightness, size, linear perspective, and texture gradient. Motion depth cues require movement and primarily refer to the concept of motion parallax. Physiological depth cues refer to accommodation and convergence, the flexing and relaxing of muscles in the eye to determine depth. Stereoscopic cues rely on having two eyes at different positions that are able to fixate on the same point. Simply having two eyes (or more) is not enough for stereoscopic depth. The eyes need to have fields of vision that overlap from which depth information can be ascertained. There is a strong association with the front-placement of eyes among predators and the side-placement in prey in the animal kingdom, likely a tradeoff between being more aware of distance to a target versus have a larger field of view. Depth cues can also be separated into monocular or binocular cues depending on whether they can function with only one or two eyes. Table 4 lists the different depth cues and provides a detailed explanation of each.

Table 4*Methods Used by the Human Visual System to Determine Depth*

| Mono / Bi | Type | Cue | Description |
|------------------|---------------|---------------------------|--|
| Mono | Static | Occlusion / Interposition | Positioning of two objects so that one blocks the other. |
| Mono | Static | Light & Shadow / Shading | Determining depth and physical features from varying intensities of light across the surface. |
| Mono | Static | Brightness | The further light travels, the less likely it is to reach the eye, making objects further away appear dim. |
| Mono | Static | Size | The larger an object, the closer it appears, unless prior knowledge states otherwise. |
| Mono | Static | Perspective | Lines appear to converge to a central point the farther they travel away. |
| Mono | Static | Texture Gradient / Detail | Nearby objects appear more detailed. |
| Mono | Motion | Motion Parallax | Objects closer appear to move faster than objects at a distance. |
| Mono | Physiological | Accommodation | Muscles responsible for focusing the lens contract and relax, providing an indication of depth. |
| Bi | Physiological | Convergence | How far the eye must turn inward to view a close object within 20 ft. |
| Bi | Stereoscopic | Stereopsis | Using differences between two slightly disparate views to determine depth. |

2.4.2 Sense of Hearing

After sight, hearing has been the most developed artificial VR stimulus. While some consider audio an afterthought when compared to the effort put into creating synthetic visual stimuli, it has been demonstrated that the inclusion of sound within VR provides alternative and supplementary ways for the participant to increase the amount of information accepted [67]. Sound can be used to reinforce interaction through simple tones, set the mood of the environment with music, or provide cues that are outside the user's field of view. For those with visual disabilities, sound is the only way to experience VR.

Sounds, regardless of the source, are vibrations moving through a medium, and for humans, that usually means through air. Vibrations create waves of pressure emanating from a source, similar to ripples moving along the surface of a pond. Importantly, sound is the movement of energy through a medium and not the movement of the medium itself. Sound waves do not carry their medium with them which is why they can be easily reproduced to create artificial stimuli. The speed at which sound waves move through a medium is dependent on the density of the molecules, with higher density allowing waves to travel faster. One other important attribute of sound is that the intensity of the wave diminishes with distance.

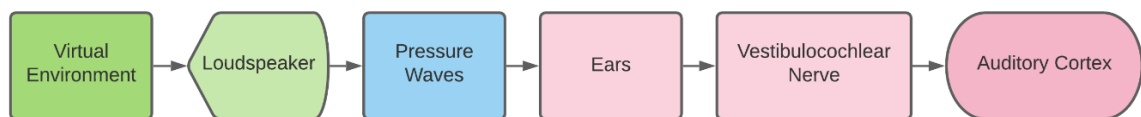
Humans can hear through a narrow range of frequencies, the number of wave peaks that pass a fixed point in one second expressed as Hertz (Hz). The range a human can hear is impacted by age, with young adults being capable of hearing sounds between 20 Hz and 20,000 Hz. The amplitude, or loudness of a sound is measured in decibels

(dB). Every ten increments in dB are perceived as doubling the intensity of the sound. For humans, 20 dB would be a whisper, while 120 dB would be the threshold for pain.

Figure 13 represents the path for providing auditory stimulation, beginning with a speaker or other device capable of vibrating the medium to produce controlled pressure waves. Passing through the medium, the waves either enter the ear or strike the pinna, the curved skin-and-cartilage protrusions on the sides of the head that focus sound into the center of the ear hole. The pinna is unique to each person and is specialized to assist with determining the location a sound originated. The auditory canal acts to enhance the incoming sounds, increasing the dB by roughly 10. The focused and amplified sound waves strike the eardrum and cause it to vibrate. A series of three bones within the ear further amplify the incoming waves by a factor of 30 and serve as a mechanism to protect the ear, tightening the eardrum when incoming sound is too loud.

Figure 13

Process for Stimulating the Sense of Hearing



The sound medium is converted from air to the saline-solution filled cochlea, which is composed of three channels. The membrane between two of these channels, called the Basilar membrane has the interesting property of causing the waveform to peak at a specific location based on the frequency of the incoming sound. This allows the ear

to associate a frequency with a position inside the canal. The organ of Corti is responsible for determining loudness by using small hairs that extend into the fluid. There are around 23,500 hairs that bend as pressure waves move through the fluid, triggering chemical reactions that travel through the auditory nerve and to the brain for processing.

Much like the neurons for processing visual stimuli, those within the auditory cortex are specialized. The general rule is that the further the neuron is within the pathway, the more specialized its role, including monitoring direction and tonal changes.

Humans have two auditory receivers: the left and right ears. The brain crosses the input signals at the cochlear nucleus, sending both left and right stimuli to each side of the brain. This combination of senses from either side is critical for sound localization, extracting 3-D information on where a sound originates. It is based on the arrival time, intensity, and acoustic shadow of the incoming sound. Arrival time refers to the difference between the stimulation of one ear from the other, and only works when the source is not directly in-front or behind the observer. Intensity of sound decreases with distance and that slight difference can be perceived because of the difference in position of the two ears. However, intensity differences are more difficult to discern if the frequency is low due to the length of the sound wave being larger than the diameter of the human head. Acoustic shadow refers to the property of higher frequency sounds being easier to block than lower frequencies. This phenomenon is similar to intensity changes, however, is processed by a different region of the brain and is distinct.

2.4.3 Sense of Touch

Touch, the sensation of feeling is a term that groups many complex systems together, which may be one of the reasons why development in artificial touch has not progressed as far. Sight and hearing are isolated to relatively small regions of the body on the head, making it simple to block out external stimulation and channel artificial sensations. Touch, however, is a full-body experience, both externally and internally. Throughout the body, there are millions of receptors for handling the sensation of touch. Mechanoreceptors are responsible for measuring pressure and deformation and assist with determining the texture of an object. Proprioception is the combined awareness of all the muscles, tendons, and joints within the body, which provide sensations for perceiving size, weight and shape [73]. Combined, these two systems represent the human haptic system. Further complicating artificial stimulation is that many of the touch senses require an object to be moving and continually sampled. If the body is stationary the sense of touch is severely hampered [93].

To create artificial stimuli for external pressure, temperature changes, and sensations for texture, the virtual environment must be capable of interfacing with the skin of the participant (Figure 14). The somatosensory cortex within the brain is responsible for processing the sensory information, which is routed through the spinal cord followed by millions of nerves throughout the human body. You can think of the nervous system as a tree with the trunk connecting to the brain and the branches emanating from it. Four types of mechanoreceptors are distributed throughout the skin at different depths. Each features a unique characteristic to respond to varying forms of

stimulation. For just one hand, there are estimated to be 17 million receptors. Hair acts as a fifth receptor, providing tactile feedback to the nerve endings that wind around the root. In addition to shape and texture, nerves are able to detect changes in temperature. Receptors connect to bundles of nerves that are split into two groups: slow and rapid adapting fibers. Slow adapting fibers immediately sense pressure and continue to be stimulated while it is maintained. Rapid fibers are active only on initial contact. Both of these types of fibers can be subdivided into punctate and diffuse fibers. Punctate fibers have sharply defined boundaries and can accurately inform the brain where a sensation is localized. Diffuse fibers have large but vaguely defined boundaries that cannot accurately inform the brain where a sensation was felt.

Figure 14

Process for Stimulating the Sense of Touch



To evaluate the tactile acuity across the body, two points of contact are made on the surface. The distance between the points is measured until the subject can no longer perceive them as separate. These thresholds, much like the density of rods and cones within the human eye, vary across the body with the back being as low as 70 mm and the fingertips as high as 2mm. Those regions with the highest sensitivity also utilize larger portions of the brain for processing.

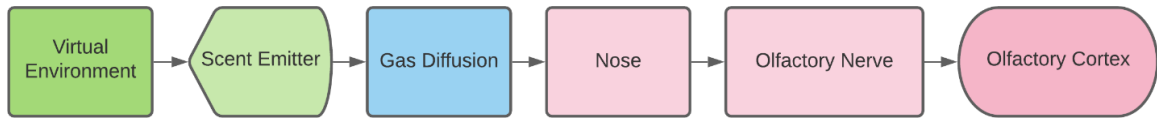
2.4.4 Sense of Olfaction (Smell) & Gustation (Taste)

The last two senses available to stimulate are smell and taste. These two senses are not typically synthetically stimulated within VR environments. Taste often relies upon smell to function properly, which is why holding your breath can often dull a foul-tasting substance. While over 30 basic smells have been identified and can be mixed, there are multiple issues with deploying such a system. Smell requires molecules to be diffused through the air (Figure 15). Whereas light can be generated through excitation of different materials with an electrical current and sound can be produced through the movement of a coil producing vibrations in air, smell requires the collection and storage of scent molecules. For a display or speaker, we are never concerned about running out of light or sound, however scent is comparable to a printer that requires ink cartridges to be replaced. Since smell works through diffusion, to remove a smell requires that the air be purged of the molecules, which can be difficult to achieve if being diffused through a room. Furthermore, the olfactory senses can be overwhelmed by adapting to the lingering smells and causing them to no longer be perceived. Smell can be channeled directly to the nose through air flow or tubes; however, these solutions are usually uncomfortable and or require movement of the medium within the VR space, which can inhibit other senses.

While difficult to implement, smell has been utilized multiple times in simulated experiences. The first commercial use of smell was in the Sensorama, patented by Morton Heilig in 1962 [2].

Figure 15

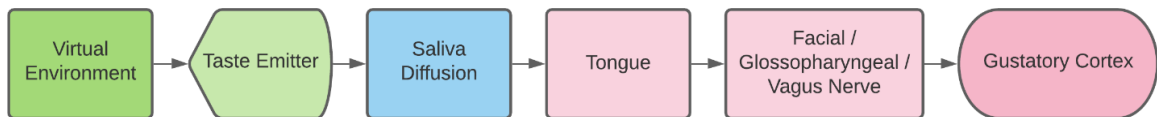
Process for Stimulating the Sense of Smell



Gustation, commonly known as taste, has extremely limited appeal. As with smell, taste requires the diffusion of molecules through saliva. Taste is strongly influenced by the sense of smell, and until smell can be properly replicated, creating systems to simulate taste provide little benefit. Further complications come from the medium that taste works within the fluids that are generated within the mouth, which are swallowed, creating a possible a health risk when sharing devices.

Figure 16

Process for Stimulating the Sense of Taste



2.5 User Tracking

The perfect motion tracking system is described as being a small, self-contained device that is able to sample all 6 degrees of freedom quickly and accurately. It should be free of occlusion, invariant to environmental conditions, and affordable [61] [68]. For VR, it is not enough to provide replacement sensations. The synthetic stimuli must match

the expectations of the user. To do so, devices that track the current state of the participant are used, whether just the head or the entire body, to adjust the virtual environment and its output accordingly. These systems are referred to as tracking systems and at minimum are used to determine the orientation of the head. When the user moves in the VR environment, whether through a controller or their own locomotion, they expect to move through the virtual world, which means that the environment moves in the opposite direction to their movement. Tracking systems can also be deployed to monitor the position and orientation of individual appendages as well as monitor biometric data such as heart rate, blood pressure, and perspiration.

There are many forms of tracking including inertial, electromagnetic, mechanical and ultrasonic. Nearly all projects reviewed in this dissertation utilized visual tracking, which will be further explained below.

2.5.1 Visual Tracking

Visual tracking refers to using light as a method to estimate the position and/or orientation of an object. This is achieved through an array of cameras, usually four or more to account for occlusion issues. Infrared light is typically used since it is invisible to humans but can be detected by many camera systems. The camera system is first calibrated using an object of known geometry. The cameras are able to calculate determine their position and orientation in 3D space. Once their pose is determined, it is then possible to estimated other objects, usually outfitted with markers, that are brought into the observation area.

Markers can either be point sources that provide a single position in space, multiple markers that combine to calculate the pose of a rigid body, or a unique symbol that can be detected using computer vision algorithms. The last option is prominently utilized in systems such as the ArUco OpenCV marker system [94]. However, marker-based systems have several limitations including resolution of the cameras, the distance of the marker to the cameras, the maximum number of possible markers determined by the encoding strategy employed, and adhering the markers to objects that are not flat or sufficiently large (Figure 17).

Figure 17

ArUco Camera Calibration and Marker Detection for Visual Tracking



Markers are further classified as either passive or active depending on whether they directly emit light, and therefore require a power source. A passive marker can only reflect infrared light emitted from another source using a retroreflective coating on the exterior. Passive markers require an external device to emit infrared light but are

lightweight and small (Figure 18). Passive markers that use a retro-reflective coating are limited to either spherical or flat shapes. The passive markers used by Advanced Realtime Tracking (ART) utilize either microscopic glass beads or triple mirrors placed on the surface to reflect light [95]. The reflective surface can be damaged through physical contact and residues such as oil and glue. A coating can be applied to the surface to protect the retroreflective coating but results in a loss of nearly 10% reflectivity. Flat markers can be temporary or permanent through the use of an adhesive but have limited visibility of only ± 45 degrees perpendicular to the surface.

Figure 18

3D Printed, Mountable Retroreflective Passive Markers for Tracking Head Pose



Active markers use a light emitting diode (LED) and require a power source, which makes them larger and heavier than passive markers (Figure 19). The LED should be equipped with a diffuser to increase visibility. Active markers can also use frequency modulation to uniquely identify each marker. This is an important distinction between a single active or passive marker. Markers are usually identified with a number

that is assigned as they are detected. If a marker leaves the observation area and re-enters, a decision has to be made on whether to reuse an existing ID or assign a new one. Since real-world objects are usually bound to one of these IDs, the choice can cause an object to lose tracking completely during a VR experience. A similar circumstance occurs when two markers come sufficiently close to one another or occlude one another and then separate. When this happens the ID of the marker can be swapped causing association issues if the markers are representing different virtual objects.

Figure 19

An Active WorldViz Vizard Infrared Point Tracker with Battery Pack



Passive markers, while inexpensive and sometimes disposable, require more than one to uniquely identify an object and provide both position and orientation. Systems such as the ART infrared tracking system require at least 4 markers asymmetrically placed on an object to create a unique marker layout for defining a non-deforming, rigid body (Figure 20). Rigid bodies can be used to track deformable objects if it is broken into individual elements corresponding to skeletal joints as seen in Figure 21.

Regardless of whether active or passive markers are used, at least 3 non-colinear points must be placed on the surface to determine the orientation of the object. More are

typically placed to safeguard against occlusion as well as reduce the likelihood of different objects from having the same configuration.

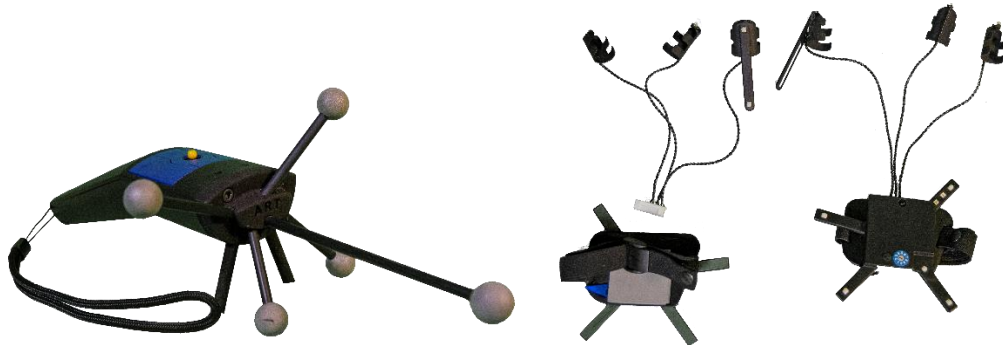
Figure 20

Retroreflective Markers Attached to Objects to Determine Pose



Figure 21

Optical Tracking Used to Find the Pose of a Controller or Fingers



2.6 Real-Time Rendering

In order to create the visuals for a real-time virtual reality environment, a method for encoding the environment that a computer can quickly and reliably process is necessary. Most virtual environments are composed of surfaces, which are orientable continuous 2D manifolds embedded with a three-dimensional real coordinate space [96]. This definition describes a surface as a non-degenerate boundary of a 3D solid, which means that the solid does not have infinitely thin features that make it impossible to define the interior or exterior of the surface. There exist many methods to define surfaces, including splines, subdivisional surfaces, and implicit / volumetric representations. However, of all the methods, the predominant method of representing a surface is through the use of vertices to encode spatial points and matrices to transform them.

A vertex encodes a three-dimensional point in space with offsets along the x, y, and z axes, represented as a four-element vector using homogeneous notation [97] [98]. Direction vectors and spatial points are differentiated by the 4th coordinate being either a 0 or 1, respectively (Equation 1). Vectors are encoded using a floating-point notation and are usually 32 bits in size.

$$\begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix} \quad \begin{bmatrix} x \\ y \\ z \\ 0 \end{bmatrix} \quad \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \quad (1)$$

A collection of vertices is referred to as a mesh, and with a specified mesh topology, a system for connecting the individual vertices can be instituted to draw a solid object. Topology refers to how multiple vertices are ordered to draw a more complex

shape, such as a line, triangle, quadrilateral, or n-sided polygon. Using the three points that define the triangle and assuming no degenerate cases, any position on the surface can be calculated using barycentric coordinates (Equation 2).

$$\begin{aligned} \mathbf{p} &= \alpha \mathbf{a} + \beta \mathbf{b} + \gamma \mathbf{c} \\ \alpha + \beta + \gamma &= 1, \quad \alpha, \beta, \gamma \geq 0 \end{aligned} \quad (2)$$

The data structure for a mesh depends on the topological and algorithmic requirements of the application [96]. For 3D modeling applications and mathematical operations that operate on the mesh, it can be more useful to describe the connections between vertices as edges and the closed surface described by at least three vertices as a face. For the purpose of rendering a virtual environment, the vertices are stored in an array, commonly referred to as a buffer [99]. The format of the buffer can either explicitly list the vertices in the order they should be processed to process and rasterize the surface or can be a list of unique vertex positions that can be referenced by another list. If the vertices within the array are stored as unique elements, then another array composed of integer values called an index array is necessary to provide the connectivity information.

Not only is topology used to determine how the object should be drawn, but it can also be used to reduce the number of drawing commands issued and the size of the mesh when stored. As an example, a quadrilateral can be drawn using two triangles that share a common edge, or two vertices. To draw this object by explicitly drawing each triangle one-by-one using a technique called immediate mode, two draw (function) calls would be

necessary with each requiring the three vertices of each triangle to be specified. However, these triangles share two vertices, meaning only 4 unique points need to be stored.

Vertices are used to describe the positions within a mesh; however, we are not limited to just defining the surface boundaries of an object. Other arrays referred to as attributes can be created to store per vertex data. For example, a 4-component color value using 8-bit representations for red, green, blue, and opacity (alpha) can be assigned to each vertex. Vertices and their attributes can be stored using several formats including multiple or interleaved. Multiple has each vertex attribute buffer appended to the last as blocks of information while interleaved combines each vertex with its specific attribute data within the buffer. Choosing multiple or interleaved can have implications if you are only attempting to draw a subset of a larger model, requiring index hopping through the dataset when using multiple. Typically, a scene is not efficiently fully packed into one of these representations, but has surfaces broken into different parts based on the needs of the application. Static elements that can be transformed as one object can be packed together efficiently, while multiple objects undergoing differing transformations may require a different approach. In many applications, vertex attribute data is restricted to being in a one-to-one relationship with each defined vertex. If you consider a vertex attribute as another dimension of the vertex data, then accessing a vertex from an array means also accessing the attributes indexed at that array element. This is an important factor that is often overlooked by novices in the field and becomes apparent in the previous example of two triangles defining a quadrilateral. If a quadrilateral is to be rendered with each triangle having a different color, then six unique vertices and their attributes must be defined. Otherwise, each triangle will share the vertex color chosen for

the shared component, causing it to blend across the surface. While this may appear trivial for such a small problem, the issue of ensuring that the vertex data is encoding the correct information and not sharing vertex attributes becomes critical in more advanced rendering algorithms such as surface normal attributes used in lighting calculations and the projection of images onto the 2D surface through UVW coordinates.

Triangles are particularly well-suited for rendering because they inherently define a 2-D plane within a limited region of space that many mathematical techniques can utilize for interpolation, intersection detection, and reflection [100]. While triangles are the underlying representation, quadrilaterals are more commonly utilized in 3D modeling applications and mesh editing algorithms. While the object is always composed of triangles to the rendering system, mesh structures based on edge connectivity and direction are better suited for defining the topology and flow of a surface [96]. These mesh structures can allow for real-time geometry manipulation and fast lookup tables for easily grabbing loops or rings. Many mesh operations are best suited when used in conjunction with the aforementioned mesh structures such as in surface smoothing, reconstruction, or retopologization. However, all surfaces will eventually be decomposed into triangles for the rendering system, whether performed directly by the artist or through automated methods. Therefore, it is important for the artist to understand how data is converted from the higher-level representations to the triangles digested by the rendering system to reduce rendering artifacts.

To create a navigable and interactive environment, meshes must be transformed; an operation that processes vectors and converts them in some way [98]. A virtual

environment is rarely composed of one single mesh, but instead hundreds or thousands of meshes, many of which are the same mesh transformed to a new location. When a mesh is created, whether through an artist or an algorithm, each point is placed within a coordinate system referred to as object or model space. The origin and orientation of the object are chosen based on convenience. For a humanoid character, placing the feet at the origin simplifies placement in the virtual world. For objects that are repeated multiple times such as walls and floors, placing the origin at the surface or a corner can make positioning faster and easier for the layout designer.

Meshes are transformed from local / model space and positioned within a common coordinate system called world space. A matrix encodes the position, rotation and scale to apply to each vertex in a mesh. Similarly, to create a view of the virtual environment from the perspective of the user, a matrix encoding the position and orientation of the head is used. An interesting quirk of the rotation matrix used in 3D rendering is that the inverse matrix always exists and produces the opposite rotation intended, allowing every object in the scene to be anti-rotated based on the camera's orientation making it appear as if the camera is actually rotating. Technically, there is no camera, only clever use of mathematical transformations to make it appear as if the viewpoint is from a specific location in world space.

The transformations utilized in rendering are affine and stored within a 4x4 matrix to match the homogeneous vectors. This matrix is capable of encoding translation, rotation, scale, and skew for meshes as well as orthographic and perspective projections (Equations 3 -7).

$$T(t_x, t_y, t_z) = \begin{bmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$S(s_x, s_y, s_z) = \begin{bmatrix} s_x & 0 & 0 & 0 \\ 0 & s_y & 0 & 0 \\ 0 & 0 & s_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta & 0 \\ 0 & \sin \theta & \cos \theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

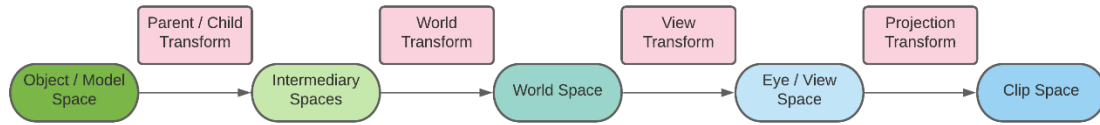
$$R_y(\theta) = \begin{bmatrix} \cos \theta & 0 & \sin \theta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin \theta & 0 & \cos \theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

$$R_z(\theta) = \begin{bmatrix} \cos \theta & -\sin \theta & 0 & 0 \\ \sin \theta & \cos \theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

Matrices are concatenated together, being mindful of the noncommutativity of matrix multiplication to create a single, combined matrix. When vertices are multiplied by the matrix, they are transformed. The matrix that moves vertices from object space to their final orientation is concatenated Model-View-Projection matrix and converts vertices from object space into clip space, a representation that converts all geometry within the view field (defined as a frustum) into a box situated at the origin [101]. Converting to clip space provides simplification in removing portions of the mesh that are not within the view's frustum as well as simplifying the mathematics necessary for intersection testing to cut away portions of a mesh that extend outside the cube (Figure 22).

Figure 22

A Mesh is Transformed Through Several Stages Before Vertices are Rasterized



The next several stages in transforming pipeline are separated from the earlier stages because they are operations that cannot be inverted. This operation amounts to dividing the vector component by the W coordinate. During the projection transformation, the W component can take on values other than 1 and dividing all components by 1 returns the vector to 3 dimensions, referred to as normalized device coordinates.

Different systems have the normalized device coordinates centered on the origin and extending to different ranges. Regardless of the system employed, all values within a set range (-1 to +1 or 0 to +1) are clipped and removed. After rasterization, pixel values are in 2D window space which can be mapped to the display device.

VR systems can exist as standalone devices or clusters or computers working in tandem to produce multi-screen visuals. For large-scale systems composed of networked computers, routing data is important. For example, in a CAVE system, multiple computers can have custom hardware built to serve a specific purpose. Tracking computers communicate with the tracking system, read in data, and produce pose information. Other computers are responsible for rendering a portion of an entire display. Yet another computer is usually designated the server, where data from the tracking

system and input devices are routed and used with the virtual world. At minimum, the server then informs each client about the current position and orientation of the viewer so they each can update their internal camera to represent the portion of the screen they are required to render. However, it is far more common that the server and clients must broadcast additional information include state changes in the virtual world or player input as remote procedure calls (RPCs). Between each of these systems can be additional hardware systems to overcome issues such as cable length restrictions, source / destination routing, audio processing, and unique input devices.

In order to manage the flow of data from various sources to the server and client computers, applications such as Trackd by Mechdyne are utilized. Trackd provides a system for abstracting devices, sensors, and other forms of input into a series of definitions in a text file that allows multiple hardware solutions to work with any Trackd supported software [102].

Chapter 3

Approach

The purpose of this dissertation is to evaluate the effectiveness of VR in the areas of visualization, simulation, training, education, entertainment, and art. Thirty-five projects completed in the Rowan VR Center from the last 17 years were identified across each of these categories and evaluated using the four elements of VR: immersion, interaction, navigation, and virtual environment.

3.1 Project Evaluation

Each individual project was evaluated based on the initial problem statement, which defines the category. The VR implementation was evaluated to determine how the elements were utilized. Finally, the project's outcomes were assessed.

1. Problem Statement – the overall purpose of the project. If the original problem statement was too vague or generalized it was broken into smaller problems.
2. Implementation – includes imagery of the final product and a flow chart depicting how the elements of VR were employed to solve the problem statement. A brief description of the final implementation was included and outlines any features or functionality as well as any hardware or software used to implement it. This section does not discuss low-level project implementation details.
3. Outcomes – a post-mortem of the project, reviewing how effectively VR was used based on the flow chart and how it may have been more effectively employed.

For the reader's convenience, the definitions, and purposes of each of the elements of VR have been restated concisely in Table 5.

Table 5

Definition and Purpose for Each Element of VR

| Elements of VR | | |
|-----------------------|---|---|
| Element | Definition | Purpose |
| Immersion | Having the senses stimulated to invoke the experience of "being there." | To assist in the suspension of disbelief so that the participant ignores the VR interface and concentrates on the experience. |
| Interaction | The ability to manipulate objects within the virtual environment. | Creating an interdependence between the user and system, making the user a part of the experience. |
| Navigation | The ability of the VR system to change the viewpoint's position and direction in a computer-generated environment. | Provide a means of locomotion through the virtual environment for exploration. |
| Virtual Environment | Synthetic sensory experiences communicated to a participant including the rules governing everything within the experience. | Produce sensory output to stimulate the participant. |

For many of the projects, the project scope was too general or overly ambitious. In these situations, the problem statement was re-evaluated based upon the final implementation. From the scope and problem statement, each project was categorized as belonging to one or more of the following categories.

- *Visualization* –any technique for creating a visual stimulus to communicate a message.

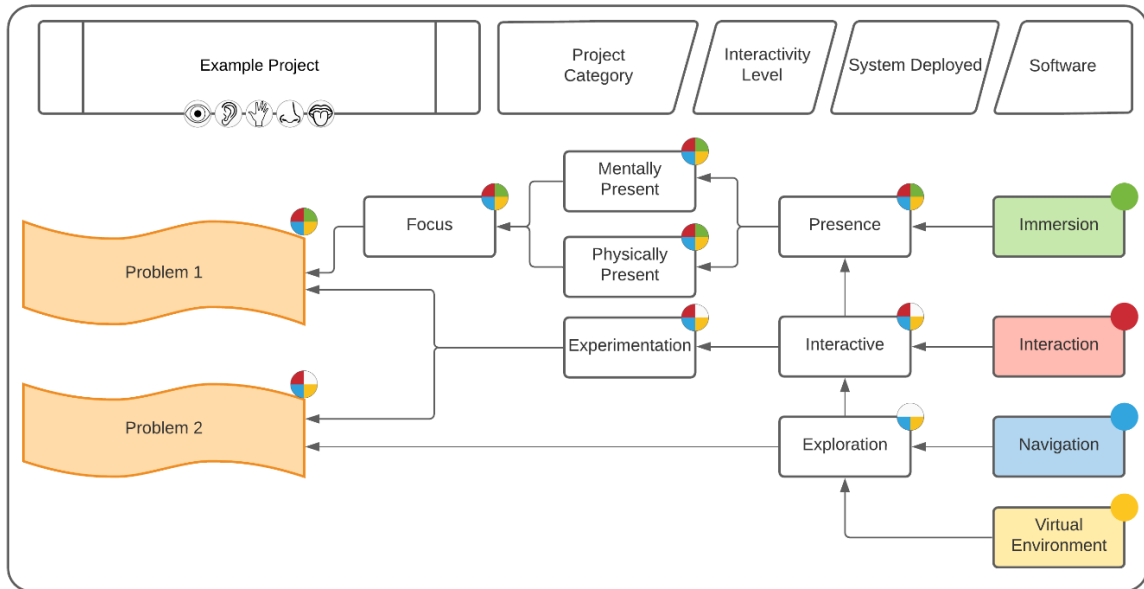
- *Simulation* – the production of a model for study, an imitation of a process or system as it operates over time.
- *Education* – refers to the process of learning or acquiring knowledge of a skill or topic.
- *Training* – the process of learning a set of procedures to complete a task. Training only requires enough knowledge to successfully complete the task, which distinguishes it from education. Training includes learning the procedures as well as evaluation.
- *Entertainment* – for the sole purpose of providing amusement or enjoyment.
- *Art* – the production of works to be appreciated for their aesthetic qualities or emotional power.

When categorizing projects, the intent was used to discriminate between categories. For example, every project utilized visualization to display information on the screen, whether that be data visualizations of sensor data to architectural renderings of CAD data for 3D objects. For categories such as education or training, visualization is a requirement but not the primary goal. Therefore, an architectural walkthrough of a virtual building would be categorized as visualization, whereas a complex training system meant to instruct a user on a set of procedures that utilizes the architectural building to accomplish its goal, even though it used visualization techniques, would be categorized as training. If every project was labeled as visualization, the category would become meaningless.

To concisely summarize the problem statement as well as how the elements of VR were utilized, whether for past or future projects, a smart flowchart system was designed. This smart system allows the user to connect the elements of VR to the problem statement and visually display what elements are being used. This smart flowchart was programmed in the online flowchart application, Lucid Chart. It utilizes conditional formatting to visualize how the elements of VR are employed. An example template of the smart flowchart system is shown in Figure 23. Starting at the top left of the graphic is the project name and the senses stimulated. To the right are the project categories, the level of interactivity, the VR systems deployed upon, and the rendering software used. The 35 projects reviewed span over 17 years, and during that time there were numerous developments in software and hardware, making it necessary to include that information. As more projects were encountered, the capabilities of the Rowan VR Center expanded, allowing for more challenging projects to be undertaken.

Figure 23

Flow Chart Template for Connecting the Elements of VR to Problems



Problems are listed vertically on the left side highlighted in orange and include a description of the issue to be addressed/investigated. On the far right are the four elements of VR, each color coded. It is not always obvious how the four elements of VR are meant to be used to address a problem, and so sub-elements are placed between to bridge the gaps. Sub-elements were directly taken from the definitions of each element as discussed in the Background chapter. They were either derived from a combination of the four elements of VR or were components that made up the definition of a specific element.

The problems and sub-elements each have a color-coded dot in the upper right corner, indicating what elements were utilized. This is meant to quickly indicate how each problem utilized VR without having to refer to the entire chart. The increase in the

effectiveness of the utilization of VR for addressing the specific problem is indicated by the increase in the number of quadrants that are filled in the chart. It is important to note that projects have limitations that are outside of the four elements such as technological, budgetary, or staff constraints.

3.2 Computation of Effectiveness

A three-step process was developed to assign numerical values to the effective utilization of the various components of VR for addressing the requirements of a specific project. In the first step, each project was mapped on to a specific category describing the overall class of projects. In the second step, specific project requirements were correlated to specific elements of VR. In the third and final step, an effectiveness score was determined to indicate the effective utilization of the elements of VR for each project category.

3.2.1 Category Mapping

In the first step, in order to determine how effective each project category was at utilizing VR, the results of the previously described flowcharts were mapped on to a rubric. Each project was assigned to one or more categories: visualization, simulation, training, education, entertainment, and art. Each row of the rubric described a specific project, and each column described a specific project category. If a project belonged to a category, a value of 1 was placed in the cell. If a project did not belong to a category, a value of 0 was placed in the cell. An example of two projects entered into the rubric is shown in Table 6.

Table 6

Flowchart Results Were Entered into a Rubric for Evaluating the Effectiveness of VR for Each Category

| Project Name | Category Mapping | | | | | |
|-------------------|------------------|------------|-----------|----------|---------------|-----|
| | Visualization | Simulation | Education | Training | Entertainment | Art |
| Example Project 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| Example Project 2 | 1 | 1 | 0 | 0 | 0 | 0 |

3.2.2 Requirements Analysis

The problem statement for each project contained one or more requirements. Each requirement was supported by one or more of the elements of VR: immersion, interaction, navigation, and virtual environment. In the second step, each requirement for every project was similarly assigned to specific VR elements as indicated in each row of Table 7. If a specific requirement was supported by a specific element of VR, then a value of 1 was placed in the cell. If the requirement was not supported by a specific VR element, a value of 0 was placed in the cell.

Table 7

An Example Table Showing the Effectiveness of VR by Comparing Project Categories and Their Usage for Each Element of VR

| Project/Requirement | Requirements Analysis | | | |
|-----------------------------------|-----------------------|-------------|------------|---------------------|
| | Immersion | Interaction | Navigation | Virtual Environment |
| Example Project 1 / Requirement 1 | 1 | 1 | 0 | 1 |
| Example Project 1 / Requirement 2 | 1 | 1 | 1 | 1 |

3.2.3 Effectiveness Score

To determine the effectiveness of the application of the elements of VR for each category of project, a score was computed as follows.

The binary value assigned to each cell in the requirements analysis table, for each VR element was summed and normalized by the total number of projects assigned to that specific category. This effectiveness score, which has a value between 0 and 1, is an indicator of how much of each VR element was employed to address the requirements for each specific project category. An effective score of 1 indicates that the specific VR element was most effectively used for that specific category of project. If all projects made maximum effective use of each element of VR, then a table summarizing these results would all have values of 1.

Table 8

An Example Table Showing the Effectiveness of VR by Comparing Project Categories to Their Usage of the Elements of VR

| | Immersion | Interaction | Navigation | VE | Project Count |
|----------------------|-----------|-------------|------------|-----|---------------|
| Visualization | 0.9 | 0.3 | 0.5 | 0.9 | 10 |
| Simulation | 0.6 | 0.7 | 0.9 | 1.0 | 5 |
| Education | 0.1 | 0.8 | 1.0 | 1.0 | 8 |
| Training | 0.5 | 0.7 | 0.8 | 1.0 | 6 |
| Entertainment | 0.0 | 0.0 | 0.5 | 0.5 | 4 |
| Art | 0.5 | 1.00 | 1.0 | 1.0 | 3 |

In Table 8, the first row contains the results for all visualization projects. In this example, the final column contains the number of projects that were categorized as

visualization. The immersion score is 0.9, which when multiplied by the project count indicates that nine out of the ten projects utilized this element. Interaction, the lowest score within the row, has an effectiveness score of 0.3, meaning that only 3 of the 10 projects utilized interaction.

3.3 Summary of VR Hardware Technologies

Table 9

Summary of the ImmersaDesk R2 VR System

| ImmersaDesk R2 | | | |
|-----------------------|--|--|---|
| Description | A transportable, VR system integrated into a shipping container. Meant for trade shows and marketing events with a setup time of under thirty minutes and a tiltable screen for either immersive or birds-eye formats. | | |
| Size (w,h,d) | Folded: | 1.96m x 1.60m x 0.86m | |
| | Operation: | 1.96m x 1.16m x 2.31m | |
| Interface | Display | 4:3 CRT projector with stereoscopic enhancements | |
| | | Proportions | 4:3 |
| | | Screen | 2.08m (diagonal) |
| | | Resolution | 1280 x 1024 |
| | 3D | IR StereoGraphics CrystalEyes active shutter glasses | |
| | Tracking | Head | Ascension Flock of Birds Magnetic Tracking System |
| Wand | | Fakespace WorldWand with 6 DOF and three buttons | |
| Software | vGeo, WorldViz Vizard, Trackd | | |
| Computer Setup | 1 dual purpose server / client computer | | |

Figure 24

The Fakepace Systems ImmersaDesk R2 Was a Transportable VR System That Could be Setup in Under Thirty Minutes

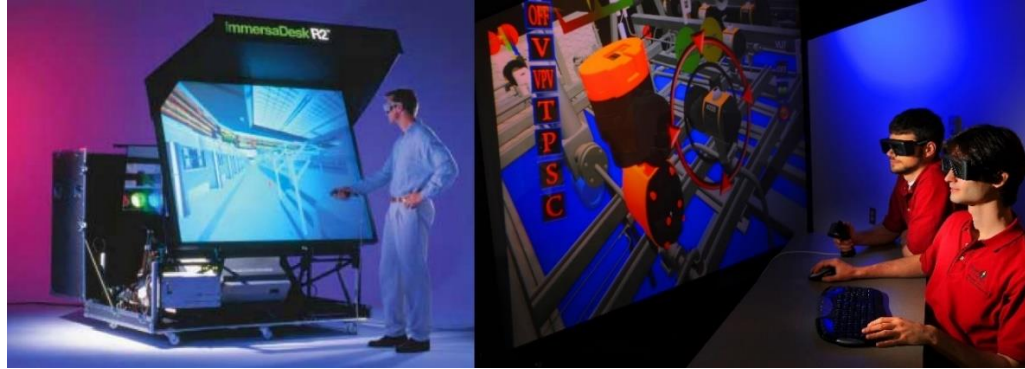


Table 10

Summary of The CAVE (C4) VR System

| CAVE™ Immersive Environment - 4 Sided (C4) | | | | |
|---|---|---|---------------------|-----------------------------|
| Description | Small group (2-3) walk-in immersive environment with left, front, right and floor projection utilizing short-throw lens and mirrors for collaborative VR experiences. | | | |
| Size (w,h,d) | 7.65m x 3.3m x 5.4m | | | |
| Interface | Display (x4) | Christie Mirage S+ 3k | | |
| | | Proportions | 4:3 | |
| | | Screen | 3m x 2.13m | |
| | | Resolution | 1400 x 1050 @ 101hz | |
| | 3D | CrystalEyes Model CE-3 Shutter Glasses | | |
| | Tracking | Position: PPT-X 8 camera infrared tracking system | | |
| Orientation: Intersense Wireless InertaiCube3 | | | | |
| Audio | Custom 2-channel speaker setup | | | |
| Software | WorldViz Vizard | Unity + GetReal3D | Trackd | WorldViz PPT Studio 2008 |
| Computer Setup | Pre-2020: | 1 server, 4 render clients, 1 tracking | | |
| | Post-2020: | 1 combined server / render, 1 tracking pc | | |

Figure 25

Mechdyne CAVE (C4) VR System

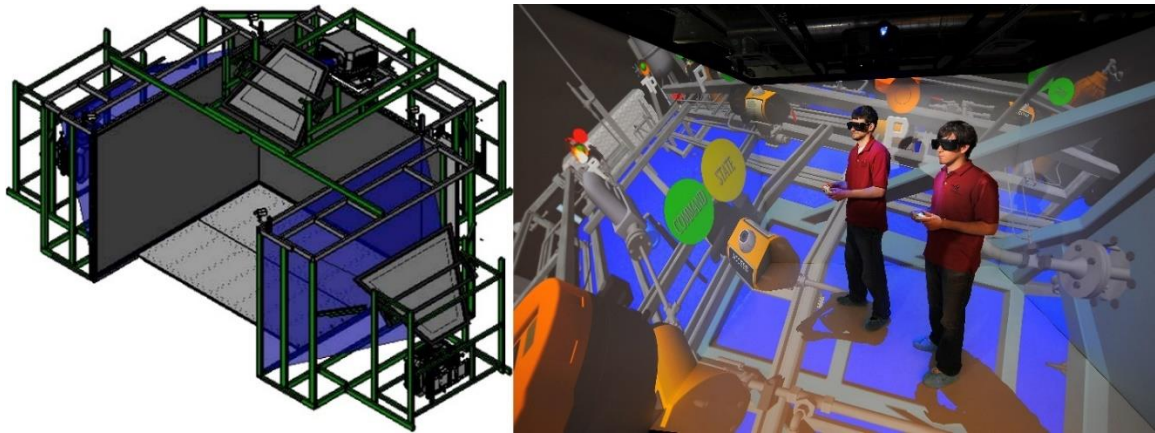


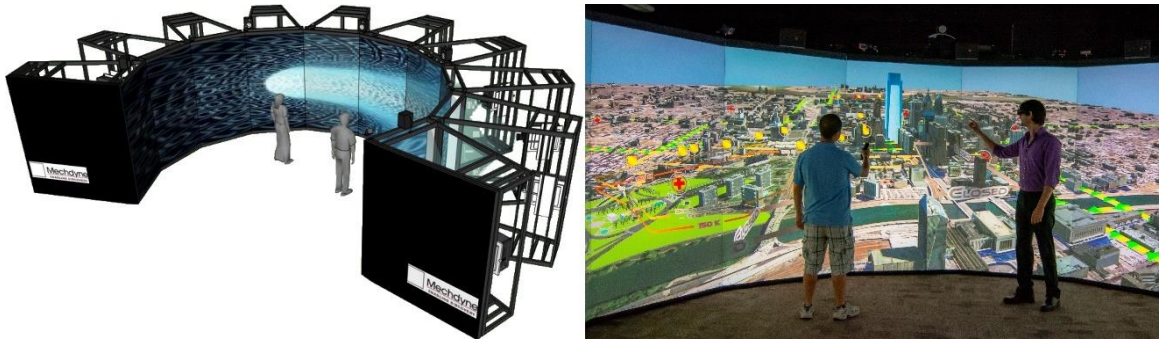
Table 11

Summary of the CAVE (C12) VR System

| Projector-based CAVE-2™ Immersive Environment (C10) | | | | | |
|---|---|---------------------------------------|------------------------------------|-------------------------|-------------------|
| Description | Large group (10+) immersive environment composed of 10 portrait-oriented projectors forming a semi-circle meant for immersive VR or multi-source video compositing. | | | | |
| Size (w,h,d) | 7.65m, 3.3m, 5.4m | | | | |
| Interface | Display (x4) | Digital Projection Titan LED | | | |
| | | Proportions | 16:9 | | |
| | | Screen | 3m x 2.13m | | |
| | | Resolution | 1920x1080 @ 120hz (locked to 60hz) | | |
| | 3D | XPAND3D X103 Infinity Shutter Glasses | | | |
| Tracking | Trackpack8 System - 8 ART Optical Tracking Cameras | | | | |
| | 2x Flystick2 | Flystick 3 | 2x Xbox 360 Controllers | Retroreflective markers | |
| Audio | 5.1 JBL Speaker system | | 10x Tannoy CVS4 mono speakers | | |
| Software | WorldViz Vizard | Unity & GetReal3D | Trackd | ART DTrack | Meeting Canvas |
| Computer Setup | 1 server, 5 render clients, 3 tracking clients, 1 composite server | | | | |

Figure 26

Mechdyne CAVE 10-Sided System



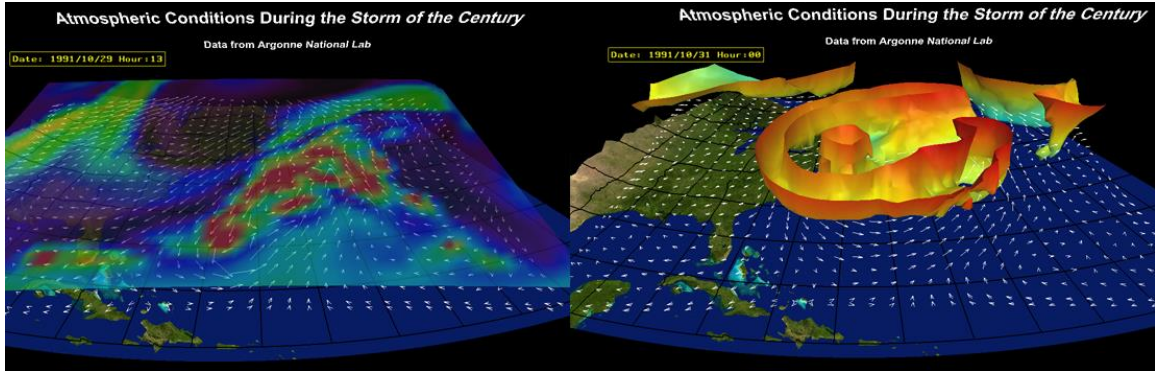
3.4 Summary of Enabling Software Platforms

3.4.1 VRCO Virtual Global Explorer & Observatory (vGeo)

VRCO vGeo is a virtual reality software platform that handles the graphics application programming interface (API) for virtual reality environments, specifically targeting scientific data exploration by reading topographic measurements and 3D models in the WRL format. Its primary focus was to easily generate visuals from data sources by producing isosurfaces, vectors, contours, textures, polylines, and text. While vGeo supported many other features, it was primarily used within the Rowan VR Center to display 3D models in the WRL format and generate data visualizations that could be navigated using a wand and head tracking unit. VRCO vGeo streamlined the generation of visuals and handled the interface between software and hardware. However, difficulty in programming new forms of interaction or accessing low-level functionality made it difficult to apply to problem domains outside of visualization. For this reason, the software fell out of use in favor of WorldViz Vizard.

Figure 27

VRCO VGeo Demonstration of Weather Data Visualized Through Vector Lines, Heatmaps and Isosurfaces



3.4.2 WorldViz Vizard

WorldViz Vizard is a VR application meant to accelerate the development of VR environments, while allowing real-time interactive scripting through the Python language. By utilizing the high-level Python language, it was easy enough to program for students within a semester to create simple virtual environments. It allowed for virtual reality environments to be made with little understanding of the graphical API functions yet allowed for advanced techniques through a series of python-to-C++ hooks, unlocking the ability to write custom shaders and control the graphical pipeline beyond what was possible with vGeo. The only issue with Vizard was that in certain circumstances, the performance of the Python language inhibited development. While the software provided the ability to create C++ plugins for performance critical tasks, it was not always simple to integrate. Eventually, the VR Center moved to the Unity engine and the GetReal3D plugin due to cost, performance, compatibility, and a larger support community.

3.4.3 Unity Real-Time Engine + GetReal3D Plugin

The Unity real-time engine started as a single platform solution for working on projects that required support for nearly any form of hardware, from mobile devices to console platforms. As more clients requested to have their virtual worlds deployed on commercially available hardware or across multiple platforms, this software became more useful. While not as fast as designing a VR application from the ground up using OpenGL, DirectX or the latest APIs, Unity provides significant performance, a well-designed software architecture, a large amount of pre-built features, and the ability to customize graphics through a customizable shader pipeline. The program is familiar to many, used to develop indie titles, real-time visualizations, and near-cinema quality movies. The GetReal3D plugin provides a simplified interface for using Unity with academic VR systems, such as the computer cluster rendering to CAVE systems. It is currently the chosen software to use when developing VR, AR or MR environments at the Rowan VR Center and no plans have been made to migrate to other software in the foreseeable future.

Chapter 4

Results

The following thirty-five projects were implemented between 2003 and 2020 at the Rowan University Virtual Reality Center. During this period, a variety of sponsors and partners sought to utilize VR to fulfill their project requirements. Projects ranged from the visualization of synthetically generated sand particles to enhancing the education of high school students about the events that transpired during the Holocaust. VR implementations utilized a variety of hardware and software.

The results are organized by project category. Each project lists a description of the problem statement and the final implementation, which includes a description and a flow chart depicting how the elements were utilized.

The final section summarizes the effectiveness scores for each project category for the elements of VR.

4.1 Visualization Category

4.1.1 3-D Characterization of Angular Materials (2002 - 2006)

Figure 28

Elements of VR Applied to Visualize and Compare the Shape Characteristics of Sand Grains

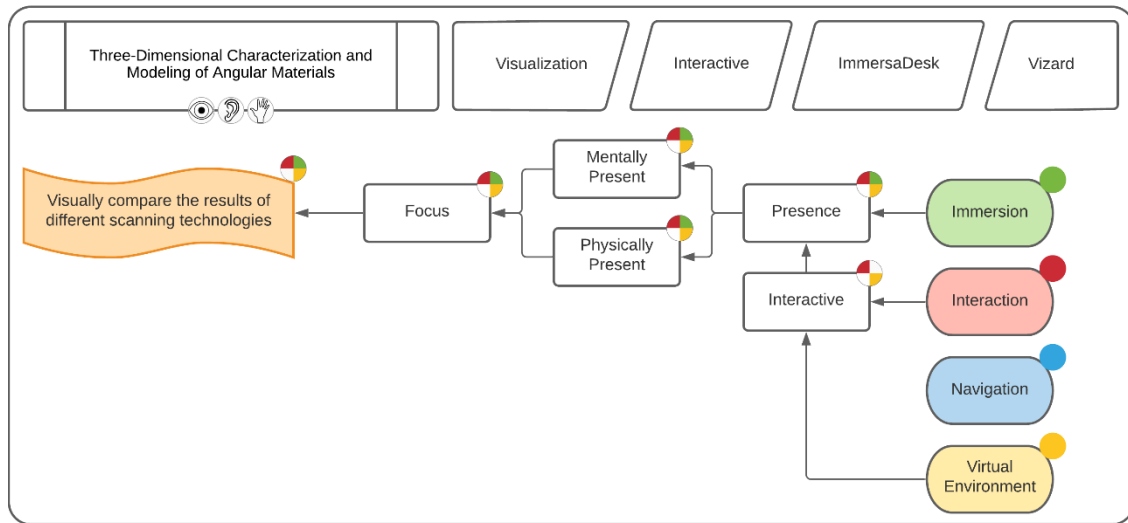
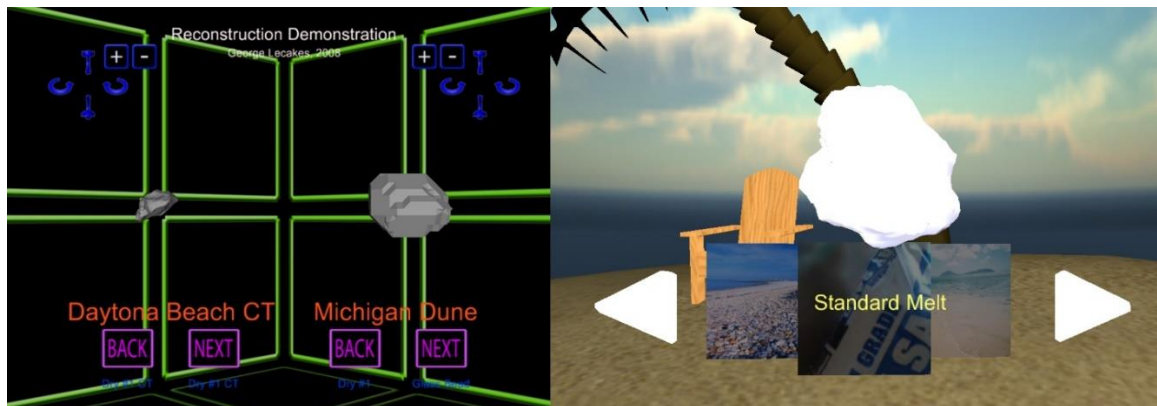


Figure 29

CT Scanned Sand Particles Were Compared Against Other Scanning Techniques (Left) and Sand Samples From Various Locations Around the World Were Compared (Right)



4.1.1.1 Problem. VR was utilized to assist in the validation and visualization of results obtained from an automated image processing algorithm that estimates the 3-D shape descriptors of particle aggregates for use in discrete element modeling. A CT scanner represents the gold standard for evaluating more cost-effective systems such as optical tomography [103].

4.1.1.2 Implementation. Different varieties of sand particles were scanned using a several different methods including optical tomography that produced 3D models. Descriptors were generated for each variety of particle, which were used to create synthetic particles for studying compaction. A user interface was created to compare the gold standard 3D models to the synthetic particles.

Figure 28 shows that three of the four elements of VR were utilized to meet the project requirement of visually comparing the results of different scanning technologies. Through the use of a virtual environment, interaction, and immersion, the level of mental and physical presence of the user was meant to lead to greater focus when visually comparing the particles. Users were able to interact by rotating the particles using a magnetically tracked wand. A second orientation tracker was added to for the user to control two particles and allow for interparticle collisions controlled. A touch-sensitive foot-operated controller was included to allow the user to cycle through the different 3D models while controlling the position and orientation with each hand.

The project had no method to navigate within the virtual world, as the primary focus was the visual comparison of the particles. By visualizing the models within a 3D

stereoscopic environment, it sought to utilize both mental and physical presence to enhance the user's understanding of the sand grains.

There was no need to create a fully immersive scene, as the inclusion of an environment as shown in Figure 29 provided no noticeable benefit. Force-feedback as well as inter-particle physics simulation between the surfaces of two particles sought to engage the sense of touch and focus the user for longer periods of time.

4.1.2 Children's Hospital of Philadelphia Child Skeleton (2009 - 2012)

Figure 30

Elements of VR Applied to CHOP Cadaver Data

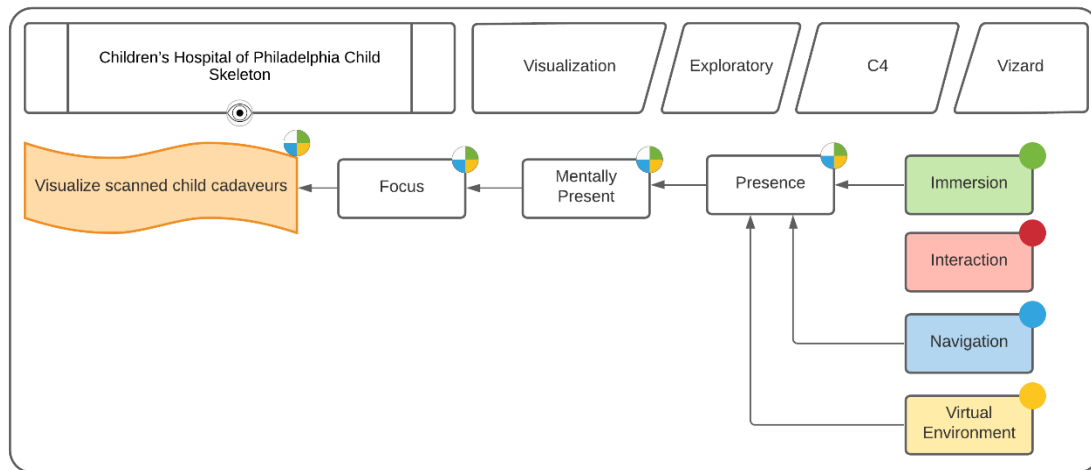
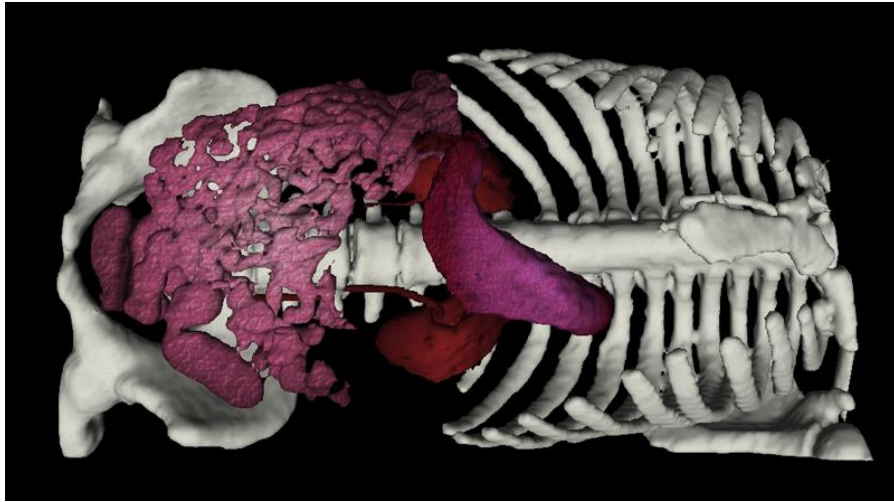


Figure 31

A Textured and Animated CT Scan



4.1.2.1 Problem. Child cadavers are in rare supply and virtual cadavers could play an important part in training medical residents.

Implementation. Volumetric data from CT scans were converted into triangulated meshes using a marching cubes algorithm [104]. Marching cubes treats the scan data as a volume of pixels called voxels and looks for differences in image intensity between each voxel to generate a surface mesh. Through careful thresholding, a triangle mesh can be generated that separates the regions of anatomy based on density and connectivity. The generated model was then subdivided to separately colorize the skeleton and organs using textures taken from photographic reference material (Figure 31). The subdivided elements were animated to create an exploded view of the cadaver and used an Xbox 360 controller to control the sequence. When activated, the chest and organs individually extended outwards for their initial location to allow the user to inspect each element

without occlusion. The controller was used to navigate through the virtual environment beyond the extents of the CAVE system. Custom vertex and pixel shaders were created to provide the appearance of soft living tissue. Collaborators from the Children's Hospital of Philadelphia (CHOP) viewed the results in the C4 system. Residents were also brought in to view the demonstration the future possibilities of blending medicine with VR.

As shown in Figure 30, this project relied on the virtual environment, navigation, and immersion to meet the requirement of creating a virtual environment to explore scanned child cadavers. The virtual environment consisted of the scanned child cadaver and navigation was achieved through motion-tracking sensors attached to the stereoscopic glass for walking within the CAVE as well as an Xbox controller. Immersion was achieved through use of the large, stereoscopic, 3D displays to enhance mental presence and focus. No direct form of interactivity was implemented in the demonstration. The animations to explode the virtual cadaver were scripted and could not be altered at runtime.

4.1.3 Living and Learning Center (2011 - 2012)

Figure 32

Elements of VR Applied to an Architectural Concept for a Living and Learning Center

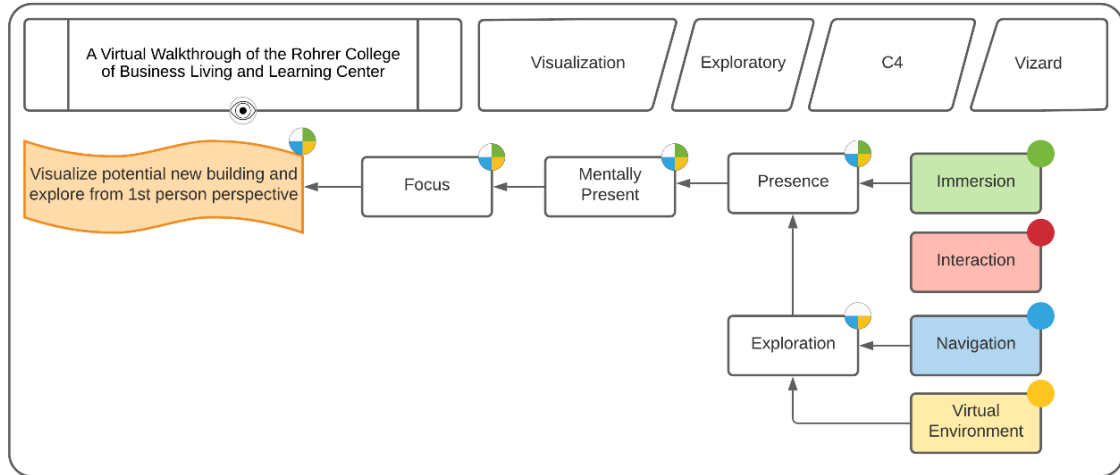
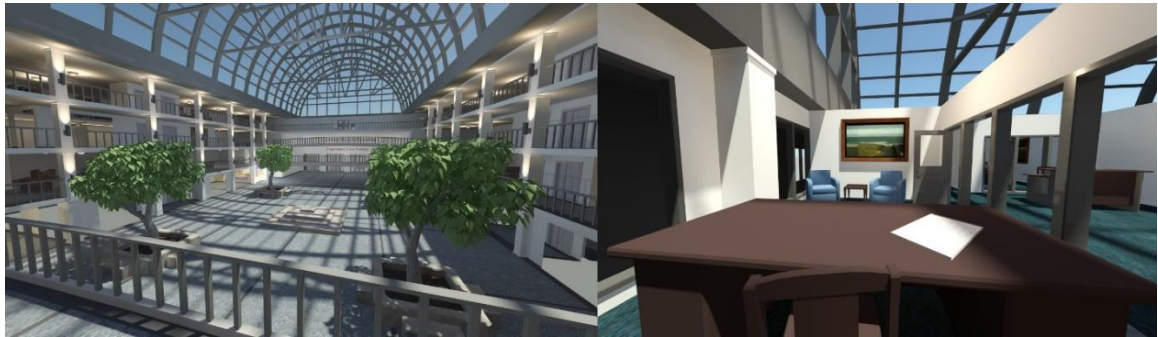


Figure 33

The Atrium and Offices Spaces Were Enhanced with Light Baking to Create Realistic Global Illumination in this Learning Center



4.1.3.1 Problem. As part of an advertising campaign, the Rohrer College of Business desired a VR walkthrough of a proposed living and learning center for students, faculty, and staff.

4.1.3.2 Implementation. Based on conceptual designs from other similar centers, a 3D walkthrough of a virtual building was created with two wings for living spaces, offices, and classrooms extending from a central glass-enclosed hallway. The VR environment was deployed in the C4 system.

Figure 32 shows that all elements of VR were used except for interaction to achieve the goal of visualizing the proposed living and learning center. The virtual environment consisted of the entryway, classrooms, and a stock room. Navigation was controlled by motion trackers on the 3D glasses for moving with the bonds of the C4 system and an Xbox 360 controller to move between locations.

No form of interaction was implemented, as the primary goal was to utilize the immersive properties of VR and the 3D visual representation of the building to create the feeling of mental presence and focus to engage the viewer (Figure 33).

4.1.4 Joint Virtual Reality Laboratory for Neuroimaging (2013 - 2015)

Figure 34

Elements of VR Applied to Visualizing Medical Data

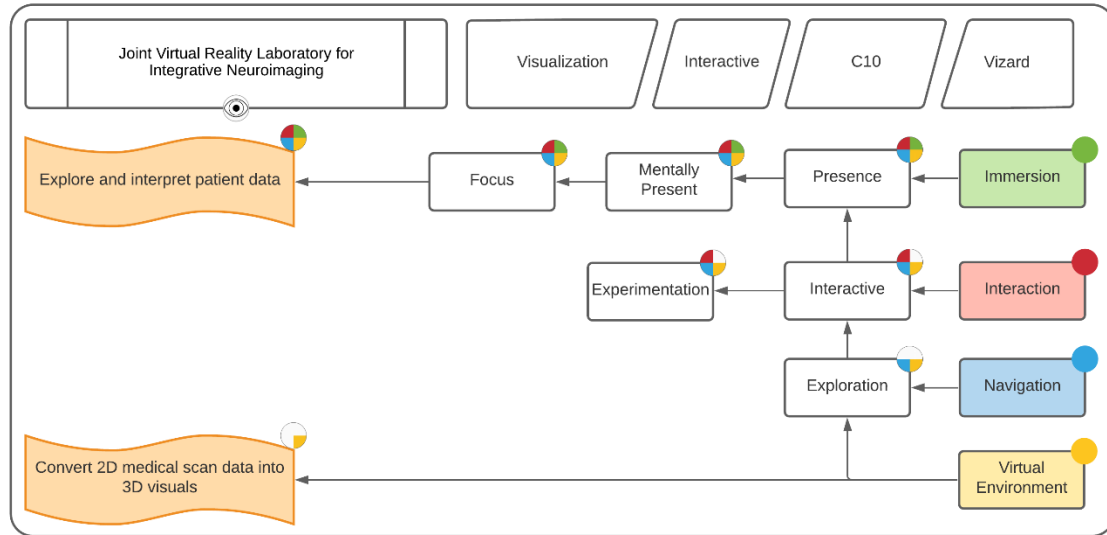


Figure 35

Initial Volume Rendering in C4 Produced Semi-Transparent Imagery (Left) and by Assigning Color to Regions of Specific Density, Cement Within a Spinal Column was Highlighted (Right)

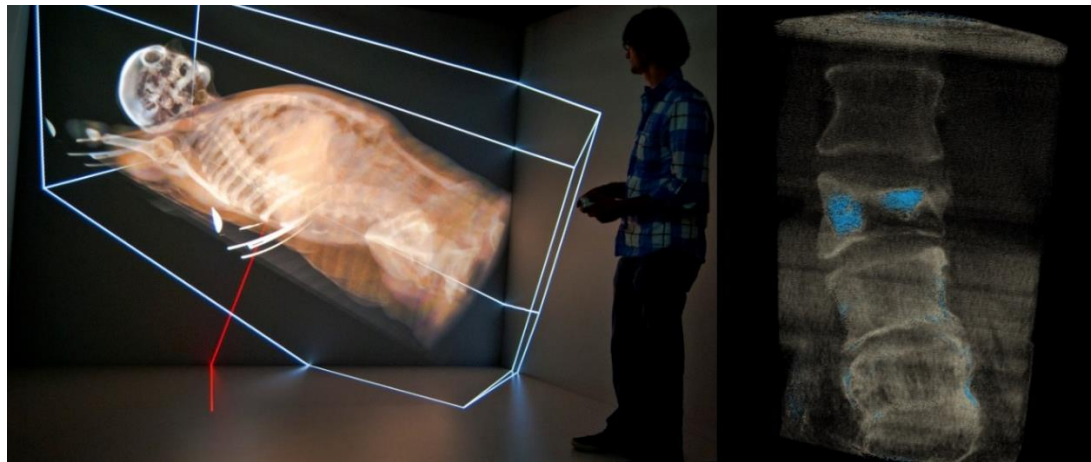


Figure 36

Anatomical Labeling System Used 3D Locations and Camera-Oriented Text to Highlight Anatomy (Left) and EEG Markers on the Brain (Right)

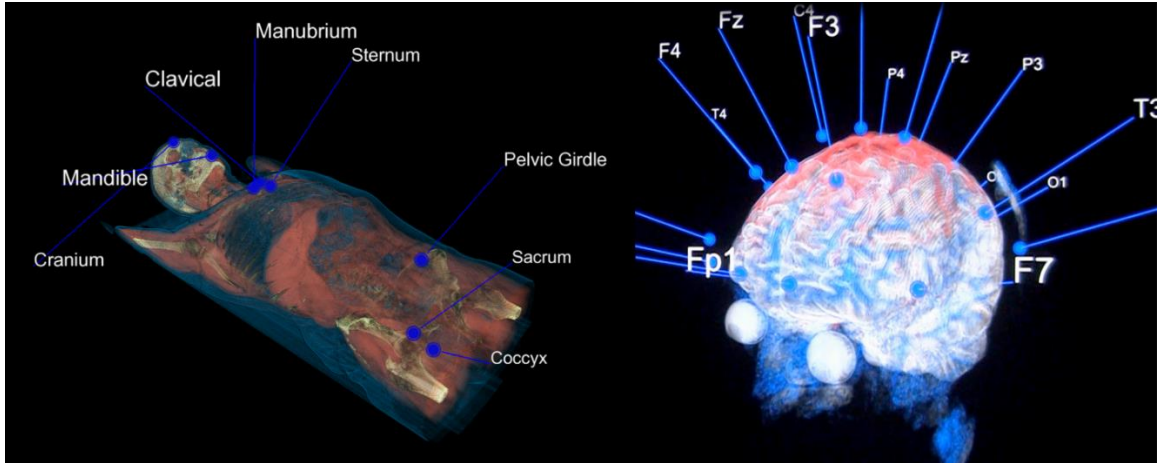


Figure 37

Using a Clip Plane, Segments of the Model Were Removed to View Interior Structures



4.1.4.1 Problem. Existing three-dimensional visualization platforms do not provide for intuitive correlation of clinical information from multiple diagnostic imaging procedures, nor do they provide users with any measure of prognostic capability. By

using VR as a platform for the integrating visualizations of multiple radiological imaging modalities including: CT, MRI, PET, and MEG, multiple image data sets inside a CAVE™ VR environment can provide a group of users the ability to distinguish redundant and complementary information for clinically applied anatomical discoveries. The interactive capability of the virtual reality environment allows users to ask, “what if?” questions and simulate multiple scenarios for pathological anatomical diagnosis, providing a powerful and intuitive platform for diagnosis and prognosis.

4.1.4.2 Implementation. Volumetric rendering techniques were used to visualize CT scan data into VR visualizations. By combining ordered arrays of 2D scans into a 3D texture and generating a series of transparent planes rendered from back to front, a volumetric visualization was produced. As the viewer navigated through the environment, the intersecting planes were continually updated so that they always faced the viewer. Figure 35 shows one of the first implementations inside the C4 system with a white bounding box representing the extents of the scanned data. Through the use an Xbox controller, real-time histogram manipulation interactivity was implemented that culled regions based upon density and allowed regions to be colorized. On the left of Figure 35 is a visualization of bone cement (in blue) meant to stabilize spinal compression fractures. By evaluating the number of voxels that occupy the blue region it is possible to estimate the volume of material used at the injected site, something difficult to determine using the techniques. Additional uses of the system were explored including anatomical labelling and electro-encephalography electrode placement (Figure 36). The visualization was migrated to the C10 system, where the larger displays provided groups between five and fifteen viewers a collaborative experience. Additional visualization

techniques were added to allow the body to be virtually cut from any angle and mapped to multiple colors (Figure 37).

Figure 34 shows that all four elements were utilized to accomplish the requirements of converting 2D scan data into a 3D visualization for exploration. The virtual environment consisted of the scan data visualized as a volume field. Pairing the visualized data with navigation through an Xbox controller provided exploration. Interactivity was accomplished by providing the user with controls to alter how the dataset was visualized including what volume regions were displayed and how they were colored. The stereoscopic displays of both CAVE™ systems were used to enhance immersion, providing a sense of mental presence, and enhancing focus while exploring the dataset.

4.1.5 Camden Health and Science Campus (2014)

Figure 38

Elements of VR Applied to Visualizing a Future Camden

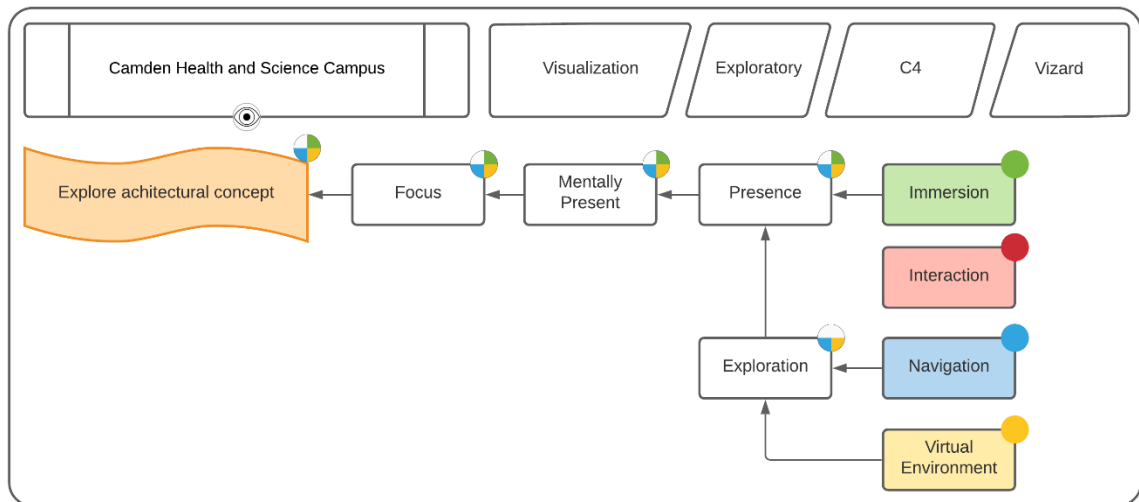


Figure 39

A Visualization of Cooper Hospital and the Medical School in 2014, Where the Participant Could Overlay Future Building Expansions



4.1.5.1 Problem. The Rowan University President’s Office requested a virtual walkthrough of a yet-to-be-conceived Health and Science Campus in Camden, NJ. At the time, Rowan had newly partnered with Cooper Hospital to create the Cooper Medical School at Rowan University. The goal was to create a virtual representation of a future Camden where the medical school expanded into a joint campus for all health and science disciplines.

4.1.5.2 Implementation. Using aerial photography, CAD models of the medical school, and imagery from various buildings that the President’s office wanted to use as inspiration, a virtual environment of the Cooper Hospital and surroundings was created. Two environments were designed to represent present-day Camden and a future Health and Science Campus. Alternating between the environments was accomplished with an Xbox controller. Five buildings were designed and several assets from earlier architectural demonstrations including the Living and Learning Center were re-purposed.

The Xbox controller was used to navigate the environment and move between different spaces including an operating room, building lobby, and classroom spaces.

In Figure 38, the elements of virtual environment, navigation, and immersion were applied to accomplish the goal of exploring an architectural concept. The virtual environment consisted of both the current and future visualization of Camden. Navigation was controlled through a position and orientation sensors on the stereoscopic glasses worn by the user inside the C4 system. This provided navigation when moving within the bounds of the system while an Xbox controller was used to move outside the C4's perimeter. No form of interaction with the environment was programmed into the virtual environment. Finally, to enhance focus of the viewer through mental presence, immersion was used through the use of stereoscopic glasses and texture light-baking for enhanced realism.

4.1.6 Papal Visit to Philadelphia Event Visualization (2015)

Figure 40

Elements of VR Applied to a Visualization of the Pope's Visit to Philadelphia

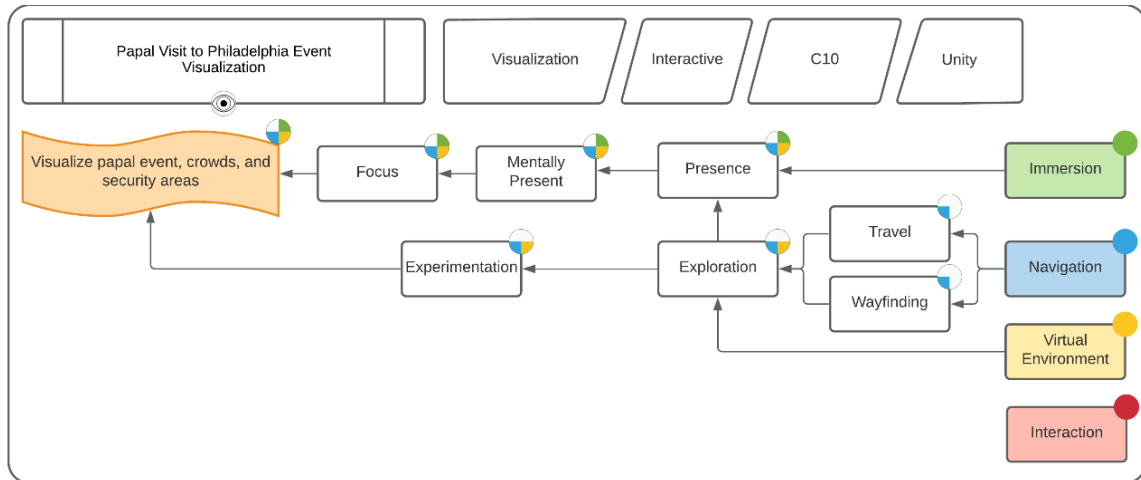


Figure 41

Using Publicly Available Event Information, Visualizations Were Created to Explore the Pope's Visit to Philadelphia in the Future



4.1.6.1 Problem. NBC10, as part of their coverage for Pope Francis' visit to Philadelphia, requested a virtual tour of Philadelphia with information about event locations, crowd size projections, logistics and security.

4.1.6.2 Implementation. Using satellite imagery and 3D extrusions of buildings, a virtual representation of Philadelphia was created and deployed on the C10 system. Publicly accessible information about event routes, street closures, and security checkpoints were overlaid on the city. Using crowd density estimates based on analysis of riot crowd density, visualizations were created to display the expected number of people that would fit in front of the Philadelphia Museum of Art for Sunday mass. Later, the demonstration was repurposed to show planned evacuation routes for emergency management.

Figure 40 shows that all elements except for interaction were utilized within the VR environment to accomplish the requirement of visualizing the papal event. The virtual environment case composed of a portion of the city of Philadelphia as well as markers and routes for the event. Due to the scale of the scene, navigation was primarily controlled by an Xbox controller, although the head was still motion tracked. Navigation was composed of travel and wayfinding, leading to exploration of the city. Even with a lack of interaction, experimentation was still possible by displaying the distance from the user's current position and the distance to the Pope. This allowed for a security expert to hypothesize where security restrictions would be located during the event. Finally, immersion through the use stereoscopic visuals and the large panoramic displays of the C10 sought to enhance focus through mental presence.

4.1.7 Fovea Drone Captured Imagery Visualization (2015 - 2016)

Figure 42

Elements of VR Applied to Visualizing Drone Photography

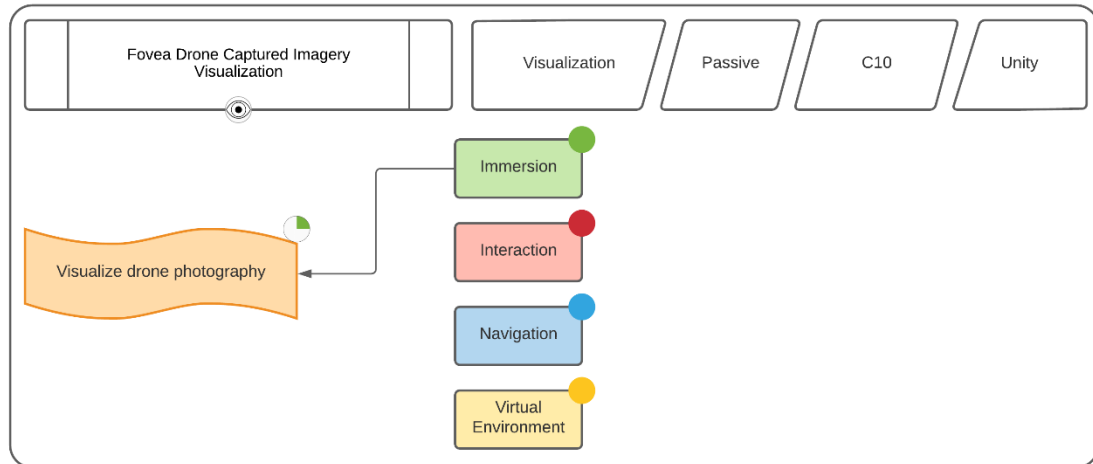


Figure 43

Visualization of I-295 During Construction



4.1.7.1 Problem. Fovea Aero Systems LLC wanted to explore using the large-scale C10 VR environment for visualizing their drone footage that recorded the progression of construction sites along I-295.

Implementation. Fovea's imagery was displayed on the large-scale C10 VR system without head tracking (Figure 43). The display was not in stereo, and all the imagery was of individual photographs with no video footage. There was no actual navigation, instead the 360-degree view was switched between several locations that had been captured by the drone and controlled through a web browser interface. As shown in

Figure 42, to accomplish the requirement of visualizing the provided drone photography, only the element of immersion was utilized. The immersive qualities of the large-scale and wide field-of-view C10 displays were utilized. The data itself was accessed through a web browser interface and there was no capability to integrate this into a 3D environment at the time. Since no virtual environment existed, there was no form of navigation or interaction with the imagery.

4.1.8 FAA Live Drone Visualization (2016)

Figure 44

Elements of VR Applied to Visualizing a Live Drone Demonstration

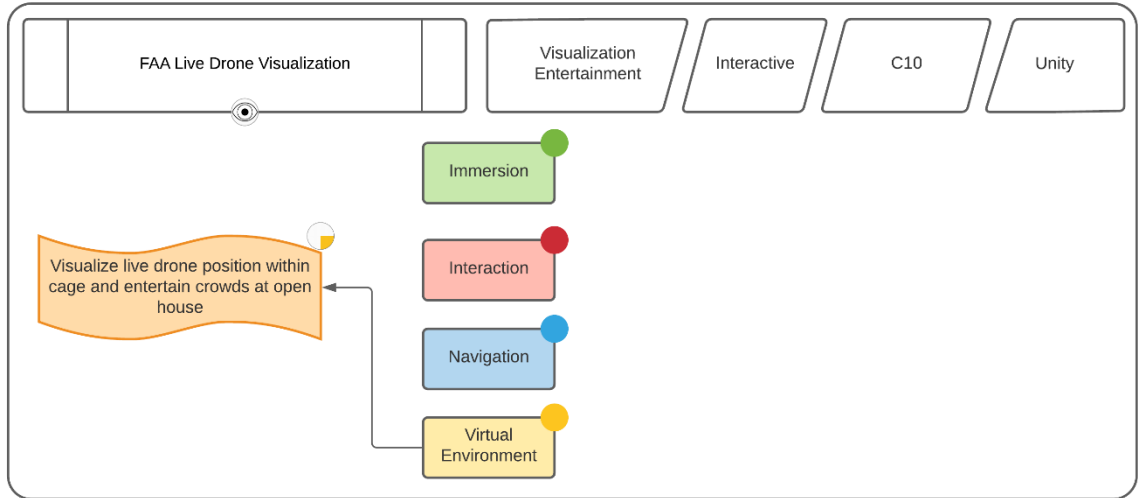


Figure 45

Live Video Feed From the Drone's Forward Camera Were Used to Determine the Position and Orientation of the Drone



4.1.8.1 Problem. The FAA requested that the Rowan VR Center utilize a custom network protocol to transmit live drone data from their location at the William J. Hughes Technical Center to the South Jersey Technology Park's C10 CAVE system. Within the CAVE, the data would be used to visualize the near real-time location of a drone within a cage at their facility.

4.1.8.2 Implementation. A live network stream was setup between the two sites that sent User Datagram Protocol (UDP) packets consisting of the position and orientation of a drone within a real-life cage to the VR Center for visualization within the C10 system. The position calculations for the drone were performed using a series of markers placed within the cage. The results from triangulating the position and orientation were then sent from the FAA's location and transmitted to the Rowan VR Center's visualization systems where the UAV was visualized and tracked. Live video feed from the drone was used to detect the markers and triangulate its position and orientation relative to the cage.

Position and orientation tracking were implemented using OpenCV in Visual Studio 2015. The OpenCV contribute libraries were used to access the ArUco functionality, which was capable of calibrating, detecting, and determining the location of markers relative to the drone. With the markers position at known locations with the cage, it was possible to utilize matrix transformation to convert the detected markers into the position of the drone relative to the cage. The drone cage was designed by a team of Rowan Electrical and Computer Engineers and Mechanical Engineers. The Parrot Bebop and 3DR Solo were flown within the drone cage for a live event.

Figure 44 shows that to reach the project requirement of visualizing the position of a drone, only the virtual environment element was utilized. The virtual environment consisted of a partial model of the William J. Hughes Technical Center, a drone cage, and a Bebop drone. There was no form of navigation or interaction for the user, and the demonstration operated as a passive experience. Stereoscopic 3D was also not utilized since visitors were seeing a live video feed of the C10 environment at the FAA’s site and would not be able to use stereoscopic glasses.

4.1.9 Glassboro Future Arts Flythrough (2018)

Figure 46

Elements of VR Applied to an Arts District in Glassboro, NJ

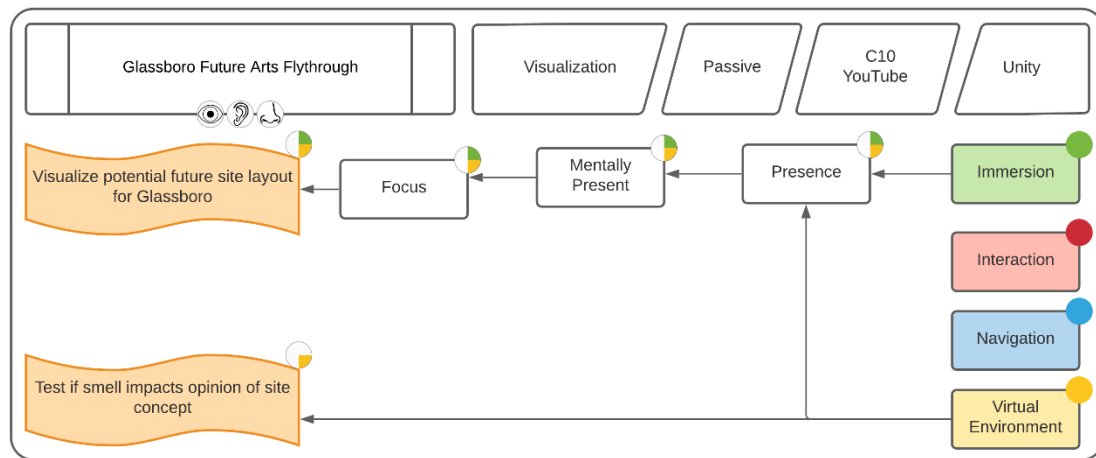
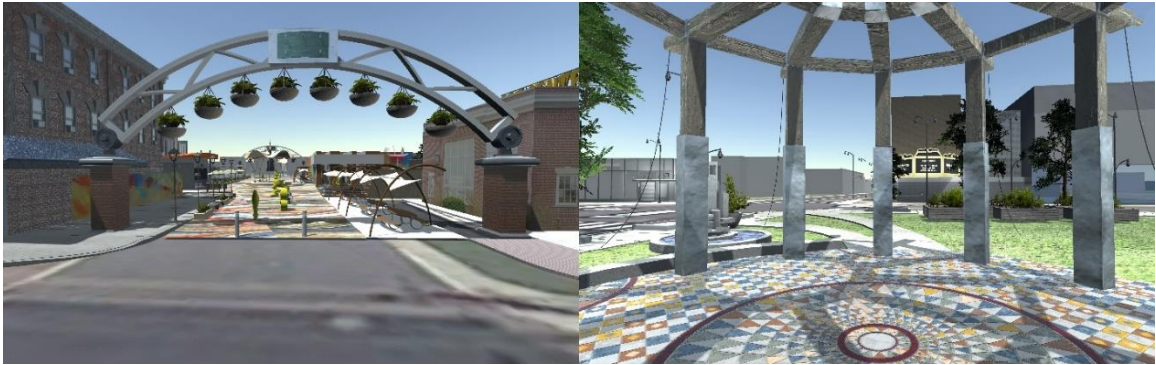


Figure 47

A Concept of the Future Arts District in Glassboro, NJ



4.1.9.1 Problem. By visualizing potential future designs for Glassboro, New Jersey, an attempt was made to measure if immersive VR technology has significant advantage over 3D GIS visualizations in order to interpret alternative future scenarios. The sponsor wanted to determine whether sensorial experiences could help participants respond better to VR simulations; and if multi-sensorial and atmospheric experiences can enhance participatory planning process, specifically the sense of smell.

4.1.9.2 Implementation. Using CAD documents exported from SketchUp by Rowan Geography students, the future Glassboro site was enhanced for real-time visualization. The models described a concept design for a future Glassboro Arts District. A bladeless fan and a collection of different scents were used to transmit the smell of grass and popcorn at different locations within the VR simulation. Groups of students were brought to see the visualization, both with and without the aromatics present. In order to keep the experience, the same, a pre-recorded flythrough of the location was

used to navigate. In addition to smell, 3D spatial sounds were added of a performer playing within the center arts district.

This was the first and only example of the VR Center utilizing the sense of smell. While initially, a prototype device was constructed that would both distribute smells throughout the space and detect particle concentrations in the air, due to budgetary restrictions, it was not completed. No direct interaction was allowed in the simulation, and it was viewed by groups of up to 15 at a time.

Figure 46 shows that only the virtual environment and immersion elements of VR were utilized to meet the requirements of creating a visualization of a future Glassboro Art's district and testing whether smell would impact the opinion of viewers. The virtual environment consisted of the SketchUp models that were conditioned to be rendered within a real-time experience. Immersion was accomplished through the large-scale C10 system, stereoscopic view, and aromatics to enhance focus and mental presence.

4.1.10 IVA Entertainment Database Visualization (2019)

Figure 48

Elements of VR Applied to Data Visualization of Higher-Dimensional Relational Databases

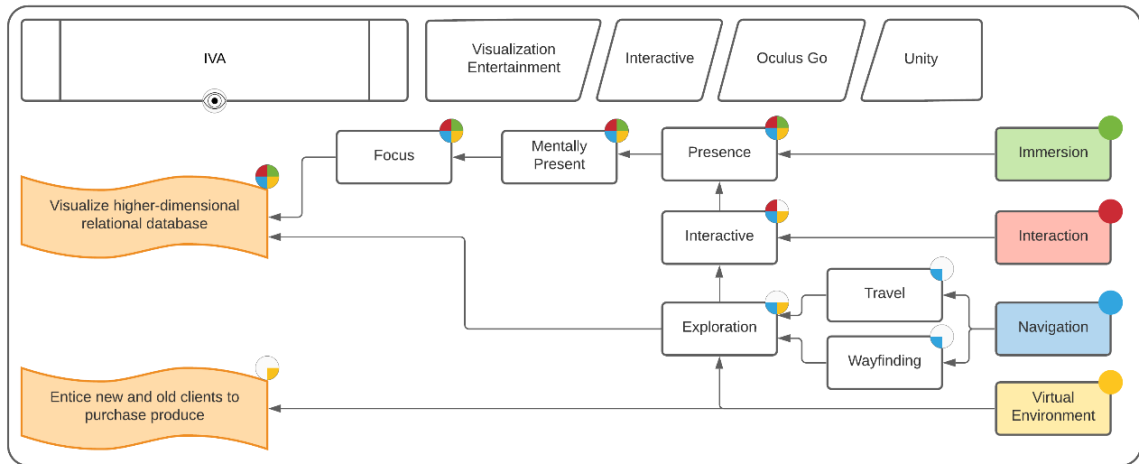
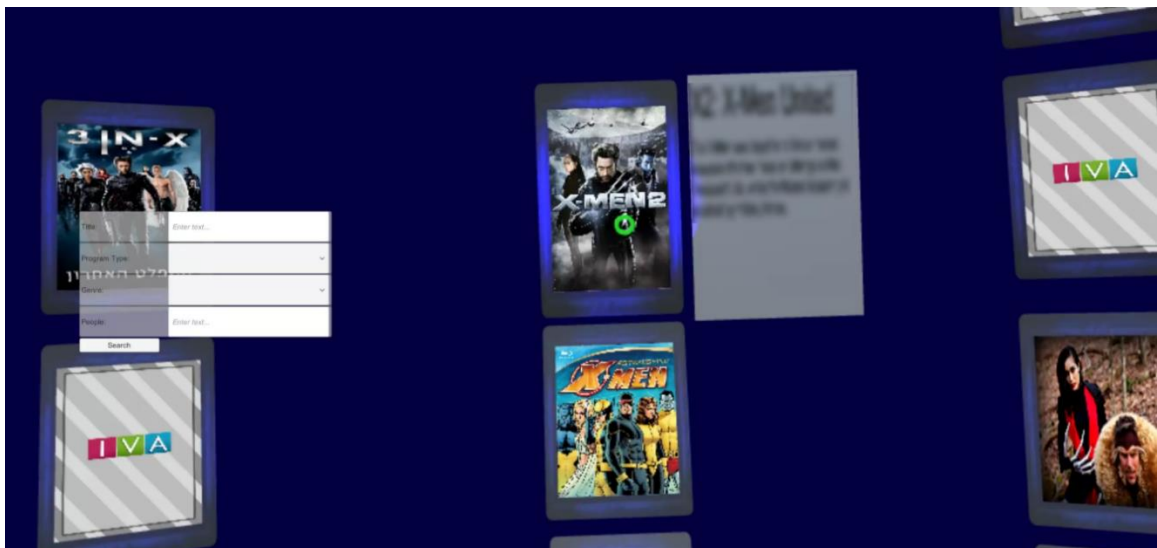


Figure 49

Entertainment Data was Visualized Within an Oculus Go for Browsing a Relational Database



4.1.10.1 Problem. RVRC was contracted by IVA, which provides discovery experiences through large relational databases of movies, television shows, and games. IVA desired a VR solution for displaying and navigating their comprehensive entertainment database. The experience would be shown during technology demonstrations by their sales team at tradeshow and other conventions such as 2020 CES.

4.1.10.2 Implementation. Over the course of 9 months, a VR application for the Oculus Go was developed to display the company's relational database of entertainment titles. IVA sought to use the third dimension to enhance visualization of their data, which was normally displayed on a 2D screen through a web browser. The virtual environment was based off existing IVA designs and their hired artist. Much of the data provided by IVA was text-based, and consistent of queries to a relational database. This posed a challenge when visualizing because many of the displays at the time did not have the resolution necessary to cleanly display long text passages (Figure 49). Various menu systems were designed for IVA; however, none matched the clients desire to see the interconnectedness of the data within their systems.

The flowchart in Figure 48 shows that this project sought to use VR to meet the requirement of visualizing higher-dimensional relational databases and entice new and old clients to purchase IVA's services. The virtual environment was generated at runtime by querying IVA's services. From the queried results, a wrap-around view of the data was presented as a series of images and icons. Navigation through the dataset was accomplished not through movement of the user, but instead by updating the wrap-

around visuals surrounding the user. By making queries and selecting specific results through the Oculus Go's wand, the viewed data would be updated and presented to the user.

The relational databases that the company wished to visualize had hundreds of connections and moving the visualization into three dimensions did not inherently solve any knowledge transference issues that a 2D interface did not already provide. Reality is perceived through three spatial and one time dimension. By placing information on a flat, 2D visualizing, it is possible to recede backwards through the third dimension to see large portions of the data without worrying about occlusion issues. In addition, the vast quantities of text information on the screen were difficult to read through the current generation HMD devices. This may be fixed in the future with technological improvements; however, processing information through reading is not the goal of VR.

4.1.11 VR Real Estate Walkthroughs (2019)

Figure 50

Elements of VR Applied to a Virtual Real Estate Walkthrough

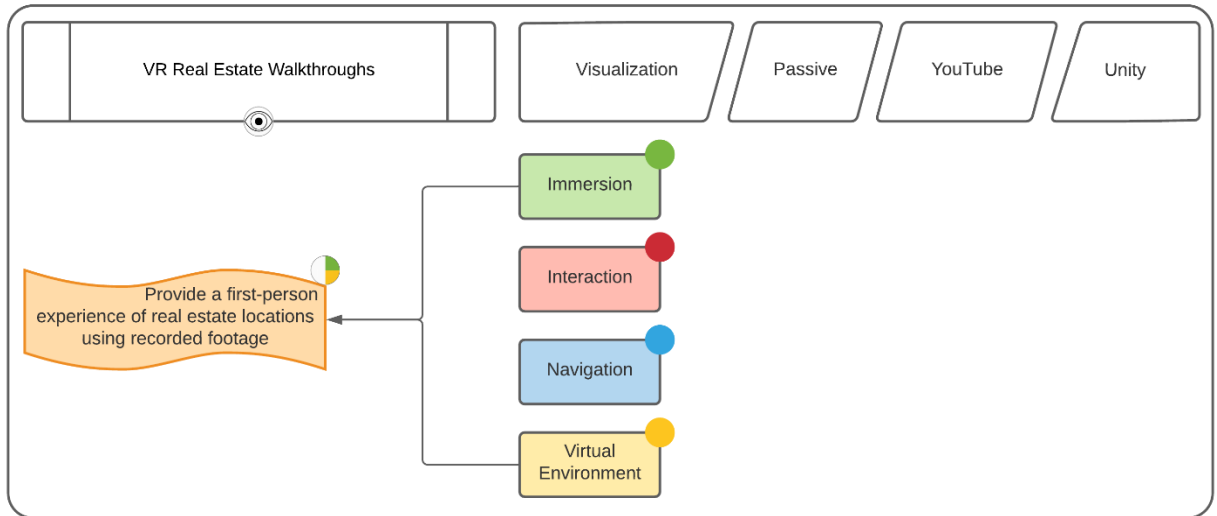


Figure 51

Full 360 Video of Homes Provided Remote Buyers a Chance to Walk the Grounds



4.1.11.1 Problem. A real-estate company was interested in creating virtual tours of properties for clients who were unable to physical travel to the space. They sought to use 360 video capturing cameras to create virtual walkthroughs of the rooms of a home that could be displayed on VR devices for immersive viewing.

4.1.11.2 Implementation. A GoPro 360 camera were fastened to a bike helmet. The cameraperson walked through the interior of a home as instructed by the real estate agent, slowly walking through the home, and pausing within each area (Figure 51). The footage was converted into a 360 viewable format compatible with YouTube and other 360 video players. Buyers would utilize an orientation tracked VR device to view the video and see the entire 360-degree field of view.

Figure 50 shows that only the virtual environment and immersion elements of VR were utilized to meet the requirement of providing a first-person experience of real estate property. The virtual environment was composed of a roughly 20-minute walkthrough of the house. Immersion, produced by the HMD that displayed the video footage sought to provide a walkthrough that closely resembled what a person would experience if they were onsite. Since the experience was pre-recorded, there were no methods of navigation or interaction present, creating a completely passive experience.

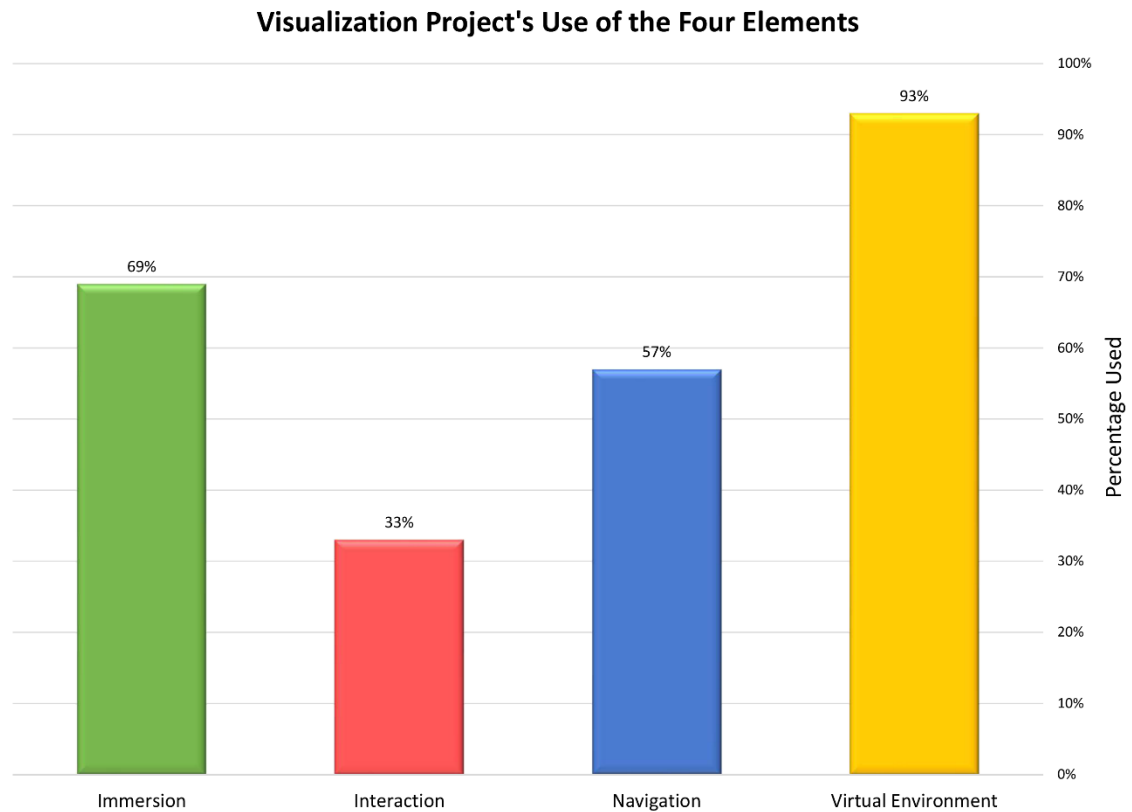
4.1.12 Visualization Summarized

Fourteen visualization projects were evaluated, with their effectiveness scores summarized in Figure 52. Typically, VR requires a virtual environment to generate a synthetic experience and was therefore had the highest score. Only one of the projects did not utilize a virtual environment, and that was the FOVEA drone visualization which

utilized VR systems to overlay non-stereo imagery. Visualization projects relied heavily on the concept of immersion, enhancing presence and focus. Visualization can be one of the simplest categories to implement in VR, as there are many methods to export data automatically and generate visualizations. With the proliferation of 3D CAD applications, it is commonplace to export architectural layouts into VR. Interaction was the least utilized element since architectural visualizations and data visualizations do not require interaction.

Figure 52

Results for Visualization's Use of the Four Elements



4.2 Simulation Projects

4.2.1 Virtual Reality Visualization for NASA Test Stand (2006 - 2010)

Figure 53

Elements of VR Applied to NASA Rocket Engines

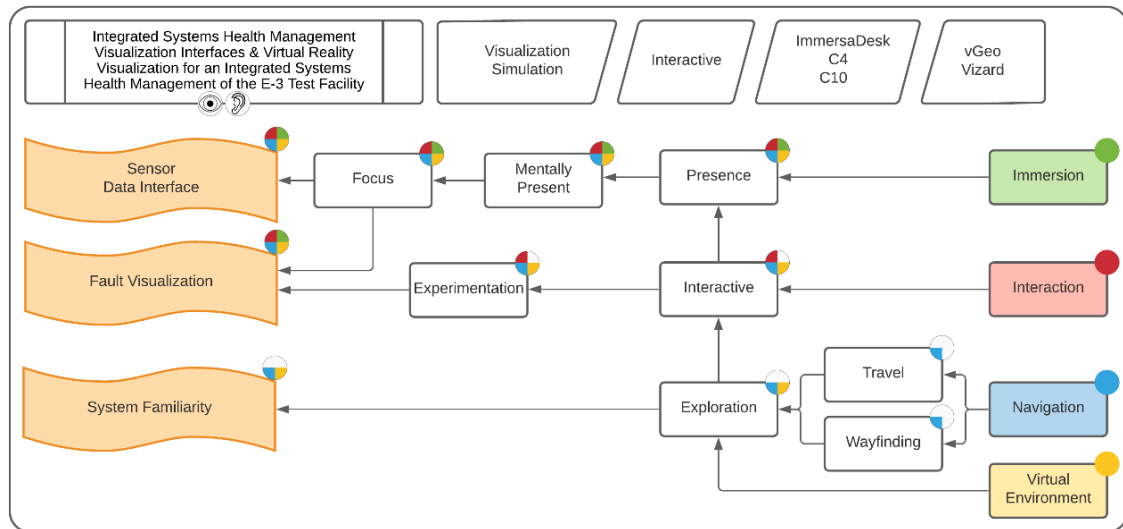


Figure 54

VRML Models Inside VGeo (Left) Were Migrated to Vizard Where Custom Visualizations Were Displayed (Right)

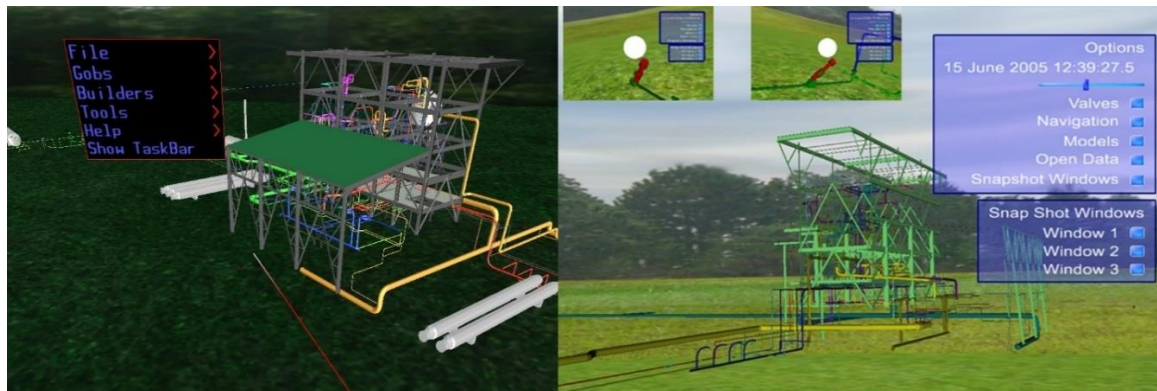
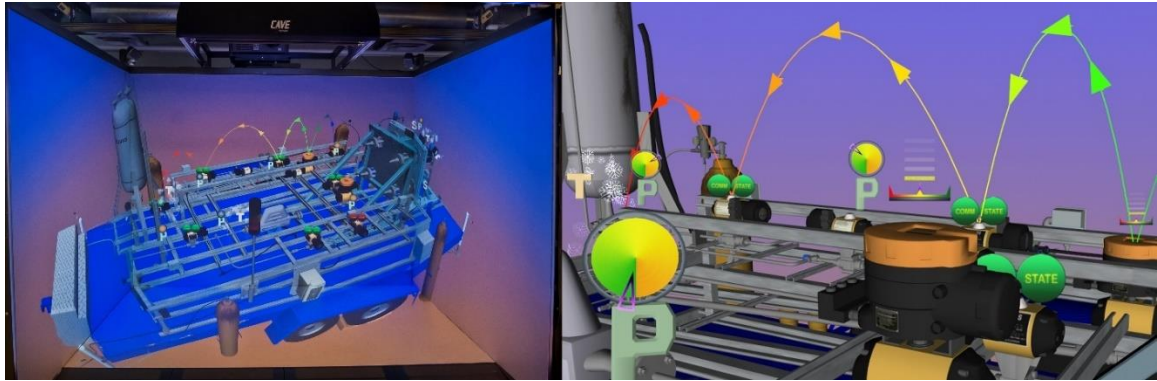


Figure 55

MTTP Valve State, Pressure, Temperature, and Other Sensor Data Visualized in the C4 (Left) with Root Cause Analysis Represented as a Series of Curves From Fault to Source (Right)



4.2.1.1 Problem. Complex structures outfitted with sensors can produce large quantities of data. An operator needs to be able to perceive the state of the system. This operation is usually performed through a computer interface and needs to be correlated with the real-life physical structure to handle maintenance or system faults. A need for enhanced human-machine communication, visualization of data, and experimental “what-if” questions through simulation was needed.

4.2.1.2 Implementation. Two rocket-engine test stands, the E-3 test stand, and the methane thruster testbed platform (MTTP) located at NASA’s Stennis Space Center in Mississippi were modeled in the VR environment. The visuals for the E-3 test stand were first deployed in vGeo and then migrated to WorldViz Vizard (Figure 54). The MTTP was implemented inside of Vizard (Figure 55). Visuals were initially generated by converting computer aided design (CAD) models into real-time approximations; however, these documents were incomplete. A majority of the 3D model was created

manually from photographic reference. Users were able to interact with the scene through head tracking and a non-tracked Xbox 360 controller. Interaction was achieved through a non-VR user interface controlled by an external operator.

Figure 53 shows that all of the elements of VR were utilized to accomplish the requirements of familiarizing the user with the system, visualize faults, and provide a visual interface of the sensor data. The virtual environment consisted of a 3D model of the test stand as well as the rules and logic that translated the sensor data into visuals. Navigation was accomplished through an Xbox controller as well as through a point-and-click interface that moved the user between different critical locations. To enhance wayfinding, a small overhead map was created so that the user could better understand their position relative to the test stand structure. Interaction and experimentation were controlled through a graphical interface allowing the user to select different recorded datasets, change the method of visualizing information, and control the rate of time when visualizing the data. Through the use of the different CAVE™ systems, their large displays and stereoscopic rendering, mental presence was enhanced to better focus the attention of the user on the virtual environment and sensor data. An additional benefit to deployment in the C4 & C10 systems was that the user was able to navigate around the test stand at a real-life scale with their own body as a reference point to better understand the structure.

One fault with the visualizations employed are that they did not utilize auditory or tactile feedback, which could have been used to reduce the amount of information processed by the users. Some sensors directly correlate to VR devices such as pipe

pressure to haptic interfaces and thermodes for temperature. The root-cause analysis system could have utilized audio cues to gain the attention of the user when focused on other areas.

4.2.2 Virtual Reality Simulation of Flooding Characteristics (2009 - 2012)

Figure 56

Elements of VR Applied to Water Runoff Simulation

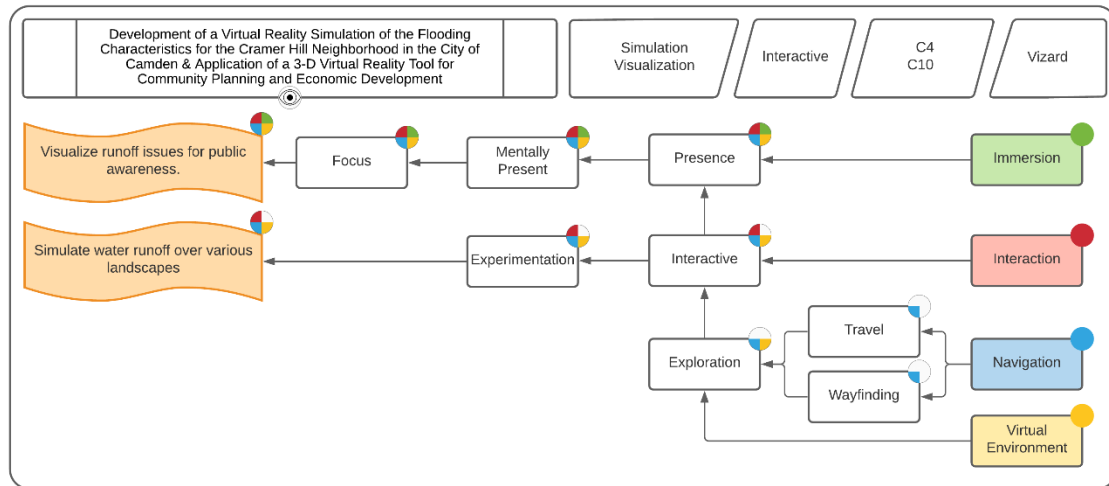
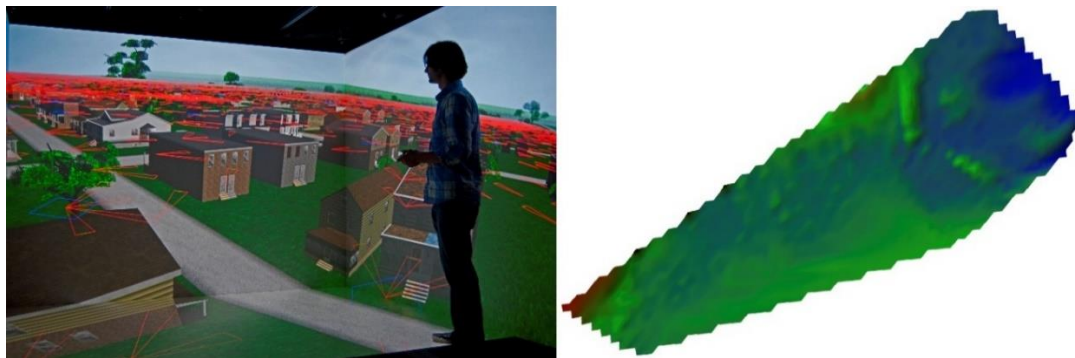


Figure 57

A Virtual Von Neida Park Where Flooding Was Simulated Using Land Use Classification and a Water Direction Simulation



4.2.2.1 Problem. Camden and Vineland suffered from chronic flooding issues due to poorly maintained combined wastewater and sewer systems in southern New Jersey. This caused quality-of-life issues, closures, and posed a health risk. The high cost of engineering analysis and construction made it difficult to investigate multiple solutions. Community support for the engineering projects can also be an issue, and VR was desired to create an intuitive visualization to educate the community on issues and options.

4.2.2.2 Implementation. Teams of students surveyed the area and gathered photographic reference material to create a virtual representation of the sites. Initially, houses and other objects were placed manually before being replaced by a procedural system that had the user draw regions of different land-use types corresponding to urban, commercial or forest. The algorithm would automatically place 3D models based on shape and classification. While this approach would not visually match reality, it provided a system to quickly create a representation for any location. A water runoff simulation was devised based on online rainfall databases and the curve number method to determine the quantity of water a simulation cell (roughly 2m x 2m) could handle. Elevation data routed runoff from high to low points. The initial application was programmed in Python but was too slow for interactive analysis and was moved to an OpenGL C++ simulation that transmitted runoff information to the C4 through a TCP connection. Simulation data was then displayed using a wireframe mesh and colorized to indicate the amount of runoff at each cell.

As shown in Figure 56, all of the elements of VR were utilized within this project to accomplish the requirements of simulating and visualizing runoff. The virtual environment consisted of topographic information for the terrain and a collection of homes classified by type to automatically populate the environment without needing manual placement. Navigation was accomplished through the use of both head tracking and an Xbox controller for navigation through the environment. Interaction was through the simulation graphical interface, which provided the user with the ability to determine the size of the storm, duration, and the time steps between simulation increments. The ability to change parameters and visually witness a 24-hour storm system and its effect on a region further engaged users.

The simulation portion of the project did not require VR to produce results. However, coupling the simulation output with VR visuals of the location allowed users to navigate the environment as if they were actually on the streets of Camden. This made it easy to explain the problems encountered in the community as if the user was onsite at the location. They were able to navigate the landscape from a birds-eye view and search for runoff before landing and inspecting the area.

4.2.3 Inverter Technology Visualization of Solar & Wind Farm (2010)

Figure 58

Elements of VR Applied to a Marketing Piece for Inverter Technology

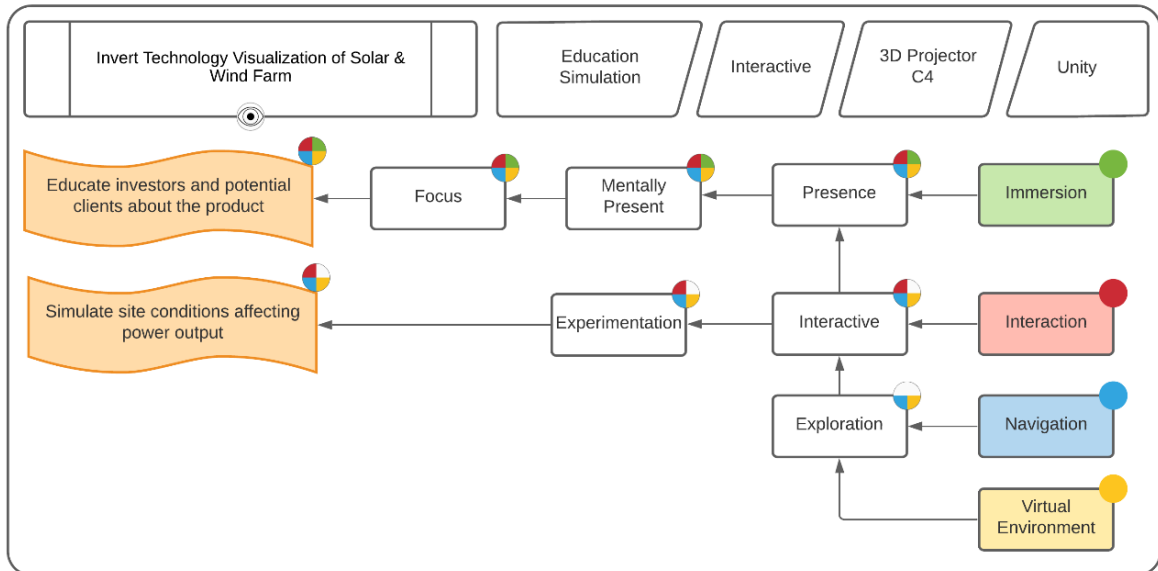
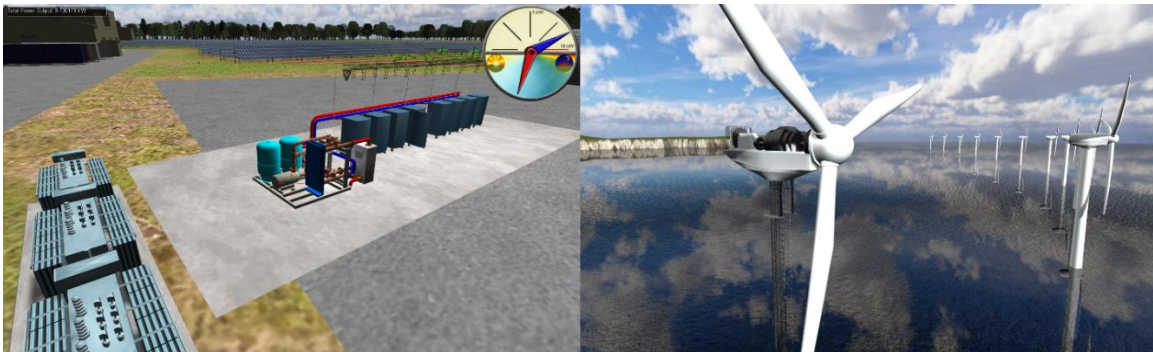


Figure 59

Users Were Able to Explore Solar and Wind Generation Systems While Receiving Real-Time Feedback



4.2.3.1 Problem. Alencon Systems wanted to market their inverter technology and propose a solar farm to Inductotherm Corporation. Alencon desired a visualization of their technology integrated into a complete energy production system from generation to distribution. The visuals were meant to be used as a marketing showpiece for attracting potential investors.

4.2.3.2 Implementation. A virtual environment was created based on aerial photography of the site and schematics provided by Alencon. The final demonstration was viewed using a portable 3D projector. While the demonstration utilized stereoscopic glasses, all the interaction was through a 2D interface that did not render properly in 3D. A simulation of the system's output based on the time, location, and placement of the solar farm was produced along with a cloud system that could be controlled by the user to showcase the system's ability to adapt to weather conditions (Figure 59). A variant of the environment was created for another tradeshow featuring the cliffs of Ireland with offshore wind turbines.

The usage of the term VR in this project was primarily to help market the product and generate interest. Figure 58 shows that all the elements of VR were used to meet the requirements of educating investors and simulate site conditions. However, the actual implementation had several issues that hindered immersion. Navigation was initially controlled by an Xbox controller, however the need for this project to be used as a sales tool meant that the operator (not the user) needed the same guided tour to be displayed with each viewing. For this reason, an on-rails guided experience was added that moved the viewer through the system while a trained professional described the different

features. Immersion suffered due to the graphical interface being superimposed on the screen rather than existing within the 3D world, which caused eyestrain. In addition, at the time of completion, portable stereoscopic 3D projectors were limited to using a proprietary NVIDIA stereoscopic technology. This limited the type of hardware that could be utilized for the project.

4.2.4 A Virtual Reality Flight Deck on a US Navy Aircraft Carrier (2010)

Figure 60

Elements of VR Applied to a Functional Virtual Drone Model

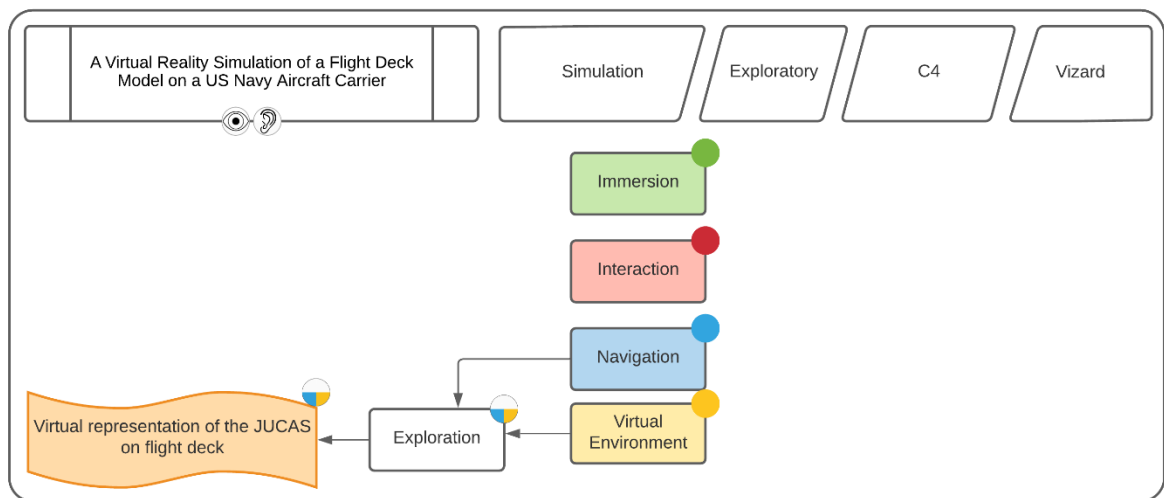


Figure 61

An Aircraft Carrier and the JUCAS Drone



4.2.4.1 Problem. The Joint Unmanned Combat Aerial System (JUCAS) was a combined US Navy and Air Force project working with unmanned aerial drones on an aircraft carrier. The initial goal of the project was to understand the complexities of aircraft management on a flight deck by creating a virtual representation of the Boeing X-45 combat air vehicle.

4.2.4.2 Implementation. A Boeing X-45 3D model was created using online reference material from publicly available sources and painted to match the Navy's color scheme. The latches, wheel wells, and other take-off and landing mechanical systems were implemented to be fully functional to the point that animations could be stopped and started in mid deployment to simulate failure of deployment. The functionality was designed to be interfaced with NAVAIRs existing systems. NAVAIR provided a CAD model of an aircraft carrier that was then optimized and repurposed to work in a real-time environment (Figure 61).

Figure 60 shows that only the VR elements of virtual environment and navigation were utilized to accomplish the goal of creating a JUCAS on the flight deck. The VR environment consisted of the flight deck and the JUCAS with takeoff and landing functionality. Navigation was performed through an Xbox controller, allowing participants to move around the flight deck or tether themselves to a JUCAS during takeoff or landing. No method of interaction was implemented, as the takeoff and landing of aircraft was handled by the computer system. While this project was deployed within the C4 system, none of the immersive benefits assisted in creating the simulation or reviewing the results.

This project was meant as a starting point for integrating external 2D aircraft carrier management software into a VR environment. However, due to external factors, it was never realized beyond integrating the Boeing X-45 3D model. A VR representation would have limited use for aircraft planners as the flight deck is a 2D surface with no need to be visualized or understood in three-dimensional space. The elements of VR would have been better put to use if this was meant to train landing signaling officers or how to safely navigate the flight deck while issuing commands.

Truck Driver Fatigue Assessment using Virtual Reality (2014 - 2016)

Figure 62

Elements of VR Applied to a Truck Driving Simulation

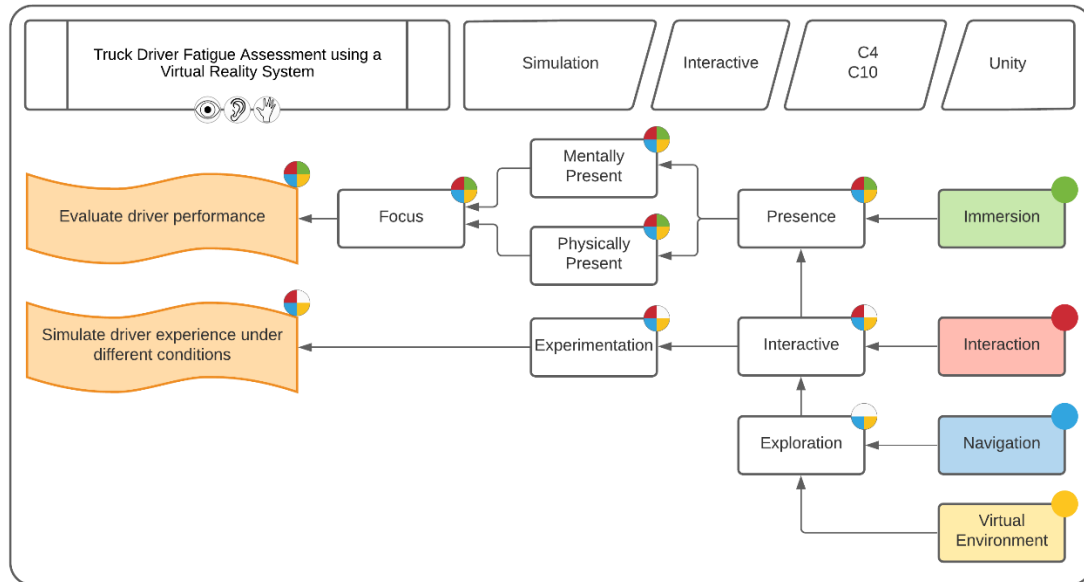


Figure 63

Fatigue Testing in the C10 Along a Virtual Section of I-95 with Traffic



4.2.4.3 Problem. Extended periods of driving without rest result in increased accidents. Current methods for testing driver fatigue require real-world testing and analysis of existing data from actual truck accidents. Many variables cannot be controlled directly in real-world testing and can lead to dangerous situations. By using a virtual environment, a no-risk testing environment can be created with all environmental conditions such controlled by an operator.

4.2.4.4 Implementation. This project was originally developed for use in the C4, however, concerns about 3D and shutter glasses causing eye fatigue resulted in the project being moved to the C10 without stereoscopic 3D. A consumer grade steering wheel, pedals and 12-gear shifter were added as the interface for controlling the vehicle. Nearly 200 miles of roadway along the east coast of the United States were cataloged by GPS and used to generate a roadway surface. Operator controls were added that controlled the time of day, and precipitation conditions. Fatigue testing was performed by testing the user's awareness by randomly placing a red dot within the peripheral view. Data was captured and stored every half second for the position of the truck, speed, and any collision incidents for later analysis by civil engineering students.

Unlike many of the previous projects, physical presence was created through the use of a driver's seat and the steering wheel interface with force feedback when collisions occurred. Multiple runs were performed with the simulation by civil engineering graduate students, collecting data on passenger fatigue, lane crossings and collisions in sessions lasting over 2 hours at a time. Better methods of fatigue testing exist but require blood testing or eye-tracking hardware that was not available at the time of testing.

Figure 62 shows that all the elements of VR were utilized to produce an environment meant to simulate driving and evaluate the driver's performance under various weather conditions. The combination of the virtual environment and free-driving capabilities allowed participants to explore the 200 miles of roadway. The steering wheel, pedals, and gear shifter allowed for the user to interact with their vehicle and surrounding. Variables such as weather and day-night cycle led to experimentation, simulating the driver's experience under various conditions. In this situation, immersion did not rely on creating a realistic, stereoscopic visualization because current technology can induce fatigue. Instead, the wide-angle C10 screens were used to provide an environment that surrounded the driver along with the driver's seat and controls.

4.2.5 Resiliency Planning Under Extreme Storm Events (2017)

Figure 64

Elements of VR Applied to a Simulation of Resiliency to Storm Systems in NJ

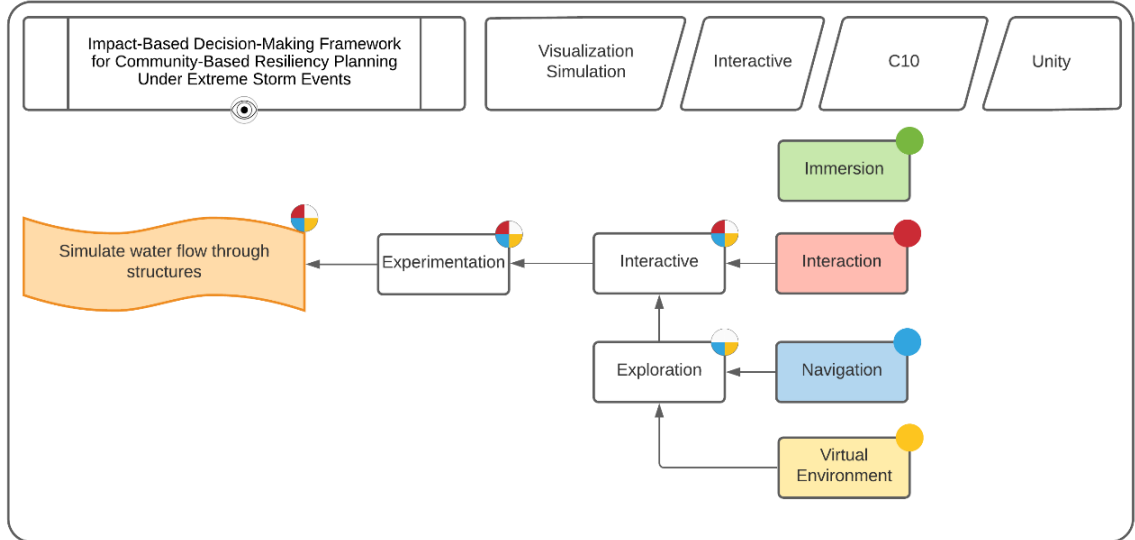


Figure 65

To Showcase Rowan's Resiliency, a Demonstration of Visuals and Simulation Technology was Created



4.2.5.1 Problem. After Hurricane Katrina, Rowan proposed a resiliency-based planning framework for extreme storm events. Capitalizing on the work done with the runoff simulation in Camden and Vineland, there was interest in creating a VR component for visualizing results.

4.2.5.2 Implementation. Two separate visualizations were created for the project, led by faculty in the Civil & Environmental Engineering department. The first visualization was of planet Earth, showing the path of a hurricane along the eastern coast. The second visualization utilized a variation of the runoff simulator to show different solutions for increasing resilience in Long Beach Island. The visualization was utilized to showcase the project and helped win the proposal, however the VR Center did not engage in the work after.

This project loosely utilized the elements of VR, however similar issues to the Camden runoff project limited the effectiveness. In this situation, satellite imagery was used with few if any visuals for the actual structures on site, losing the appeal of virtual walking through the streets of the location. Interaction and control of the simulation was also not intuitive using the Xbox controller and would benefit from a gestural or motion tracked implementation.

Figure 64 shows that all the elements other than immersion were utilized within this project to accomplish the requirement of simulating water flow in a coastal region. While the C10 system was utilized, there was little need for the stereoscopic capabilities as a birds-eye view of the location was adopted. Stereoscopic vision is only valuable when objects are within 20 meters of the viewer. The virtual environment was composed

of elevation data pulled from an online database. The water obstruction visualization was created through intersection checks over a portion of the terrain to determine where obstacles existed. Navigation could be either controlled through an Xbox controller to freely roam around the area or on a guided tour of specific important locations. Interaction was through a series of menus that controlled the different options available for a township when handling resiliency.

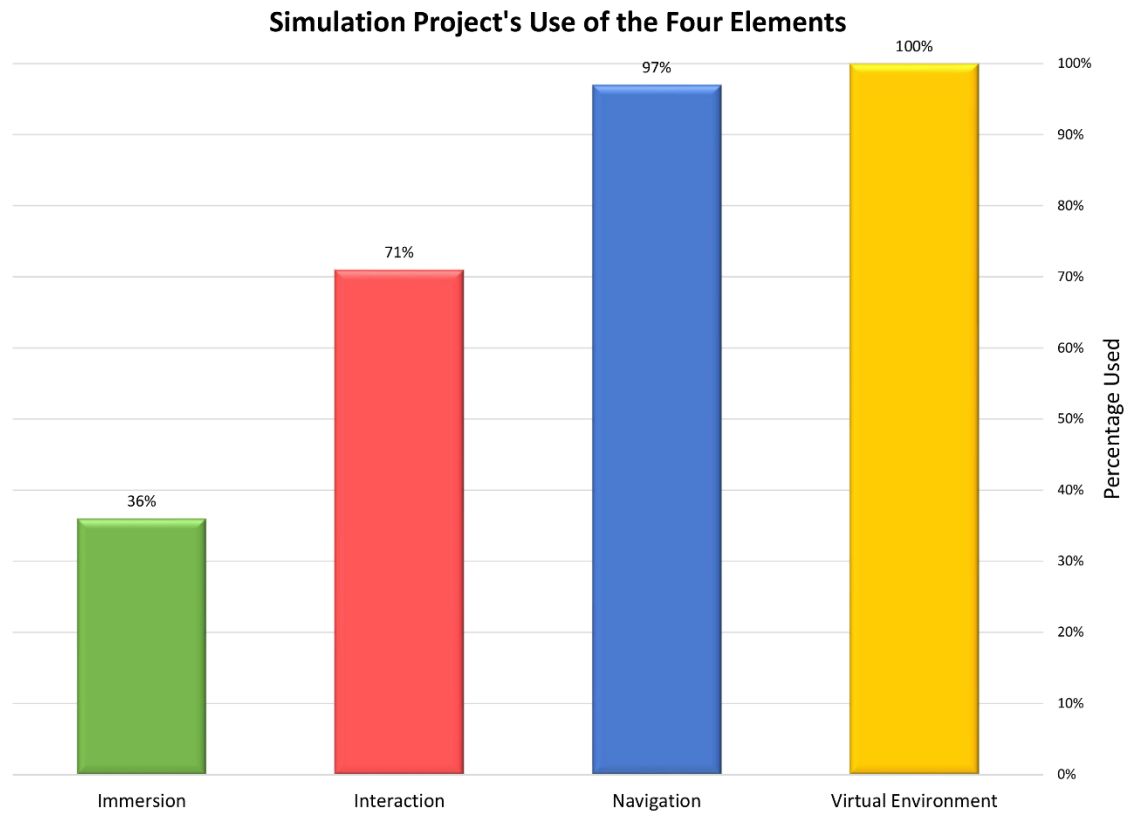
4.2.6 Simulation Summarized

Eight simulation projects were assessed, with their VR element scores summarized in Figure 66. VR requires a virtual environment, therefore the VE element received a score of 100%. Simulation projects relied the most on navigation (97%), followed by interaction (72%) and finally immersion (36%). Unlike visualization, which leveraged on VRs enhanced ability to immerse the participant, simulations relied more on navigation and interaction. Navigation was utilized the most in order to examine results, many of which correlated to locations in 3D space. However, simulation work itself does not require a 3D world to visualize the results, which is why the use of immersion is the lowest of the elements. Interaction was used in order to modify the simulation input or initial conditions and test scenarios.

While at first glance it would be correct to assume that a simulation should utilize everything a visualization project requires to visualize the results of the simulation, it is not always necessary to output results into a virtual environment for viewing. Also, in some situations, VR can be detrimental such as when used in the driver fatigue study where the usage of stereoscopic 3D causes eye strain and fatigue.

Figure 66

Results of Simulation's Use of the Four Elements



4.3 Education Projects

4.3.1 Visualization and Interaction in the Cretaceous Period (2009 - 2010)

Figure 67

Elements of VR Applied to an Immersive Dinosaur Experience for Kindergarteners

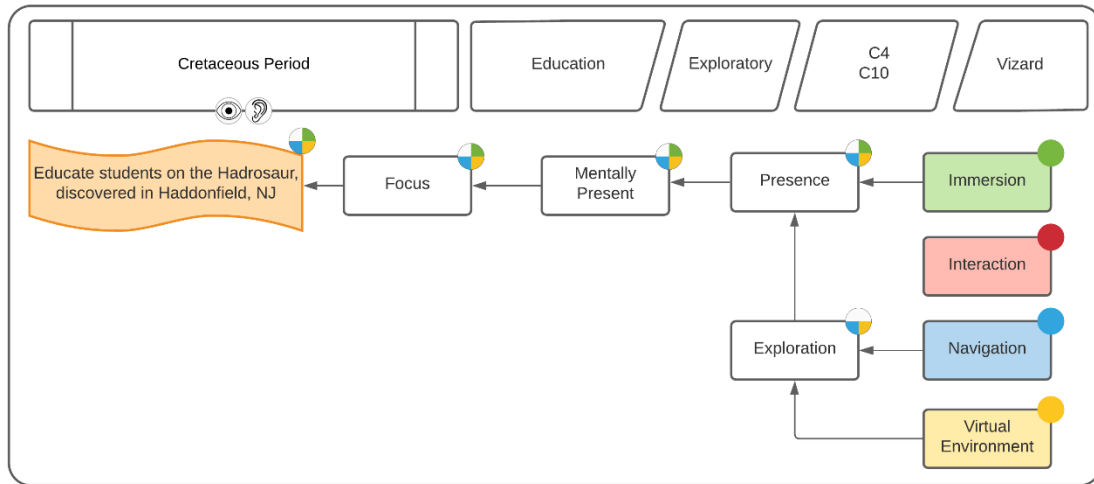


Figure 68

A Tyrannosaurs Rex Stalks a Hadrosaurus (Left) While Michio Kaku Watches During a Demonstration for his Television show, Sci Fi Science (Right)



4.3.1.1 Problem. Classes of elementary students would visit the Rowan VR Center, one in particular was from Haddonfield, New Jersey where the Hadrosaurus was discovered. An educational VR demonstration was requested that would enhance existing curriculum on the subject.

4.3.1.2 Implementation. Virtual representations of a Hadrosaurus, Tyrannosaurus rex, and Pteranodon were modeled, rigged, and animated. A simple behavior system was designed to allow them to navigate an environment from the Cretaceous period. Initially, the animals behaved as carnivores and herbivores as they hunted for food. This functionality was removed in order to appeal to younger visitors and the school's non-violence policy. Vegetation was added that grew using a genetic algorithm encoding properties such as size and color to integrate into the hadrosaurs consumption of plant matter. This feature was never fully implemented but is used to randomly generate the vegetation in the surroundings. While the graphics were primitive even for the time, the demonstration was popular and was prominently featured on the Discovery Science Channel with Michio Kaku (Figure 68).

Figure 67 shows that in order to accomplish the goal of educating students about the Hadrosaurus, all the elements of VR were utilized except for interaction. The virtual environment consisted of the terrain and dinosaurs, whose behavior was dictated by a state machine that controlled their animations. Navigation was handled through an Xbox controller. To immerse the user, the C4 system and its stereoscopic rendering capabilities were utilized to enhance mental presence and focus on the content. There was no form of interaction on the part of the user, who could only freely roam around the environment.

Visitors were shown how to use the Xbox controller to navigate the environment and would be left to explore as a passive spectator. The subject matter and the expectations the viewers had of how the dinosaurs would behave made it engaging without requiring interaction.

4.3.2 Monarch Butterfly Lifecycle (2011)

Figure 69

Elements of VR Applied to an Educational Piece on the Virtual Monarch Lifecycle

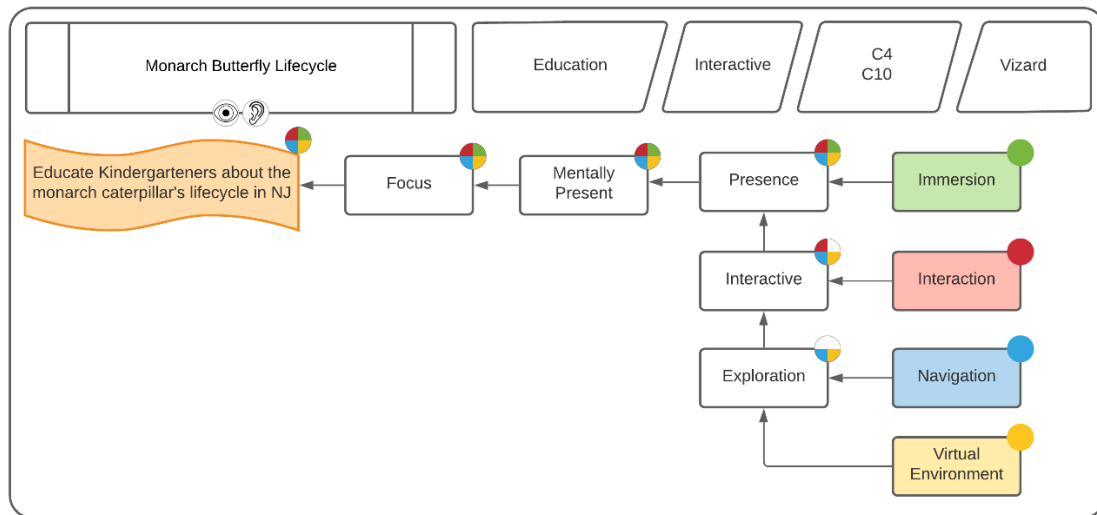


Figure 70

Visiting Elementary School Students Viewing the Metamorphosis of a Virtual Monarch Caterpillar into a Butterfly



4.3.2.1 Problem. Classes of elementary students would visit the Rowan VR Center. The Monarch butterfly's lifecycle is a cross-curricular study throughout the K-8 grade levels. An educational VR demonstration was requested that would enrich existing curriculum on the subject.

Implementation. A virtual garden was modeled after a school in Haddonfield, New Jersey where the students grew milkweed each year to raise caterpillars that were then released during an annual parade. An interactive caterpillar was created that could be controlled by an operator to react to the participants. It would undergo the major lifecycle changes before finally turning into a chrysalis and emerging as a butterfly. It was deployed in the C4 and C10 systems and used headtracking and an Xbox controller for navigation around the garden (Figure 70).

Figure 69 shows that all the elements of VR were utilized to meet the requirement of educating Kindergarten students about the caterpillar's lifecycle. The virtual environment was composed of the visiting school's grounds and the animated caterpillar. Interaction was controlled by a lab technician and not the computer. Participants were told to speak with the virtual caterpillar and the technician would choose an appropriate response, causing the caterpillar to motion yes, no or dance. Having the caterpillar seemingly respond to the questions of the students greatly heightening the level of perceived interaction. The operator would ask yes or no questions, treating it as a real being that helped further engage the students. Immersion utilized the stereoscopic and large size of the CAVE™ systems to enhance mental presence and focus on the content. This helped to reinforce the subject matter the students had already learned at school by allowing them to interact and answer questions about what they were seeing within the CAVE™ environment.

This demonstration has been one of the most popular VR demonstrations with visiting classes to the Rowan VR Center. For young visitors it caused a range of emotional responses from delight and cheer to fear and panic at being approached by a human-sized caterpillar.

4.3.3 Virtual Green School Simulation in the CAVE® (2012)

Figure 71

Elements of VR Applied to an Education Game About Environmental Impact of Our Choices

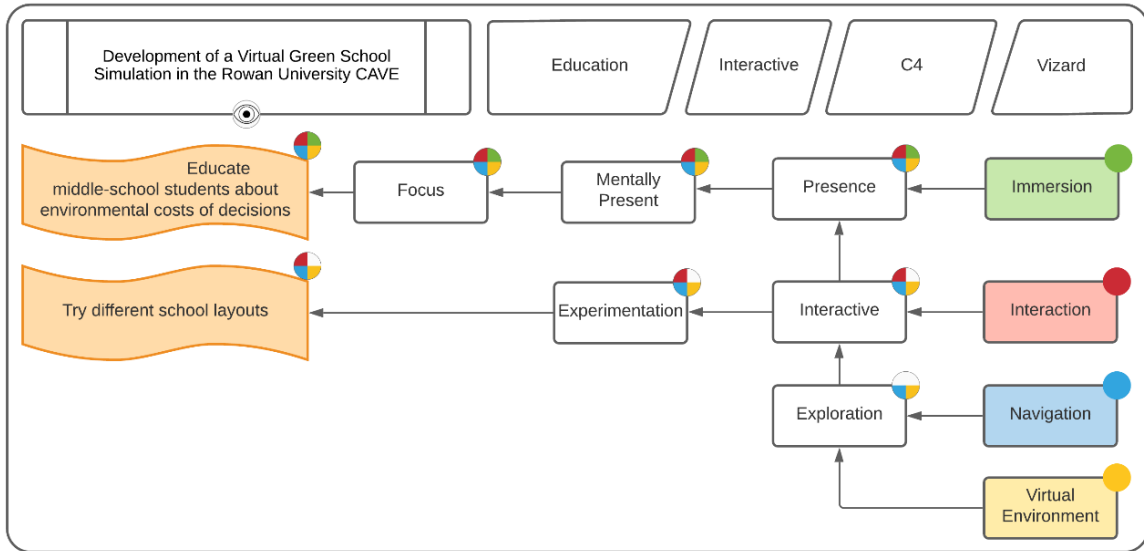


Figure 72

In a Simulated Green School, Participants Tried to Build an Environmentally Conscious School Without Breaking a Budget



4.3.3.1 Problem. The Education Information and Resource Center (EIRC) was interested in creating a VR game to educate students about the environment and the impact daily choices can make on it.

4.3.3.2 Implementation. Working in collaboration with a member of EIRC, the concept of a virtual green school was developed where the participant would construct a school and choose different equipment. Factors such as initial cost, energy consumption, waste generation, disposal and the long-term effects on the environment were factored into each item, educating the player as they explored different methods of meeting the demands of the school, teachers, and students. The game was deployed in the C4 system and controlled using a mouse and keyboard.

Figure 71 shows that all the elements of VR were utilized in this project to accomplish the requirements of providing students with the ability to experiment with different school layouts and educate them about the environmental impact of their decisions. The virtual environment consisted of two parts, the static walls, and floors along with any interactively placed equipment and furniture. A rule system was added that evaluated the choices the user made and determines how environmentally conscious they were. The ability to create their own school and see the ramifications of their choices led to experimentation. While immersion was meant to be included through the use of the C4 system, the method for handling the user's perspective and navigation controls inhibited the feeling of presence.

Numerous issues caused this project to not reach the final objective. While the elements of VR were targeted, they were not properly utilized in the project. The choice

to use a top-down, third-person view meant that most objects were outside the range where stereoscopic 3D was effective. This view also meant that most of the walls of the C4 had nothing to visualize since nearly all the content was on the front and floor screens, gaining no immersive benefits. The interface was difficult to translate into VR and required numerous text and pictorial icons that were poorly rendered on the low-resolution screens. However, the interaction elements of choosing and placing objects and rotating them around the room was successful and incorporated into several other projects. While the project was limited to using available hardware, the inclusion of a gestural or glove-based system and incorporating a first-person perspective where the user could build their school around them may have better used the elements of VR to create an engaging product.

STEM Learning through 3D Technologies (2015 - 2016)

Figure 73

Elements of VR Applied to Educating Students Using VR and the Subject of Dinosaurs

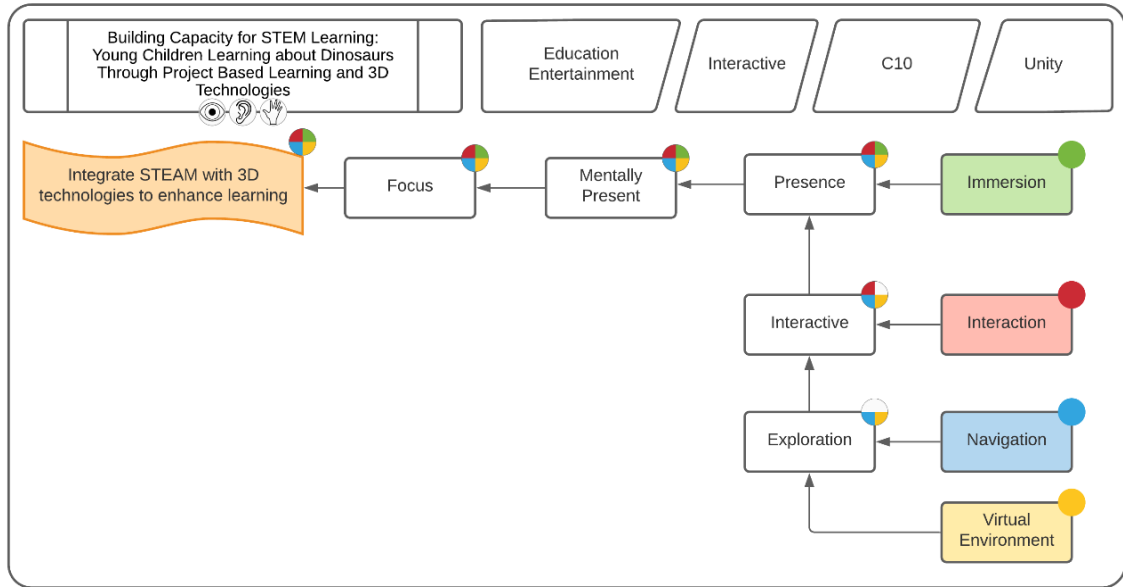


Figure 74

Children Cheer as They Reach the End of the Dinosaur Learning Module (Left), While Two Students Control a Carnivore and Herbivore in the Eating Portion of the Module (Right)



4.3.3.3 Problem. The project investigated the question: how do using integrated STEM learning and 3D technologies build capacity and skills in children from underrepresented communities for future science experiences and learning?

4.3.3.4 Implementation. Four modules were created each covering a different lesson as directed by the principal investigator for the project. Modules were controlled by two players, and focused on dinosaur eating habits, nesting behavior, a mixed reality interactive skeleton, and a narrative on the different features of dinosaurs. Each player used an Xbox controller to navigate their dinosaur in a competitive game to either be the first to reach the end or collect all of the supplies to create a nest. An MR experience was designed where 3D printed dinosaur skeletons were tracked in the VR environment. When the bone came sufficiently close to the correct position and orientation of the missing pieces on the virtual skeleton, it would snap in place.

Figure 73 shows that all elements were utilized in this project to integrate Science, Technology, Engineering, Art, and Mathematics (STEAM) with 3D technologies. The virtual environment was composed of a Cretaceous period forest. Players navigated and interacted with the environment through the use of one or more Xbox controllers. Objects within the environment such as plants were investigated to determine whether their dinosaur was an herbivore or carnivore. In the second virtual environment, players explored a forest area and collected the materials necessary to create their own nest. For the Tyrannosaurs-rex skeleton, between one to eight students would bring in 3D printed portions of the skeleton and use them to find where they were missing using motion tracking. Using the large-scale C10 system, classes of students were surrounded by a

stereoscopic 3D environment, which enhanced their mental presence and focus on the material.

Four groups of students visited the center to experience the dinosaur learning modules. Students were highly engaged and naturally formed teams cheering for their player to win. The MR dinosaur skeleton experience allowed up to 8 users at a time to interact with the VR environment. The real-life objects interacting with the virtual environment increase user engagement.

4.3.4 VR Recreation of Occupied Warsaw, Poland (2019 - 2021)

Figure 75

Elements of VR Applied to a Recreation of Warsaw, Poland During German Occupation

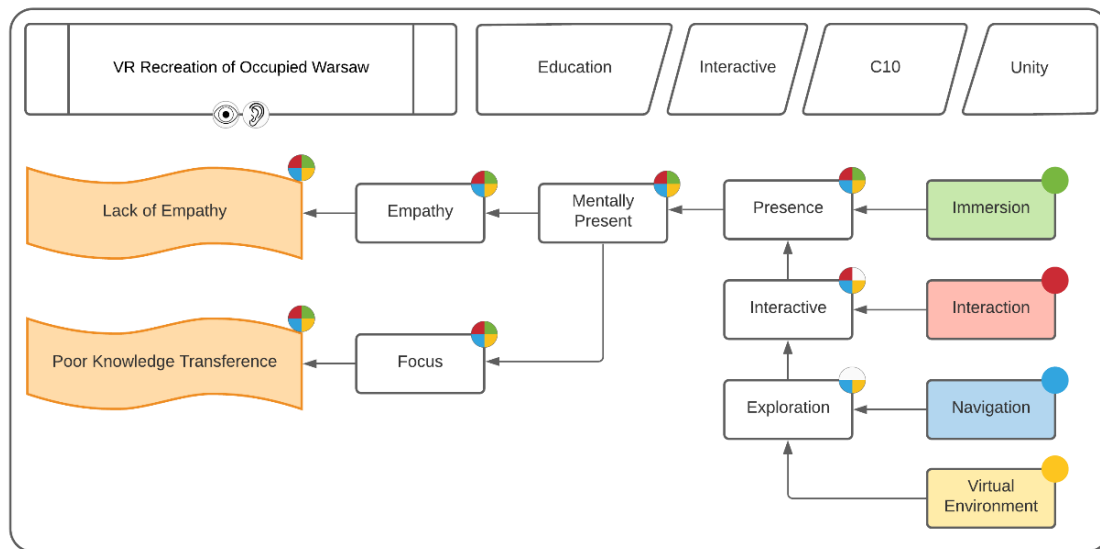


Figure 76

Large Interior and Exterior Environments as Well as Avatars Inside Warsaw



4.3.4.1 Problem. Holocaust education in America, vital in the study of history and humanities, has not been modernized. Even the basic facts surrounding the Holocaust are not being absorbed by middle and high school students. The purpose of this project was to utilize not only the elements of VR, but the association it has with entertainment and cutting-edge science to create a recreation of Warsaw, Poland in the 1940s during German occupation to explore and learn.

Implementation. As of Winter, 2021 the project is still in development by the team. However, fully realized vertical slices of the project have been created and demonstrated to audiences. While the initial draw of VR as entertainment and cutting-edge technology assists with engaging students, the hope is that making the participant mentally present during this time, witnessing the conditions and events will invoke engagement and empathy, resulting in higher knowledge transference. Several locations including the soup kitchen and streets of Warsaw were created virtually from photographs and literature (

Figure 76). As Figure 75 shows, all the elements of VR were used to accomplish the requirements of enhancing knowledge transference and making students more empathetic to the plight of the Jewish people in Warsaw. The virtual environment consisted of four locations, a communal dwelling, street area, soup kitchen, and train yard. Users explored the area by navigating with a standard game controller. Users interacted with glowing objects to uncover additional information about people, places, and objects. Early versions of the project were displayed inside the C10 system and utilized stereoscopic 3D to immerse users in the time period, which we theorize will enhance focus of the material leading to enhanced knowledge transference. By seeing the lives of those subjected to the conditions inside of Warsaw, Poland the goal is to enhance empathy.

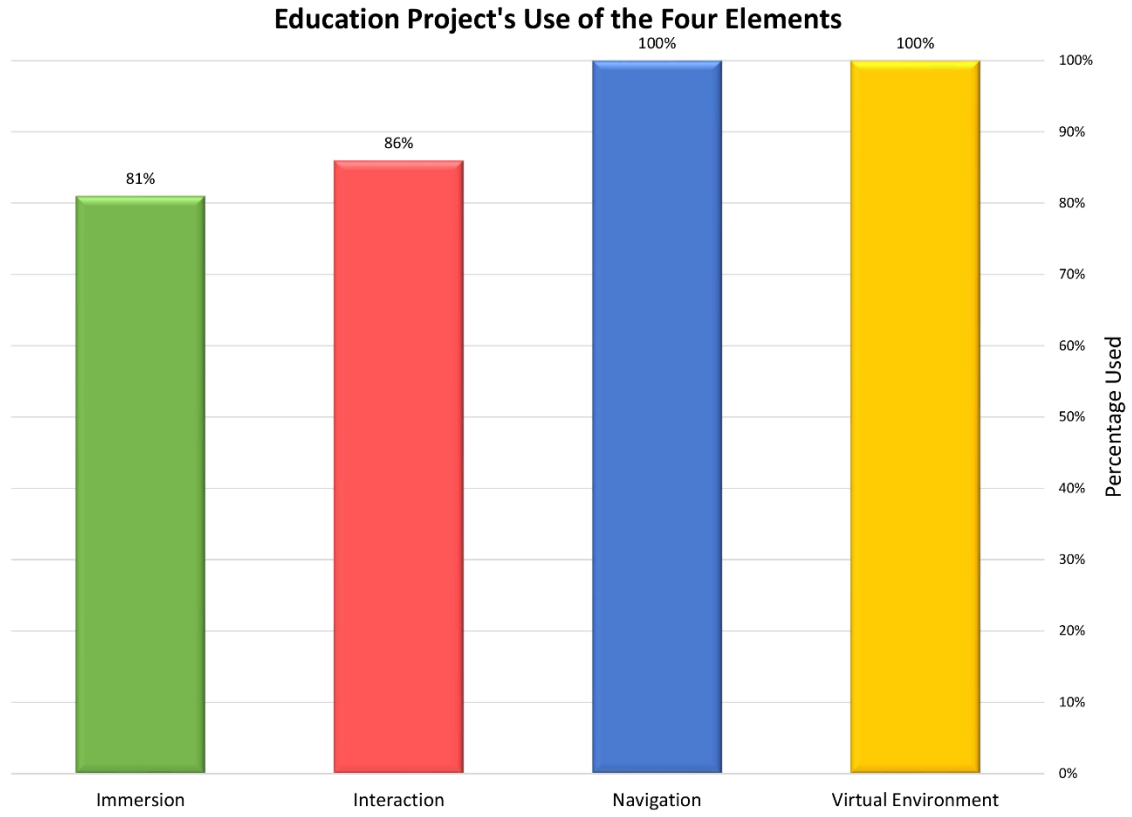
The project has yet to be deployed in front of its intended audience. However, private viewings by interested parties have shown high levels of immersion and empathy. Final limiting factors will be the platform to deploy the content upon as well as the effectiveness of the teaching lessons that accompany the VR implementation.

4.3.5 Education Summarized

Seven education projects were assessed, with their VR element scores summarized in Figure 77. VR requires a virtual environment, therefore the VE element received a score of 100%. All education projects used navigation (100%), followed by interaction (86%) and finally immersion (81%). The educational projects utilized user agency and self-exploration to learn more about the topic, leading to high usage across all the elements of VR.

Figure 77

Results for Education's Use of the Four Elements



4.4 Training Projects

4.4.1 Firefighter Concept (2013)

Figure 78

Elements of VR Applied to Firefighter Training

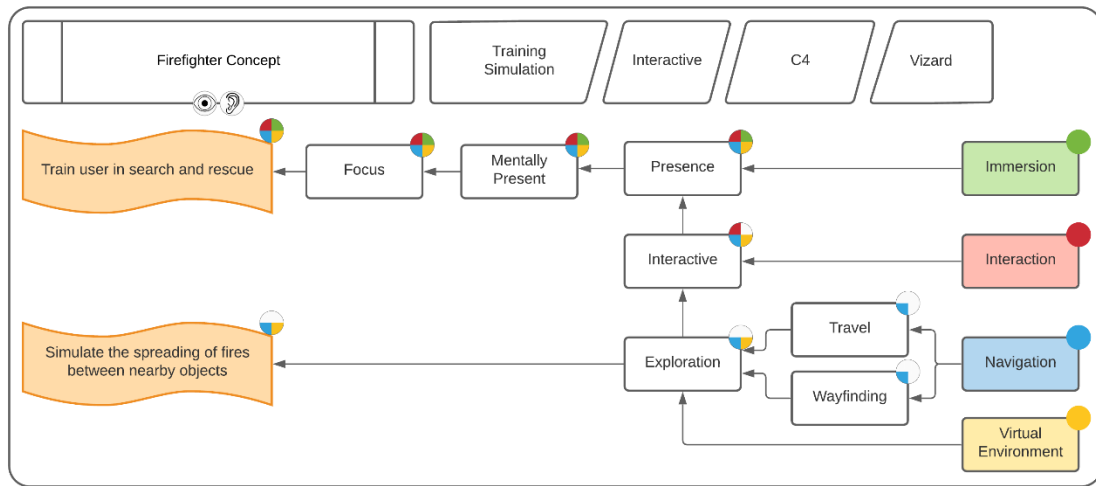


Figure 79

A Firefighter Attempts to Extinguish a Virtual Fire That Spread From a Random Source, in This Case a Refrigerator



4.4.1.1 Problem. A proof-of-concept for first responders to utilize VR in firefighter training for determining the location of a fire and rescue unconscious victims.

4.4.1.2 Implementation. A three-floored apartment building was created in VR with objects each having their own properties including likelihood of starting a fire, and likelihood of being ignited by nearby elements. The space utilized an algorithm to connect nearby objects to determine how fire would spread through a building. The participant would start outdoors and move through the building to find unconscious victims of smoke inhalation. Particle systems of smoke and fire were used to obstruct the view of the user. A controller was utilized for navigation as well as to control a portable fire extinguisher that could be used to put out the fire if caught early enough. Custom shaders were designed visualize objects igniting and burning over time.

Figure 78 shows that all the elements of VR were utilized to accomplish a simulation of fire spreading within an apartment complex that could be used to train search and rescue members. The virtual environment consisted of a three-story building with each floor having three rooms. For each object within a room, a list showing the proximity of all other objects was generated and the closest objects were connected using a look-up table. At runtime, a fire would randomly be associated with an object and would spread over time to adjacent objects. Using an Xbox controller, the firefighter navigated the environment looking for the source of the fire and any unconscious people. The firefighter was able to interact with the environment through the use of a hose that could spray water. Immersion was provided by the C4 system and the first-person

perspective of the simulation, providing mental presence and focus to the user during training.

This project was a concept piece, and so there were limitations involved that prevented certain elements from being fully utilized. To increase presence, physical devices could have been utilized such as a mock-fire extinguisher with a motion tracked nozzle and connected to a simple controller that would add the realism of a fully loaded firefighting moving through the hallways. The different levels did not feature distinct features and incorporated the same elements multiple times, making it difficult to navigate. This demonstration could have also utilized the incorporation of during the early stages of the fire, allowing the user to rely on more than just sight to identify the source. Finally, thermodes on the hands would have allowed the firefighter to utilize touch to sense whether a door was safe to open.

4.4.2 A Virtual Reality Training for Cold Spray Application (2015)

Figure 80

Elements of VR Applied to Cold Spray Training

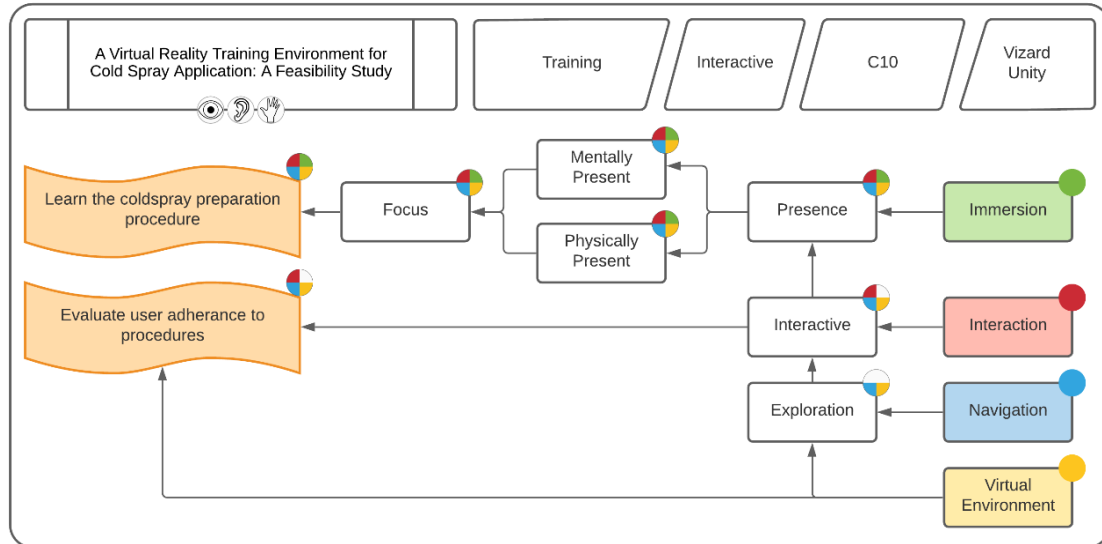


Figure 81

Trainees Would Go Through All the Steps of Cold Spray Preparation Including Safety and Interactive Computer Menus



4.4.2.1 Problem. The United States Army Research Lab (ARL) sought to use immersive VR technology to conduct a feasibility study on the use of VR training simulations for cold spray application. They desired a VR demonstration capable of replicating the procedures necessary to operate the VRC Gen III cold spray system using stereoscopic rendering.

4.4.2.2 Implementation. A training application for the VRC Gen III system was designed and created using the Unity engine for use in training soldiers in cold spray preparation and application. Over 30 step-by-step training objectives were tracked within the simulation that covered the entire cold spray process. The trainee would use a 3D printed representation of the cold spray device inside of the C10 virtual environment. This training simulation allowed the user to practice the steps necessary to prepare the cold spray system without the need of expensive equipment. Each step in the process was monitored and the user would only be able to continue if they complete each step-in sequence. Automated assistance and progress tracking user interface elements could be disabled to evaluate the trainee without guidance. A full demonstration of the prototype occurred at the 2014 at the Cold Spray Action Team (CSAT) summer meeting using a non-immersive, touch display.

Figure 80 shows that the achieve the requirements of learning and evaluating cold spray procedures, all the elements of VR were utilized. For evaluating the user's adherence to procedures, the virtual environment, navigation, and interaction elements were used. The virtual environment consisted of a room outfitted with the materials and equipment to setup and perform a cold spraying as well as a series of rules to evaluate the

user as they completed the steps. Navigation was achieved with an Xbox controller or ART Flystick. Interaction through buttons on the control activated specific objects during training to grab, move, and activate materials and equipment. Immersion inside the C10 was achieved through stereoscopic rendering of the scene as well as the use of a 3D printed replica of a cold spray gun that was motion tracked, providing both mental and physical presence. This was used to enhance the trainee's focus and help them learn the cold spray procedure.

The cold spray project required all the major components of VR to successfully create a training tool to evaluate the trainee's understanding of the cold spray preparation process. It utilized an immersive environment containing all the elements necessary for implementing cold spray. It used 3D printed replicas of equipment for physical presence, tracked by the system to spray virtual objects. At the time, a proper understanding of the mechanics was not provided to produce a true-to-life simulation of the cold spraying process, instead a simple deformable mesh was implemented and deformed as sprayed upon. The only element that doesn't require immersion is the evaluation of the candidate, however, evaluation in VR is simple to do since the rules are already part of the simulation.

4.4.3 Virtual Health Assessment Training Exam (2019)

Figure 82

Elements of VR Applied to a Training System for Physical Examination

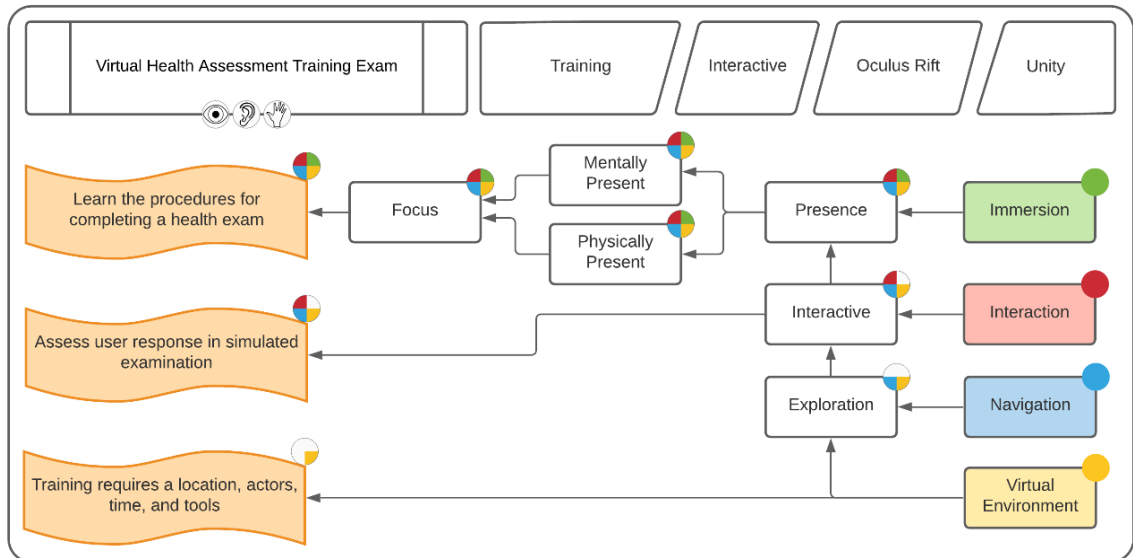


Figure 83

During Training, the User Can Grab and Manipulate a Number of Tools for Inspecting the Body



4.4.3.1 Problem. A VR simulation was needed to replicate the final exam for nursing students who would conduct a head-to-toe physical examination on an actor. Due to the rising costs associated with renting space and personal to practice and perform these examinations, a virtual solution was desired that students could practice with at their discretion.

4.4.3.2 Implementation. An avatar was placed in the scene but was given no behaviors or functionality and served only for performing the various steps in the examination. It was deployed on the Oculus Rift S using the dual hand controllers. Various medical tools were placed around the scene and used to interact with the patient for viewing their ears, and nose. A whiteboard present in the room provided instruction on the steps necessary to complete training.

Figure 82 shows that all the elements of VR were utilized to handle the three requirements of the project. Training typically requires resources such as a physical location, hired actors, equipment, and monitoring the trainee's progress which is performed by the virtual environment. Navigation was accomplished with Oculus Rift S Touch Controllers. To assess the user's performance, interaction between the users' controllers and the virtual tools / instruments were monitored. Through the Oculus Rift S HMD, immersion was provided with a motion-tracked stereoscopic view.

4.4.4 Art, Engineering & Medicine for Entrustability (2019 – Present)

Figure 84

Elements of VR Applied to a Surgical Trainer for Total Hip Replacement

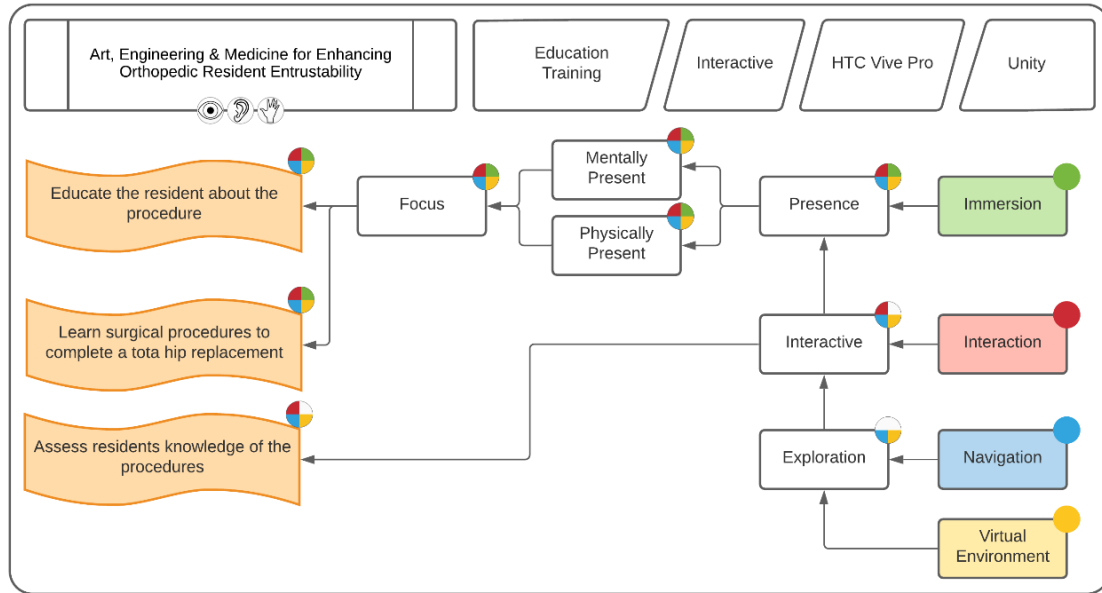
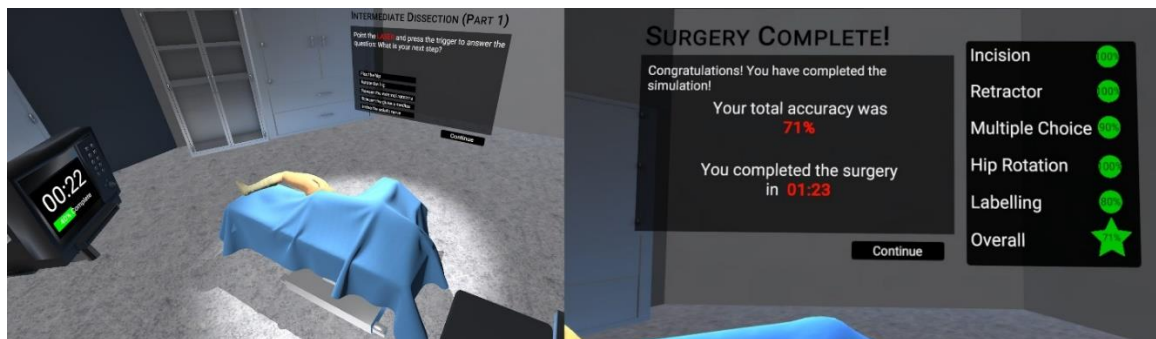


Figure 85

A Virtual Operating Room That Monitors the Actions of the Users and Provides an Accuracy and Overall Assessment



4.4.4.1 Problem. At the time of graduation, orthopedic surgery residents are not prepared to operate independently at a high level, because residents are having fewer opportunities provided to them by the attending surgeons for deliberate practice and autonomy in the operating room. This project seeks to create a realistic simulator for this open surgical procedure using highly realistic visual effects will allow learners to explore surgical anatomy in three dimensions and practice the steps of the procedure without any risk to patient safety. The simulator will provide objective feedback about a trainee's performance and give data to attending surgeons to support and encourage their entrustment of responsibility to resident surgeons.

4.4.4.2 Implementation. Nearly one-third of the twelve steps necessary to complete the procedure have been developed using the HTC Vive Pro HMD and dual tracked controllers. The simulation includes two modes, which can be swapped between seamlessly as the trainee makes mistakes. While being assessed, should their score fall below a set threshold they are taken to a review session before moving onto the next area of assessment (Figure 85).

Figure 84 shows how the elements of VR were utilized to handle the three project requirements. The virtual environment consisted of an operating room and left hip of a virtual patient. Navigation is controlled with the HTC Vive Pro controllers and Lighthouse motion tracking. Assessment was handled through the combination of virtual environment, navigation and interaction. Immersion, provided by the HTC Vive Pro HMD's stereoscopic rendering was meant to enhance mental presence. The hand-held

controllers would provide physical interaction and presence, enhancing focus and fulfilling the requirements of learning and educating the resident about the procedure.

This project is currently in its final phase, with testing and evaluation to begin in summer 2021. It is poised to utilize all the elements of VR and only challenged by creating an intuitive interface that residents are able to easily understand and manipulate.

4.4.5 Virtual Reality Solutions for Turret & Gunner Protection (2019-2020)

Figure 86

Elements of VR Applied to Battlefield Training and Threat Identification

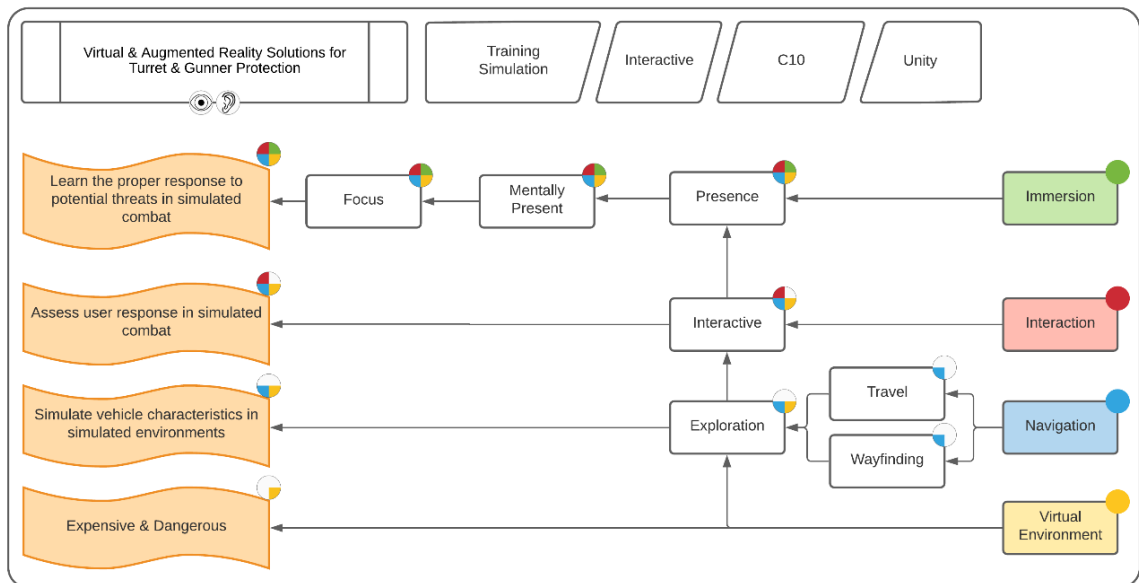


Figure 87

During a Scenario, Suggestions Were Provided, and the Decisions the Operator Makes, Monitored Including Damage to the Vehicle Visualized as a Color Map



4.4.5.1 Problem. There is a critical need for protecting exposed crew members and gunners operating in tactical and armored vehicle turrets used by the United States Army. A virtual environment would provide the ability to enhance combat awareness, threat detection, and target identification in soldiers.

4.4.5.2 Implementation. The Rowan Virtual Reality Center has successfully prototyped a training simulation for the Joint Light Tactical Vehicle to enhance the capabilities and safety of military personnel. This included creating a virtual training environment that is realistic and closely simulates a combat environment. A 3D model of a JLTV was refined and imported so that the vehicle was accurately portrayed and could be utilized in VR. Systems were developed to analyze and display damage on the JLTV so that the threats and risks to the vehicles can be analyzed after the simulation. To enhance the capabilities of personnel, a threat detection system was implemented to enhance combat awareness. In the future, we hope to further realize the vehicle by adding

more components such as electrical systems, and to start testing the simulation for feedback.

Figure 86 shows how the elements of VR were utilized to handle the four project requirements of providing affordable and safe training that properly simulates the driving experience of the JLTV while training users in threat response and assessing their responses. The virtual environment solved the expensive and dangerous aspects of training and consisted of a small town with virtual insurgents, IEDs, and a virtual JLTV. Navigation was controlled with an Xbox controller, moving the vehicle through the environment, and controlling the gunner turret, which solved the need for a simulated vehicular experience that could traverse the environment. Learning the proper response to threats was a combination of all the elements, with immersion provided by the HMD enhancing mental presence and focus.

This project utilized all the elements of VR in order to enhance learning during virtual training exercises. Plans to continue this project in subsequent years will integrate additional hardware and senses to include physical presence to increase trainee awareness of the environment.

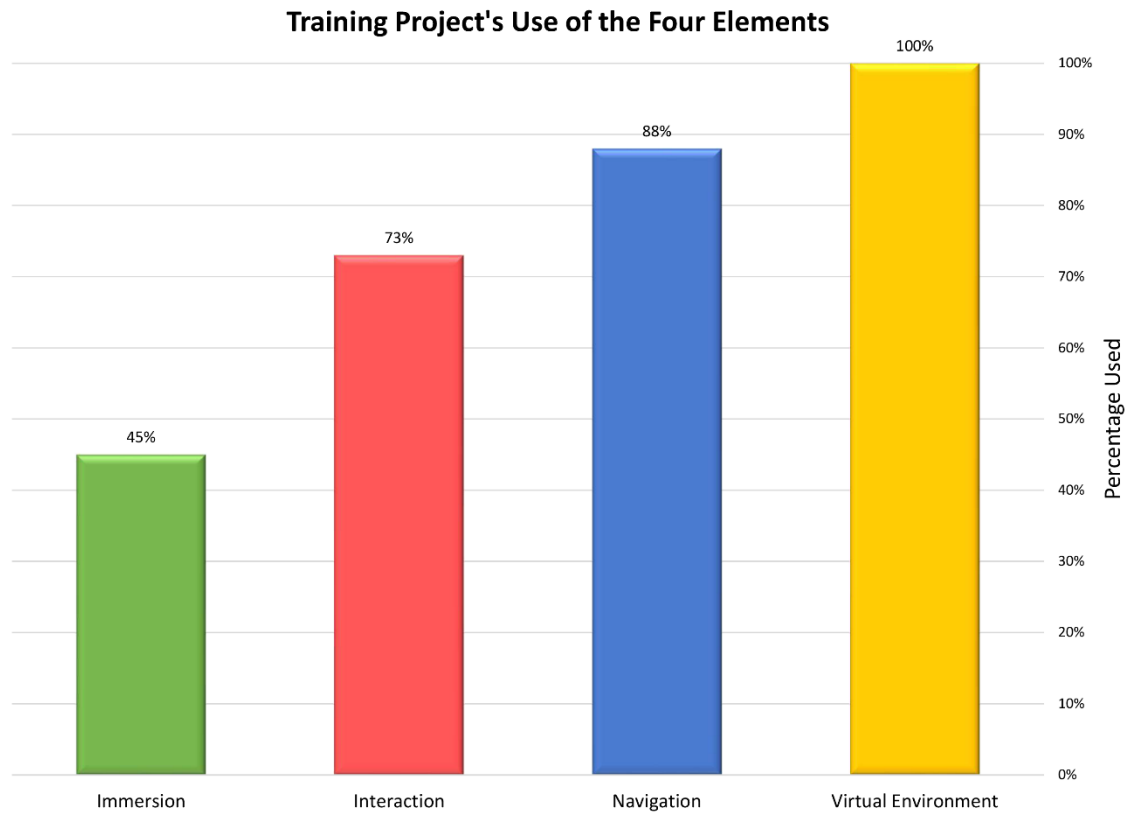
4.4.6 Training Summarized

Five training projects were assessed, with their VR element scores summarized in Figure 88. VR requires a virtual environment, therefore the VE element received a score of 100%. Training projects relied on navigation the most (88%), followed by interaction (73%) and finally immersion (45%). Similar to education, training projects utilized user

agency and self-exploration to learn a procedure. For assessment, having a virtual environment that controlled all aspects provided the ability to assess and record progress.

Figure 88

Results for Training's Use of the Four Elements



4.5 Entertainment Projects

4.5.1 Support Staff Retreat (2009)

Figure 89

Elements of VR Applied to Staff Entertainment

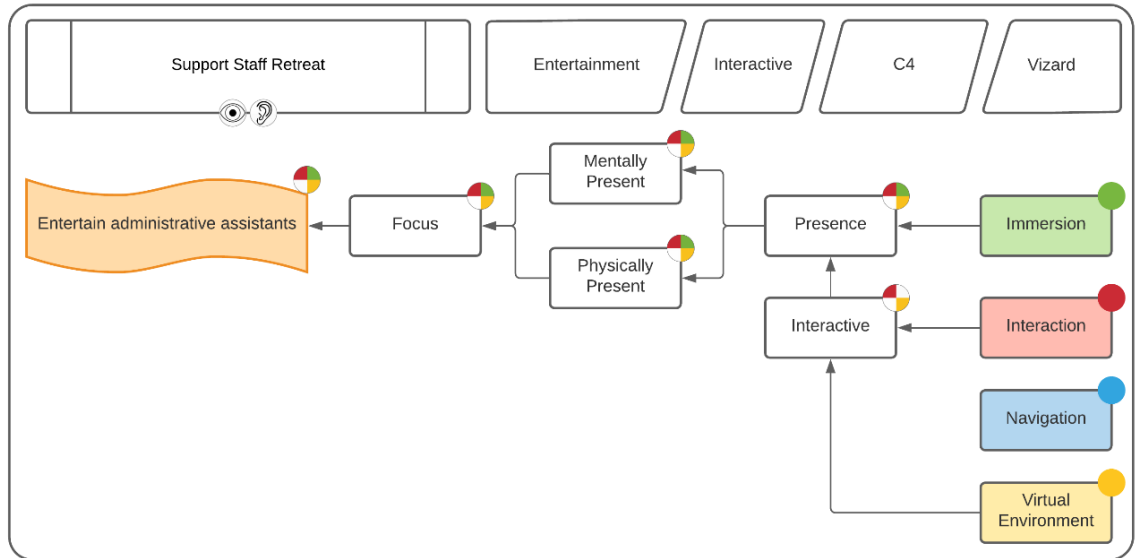


Figure 90

Staff Took Control of a Mallet and Tried to Knock Their Department's Head Back Into a Mole Hill



4.5.1.1 Problem. Rowan support staff requested a demonstration of VR technology during their yearly retreat. A demonstration that would provide interaction and show off the 3D and tracking capabilities of VR was requested. This demonstration was meant to be entertaining while introducing them to VR.

4.5.1.2 Implementation. The common theme of each staff member assisting a staff or administration member was used to engage the participants. An interactive game based on the arcade game Whack-a-Mole was created through the use of a motion tracked Xbox controller. The user entered the C4 while holding the controller in front of them and the tracking system converted their movements into motions for a comically large mallet. Press a button on the controller caused the mallet to perform a striking animation and collision detection within the virtual environment would determine if a hit occurred. Signs with pictures of various staff members in engineering would emerge from the holes at random intervals. Striking a sign would cause it to recede back into the burrow temporarily. (Figure 90). Shadows were not possible to implement at the time, which caused difficulty in determining the spatial relationship between the virtual mallet and the signs. To help the user a target was placed at the burrow the mallet was nearest help indicate what would be struck. Audio cues were added to indicate a hit or miss. A score was kept in the upper right corner to make the game competitive among the staff members.

Figure 89 shows how the elements of VR were utilized to handle the requirement of entertaining the administrative staff. The virtual environment consisted of a series of mounds and signs that would rise randomly. The player was limited to the area directly in

front of the mounds, so no navigation was used. Interaction was through a motion-tracked Xbox controller that was used to position the large mallet. A button on the controller could be pressed to swing the mallet. Immersion relied upon the stereoscopic 3D rendering inside the C4. With the combination of immersion, interaction and the virtual environment, the goal was to enhance mental and physical presence, leading to enhanced focus to engage and entertain the staff.

While the concept caused laughter in the group, when asked to play the game only one member of more than eight administrative assistance volunteered to try. The participant had difficulty maneuvering the mallet and discontinued after a few minutes of play. A number of factors involved may have led to the brief experience including reluctance to hit their employer with a mallet. The group was also unfamiliar with the technology, but even so, this means the project failed to enhance human-machine communication and provide an intuitive experience. Group VR experiences and how they are perceived are depended on the mentality of the collective group, as Kreuger demonstrated in his artificial reality pieces [21].

Physical presence could have been further enhanced if a mock mallet was actually utilized rather than a controller, which features numerous buttons and input controls that were not necessary. The mallet's speed and orientation could have been used to determine a swing as opposed to movement. At that time, the VR Center did not have the capability of rapidly prototyping new controllers through 3D printing.

4.5.2 Virtual Inauguration (2015)

Figure 91

Elements of VR Applied to a Virtual Inauguration

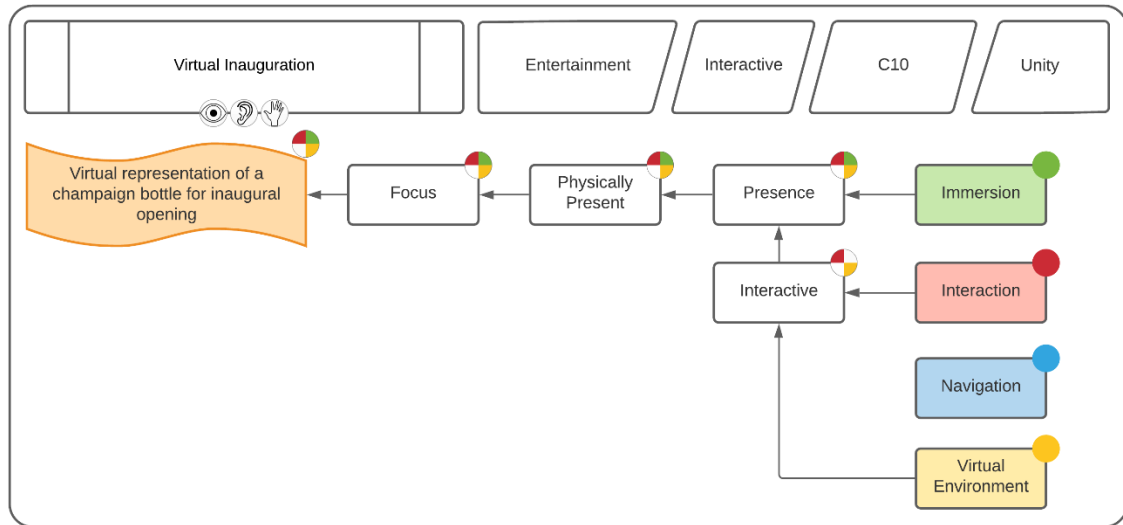


Figure 92

For the C10's Grand Opening a Virtual Inauguration Was Created Using a Champagne Bottle and Retro-Reflective Markers



4.5.2.1 Problem. The Rowan VR Center needed to celebrate the grand opening of the new 10-sided C10 system, however, conventional methods of inauguration through the breaking of a bottle would damage the nearly \$2 million dollar system. A virtual method was required that would also showcase the new technology and interactivity.

4.5.2.2 Implementation. An inexpensive bottle of sparkling wine was purchased, and retroreflective markers were glued to the surface to create a trackable object for the President of Rowan to swing (Figure 92). Upon completing the motion, a series of balloons and confetti were launched into the virtual environment.

Figure 91 shows how the elements of VR were used to create a virtual inauguration. The virtual environment consisted of the Rowan VR Center logo and celebratory balloons and streamers that would be activated through the interaction of the motion-tracked sparkling wine. No navigation was present in the demonstration as it was unnecessary and would complicate the action of swinging the bottle and colliding with the VR Center logo. Immersion relied on the large-scale C10 system. Stereoscopic rendering was not enabled so that guests could see the event without the need for glasses. Through the use of the new, large-scale C10 and the novelty of swinging a real, motion-tracked bottle, the goal was to enhance audience focus during the event.

This was the first project created specifically for the C10 system, utilizing the new tracking system capable of identifying unique rigid bodies that were registered. This would be the first instance in the VR Center where real-life objects were introduced and used by the participant to interact with the virtual environment.

4.5.3 Bane Halloween Experience (2017)

Figure 93

Elements of VR Applied to a 10-Minute Entertainment Experience

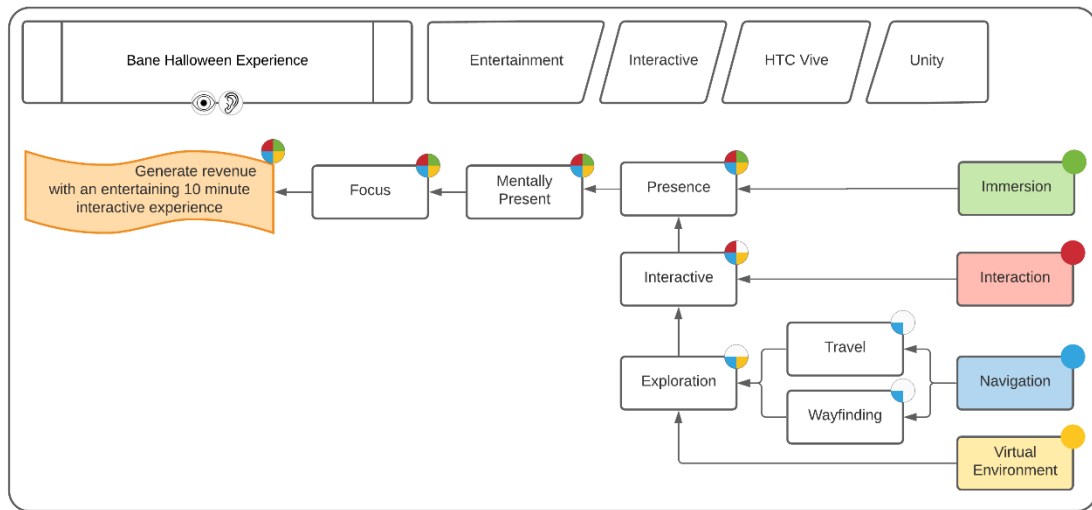


Figure 94

Players Had to Escape a Secret Installation in This VR Teaser Experience



4.5.3.1 Problem. A haunted house Halloween company was interested in creating a VR experience for participants to play while waiting in line. Lines would be hundreds of people long and could take hours to get through, causing customers to leave early. After testing The Rite Halloween experience previously created, the company wanted a new original VR game implement in the HTC Vive.

4.5.3.2 Implementation. A ten-minute escape game was created over the course of two months before the company opened for the Halloween season. It was deployed on the HTC Vive HMD, one of the few VR systems targeted for home use. The game centered around an abandoned military site that was being filled with toxic gas, limiting the player to a 10-minute experience before they died from exposure.

Figure 93 shows that all the elements of VR were utilized to meet the project requirement of generating revenue through an entertaining 10-minute interactive experience. The virtual environment consisted of a series of locked rooms that required keycards to access. As the game relied on the users finding their way through the environment and finding keycards, travel and wayfinding led to exploration. The HTC Vive controllers were used to interact with the environment, including picking up objects and interacting with furniture. Immersion relied on the HTC Vive HMD to provide a stereoscopic rendering of the environment. The combination of all the elements led to mental presence in the environment and focus, necessary to entertain and hold the attention of the player for the full ten minute experience.

The game was played by visiting customers, waiting in line to see the Halloween attraction. Limited data was made available to the Rowan team on how effective it was

at entertaining guests. In subsequent years, the demonstration has been shown at the Rowan College open house for potential students and has been well received.

4.5.4 Bane VR Escape Room (2018)

Figure 95

Elements of VR Applied to a Networked, Multi-User, Virtual Escape Room

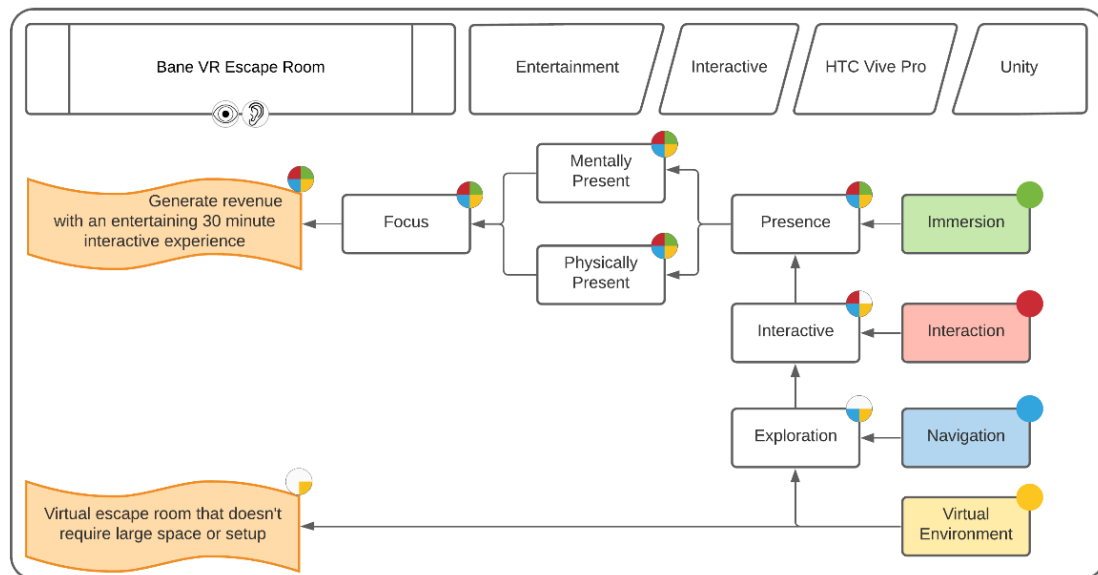


Figure 96

The Virtual Escape Room Featured Various Rooms With Multiple Puzzles



4.5.4.1 Problem. A haunted house Halloween company desired to expand into virtual escape rooms. In the off-season, the company offered real escape rooms. However, these required considerable time to create and implement, and usually only one copy of the escape room existed. There was interest in creating virtual escape rooms that would require no physical setup and feature experiences that would be impossible or dangerous in the real world.

4.5.4.2 Implementation. A two to four player, locally networked VR experience was implemented using Unity and four HTC Vive systems using lighthouses for tracking. Players had to escape four different rooms, each with puzzles and challenges blocking their path.

This concept piece utilized all the elements of VR to produce a networked multiplayer experience where all participants were able to view and interact with the virtual environment from their own perspectives. Physically held controls with motion tracking and head tracking allowed players to see what people were looking at and interacting with in the virtual environment. There were numerous difficulties in having the four players exist within the same space, both virtually and in real-life as the VR technologies being utilized were still new.

Figure 95 shows how the elements of VR were utilized to handle the requirements of creating an entertaining experience that also does not require the large space needs of a traditional escape room. The virtual environment solved the issue of space by making all objects virtual. Navigation through the environments was through the Lighthouse tracking system, where users would walk around a life-sized empty space that was filled

with virtual objects. Interaction through the HTV Vive controllers allowed players to pick up objects and solve interactive puzzles. Immersion through the Vive HMD provided the sensation of presence. Coupled with the hand-held controllers, both mental and physical presence were achieved, enhancing the focus of the user and providing them with an entertaining and engaging experience.

4.5.5 Bridgeton Gravity Demonstration (2019)

Figure 97

Elements of VR Applied to an Educational Experience About Gravity

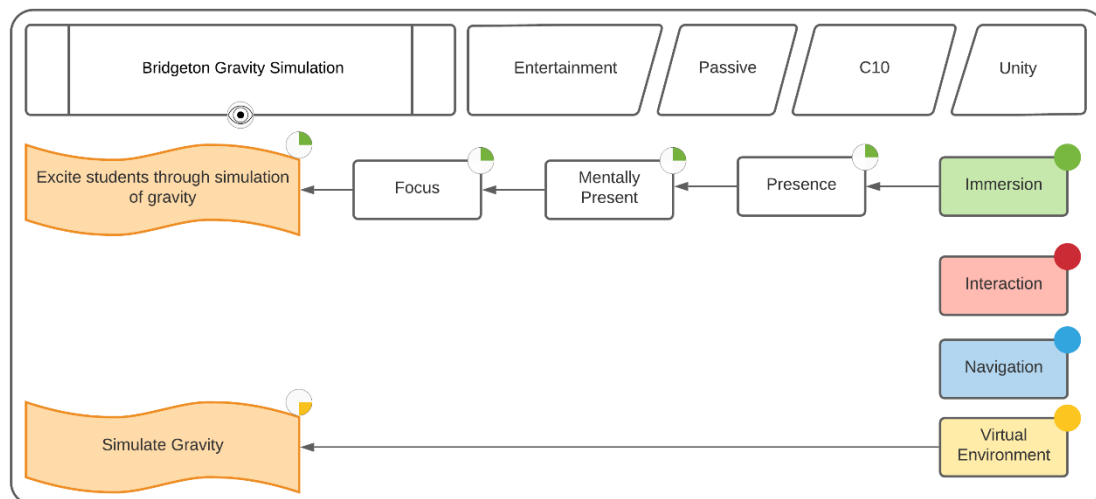
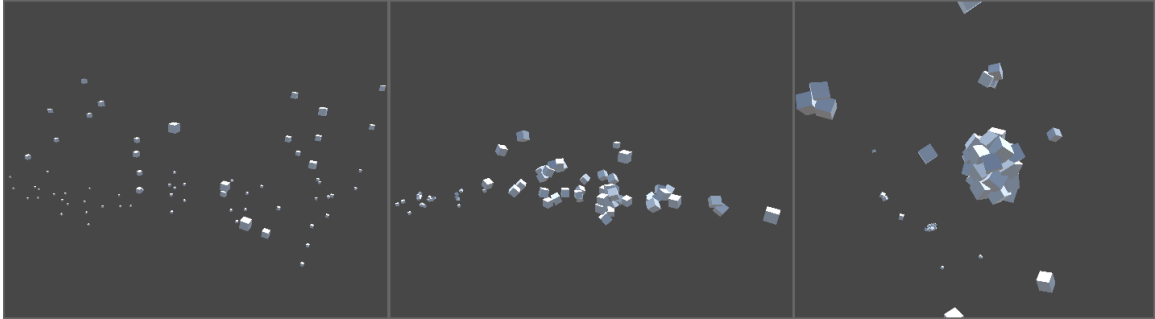


Figure 98

Using Newton's Equation for Universal Gravitation, Cubes Attract Until They Coalesce, Form Stable Orbits, or Are Ejected



4.5.5.1 Problem. Rowan Innovations at the South Jersey Technology Park requested the Rowan VR Center for a demonstration involving high school physics for a visiting group of students.

4.5.5.2 Implementation. To simple simulation involving the calculation of the gravitational forces between nearly 100 particles was created. Users were able to throw virtual cubes or spheres into the simulation using a tracked controller and watch their impact on the orbits of other objects in the scene. After sufficient time passed, objects either coalesced or flung outwards via the slingshot effect and away from the blocks.

This demonstration was a simple simulation with the intent of educating students on how the force of gravity can cause particles to coalesce into larger objects, creating planets and solar system. This project was constrained by a two-week due date and no funding. Far more elements of interactivity could have been utilized to enhance learning such as real-life tracked objects that would influence the virtual environment such as

holding a black-hole or other large gravity well. Holding an object adds physical presence into the simulation, greatly enhancing focus.

Figure 97 shows how the elements of VR were utilized to handle the requirements of simulating gravity and exciting students. The simulation consisted of fifty objects shaped as cubes or spheres. During each physics update, interparticle forces were calculated to simulate the attraction due to gravity. Since this was meant for classes of 15 or more students, no navigation or interaction was present. The immersive nature of the C10, including its wrap-around screens and stereoscopic rendering were relied upon to provide the sense of immersion.

4.5.6 The Rite Halloween Group Experience (2015)

Figure 99

Elements of VR Applied to a Halloween Multi-User Entertainment Experience

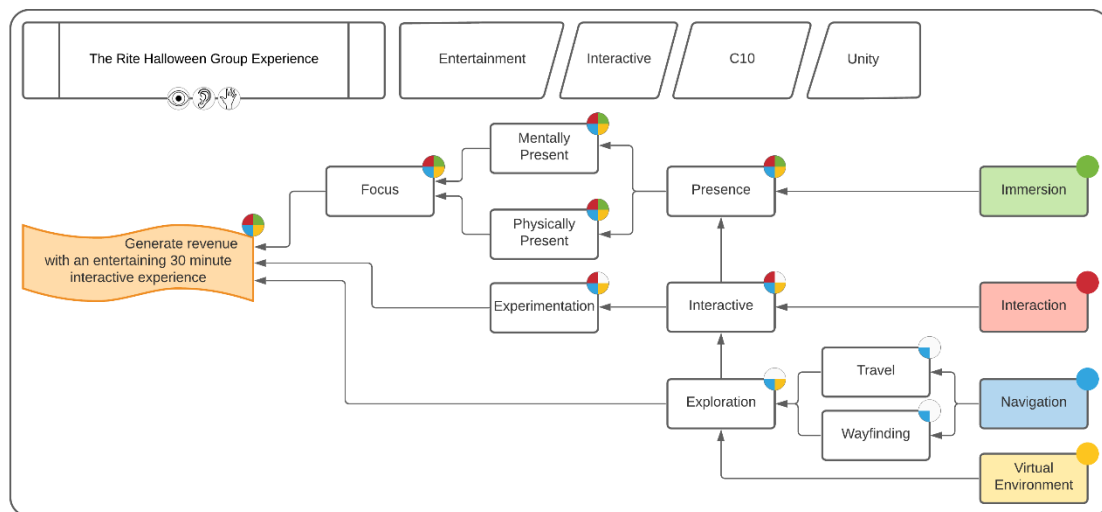
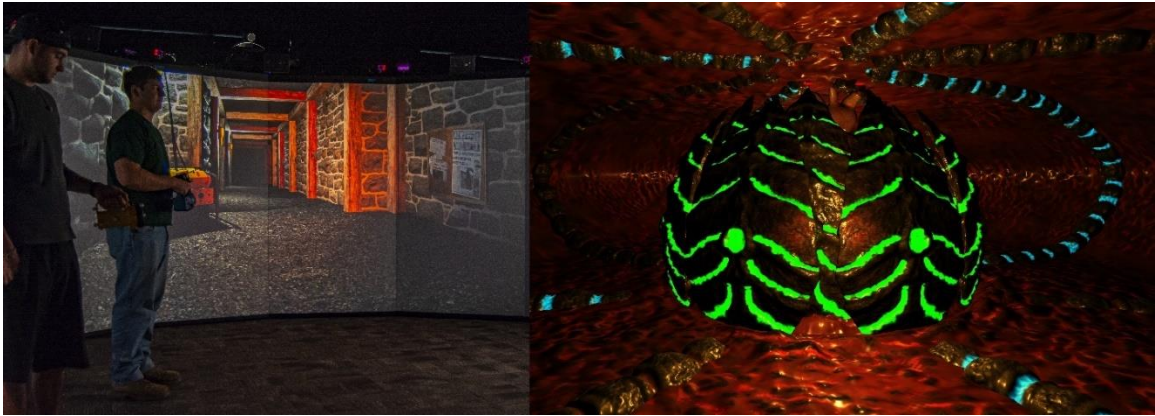


Figure 100

A Group of Players Used Tracked Controllers and Flashlights to Complete Challenges



4.5.6.1 Problem. The large-scale VR systems deployed in the VR Center are not in continual use. Therefore, a decision was made to create an interactive VR experience in the C10 for entertainment purposes. A virtual game would be created, using the novel features of the C10 to entice potential customers to determine if it is feasible to utilize expensive, large-scale systems for generating revenue.

4.5.6.2 Implementation. A thirty-minute virtual reality experience was created for groups of three people using a pose tracked Xbox controller and two flashlights with retroreflective markers and portions of Xbox controllers inside to control flashlights. The experience was over three stages featuring an abandoned mine, a monster-ridden sewer, and a laser battle with an abstract biological entity from inside its own body. Initially, four participants were involved, the last using a radio to listen for clues and hints but was removed due to difficulty in hearing the radio and that member of the team feeling left out of the interaction. One player controlled the group's movement while the other two had color-coded flashlights that would only stay lit for 20 second before requiring a

recharge. Players had to coordinate their flashlight usage and work together in the dark environment provided. Teams of players were charged 20 dollars for the 30 minutes experience with nearly twenty playthroughs occurring before deciding to end the experience.

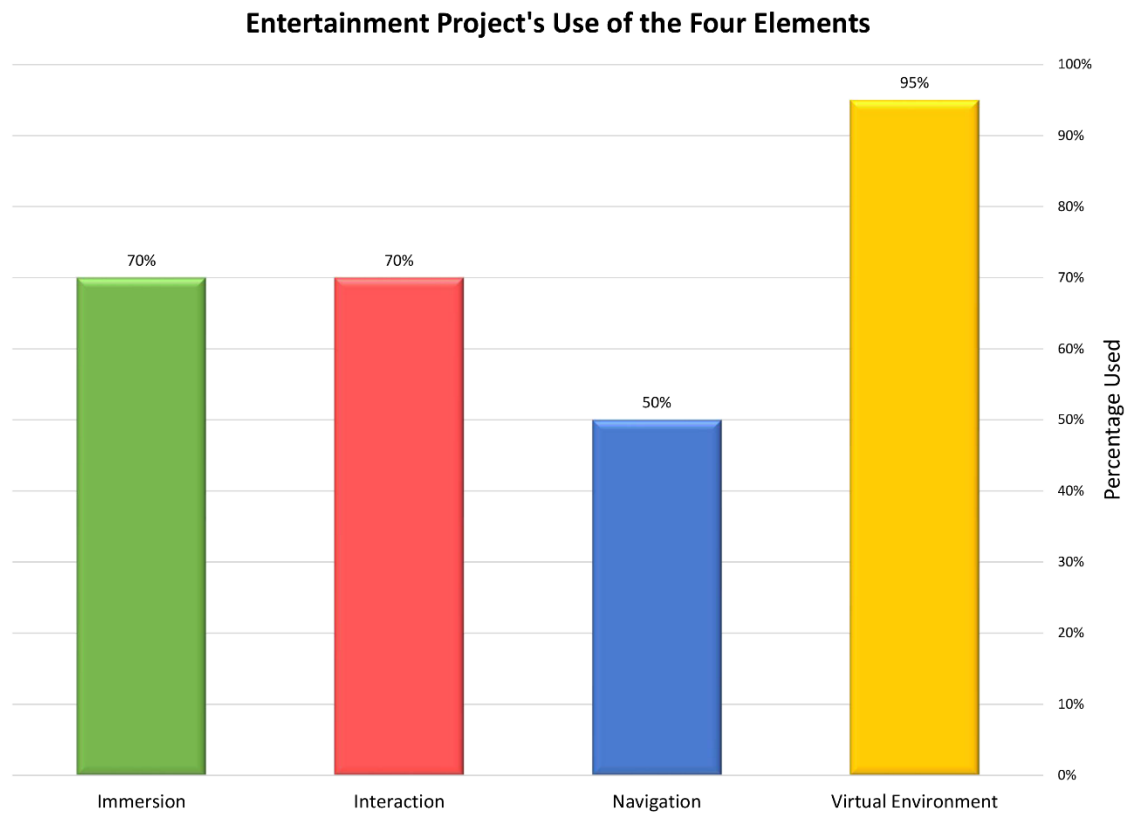
As shown in Figure 99, The Rite Halloween experience utilized all the elements of VR to effectively create an entertaining experience that would lead to future commercial projects. The virtual environment consisted of three locations, an abandoned mine, a sewer system, and the inside of a Lovecraftian monster. Players used their motion-tracked controller and flashlights to navigate the dark environment, working together to travel and find their way. The controller and flashlight also acted as methods of interaction, with the lights scaring away threats and acting as weapons later in the experience. Immersion utilized the C10's wide field-of-view and stereoscopic rendering to create an immersive experience that focused and engaged players.

4.5.7 Entertainment Summarized

Ten entertainment projects were assessed, with their VR element scores summarized in Figure 101. Nearly all VR requires a virtual environment, therefore the VE element received a score of 95%. Entertainment projects relied on navigation (70%) and interaction the most (70%), with navigation the least (50%).

Figure 101

Results for Entertainment's Use of the Four Elements



4.6 Art Projects

4.6.1 Art & Engineering – Enhancing Dance (2012)

Figure 102

Elements of VR Applied to Exploration of Dance and VR

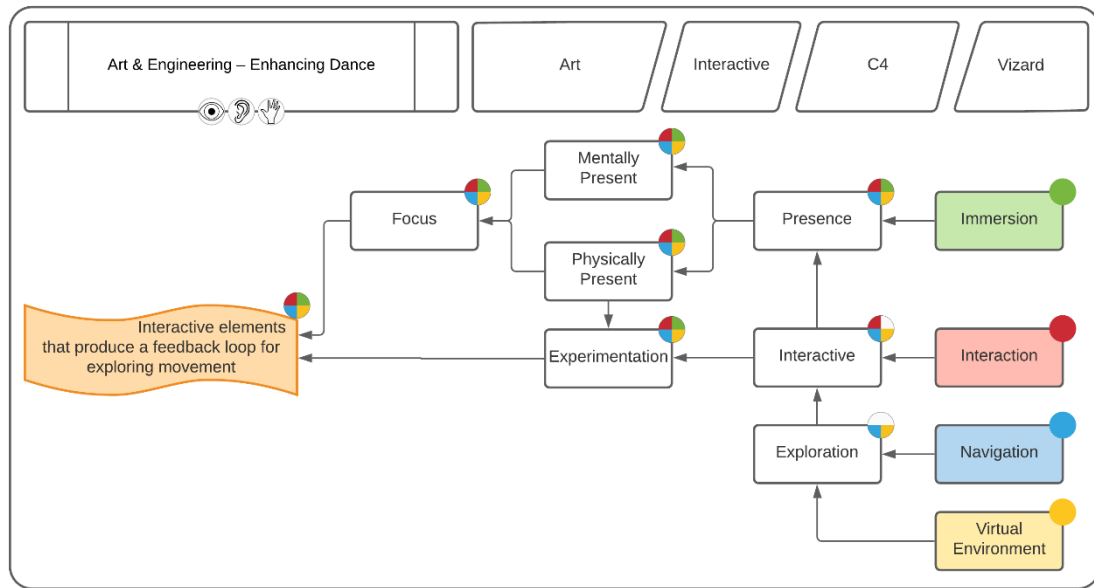


Figure 103

Many Virtual Environments Were Created to Explore Dance and VR Including a Psychedelic Police Box and Aquarium



4.6.1.1 Problem. This project explored the use of VR and 3D environments to enhance dance performance & choreography.

4.6.1.2 Implementation. Several environments were created exploring different methods of interaction with a virtual environment. The first was the interior of an aquarium with assorted fish (Figure 103) that utilized a behavior system composed of basic methods of locomotion such as follow, flee, and wander, producing vectors that were weighted based on a programmed personality for each entity and combined to animate the fish. One motion tracker was used that the fish were strongly associated to follow. The tracker motion was analyzed to detect abrupt changes in direction that would cause the environment to change color. This behavior system was utilized in several alternative environments using assets from prior projects including flying dinosaurs and floating police boxes. The final scene created utilized three motion trackers to follow the head and hands of the dancer. These motions were copied to several abstract avatars behind the dancer to create the illusion of a well-choreographed dance team.

As shown in Figure 102, all of the elements of VR were leveraged to meet the requirement of an interactive experience for exploring movement. The virtual environment consisted of a series of psychedelic experiences that utilized abstract shapes and ranges of vibrant colors. Navigation relied on the dancer's movement in the space, which also led to the interactive components through one or more motion trackers. The virtual environment featured several rules that changed the experience based on the dancer's movement, allowing for experimentation. Both physical and mental presence relied on all these elements as well as the C4's stereoscopic rendering. Through an

enhanced sense of presence, dancers were engaged with the virtual environment. It was through the combination of focus and experimentation that the requirements for this project were met.

4.6.2 Sticky Dance (2016)

Figure 104

Elements of VR Applied to a Choreographed Dance Exploring the Bonding Between Two People

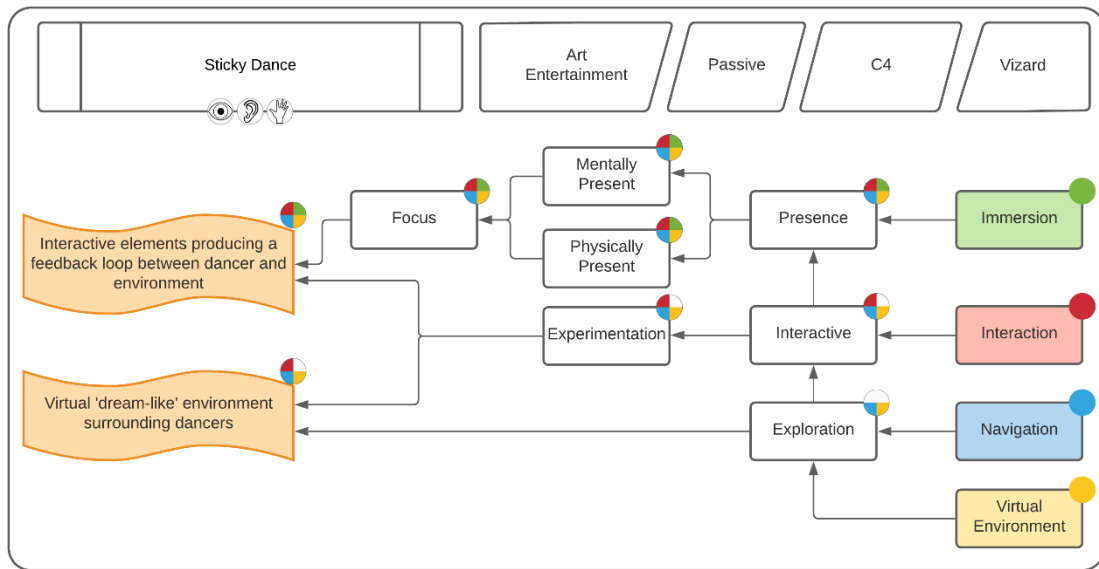


Figure 105

Scenes Were Filmed Within The CAVE to Create a Dream Sequence



4.6.2.1 Problem. “STICKY” desired to use VR to explore the nature of bonding between two humans through imagery, examining sticky situations in relationships through a multi layered use of movement, 3D media, film animation, music, and text. Professor of Dance, Melanie Stewart had already worked with the Rowan VR Center through her modern dance course and work with a dual major dance and engineering major. This project would capitalize on the early movement experiments in the CAVE, but this time for a live audience.

4.6.2.2 Implementation. Based on studio research, experimentation, and movement/text created by Eun Jung Choi and Guillermo Ortega Tanus, Professor Stewart directed the sequences filmed in the CAVE, with a virtual environment overlaid with imagery by Raymond Ercoli and Liz Goldberg in Film Animation. The virtual

environment was controlled by a student. The dancer reacted to the movement of the VR environment. When the couch was hastily moved, the dancer flung their body onto the floor in response. In many ways, the VR system operated opposite to the typical exchange, where it is the simulated environment reacting to the user. Several scenes were recorded, some of which were re-projected into the CAVE environment. The final footage was projected onto a large screen during the stage performance at the premiere in Mexico City and in Philadelphia. They were used as dream-like sequences, showing the inner-mind of the performer.

Figure 104 shows that all of the elements of VR were utilized to meet the requirements of producing an interactive environment that reacted to the dancer's movements and create a dream-like experience. Through the combination of the virtual environment and the motion-tracked dancer, exploration within the space was possible. In this case, exploration referred to understanding the feedback loop between dancer and virtual environment and how best to use them. Immersion, created by the C4s large-scale screens, provided a feeling of mental and physical presence viewed by the audience, not the dancer. The dancer, through their exploration of the virtual environment and carefully staged choreography, made it appear as if they were physically part of the virtual environment.

This project was the culmination of the lessons learned in prior years. It explored an interesting dynamic where the real-life performer reacted to the environment as opposed to the environment reacting to them. Through the use of their entire body, their reactions made them appear to be part of the virtual environment, even without any form

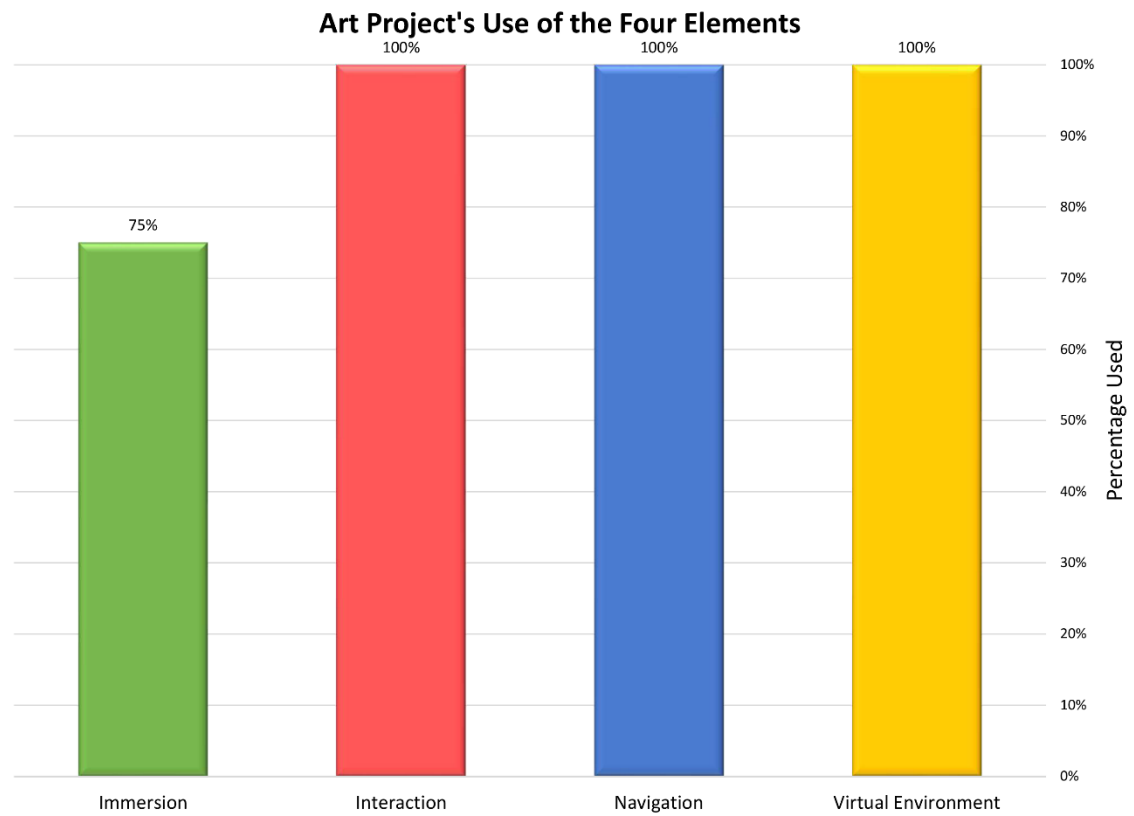
of motion tracking or interaction. In this situation, it wasn't the performer in the CAVE that needed to be immersed, but the audience watching the pre-recorded footage of the virtual environment.

4.6.3 Art Summarized

Two art projects were assessed, with their VR element scores summarized in Figure 106. VR requires a virtual environment, therefore the VE element received a score of 100%. Art projects utilized navigation (100%) and interaction the most (100%), with navigation the least (75%).

Figure 106

Results of Art's Use of the Four Elements



Chapter 5

Conclusions

Steven Spielberg, the director of the 2002 science fiction action film *Minority Report* is said to have created a “think tank” of expert technologists to envision a plausible “future reality” for the year 2054 [103]. Despite enormous advances in computation, display, and communications, the augmented reality technology depicted in the movie still remains the “holy grail” for VR, AR, and MR environments in 2021. The research work presented in this dissertation has surveyed the gamut of commercially available simulated environments, followed the evolution of VR devices, and deployed them in a diverse set of applications from virtual surgical training systems to a depiction of the Warsaw Ghetto during the Third Reich.

The myriad of examples presented in this dissertation follow a common process to determine the path for the design, development, and implementation of the VR environment. In the application areas encompassing modeling, simulation, training and education, this dissertation has critically evaluated the appropriate and effective use of VR across problem domains using the elements of immersion, interaction, navigation, and virtual environment.

The specific contributions of the research work presented in this dissertation are:

1. An evaluation system was developed to classify each potential application of VR into a specific category. The categories are: visualization, simulation, education, train, entertainment, and art.

2. A systematic flow chart was designed and developed to connect the elements of VR to the specific problem requirements. These elements of VR are: immersion, interaction, navigation and virtual environment.
3. A three-step process was developed to assign numerical values to the effective utilization of the various components of VR for addressing the requirements of a specific project. In the first step, each project was mapped on to a specific category describing the overall class of projects. In the second step, specific project requirements were correlated to specific elements of VR. In the third and final step, an effectiveness score was determined to indicate the effective utilization of the elements of VR for each project category.

Visualization-based projects showed the highest use of immersion, enhancing presence and focus. This category also saw least use of interaction, and modest use of navigation. In general, visualization projects are the easiest to implement, because of a proliferation of established pipelines and software to visualize data.

Simulation-based projects made maximum use of the navigation element of VR, significant use of interaction and little use of immersion. Navigation allowed the user to effectively examine 3D space-correlated information; interaction provided the user to ask “what if?” questions and examine various scenarios.

All the elements of VR shone in education-based projects. Maximal use was made of navigation, interaction, and immersion, in that order. As expected, education occurs most effectively when the learner is actively engaged and is enabled to possess the agency to direct their learning.

Training-based projects followed closely on the footsteps of education-based projects. The order of the use of VR elements was similar: navigation, interaction, and immersion; however, individual effectiveness scores varied reflecting the subtle differences between training and education.

Entertainment-based projects were the hardest to evaluate because there is no standard definition of what is entertaining to various audiences. These projects showed higher uses of immersion and interaction, and not insignificant use of navigation. With its vast resources, impact and reach, the entertainment industry has driven advances in virtual/augmented/mixed reality. The plummeting cost of the access to VR technology is largely a result of investments made in the entertainment industry. It would be easy to state that VR triumphs in this application alone. However, this dissertation, having developed an objective measure of evaluating the effective utilization of the components of VR, can show that there are other societal benefits in addition to entertainment.

Not surprisingly, the VR elements of interaction and navigation had their maximal impact in the field of art. VR offers a convincing relation to the visual representation of space. It provides the aesthetics to enable a heightened sense of user-experience and engagement. While this dissertation examined very few projects in this category, there is considerable potential to explore further expressions of art using VR.

In summary, the research work presented in this dissertation demonstrates the hypothesis that the greatest scientific value-add of VR/AR/MR technologies is in the area of training and education, with modest advantages for modeling and simulation.

The evolution of technology intuitively points in the direction of the movement towards MR, and away from purely VR and AR. As the transformation of the enabling visualization environment for modeling, simulation, and training, gathers pace, it becomes all the more important to design and develop objective measures for measuring effectiveness. And that will be a large part of the future work that will be generated from the research work presented in this dissertation. Most testing of virtual experiences for education is largely subjective. Objective, psychometric methods to quantify the value-add of MR experiences for modeling, simulation, and training will go a long way in embracing the technology as it becomes more affordable and ubiquitous.

From times immemorial, the ability to visualize complex problems, explore potential solutions, and communicate results, is critical to scientific progress. Although visualization does not create new science, it has enormous potential to enable it. It is hoped that the research work described in this dissertation will, in some small step, advance the cause of immersive, interactive, and navigable virtual environments.

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