Virtual Presentation Methods for Physical Artifacts

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An Interactive Qualifying Project Report

Submitted to the Faculty

of

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Arts

in

Interactive Media and Game Development

25 March 2022

APPROVED:

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Abstract

This report reviews methods for virtually presenting physical artifacts too cumbersome or delicate to display by conventional means. It was initiated to address issues faced by the Worcester Art Museum, which is preparing a comprehensive exhibit of the Higgins Armory Collection. Several technologies are assessed, including optical illusions involving mirrors, various forms of holography, and pseudo- and autostereoscopic displays. Practical considerations led to the recommended use of 2D digital monitors incorporating high spatial resolution, extended colorspace and advanced frame rate capabilities, coupled with hands-free sensors that allow viewers to interact with displayed images.

Contents

1. Introduction

John Woodman Higgins was an industrialist who grew up in the late nineteenth-century in Worcester, Massachusetts. At the time, the city was a center for American manufacturing, and his father, Milton Higgins, was already leading the steel industry there. When he came of age, the father and son purchased the Worcester Ferrule and Manufacturing Company, renaming it to Worcester Pressed Steel and selecting an armored knight as their logo.

John Higgins developed an interest in medieval and Renaissance arms and armor at a young age. With the help of Bashford Dean, the Curator of Arms and Armor at the Metropolitan Museum of Art in New York, and a post-World War I economic depression in Europe pushing medieval artifacts onto the market, Higgins began assembling what would eventually become a world-class collection.

Figure 1. The Great Hall of the original Higgins Armory Museum.
Source: Worcester Art Museum archives.

By 1927, the Higgins collection had grown enough to justify the construction of the Higgins Armory at the front of the Presteel factory. Construction began in 1928 and finished in 1931, opening to the public in the same year (Figure 1). The exterior boasted a glass and steel Art Deco style, with the interior giving the impression of a medieval great hall.

It was divided into two wings, one ancient and one modern. The ancient wing had the floorspace to house the expansive set of weaponry and armor Higgins had spent the last decade collecting, whereas the modern wing housed a showcase of the evolution of metalworking, including modern examples such as an automobile engine and a Piper Cub airplane. Tours of the adjacent factory were also offered to guests.

John Higgins passed away in 1961, leaving behind his armory and steel factory. The factory closed about a decade after his death, but the Armory remained open to the public until 2013. Compounding financial issues coupled with the expensive maintenance of the building forced its closure.

The collection was acquired by the Worcester Art Museum and came under the curation of Jeffrey Forgeng, at the time a faculty member of Worcester Polytechnic Institute. Since then, Dr. Forgeng has endeavored to find ways to preserve and display as many of the 1,500+ items in the collection as possible within the limited space available in the Worcester Art Museum, as per a legal agreement governing its donation. Current plans will relocate the collection into the Museum's Library wing in 2025, utilizing an "open storage" display style which packs related items closely together to maximize efficiency.

Figure 2. Desiderius Helmschmid, Right Gauntlet of Prince Philip II of Spain (1549-1550).
Source: Worcester Art Museum, Ref ID 2014.1155.14.

The Higgins Collection contains items of considerable historical significance and beauty, such as a pair of ornamental gauntlets once owned by Philip II of Spain (Figure 2). It can be difficult to appreciate the detail and workmanship of such artifacts when enclosed within a glass display case. Some pieces, particularly those incorporating centuries-old textiles, degrade when exposed to normal room lighting, and cannot be exhibited by conventional means.

We met with Dr. Forgeng at the beginning of this project. Although he feels that virtual display technology is not optimal in the sense of bringing physical objects onto the museum floor, its use will make it possible to exhibit multiple items in a single location while avoiding the hazards of moving and exposing fragile artifacts. He expressed a desire for as much of the real-life detail to be captured as possible, with the added potential for Museum visitors to visually interact with displayed objects. With these goals in mind, we began looking for innovative ways to bring new life and accessibility to the Higgins collection.

2. Survey of display techniques

2.1. Pepper's ghost

"Pepper's ghost" is the nickname of a method for producing the illusion of an image projected into space that is widely used by theaters, concerts, darkrides and amusement parks. Named for John Henry Pepper, an English scientist who began popularizing the effect with live performances in 1862, this effect utilizes an offstage subject (often a live or simulated actor) viewed by means of a semi-reflective mirror tilted towards the audience. Careful arrangement of the presentation geometry and lighting allows a ghostly reflection of the subject to appear in the space behind the invisible pane. Clever choreography can make the subject seem to interact with real objects located in this space.

Figure 3. A Pepper's Ghost illusion in the *Haunted Mansion* attraction at Disney amusement parks.
Source: Disney Studios.

Disneyland's Magic Kingdom hosts *The Haunted Mansion,* a popular darkride which makes extensive use of the Pepper's ghost illusion. When riders enter the Grand Hall, a variety of "ghosts" are seen dancing together, along with elderly ghosts sitting at a dinner table (Figure 3). The ghosts are actually brightly lit animatronic figures located outside the observer's field of view, reflected off an array of semi-reflective mirrors installed between the Great Hall setting and the riders.

Outside of theme parks, illusions based on Pepper's ghost are typically used in theatrical plays and concerts. Deceased stage performers such as Tupac, Michael Jackson and opera diva Maria Callas have been digitally "resurrected" onstage using this technique. Virtual acts like the Gorillaz also utilize the effect to present fictional band members in front of live stadium audiences. (Farivar)

Pepper's ghost illusions are often described as 3-dimensional. This is true <u>only</u> if the subject being reflected in the mirror is itself 3-dimensional. If the subject is 2-dimensional (such as the digital projections used to display the performers in the virtual concerts noted above), its reflection will also be 2-dimensional, although its apparent location in the space behind the mirror may give viewers the <u>impression</u> of solidity, especially if the total light path between the subject and the viewer (including reflections) is greater than approximately 30 feet. At this distance, our two eyes no longer receive sufficient binocular disparity to support stereoscopic depth perception.

2.2 Pepper pyramids

A recent variation of the Pepper's ghost technique allows a 360-degree view of an object that appears suspended in space. It employs an array of four semi-reflective trapezoidal planes arranged in a pyramid, with the point of the pyramid facing downward. Each face of the pyramid reflects a separate, perspective-corrected view of an object displayed on a digital monitor placed underneath, facing upward. In most cases, a single monitor is used to display all four views simultaneously.

Figure 4. Bjister Bjorn, *Holographic Pyramid Upside Down*.
Source: Glimm Screens International, TB Haren, The Netherlands.

A viewer moving around the pyramid sees a different perspective of the displayed object reflected in the plane they are facing, creating the impression that the object is "floating" inside (Figure 4). The displayed images can be animated to add rotation, motion blur, particles and other visual effects to enhance the illusion of reality.

Because the images reflected by the faces of a Pepper pyramid are 2-dimensional, the images of the object observed in the pyramid are also 2-dimensional. Nevertheless, the ability to walk around the pyramid and see perspective-correct views from every angle can create a persuasive impression of solidity for non-critical viewers. (Roslan 171)

Pepper pyramids can be built inexpensively at small scales by using acrylic plastic for the reflective surfaces. Such devices are widely marketed as a 3D viewing accessory for smartphones. The palm-sized pyramid is placed directly atop the phone's screen, which displays the four images required to create the effect.

The maximum scale and resolution of objects appearing within a Pepper pyramid are limited not only by the dimensions of the optical apparatus, but also by the size of the four images reflected in its faces. Since a single digital monitor is typically used as an image source, pyramids rarely exceed a height of 12-16 inches. Yet even an exhibit this small occupies a significant amount of floor space, especially when the area required to accommodate surrounding spectators is taken into account. Floor space is often at a premium in museums, particularly the area designated for the future Higgins Armory exhibit, which makes deployment of a Pepper pyramid in such a setting impractical.

2.3 The Mirascope and parabolic reflectors

Another mirror-based technique capable of producing a truly 3-dimensional display of solid objects involves the use of parabolic reflectors, specially-curved surfaces that direct parallel rays of light towards a chosen focal point. These are often used for automotive rear-view mirrors, and as wide-angle security viewers in stores. ("Convex Mirror and Applications" 08:35–12:24) Other use cases include lighthouses ("Reflectors" by Thomas Tag | US Lighthouse Society), confocal microscopy (Lieb and Meixner 458-474) and telescopes (Thomas and Lemelson).

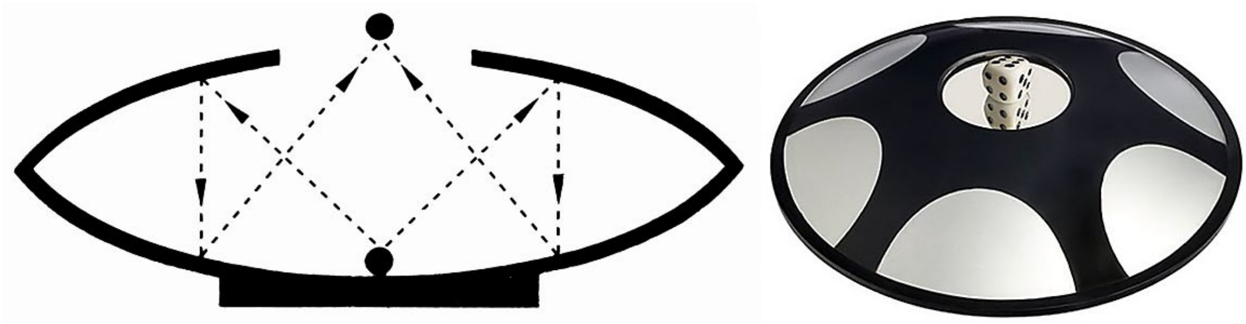

Figure 5. Optical paths and resulting 3D image produced by a classic Mirascope. Source: URL.

A simple device using parabolic mirrors for 3D imaging, the Mirascope, was first described in the 16th century by Giovanni Battista Della Porta. (Sparavigna) It consists of a matched pair of concave reflectors assembled rim-to-rim. The upper mirror has a round opening at the top. If an object is placed at the bottom of the lower mirror, an observer peering sideways into the top of the Mirascope sees a 3-dimensional image of the object “floating” above the opening (Figure 5). The phantom object can appear eerily realistic, depending on the quality and accuracy of the mirrors, and the lighting used to illuminate the interior.

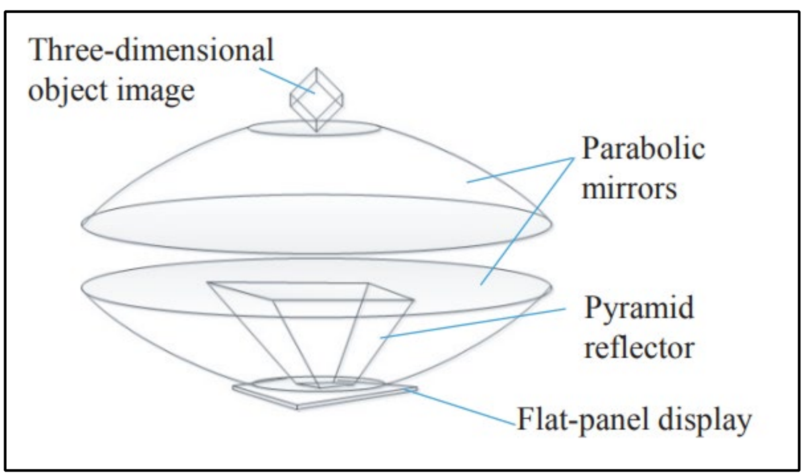

Figure 6. Combining a Mirascope with a Pepper pyramid to produce virtual 3D imaging.
Source: URL.

The object reflected by the mirrors does not necessarily need to be physically present. Figure 6 shows how a Pepper pyramid positioned atop a digital monitor mounted at the bottom of a Mirascope will produce a pseudo-3D image of an object displayed by the upward-facing monitor. (Matsumaru et al. 659-660)

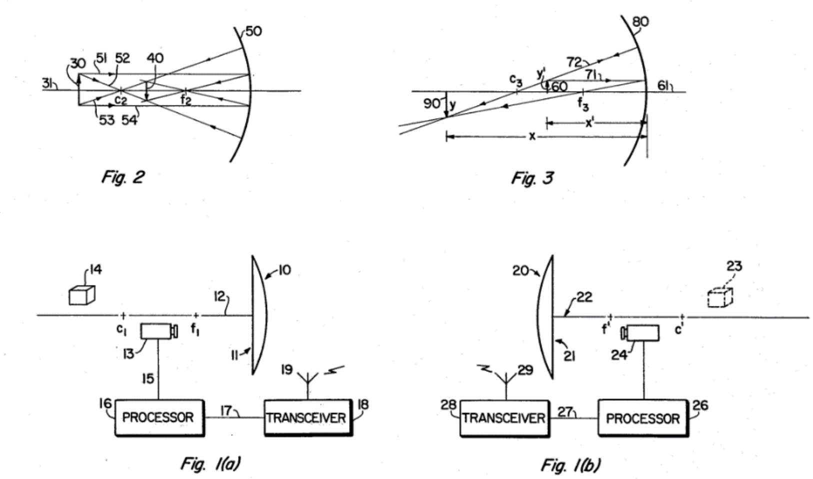

Figure 7. Patent diagram for Valerie L. Thomas' Illusion Transmitter. Source: [URL](URL).

It is even possible to transfer an 3D image from one parabolic mirror to another at an arbitrary location via an Illusion Transmitter. This technique was patented in 1980 by Valerie L. Thomas, a NASA scientist working on Landsat, the satellite that sent the first multispectral images of Earth from outer space. ("Valerie Thomas | Lemelson")

As shown in Figure 7, an object is placed away from the focal point of the source mirror, inverting it to the bottom side. A camera records the resulting reflection, processes it and sends the image data to the destination mirror, where it is projected into the mirror to reconstruct the 3D object image. This technology is still used by NASA.

The Higgins Armory exhibit could conceivably employ basic Mirascopes to display individual artifacts, or one of the digital alternatives to display a variety of artifacts with a single device. Switching from one object to another would be as simple as selecting different images for display.

Unfortunately, high-quality optics for these applications would be prohibitively expensive to obtain. Also, the maximum size of objects viewable using parabolic reflection is quite limited unless the mirrors are very large, requiring valuable floor space.

Figure 8. A deluxe 4-bladed 3D fan, and an image produced by a 2-bladed tabletop model. Source: URL.

2.4. “3D” fans

Fans with multicolor LED strips integrated into the blades have become popular attention-grabbers in recent years, particularly in Asian countries. By rotating the fan at high speed (typically between 750 and 900 RPM) and rapidly modulating the pattern displayed by the LEDs, full-color images, animations and even movies can be shown that seem to “float” in space. 3D fans are often deployed for advertising in public spaces such as markets, transportation hubs and trade shows.

Although aggressively touted as a “3D” volumetric imaging technology, the pictures created by these devices are strictly 2-dimensional, limited to the plane of rotation. Image quality varies depending on the number of blades (usually either two or four), the number and density of the LEDs mounted on each blade, the rotation speed and the level of ambient light in the environment. Even high-end professional units compare poorly with standard PC monitors in terms of resolution and colorspace, and all models exhibit an obvious raster pattern of concentric circles. Animations must be perfectly synchronized to the rotation speed of each specific unit to avoid jitter and choppiness.

The rapidly spinning blades pose a serious safety hazard if deployed at ground level without a protective barrier. They also make a lot of noise, particularly when grouped together in arrays to produce imaging “walls,” and tend to overheat after less than an hour of uptime, which impacts their ability to be observed and appreciated throughout the day. (Salo, et al. 3) These drawbacks make it difficult to recommend their use in a museum-quality exhibit.

2.5. Parallax barrier/lenticular 3D displays

Another technique for producing a 3-dimensional display involves the use of a parallax barrier, a device that is placed as a transparent layer over a 2-dimensional image, which can be printed or displayed on a screen (Shi et al. 2). This allows two images to be interlaced, giving each eye a unique image that gives the illusion of depth. It works by interlacing vertical strips of the images for the left and right eye. “To do this it has an array of slits – known as a parallax barrier – in front of the screen to ensure that each eye sees only the strips it is meant to, as long as the user stays within a narrow viewing area.” (Hecht, Jeff.).

Parallax barriers are used in a handful of consumer products designed to produce 3D images that do not require the use of special viewing glasses. Nintendo’s 3DS handheld gaming console (released in 2011) is a well-known example.

Figure 9. Nintendo’s 3DS handheld gaming console. Source: Nintendo USA.

The 3DS is a dual-screen device, with the top device being an LCD screen with a parallax barrier (Figure 9). Later models of this device included an extra front-facing camera that tracked the observer's eyes, to manipulate the images by distorting the parallax barrier to work from more horizontal views. Nintendo has been experimenting with this kind of technology for years, with the company trying to progress and begin experimenting with augmented reality tools prior to the 3DS. Before that product was released, Nintendo were planning to release a 3D screen for their fourth main-line console the Gamecube. Satoru Iwata, former president of Nintendo, explained:

“The Nintendo GameCube system actually had 3D-compatible circuitry built in. ... It had the potential for such functions,’ Iwata told an interviewer. ‘If you fit it with a certain accessory, it could display 3D images. ... Nintendo GameCube was released in 2001, exactly 10 years ago. We'd been thinking about 3D for a long time, even back then.” (Thorsen *GameCube almost had 3D functionality*).

When the observer is looking at the screen, there are two forms of disparity known as both crossed and uncrossed. According to Mangiat and Gibso, “Crossed disparities appear in front of the display and uncrossed disparities appear behind the display.” (Disparity remapping for Handheld 3D Video Communications) Both disparities have varying vergence distance, with the crossed disparity being shorter than that of the uncrossed disparity. The effect is very impressive, however there is a significant caveat to this type of optical imagery.

Figure 10. Digital 3D images displayed by the lenticular monitors sold by Looking Glass.
Source: Looking Glass Studios.

The Looking Glass devices utilize updated lenticular technology to display a 3D image, allowing a small group of observers within the display's viewing cone to see the effect without the need for special glasses or a head-mounted-display. (Factory) It uses an image composed of 45 different perspectives to draw at several points of view. The RGB components of the image are split into subpixels to be allocated and mapped to the display (Sebastion. “I could hardly believe my eyes! - Looking Glass Holographic Monitor”). The display’s depth and manipulation of the subpixels create a stereoscopic effect similar to a parallax barrier (Figure 10).

The problem with these displays is their affordability. Three models are currently offered by Looking Glass. The Portrait model costs $399, at the size of a 7.9" display, which is too small small for the purposes of our design (Factory). The largest model is the 32" 8K Gen2, priced at $17,500 (Factory).

Digital Holography has always struggled with maintaining the detailed accuracy of the image versus the cost of displaying it. Not only that, but drawing a 3D holographic image takes a lot more processing power from the connected PC as well. To draw enough power to get a smooth image on the display, we would likely require a top-of-the-line graphics card to do so.

On the other hand, the Looking Glass Display is one of the more promising applications of Digital Holography. Not only does it offer a high-resolution autostereoscopic display, but the display also comes with its own software for the user to experiment with. It also has a wide amount of support for Blender (Foundation, Blender.), Unity (Technologies, Unity.), Unreal Engine (Unreal Engine), and the SDK (Software Development Kit) which allows further compatibility with other 3D software (Looking Glass Documentation). The device seems to be fairly open, having a wide amount of support for the user to develop with. The addition of compatibility with both game engines Unity and Unreal makes the option of interactive software more practical than other forms of holography.

Interactive Holography is an experience yet to be commonly experienced by the general public. Very few examples of high-resolution 3D gaming exist for autostereoscopic displays, making the Looking Glass devices to be a more interesting candidate for IMGD to work with. The unique display and design would also be beneficial for the Worcester Art Museum to achieve a stunning effect to visualize the artifacts, although the display would likely require more maintenance than a traditional monitor.

2.6. Holography

2.6.1. Analog holography

Holography is an imaging technique invented in 1947 by Hungarian scientist Dennis Gabor, in which light waves are recorded and stored to later be reconstructed (Isik 232). The recorded waves of light are known as holograms, though there is some contention to what we classify as a hologram. Even though we will often refer to them as holograms, what we are actually referring to is the Holographic Object. The Holographic Object is the reconstruction of the recorded object.

Analog Holography is a classification of holography that utilizes Holographic Optical Elements (HOE). “In analog holography (AH), the conventional recording of light scattered from an object along with a reference wave is recorded on an analog recording medium” (Nahmetallah & Banerjee 472). Holographic Optical Elements are the physical tools in holography, more specifically mirrors, prisms, and lenses. Depending on the elements used, we can achieve different kinds of holograms. Transmission, reflection, single beam, and a plethora of other holography methods have emerged from different use cases of these elements (Isik 232). To put it simply, different angles, positions, beams, and other optical elements allow holographers to achieve these forms of analog holography. Analog holography is the oldest and most common format to create holograms, as there have been techniques found utilizing optical elements.

Since the discovery of capturing objects through the means of recording light on a holographic plate, there have been a variety of solutions to craft an analog hologram. In Holographic Interferometry, the holographer uses a technique known as interference. Essentially, when two waves cross into one another, a pattern is formed known as a standing wave. You can perform a Constructive Interference to add waves, or you can completely negate some of the waves through a Destructive Interference. The waves that are bounced off of the object to create the hologram are referred to as the Object wave but they need a Reference wave to cause the interference. “You can’t have interference without something to interfere with. So a second wave of light that has not bounced off an object is used to perform this function. It is called the REFERENCE wave.” (Holographic Studios Interference). A beam is sent from one mirror to another, where the beam is then split onto two separate lenses. When the two beams of light meet, we create the standing wave pattern through the interference (MIT OpenCourseWare 03:15–05:21). With the standing wave pattern created, the waves of light are captured onto the holographic film to create the hologram (Figure 11).

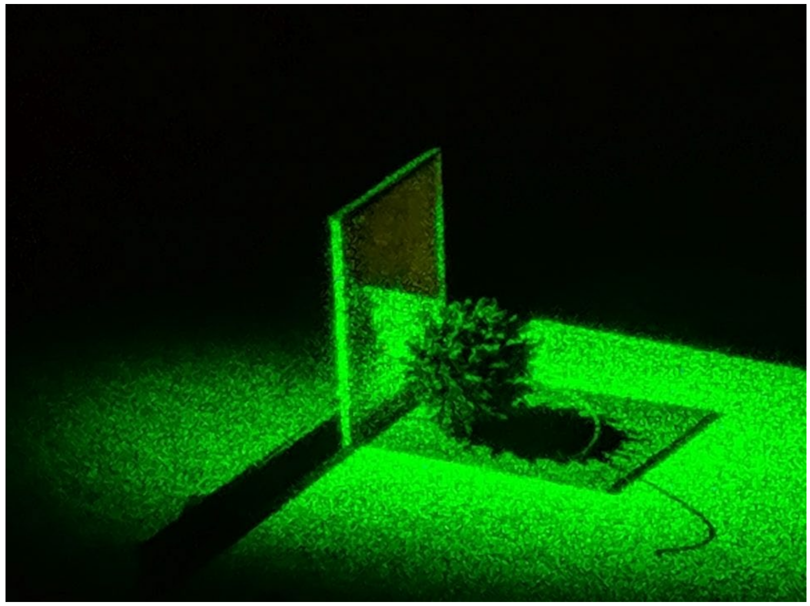

Fig. 11. Holocenter. *How are images recorded in a hologram?* Reflection Hologram. The Center for the Holographic Arts, Hudson Valley, NY.

To capture a hologram through Holographic Interferometry, the hologram needs to be on a completely stabilized surface. Due to the sensitivity of the directed beams of light, the process of creating the hologram relies on the fringes created from two of the stable beams of light (Jeong). These beams cannot be affected by outside interference, as the fringes would not remain stable. To describe the results, any vibration from an outside influence can accidentally cause errors in the process of capturing the image. On a stable surface, the hologram will not be influenced by outside sources, like the vibrations of a car passing by. Holographic

Interferometry can also capture movements of breath and blood under a person's skin through the use of a double laser pulse (Holocenter).

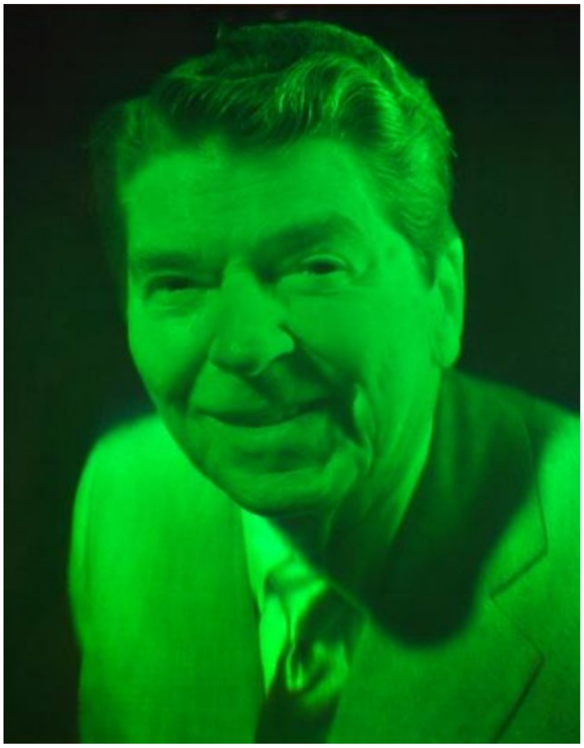

Fig. 12. Bjelkhagen, Marhic. *Ronald Reagan pulsed Hologram Portrait* (1991) Reflection Hologram. Author's Personal Collection.

Pulse Lasers are devices that emit a brief beam of light at a femtosecond (Masahiro, et al). Prior to the use of the pulse laser, holograms were captured through the process of long exposure of a stationary object. This meant that only certain objects could be recorded as holograms, making it impossible to record a person without the recording process to capture errors from a moving object. With a pulse laser, the quick emission of light produced can capture objects that are prone to motion. This made it possible to create holograms of people, more specifically the 40th President of the United States, Ronald Reagan (Figure 12). Reagan was the first U.S. president to be captured in a holographic portrait (Taylor 3). Since then, other presidents and world leaders have been captured through holography via a pulse-laser system.

There are quite a few formats of film that holograms can be captured on. Holographic film is composed of silver halide crystals that can capture high resolution holograms (Integraf). These crystals are photosensitive to particular wavelengths of light, making some of the holograms monochromatic captures of the object. In fact, some of these sheets of film allow red, green, and blue shades, classifying them as full-color holography, though it should be noted that the holographic object isn't going to contain the same colors as the real object.

Holographic film can also be composed of photopolymer instead. This type of film has less depth than the silver halide, but the images have a wider view and appear brighter (MIT Museum). Holograms can also be recorded onto plates. Commonly sold Holographic plates are typically composed of silver halide and glass. Glass Plates offer more stability when compared to film, and faster processing for high-resolution effects. Some plates are also made of hard plastic, and photopolymer film even uses plastic backing. The plastic makes the film sturdier when laminated, and allows for holograms of larger size to be captured.

2.6.3. Digital holography

In contrast to the analog method, Digital Holography is another means of creating holograms. Instead of using Optical Elements to achieve the hologram, Digital Holography utilizes Holographic Electronic Elements (HEE) such as computers, crystal Displays, and cameras. The object is recorded by a digital recording device and reconstructed through a computer. “Reconstruction of the hologram is done by using computational tools that simulate the propagation of light through the hologram and its subsequent diffraction to finally yield the complex optical fields that reconstitute or reconstruct the image” (Nametallah & Banerjee). The objects are reconstructed through computational algorithms, where parameters of the hologram are sampled on a mesh (Picart, Gross, & Marquet). This mesh corresponds to the number of points needed to reconstruct the object to a 2.5D volume.

Recording and reconstructing an object through a digital method comes with benefits when compared to the Analog Method. For one, capturing and reconstructing an object digitally takes far less time than it would through optical elements. Digital Holography also doesn’t require as much physical space when compared to Analog Holography. Setting up the electronic elements is far more compact, making the process of creating the hologram more efficient and practical. On top of this, although you can copy and multiply holograms through optical elements, it is more efficient and practical to do so electrically. To put it simply, computational algorithms are great for the purposes of quickly capturing the angles needed to make digital holography.

While Digital Holography does come with practical benefits, it isn't completely superior to Analog Holography. Using Analog Optical Holography tends to result in better resolution when compared to the digital methods. Constructing a holographic image through a digital means is less economically efficient when compared to analog options. Processing a high-resolution digital hologram and replicating it on a digital display also requires double the resolution to simulate one holographic image for each eye. By dividing a processed image to each eye, you are essentially cutting in half the quality you would get from the original image. To put it simply, capturing holograms through light, using analog means, is trivial when compared to the cost of

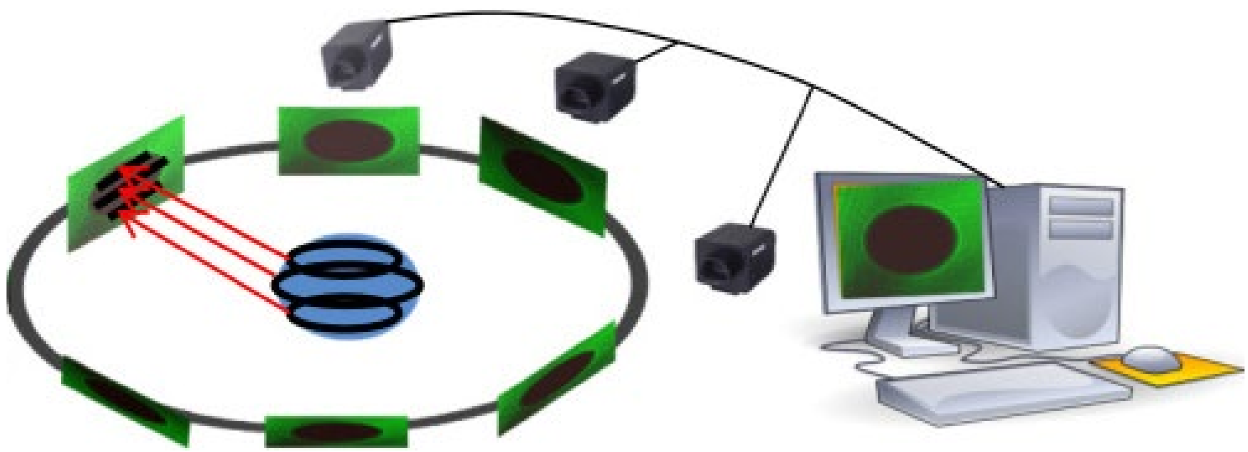

Fig. 13. Nehmetallah et al. *Schematic of the RTT setup.* Schematic.

digital holography. "The resolution is defined as the full width at half maximum (FWHM). Thus, for the same pixel size of CCD, the resolution decreases with the increase of the reconstruction distance" (Wu and others. 157). The additional cost of doubling a display's resolution is quite significant, as there have been very few examples that have found optimal ways to approach the problem.

No matter the type of holography though, there are two camps of classifying what kind of hologram is being seen. "There are many types of holograms, and there are varying ways of classifying them. For our purpose, we can divide them into two types: reflection holograms and transmission holograms." (Jeong). Classifying them under these two types allows us to better describe the illusion the observer experiences when looking at the hologram. Another way to classify 3D imagery would be whether or not the illusion requires a head-mounted-display (HMD) or eyewear for the illusion to work. If the illusion doesn't require the need for a head-mounted-display or eyewear, we refer to it as an autostereoscopic display.

2.6.4. Reflection holograms

The most common form of both Analog and Digital Holography that is seen is referred to as a Reflection Hologram. They are named as such due to the fact that the holographic object is a holographic reflection of the object. Like a true reflection, the object's position is inverted on the other side. These types of holograms are captured holographic film-planes and are illuminated by a light on the observing side of the hologram. This light shines at a specific angle and distance, reflecting the object on the opposite side of the observing area through the plane. The holographic image is composed of the holograms reflected light, and when the light is properly aligned onto the plan it creates the illusion (Figure 14).

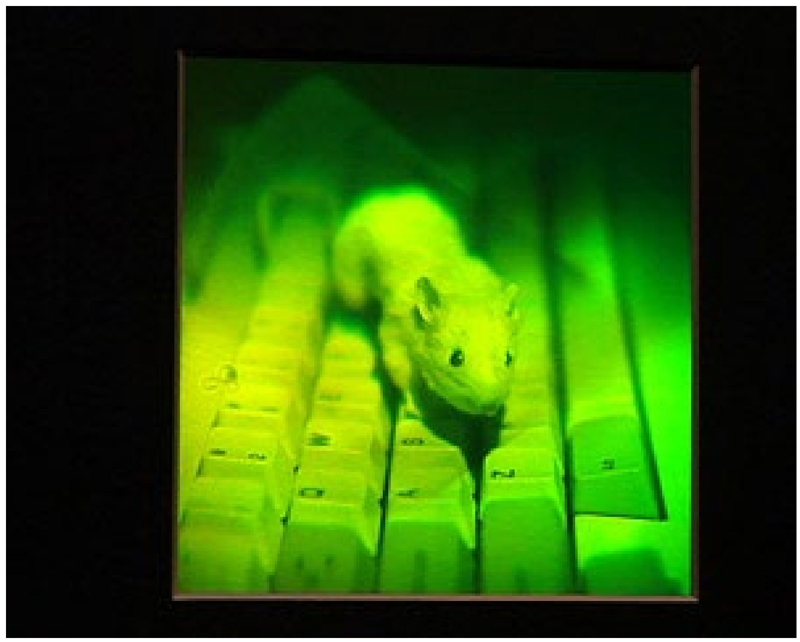

Fig. 14. Holographic Studios *Computer Mouse* Reflection Hologram. 8" x 10". Holographic Studios, New York, NY.

Another form of reflection Holography is known as the Denisyuk Hologram. Founded by Russian physicist Juri N. Denisyuk, this hologram is a reflection that utilizes a single beam for both the object and reference waves to create the interference (Isik). It is a common form of reflection holography, used to record objects to artistically display the hologram at a gallery and or museum. This form of reflection holography is described to have a smaller depth, but the most visually stunning effect these holograms have is their recorded detail. There are other forms of Reflection Holography that holographers have experimented with to achieve Holograms with better depth. Multi-Channel Holography is another method of reflection holography that incorporates multiple methods of exposure. The idea boils down to taking more than one holographic plate, and layering the plates to be exposed by the light patterns. Instead of creating the illusion of a three-dimensional hologram through one plate, you can take two plates to reflect a holographic image.

The benefits of Optical Reflection Holograms are certainly impressive as the light captures a great amount of detail in the hologram. Jeong describes the effect:

"Their images optically indistinguishable from the original objects. If a mirror is the object, the holographic image of the mirror reflects white light; if a diamond is the object, the holographic image of the diamond is seen to sparkle." (Jeong).

An idea emerged when we considered this option for the exhibit, as the detail was one of the more impressive aspects of interferometry. In the event that a magnifying glass was accompanied for such a hologram, observers would have the ability to see the fine detail of the holographic object as if it were actually there.

2.6.5. Transmission holography

A Transmission Hologram is another common form of holography that is often compared to Reflection Holograms, due to the fact that they have the opposite effects of Reflection Holograms. This type of hologram can be achieved through analog and digital means. Instead of reflecting the holographic object to the opposite side of the film-plane, a

Transmission Hologram transmits the object to the same side as the observer. The process of capturing these objects in an analog fashion is similar to reflection holograms, though it requires different utilizations of the optical elements (Figure 15).

"In the reflection hologram only selected wavelengths (colors) are reconstructed while the transmission hologram diffracts all the wavelengths of light so it can have a rainbow appearance. The hologram does not change the wavelength (color) of light but controls how light is redirected." (Holocenter. "Different Types of Holograms.")

Fig. 15. Jeon et al. *A-Transmission-Hologram-Hero* (2002) Transmission Hologram. INTEGRAF LLC South San Francisco, CA.

An object is placed behind a barrier and a reference beam is cast from the side, reflecting off the barrier and to the object. A beam splitter must also cast light onto it in the same manner from the other side of the object in question. When these lights cross, they create the illusion of the object in front of the barrier, tinted to whatever color the lights are. The image that is captured through transmission can be bigger than that of the plate.

2.6.6. Multiplex holography

When it comes to comparing other forms of holography and optical imagery from one another, there are elements unique to the visual aspects. Some holograms have particular advantages over the others, such as a large range of angles to observe the hologram from.

Multiplex Holograms are a perfect example, as this form of autostereoscopic holography allows the observer to have different horizontal or vertical views of the hologram by a means of layering images. Multiplex Holography utilizes similar practices to planar holography, however, the effect is often used to make 2D images appear to be floating in place. A big advantage to this however comes from its practicality, also if you were to construct a multiplex hologram with several planes to draw the holograms, the result allows for full 360 illusions of a floating 3D optical image. The real challenge of developing this hologram is capturing the multiple angles needed to pull off the illusion. After thorough research, we found that you can capture the angles through a variety of methods.

A traditional and simple multiplex hologram is rather simple to create, as there is only 1

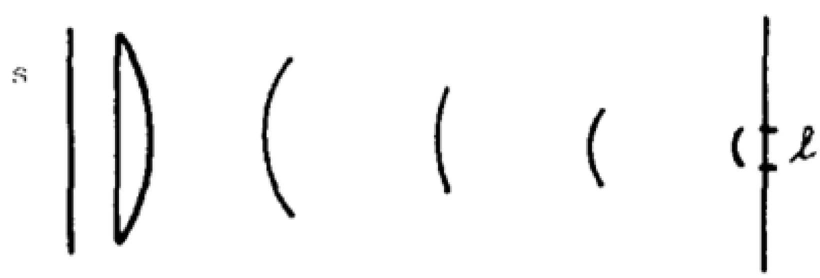

Fig. 16. Chen et al. *Fig 1. The Method of Multiplex Holography* (1983) Figure. The University of Michigan, Ann Arbor, MI

image plane needed in order to get the desired effect. As described by Hsuan Chen and others: “The transparency s is illuminated with a coherent light beam, and a lens concentrates the light so that all parts of the object make contributions to the slit aperture.” (Chen et al. 98). Once the described beam hits a zero spatial frequency component, the beam is then diverged in order to fill the aperture lens, creating multiple holograms from the casted curvature (Figure 16). This gives a strong illusion of depth, furthermore it allows the hologram to have a small variety of angles from one image plane. On the other hand, though this type of model displays a fundamental multiplex hologram, the range is limited to one image-plane.

The other form of parabolic Mirror would be the Convex Parabolic Mirror, with its purpose of directing the light away from the focal point as another tool for manipulating holographic imagery (“Convex Mirror and Applications” 01:16–7:41). By finding a means to manipulate a holographic image and have it projected onto a convex parabolic mirror, you can enlarge the horizontal and vertical viewing zones of the hologram. Researchers at the Osaka Research Institute of Industrial Science and Technology experimented with the use of Convex Parabolic Mirrors for this very reason, as those associated with the project were trying to determine a form of wide viewing holography (Sando et al.). It ultimately led to them constructing a means to direct a reflection hologram onto a convex parabolic mirror to combat the vertical limitations of a cylindrical multiplex hologram. The purpose of the paper was to find a reasonable means to project a hologram that was observable from a wide-range of perspectives both horizontally and vertically. They were faced with a challenge when it came to deciding on which type of holography they would use, with the challenge being to find a hologram that fit their specific criteria.

When beginning their research, the form of holography they chose to start experimenting with was a planar hologram as it was a classic form of holography, still the researchers weren’t entirely impressed by the results. They didn’t like how limited the vertical and horizontal views were to the observer, as they would have to look directly at the hologram’s plane to get the effect. The next hologram they experimented with was a cylindrical multiplex hologram, which offered more freedom to view the optical image horizontally, as the shape of the multiplex hologram allowed particular planes to be seen from different horizontal views. However, if an observer were to view the cylindrical multiplex hologram from different vertical angles, more specifically above the cylinder, the image wouldn’t remain consistent as some angles give a more limited view of the hologram due to the image being presented on its planar shape. This led them to what they considered the “ultimate shape”, as it had the perfect viewing zone for the hologram. On the other hand, a true spherical mirror has a few drawbacks when compared to the researcher’s previous efforts. Due to its large curvature, spherical mirrors do not converge the parallel rays of light into a focal point, as the rays of light diverge from one another (“Spherical and Parabolic Mirrors” 01:49–04:57).

Consequently, this demonstrates that true parabolic-shaped mirrors are the only mirrors that reflect the rays of light on a focal point. As another consequence of the mirror’s shape, the optical image must be projected on the exterior of the reflector rather than the interior. In response to this, Sando and others (Sando et al.) ditched the multiplex hologram as they discovered a means to use planar holography in this use case. To cast a hologram onto a convex parabolic surface, the researchers shined a laser through a spatial filter and lens to cast a

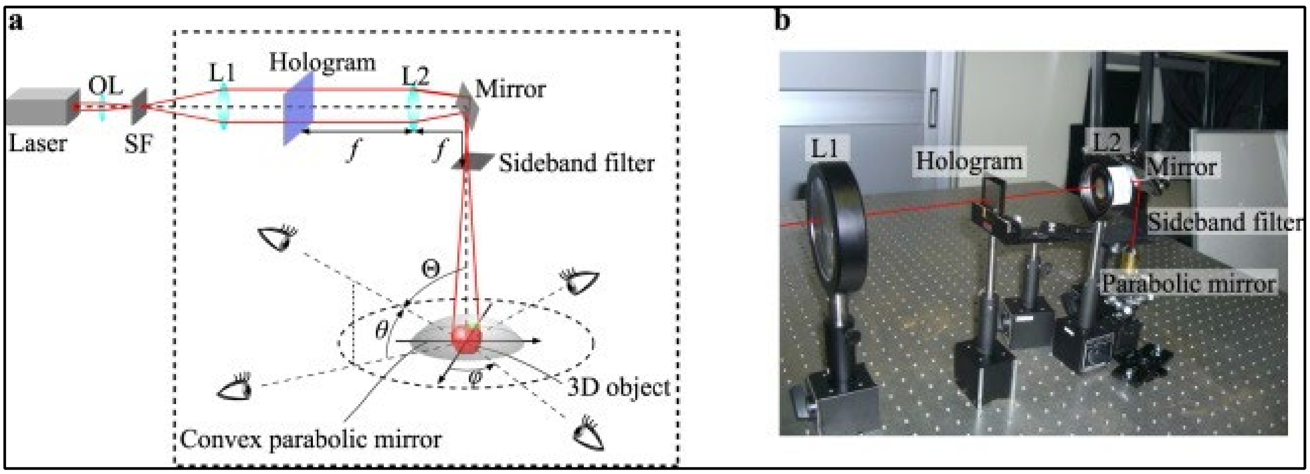

Fig. 17. Sando et al. *Figure 4* (2018) Schematic and Photograph. Utsunomiya University, Utsunomiya, Japan.

reflection hologram. The reflection is then cast through another lens and reflected off a mirror through a sideband filter, allowing the hologram to be projected onto the convex parabolic mirror (Figure 17). This type of holography is known as a Fourier Transform Hologram, since the range of the vertical viewing zone is determined by the shape of the parabolic mirror.

Similar practices do exist to create Multiplex Holography, and the results are substantially more promising when compared to this form. Multiplex Holograms can also be formed in a similar fashion to lenticular printing. Lenticular printing is a common optical illusion that interlaces multiple images together, causing the type of image the observer is seeing to shift depending on the angle they are viewing it from. Spatial Multiplexing Holographic Combiner for

Glasses-Free Augmented Reality, an article in the published journal *Nanophotonics*, lenticular printing is referred to as self repeating, making motion of the 3d imagery limited (Shi et al. 2). However, lenticular multiplex holography has great advantages over the traditional practice of lenticular printing. Not only that, but it can be processed through either analog or digital means. In the case that we were to approach this through an analog method, we could follow a similar practice that is seen by Hsuan Chen and others (99-100). This form of lenticular analog holography requires setting up two imaging systems in order to display the planes on a lenticular array.

On the other hand, we can produce lenticular multiplex holography through digital practices.

After further research, there is a ton of evidence pointing towards limitations with Multiplex Holography in regards to the resolution. When you interlace an image, the screen displays two sets of images through manipulating the screen, splitting in a lenticular fashion between the two, meaning that the resolution of the screen is essentially halved. In summary, if we were to utilize a Parallax Barrier as our method, we would have to necessitate double the desired resolution to get the clear image we wish to achieve. Though this problem is commonly found in digital holography, this particular limitation is not reserved to digital means either, as this is a sacrifice multiplex holography has often had to tackle when working with interlaced optical imagery (Chen et al.).

Multiplex holograms can also be captured digitally, and processed as a full 3D image you can view from multiple angles. Yih-Shyang Cheng and others developed a technique to capture a full 360-degree image-plane through a process known as one-step recording (Cheng et al.). It is a fairly complex system, but to summarize the capturing process (14014-14018): the recorded object sits on a rotating plate where a camera captures it as the object spins. It is then placed onto a detector plane, where that 2D image is magnified onto the LCD object plane. It is here where the image is adjusted on the recording film plane by the same rotation of the recorded object. This form of holography, along with the prior described techniques, are drawn on a single plane meaning it can only have one viewer at a time. In spite of the fact that we are drawing a 360-degree image on a plane, we only have the ability to observe the hologram from one angle. However, this type of holography comes with great benefits when compared to traditional multiplex holography. For example, the hologram has a wide vertical-angular range for the viewer (14021). Though it is a bit more complicated than it seems as the width-height ratio is dependent on the distance the viewer is seeing the hologram. The further away you are from the image, the less effective the illusion will be (14020).

The one step process was developed in 1972 by Lloyd Cross and it was one of the first forms of animated holography. “The process combines cinematographic and holographic techniques to display a short animated image loop. By either rotating the cylinder or if the viewer walks around they see the image animated.” (Holocenter). The sequence of film allows for animation, and is often laminated onto a cylinder (Figure 18).

Fig. 18. Chris Outwater. *Logan’s Run* Cylindrical Multiplex Hologram. Multiplex Company Laboratories, San Francisco, CA.

The prior article does reference another form of common multiplex holography, referred to as Cylindrical Multiplex Hologram, or Integral Stereogram Holography (Razutis. Portraits of Sharon by Lloyd Cross 00:00–00:17). These holograms are either inside a cylinder or on the top of a cone, and they are processed in an integral way as a sequenced-image (Cheng and Chang Image-plane cylindrical holographic stereogram). Due to their nature, the integral image doesn’t cleanly connect when wrapping around the cylinder. The slit of where both ends meet is fairly noticeable, ruining the effect if you tried fully walking around the hologram. These holograms were featured in the 1976 film, *Logan’s Run* (Logan’s Run, 1976). The film utilized the sequenced images to make the holograms appear as if they were talking. You can see the same effect in multiplex holograms by Lloyd Cross, for example the “Portraits of Sharon” and “The Kiss (II)” (Lloyd Cross & XAR3D). Cylindrical Holograms do not need to be a full cylinder either, as the Kiss hologram only has a viewing zone of 120 degrees. However, if we were to use a 360 degree cylindrical hologram, we could use similar practices from Logan’s Run to fully rotate the hologram by use of a motor.

Figure 19. Abrasion Hologram.

2.6.7. Abrasion holography

The field of abrasion holography is often diminished by more promising methods of projecting an image into a space. It has some severe limitations in what it can project, in that it is limited to projecting rounded shapes and objects. The field is expanding, however, as previously only circular, symmetrical designs could be projected from the base plates.

Plexiglas and other plastic plates are reportedly the most common bases used for this type of holography (Figure 19). However, they lack fidelity due to the irregular structure of their molecules. Copper and aluminum sheets fit the task better, for this reason, regular structures, and reflective properties lend themselves well to the task. Carving a pattern with a diamond-tipped drill at a 45-degree angle will project the pattern either above or below the sheet, depending on which way the angle faces. In order to create an image floating freely in space, the angles must intersect at some point nearby. This means that the angles cannot be exactly 45 degrees, and must instead subtly tilt towards each other.

The view of this projection is limited, though. Being too close or too far from the panel will distort the viewer’s perception of the image, as will being on the improper angle. An easy way to fix this is to establish a barrier around the display from which it is assured the proper version of the image will be seen. There is also the matter of carving the pattern into the plate, which requires machine-like precision to successfully create the effect. This can be done by hand to lesser effect, however, much of the detail will be lost due to the hardness of the plate compared to the consistent pressure required to accurately create the illusion, as well as a thin margin for human error.

For the purposes of the Worcester Art Museum, abrasion holography is not a valid choice. This setting requires life-like detail of irregularly shaped objects, which hand-carved plates cannot replicate. Even devices designed to scratch a hologram into a plate would not be applicable for our purposes of properly displaying the Higgins armory (Miller, Wrachford, & Kennedy). The desire for color also rules this out, as that would require a much more sophisticated kiosk than would be practical for the available space. It also lacks the required depth to convincingly bring forward a 3-dimensional object into a holographic space. The cost of the plates would also grow exponentially as more need to be made for larger objects until the complete collection is documented. This also creates another storage problem, as there is now a physical projection plate paired to every object in the armory. Based on how many requirements this form of media misses, abrasion holography is overall a poor choice for the task at hand.

2.7. High-fidelity digital imaging

The Worcester Art Museum's primary requirement for a high-resolution image brings this proposal to a crossroads of sorts. While a holographic display is interesting and would certainly draw some curious patrons, if done incorrectly, it would be nothing more than a novelty. This brings up the need for a practical, reliable solution.

A computer monitor offers this at a reasonable cost. Because of their widespread use for personal computers, monitors are highly available in a wide variety of specifications. For our purposes, one with a refresh rate of at least 144kHz to provide a clear, smooth animation would be required to enable the Pulfrich effect (see below). Considering the space we have to work with, one large enough to be clearly viewable from a distance with support for a portrait display mode would also be advantageous. Setting the display like this has two practical benefits; one in that many items in the collection are oblong, and two in creating a more unique experience as opposed to a monitor set in the standard landscape view. While this is really just a computer monitor that has been turned on its short side, this simple change creates the sense that the screen was brought in specifically for the exhibit. Additionally, recent developments in display technology enable high dynamic range (HDR) monitors, which are able to display a broader spectrum of colors than traditional displays. This creates more vivid images with a far higher upper limit for the amount of detail that can physically be rendered by the monitor.

A handful of potential monitors varying in price range and the quality of their images were considered for this endeavor. At the top of the range is the Asus ProArt Series PA32UCX Mini LED 4K HDR Professional Monitor (Sebastian, "HDR Monitor," 1:58). This $4,000, unusually thick HDR monitor has the dynamic range to display both the darkest darks and lightest lights in the same frame without making visual sacrifices on either end of the value spectrum. It represents the current bleeding edge of this technology and would provide an uncompromising image to the Worcester Art Museum. It achieves its extremes in contrast via a quantum dot layer and over 1000 local dimming areas, which are able to raise and lower the light level in specific spots of the screen to maximize the visible color range. These are also meticulously calibrated before being shipped from the factory, and come with verification of this process.

Their largest flaw comes in the ambient lighting of the room, as too much light can reflect off the screen and diminish the image. In the controlled lighting of the museum and the IMGD wing at Worcester Polytechnic Institute, this expensive monitor would be ideal if it was not for the price point. The step below this is the Samsung CHG90 (Figure 20), an HDR 600 ultra-wide monitor. Mounting this curved monitor to a wall would enable it to be turned on its side, and because of the excessive length of it, this would enable a digital display of polearms and full suits of armor. This one comes with a sacrifice in visual range, however, as it cannot manage the same range of lights and darks as the Asus ProArt. Given the subject of this project, it should prove acceptable for display.

Next is the Acer Nitro VG271, the first standard-sized monitor in this paper capable of HDR displays. This monitor requires a connection to a graphics card via HDMI cable to enable the HDR setting, which is not much of a problem as a personal computer equipped with a graphics card will likely be a necessity as well. This monitor lacks local dimming, unlike the previous two

Fig. 20. Samsung, *CHG90 QLED Gaming Monitor*, Suwon-si, South Korea, accessed 15 Feb. 2022 <https://www.samsung.com/us/computing/monitors/gaming/49--chg90-qled-gaming-monitor-lc49hg90dmnxza/>

that have been discussed, which puts a hard limit on the dynamic range of this display. If budget becomes the primary concern of this section, then the Acer Nitro seems like a promising compromise but pales in comparison to its more expensive superiors.

2.7.1. Capturing the objects

The artifacts need to be translated to a digital format, which presents us with the issue of how to do this. There are several methods that could forge a high-fidelity replication of a real-life object, though the hardware required to make and display these is both expensive and hard to come by. Our options include a new technology known as a Pulse Laser and some more traditional methods like photogrammetry and 3D modeling. There is also the potential of a LiDAR (Figure 21), a concept that has existed since the 1960s but has only recently become practical for deployment.

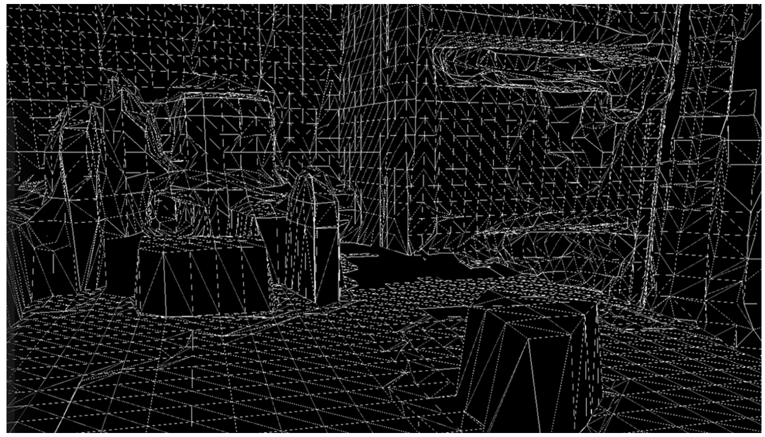

Fig. 21. GeoSLAM, *3D Environment Recreated from LiDAR Scan,* Knottingham, United Kingdom, accessed 18 Feb. 2022

Pulse Lasers are considerably safer for us to use if we considered Analog Holography to display these objects. In prior capturing techniques to Analog Holography, long exposure to light could cause problems when trying to make holograms of objects sensitive to light. If any vibrations disturbed the object even slightly during the exposure, the entire image would become blurred and unclear. Pulse lasers solve this issue by showering an object with a sudden, intense laser burst that captures the image instantly. Unfortunately, this process requires a specific laser rig with the capabilities to generate a pulse laser. While Worcester Polytechnic Institute has a holography lab with this equipment, we were unable to gain access to it after repeated attempts to contact its overseer. Because of this impassable obstacle, we have

Fig. 22. Forgeng, Jeffrey. *Outside Bakes* 3D Model. Worcester Art Museum, Worcester, MA

decided it is in our best interest to disregard a pulse laser scan as a practical option despite its promising detail.

As such, we must turn to other considerations. Photogrammetry is a process that involves taking numerous pictures of an object from every conceivable angle. These photos are then processed by a script that identifies and builds an object in a digital modeling software, such as Blender or Maya (Figure 22). This process sometimes struggles to identify dark, reflective objects and produces higher quality results when the lighting in the photos is controlled and even. When the script correctly identifies and builds a model, the detail is comparable to real life, which makes this a valid candidate for the project. The largest downside is how time-consuming this process is. It can take several attempts to get a usable translation of an object, each of which requires roughly 100 photos and several minutes circling the object and taking them. The script also requires several hours to process each set of images, which extends this endeavor far beyond the time frame of the pulse laser.

This leaves the recently developed LiDAR (Light Detection and Ranging), a method of digital mapping that fires laser beams from a scanner, then measures the time it takes for each laser to reflect back to the scanner to create an accurate 3D topographic map of the scanned area (Figure 23). This is exemplified best by GeoSLAM, a company that has been innovating with LiDAR since 1999: "LiDAR works in a similar way to Radar and Sonar yet uses light waves from a laser, instead of radio or sound waves." (GeoSLAM) Conceptually, radar has evolved to use laser technology rather than soundwaves, which grants a much faster and more accurate response. These lasers fire in rapid pulses and quickly generate maps using hundreds of thousands of reference points. If applied on a smaller scale, this technology could be used to create point clouds of the items in the Higgins Collection, which can be exported to a 3D modeling software and processed into models themselves. The equipment to do this is expensive, however. The model we are interested in, the ZEB Revo RT, deploys 43,000 points per second, has an effective range of 30 meters, has a relative accuracy of up to 6mm, and boasts of real-time processing speeds (GeoSLAM). One example provided on GeoSLAM's website shows a point cloud taken during a

Fig. 23. GeoSLAM, *Zeb Revo RT*, Knottingham, United Kingdom, accessed 18 Feb, 2022 <https://geoslam.com/solutions/zeb-revo-rt/>

20 minute run up and down a ski slope (Figure 24). There is no provided context for the cloud beyond a title, but the map is so detailed that the cables of the ski lift were mapped along with the side of the mountain. This model has the capabilities to map an entire building given the time to fully explore it but is also able to make and save point clouds of smaller objects with accurate color replication. It already sees use at several universities and institutions around the world, as well as architecture firms, mining companies, and the Queensland Police. Because this technology does not rely on global positioning data like most modern mapping tools, it can be taken to areas that have been previously considered too difficult, dangerous, or impossible to chart, like derelict buildings and cave systems. The speed and accuracy of these scans would allow for the rapid digitization of the shapes of every object in the collection, which later can have matching textures applied to them later by an experienced 3D artist.

2.7.2. Pulfrich effect

The Pulfrich phenomenon occurs when there is a slight temporal desynchronization in visual information being processed by the eyes, which creates the optical illusion of the third dimension of movement when, in reality, there are only two. This is most commonly achieved by covering the dominant eye with a slightly darkened filter and playing a video at a stable frame rate of at least 60. The phenomenon can also occur as a symptom of multiple sclerosis and unilateral cataracts, as the exact cause of the effect is a

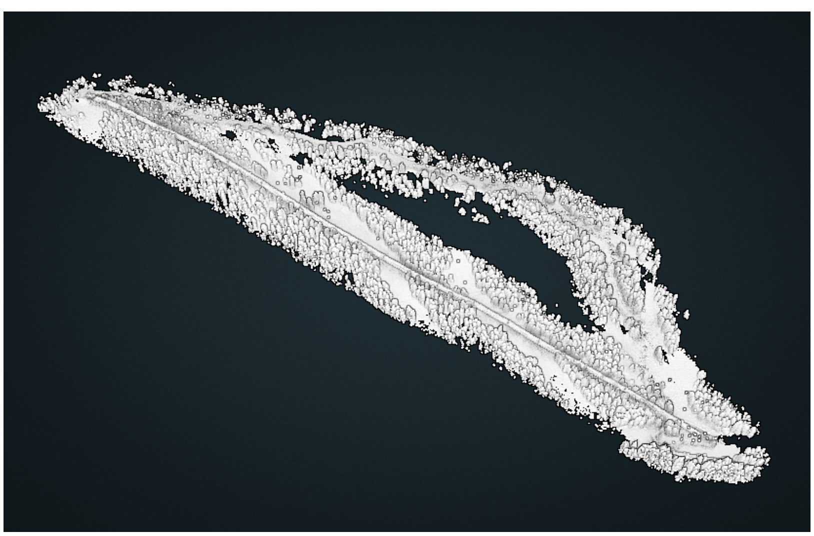

Fig. 24. GeoSLAM, *LiDAR Scan of a Ski Slope*, Knottingham, United Kingdom, accessed 18 Feb. 2022 <https://geoslam.com/solutions/zeb-revo-rt/>

desynchronization of the electrical signals processed by both eyes (Figure 25). In more basic terms, imagine two pathways that lead to the same destination, but one takes slightly longer to walk due to the fact that obstacles have formed, in the event of illness, or deliberately placed, in the case of purposely invoking the Pulfrich phenomenon.

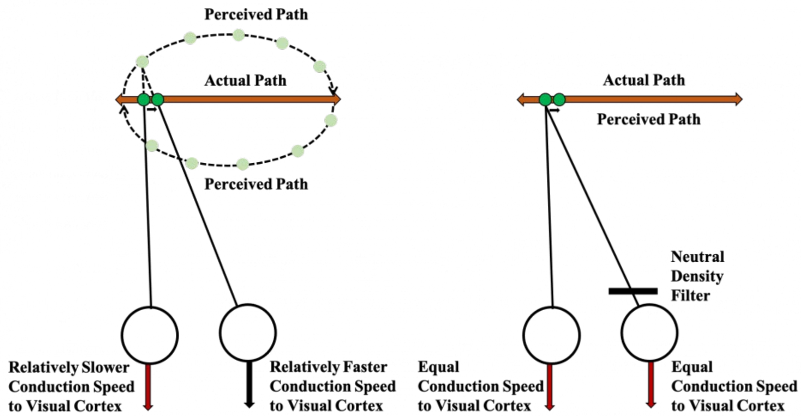

Fig. 25. EyeWiki, *Diagram demonstrating the Pulfrich Phenomenon*, accessed 08 Feb. 2022 <https://eyewiki.aao.org/Pulfrich_Phenomenon>

Because of the ease of access to the Pulfrich phenomenon, it is worth considering what a foray into exploiting it would mean. The image displayed by the effect matches the resolution of the video, so there is no concern for a loss of fidelity. The video must remain at a stable `FPS, however, as the illusion breaks if any frame loss occurs. Additionally, if the video is played in reverse or manually rotated backwards, an inverse version of the effect may occur, which has been known to cause feelings of nausea in viewers. Invoking the phenomenon at all would also require a high-fidelity computer monitor capable of displaying a to-scale medieval weapon, the more pixels the better.

3. Interactivity

In a majority of the content we found, related to the Looking Glass Display, we found that the device was often accompanied by a gesture-based motion device known as the Leap Motion. Leap Motion is one of Ultra Leap's many branded gesture-controlled devices, and it is sold for the price of $99 (Ultraleap). The device allows the observer to control a motion-based interface, which tracks both their hands and fingers. Essentially, the tracking allows for the software to recognize gestures and other actions to control the included software. The device is also compatible with other 3D software to allow easy and efficient integration.

We took a keen interest in the Leap Motion as it offered great opportunities for us when it came to interaction. With the main purpose of the device being to offer more intuitive ways for interacting, we've considered the Leap Motion to be a great candidate for controlling not only the interface of our design but also interacting with digital copies of artifacts from the Higgins Armory. Its lack of a physical control interface works well with the Worcester Art Museum's desire for both accessibility and affordability and completely removes any concern for damage to a physical controller. This also allows for a bridge to be built between the physical and digital sides of the armory. Guests can utilize the Leap Motion controller to select and interact with objects they could otherwise only view from one angle behind a glass barrier. While we cannot fully destroy that barrier with the technology available to us, the Leap Motion controller lets us take a step in the direction of doing so.

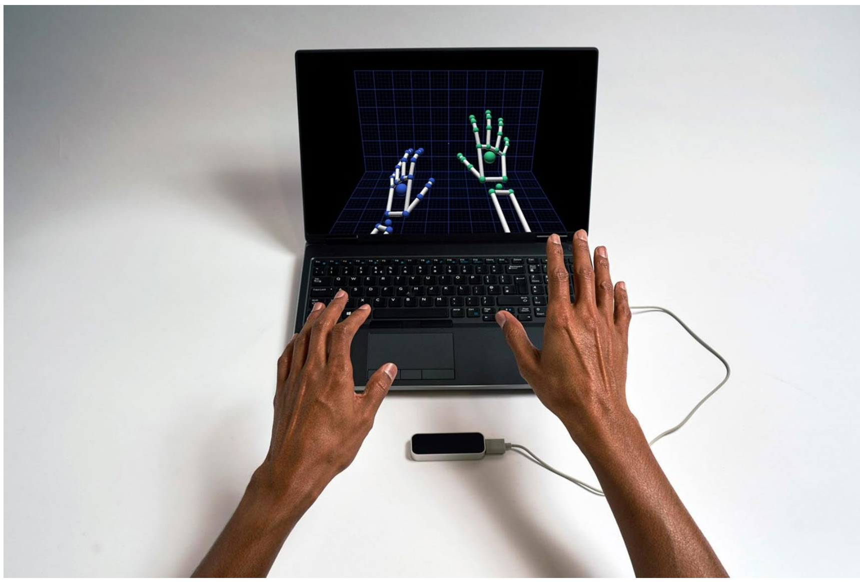

Fig. 26. Ultraleap *HERO-UltraLeap Product* Motion Control. Ultraleap, Mountain View, California

As of the writing of this paper, Ultraleap distributes two hand-tracking controllers. The first, the Leap Motion Controller, is a small and highly accurate hand tracking device with very low latency (Figure 26). The second, the STRATOS Inspire, has identical specifications to the Leap Motion Controller on a larger scale, with the addition of ultrasonic haptic feedback. This simulates the feel of a real physical object in an empty space via projecting ultrasonic waves into the space that appears occupied, which bounce off the user's hand to provide the sensation of touch. Haptic feedback is currently an emerging technology that most commonly sees use in virtual reality headsets for the purposes of setting a protective boundary around the user and simulating the sensation of touch for objects in the virtual space. While impressive, this barely scratches the surface of the potential applications for this technology.

For the purposes of the Worcester Art Museum, the STRATOS Inspire would be an unnecessary expense but would enhance the experience of interacting with a holographic display. The Leap Motion Controller, however, is a worthy expense. If a guest at the museum never needs to physically touch the controller for the exhibit, there is a much lesser chance they will inadvertently damage it.

4. Audio

The Soundlazer is a technology we were introduced to early on in our research. It is a parametric speaker, meaning it uses short-length ultrasonic soundwaves to target sound to a specific area (Figures 27, 28). This is opposed to most speakers, which are built to broadcast sound as far as possible. While not a hologram in its own right, when used in conjunction with them, they can help create a powerful illusion.

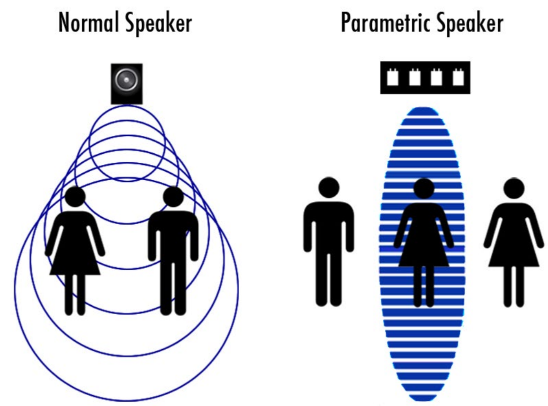

Fig. 27. Soundlazer, *Diagram demonstrating the difference between normal and parametric speakers*, accessed 10 Feb. 2022 <https://assets.newatlas.com/dims4/default/2493e14/2147483647/strip/true/crop/1024x680+0+0/resize/1024x680!/quality/90/?url=http%3A%2F%2Fnewatlas-brightspot.s3.amazonaws.com%2Farchive%2Fsoundlazer-9.jpg>

Utilizing a staggered array of small, carefully angled ultrasonic speakers, soundwaves can be directed with a high degree of specificity. Rather than create their own sound, these speakers use ultrasonic waves to recreate sounds that operate in the 40kHz range, far above human hearing.

They demodulate naturally as they travel through the air, coming down to an audible range in a specific area dependent upon the direction, size, and power of the source speaker.

These types of speakers already see widespread commercial use in several sectors. Museums and art galleries have been known to sometimes deploy parametric speakers above and around displays to provide localized ambiance, appropriate music, historical context, or some other relevant audio. Visitors to museums often care most about how immersive their visit can be, so localizing sound around exhibits can create a powerful reason to make several visits. These speakers also see use in auditory illusions already, by throwing a sound to a surface or hologram and making it seem as if the sound is coming from the surface. Practical uses for this included haunted houses, meditation rooms, spas, and other areas where ambiance can be desirable. Public address or PA systems often use directional speakers in busy areas along the lines of train platforms and bus stations, where a lot of people need to know specific information quickly. Using arrays directed into queues, this information can be quickly distributed to the people that it is applicable to. These types of speakers also can improve the quality of life of individuals with hearing impairments by specifically targeting their television's sound directly where they are seated. This reduces the strain on less-sensitive ears and helps eliminate the need for excessively high volume in the house.

Fig. 28. Soundlazer, *Soundlazer #SL-01 Open Source Parametric Speaker*, Noise-B-Gone, accessed 10 Feb. 2022 <https://noisebgone.com/produkt/soundlazer-sl-01-open-source-parametric-speaker-120db-ultrasonic-output-30ft-range/>

Parametric speakers can also see widespread use in the office. Workplace happiness is always a concern, and many people like to work in some level of comfort. Installing directional speakers overhead in cubicles and open spaces allows for the worker to control their own music, which can have a profound effect on their mood and productivity. The luxury of being able to tune out your coworkers and still have them nearby is highly valued in today's society, so having a personal music bubble around you as you work is enticing to the common office employee.

Functionally, these speakers work by making an array of smaller speakers output a sound in a 15 to 30-degree cone at a high frequency, which then demodulates to an audible frequency as it travels through the air and hits surfaces in its path, reflecting around the room in tight paths accordingly. This is opposed to standard speakers, which typically output sound in an 80 to 90-degree cone and fill a room as much as possible (Figure 29). Some traditional coil speakers boast of a tight 50-degree broadcast range, though they still produce more falloff outside of the optimal range than a parametric array.

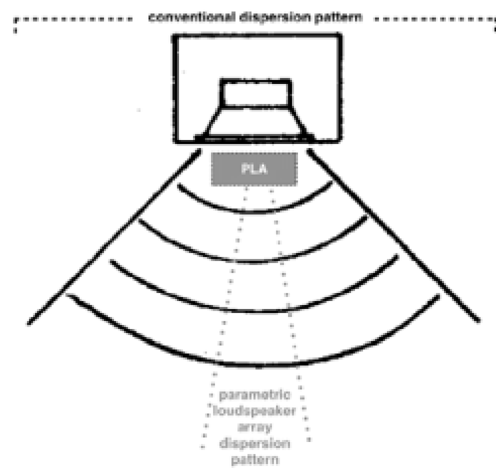

Fig. 29. Soundlazer, *Diagram demonstrating the soundwave cones produced by conventional and parametric speakers*, accessed 10 Feb. 2022.

5. Conclusions

After finalizing our research and determining both the benefits and drawbacks of each method, it was time for us to consider what our best approach would be for the Worcester Art Museum. The goal of our research was to find the best course of action for creating an interactive exhibit, and then select which of these applications properly benefitted the Higgins Gallery. The method that we were going to pick had to fit a great portion of our desired criteria both on its own and when compared to our other options. We wanted the interactivity to take advantage of modern technological methods to create an exhibit that could only be done today. The more contemporary or advanced the exhibit would be, the more likely it is to offer a new experience to museum-goers. This would allow the exhibit to be unique, as we wanted it to fulfill an experience that has still to be established at a museum, or more specifically the Worcester Art Museum.

Aside from the user experience, our interactive exhibit would need to be of low-maintenance to give the project better longevity. On the other hand, we would prefer if the technology was also applicable to not just the Higgins Armory, but any gallery that the museum wanted to showcase. Having a dynamic system that could feature a changing variety of selected artifacts also provides new experiences contained within the system. In spite of the fact that this approach could give the project a greater lifespan, we have to consider the fact that it does broaden our goal for the exhibit. Not only that but there is a fine balance between how modular our approach is, versus how much maintenance our system would need.

The interactive exhibit would need to fall under the limitations of the space we currently have to work with. When discussing with Jeff Forgeng, curator of the Higgins Collection, in regards to where the exhibit should be placed, he was quick to direct us to the two iPad booths that sat next to the showcase (Figure 30). The booths were meant to be fitted with ten-inch iPad displays. Since the booths weren't being used by the museum, we felt that the provided

Fig. 30. David Sand, *Interactive iPad*, Worcester Art Museum, photo taken 17 Feb. 2020.

area would fit the specifications of the kiosk. This also allowed us to determine how much space was practical for our interactive showcase. A space of 36” x 10” x 72” has been allotted along either side of the staff weapons display case, which houses some of the historically significant items of the collection in Open Storage pullout drawers. Jeff spoke of a desire for virtual versions of these items to existing alongside the physical display of them, as much of the detail cannot be freely viewed due to the limitations of a museum setting.

For instance, a triangular Tibetan ritual dagger, called a phurba, can only be viewed from one angle as it exists in the back of the display case (Figure 31). In order for it to be fully appreciated, a 3D model made from photographic imaging of the dagger could exist alongside it, which either rotates at a set pace or can be freely moved by the viewer through an interactive touch screen. This dagger would now be displayed in high fidelity imagery alongside the real-life object, forming a memorable connection between the digital and real-world so it can be fully studied by the observer. There is also a set of ornate tsubas on display here, guards that fit on most Japanese swords that were designed to provide balance and hand protection for the wielder. Because of their coin-like design, only half of each tsuba can be observed which limits the amount of detail shown to the observers. This kiosk design solves that issue in the same way as the dagger, allowing the viewer to manipulate a digital replica to study the other sides of the objects.

Fig. 31. David Sand, *Tibetan Ritual Dagger*, ref. ID 2014.113, Worcester Art Museum, photo taken 17 Feb. 2022.

When it came to making the decision of what our interactive exhibit would be, our final analysis led us to decide that the most practical approach would be a virtual gallery where observers could interact with an object. We think creating a program that acts as an interactive gallery for a variety of different formats of digital files would be perfect for the Higgins Gallery. Not only that, but in the case this gallery was to implement our dynamic system it would benefit other institutions as well. Given the amount of time to develop the software, we believe IMGD could benefit from experimenting with the software as well. When developing the program we have to make sure that the software has great longevity and low effort means of implementation.

Bringing these objects forwards as holograms utilizing the Pulfrich phenomenon seems to be the most likely candidate, if any, for a 3-dimensional display. For the Worcester Art Museum's purposes, this is an unnecessary step. The curator's desires do not fall in line with our hopes of bringing forth these historically significant objects into a holographic display. On the other hand, a kiosk consisting of a high fidelity monitor, interactive touch screen display, and virtual versions of real-life objects in the room is within Worcester Polytechnic Institute's capabilities.

Fig. 32. Ultraleap *IMC 03* Motion Control. Ultraleap, Mountain View, California.

Our prior research with optical illusions, 3d imaging, and specifically autostereoscopic displays could also be considered for this exhibit. The evidence suggests that adding what we would consider an additional gimmick to the display could provide interesting visualizations and interactivity to the exhibit. However, when deciding whether or not these options are going to be implemented, the development of the software should also consider the scope. If these ideas were to be considered to be a part of development, we should stress that they should be additional features to an already developed product. Our main focus for the exhibit is a program that acts as a gallery for the user to modularly implement their own files for display. These 3D effects would only work for particular files, as not all universal formats are capable of displaying 3D graphics.

Aside from simply displaying the files, we also would need to implement ways for particular ones to be interacted with. For instance, a 3D object should allow users to observe and interact with it by controlling what angle the object is facing in order to be interactive. There are a couple of ways to approach this, for one we could use the interactive touch screen display to manipulate the object. Although this seemed like the more efficient route, we were still intrigued by gesture-based motion sensors like the Leap Motion (Figure 32). Due to the device being a low-cost option in addition to offering a more unique method to interaction, we believe that implementing such a device to the kiosk would offer a great user experience.

There are other forms of interactive experiences that can be tacked on as additional gimmicks to the kiosk. Not all forms of interactive experiences are handled by an observer through an interface as previously proven from our research with audio. There are different ways the kiosk could utilize the speakers that we researched, though we think that the interactivity that comes with these speakers is trivial compared to the other options we have. We also fail to see what the kiosk gains by having different audio options in a museum environment. The true focus of the exhibit is the software, and how observers can interact within the software to view a gallery.

It is possible to argue that the kiosk having interaction support for just one person does turn the exhibit into a single-user experience. Though this is true, we still think that the exhibit's high-fidelity screen should offer enough interest for those who aren't interacting with the kiosk. Furthermore, we consider the interaction to be the focus of our exhibit as it adds a more personal experience to the kiosk, rather than a non-interactive exhibit as an observed experience. We believe that the interactive part of the exhibit is integral to a unique museum exhibit. The average museum visit is memorable, yes, however, memorable interactivity is hard to come by in this setting.

Renovations that are planned for the Worcester Art Museum in 2025 will see its library moved elsewhere, with the Higgins Collection moving to occupy the space. The plans still require a digital display option, so this project will have longevity beyond the short interim period remaining until then. Our hope is to make visits to the Worcester Art Museum much more memorable by bridging the gap between physical and digital objects with this kiosk.

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