The Design and Development of a Monochrome Volumetric Display Using Laser Diodes and a Rotating Helix Structure

By

Seth Andrew Barger

Bo Tang	James Fowler
(Director of Thesis)	(Committee Member)

Seth Oppenheimer

(Shackouls Honors College Representative)

Honors Thesis submitted to Shackouls Honors College, Mississippi State University, Spring 2021

The design and development of a monochrome volumetric display using laser diodes and a rotating helix structure

By

Seth Andrew Barger

A Thesis
submitted to the Faculty of Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Computer Engineering
in the Shackouls Honors College
in the Bagley College of Engineering

Mississippi State, Mississippi
December 2020

ACKNOWLEDGEMENTS

I would like to thank Dr. Tang for giving me the opportunity to build and research this innovative new technology under his supervision.

I thank Dr. Gurbuz for allowing me to perform research with his team for two years of my undergraduate studies.

I thank my parents for encouraging my creativity and supporting me emotionally and financially.

I thank my committee for their comments and feedback on this thesis.

I thank my creator and savior Jesus Christ.

Name: Seth Andrew Barger

Date of Degree: December 11, 2020

Institution: Mississippi State University

Major Field: Computer Engineering

Major Professor: Dr. Bo Tang

Title of Study: The design and development of a monochrome holographic display using laser diodes and a rotating helix structure

Candidate for Degree of Bachelor of Science

As electronic displays and televisions reach near-perfection, the limit of two dimensions has become more evident. Since conventional display technology will soon stale, it is imperative to find new ways of displaying images. This study uses the persistence of vision as the launching point for an original volumetric display technology, fooling the human eye into seeing a volumetric image. Using a rotating helical apparatus and an array of projecting laser diodes, a successful prototype was produced which is capable of displaying a true volumetric image. Based on the success of this primitive experimental prototype, this technology is ready for expansion and improvement. To fully realize this technology, refresh rates of light-emitting laser diodes must be improved upon and new light-reflective materials should be researched for application on the helical apparatus. Additionally, with the relative simplicity of this design, manufacturing and materials will be quite affordable, making this a viable consumer product.

Key words: laser diodes, array, helix, volumetric, voxel, persistence of vision, projection, refresh rate, phosphors, hologram, raster

TABLE OF CONTENTS

CHAPTER I: INTRODUCTION

Background

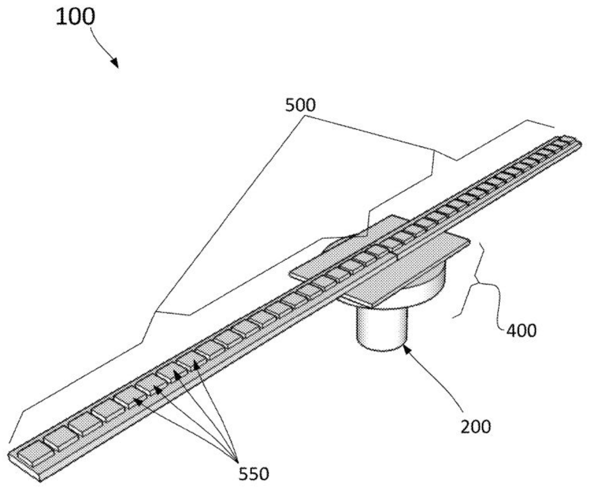
Throughout the latter half of the nineteenth century, photographers tried to capture and display events in their lives, eventually producing the first successful full-motion short in 1890. Since 1902, cinemas have captured the attention of audiences globally resulting in billions of dollars of revenue for massive productions such as *Avengers: Endgame*. Now, electronic motion picture displays have become the norm and even necessary with COVID-19 for people in the workplace, school, or at home. Modern televisions feature higher resolutions than the human eye can distinguish from the standard distance sitting on a couch [7]. Although technologies like Liquid Crystal Display (LCD) and Organic Light Emitting Diode (OLED) have nearly perfected showing images in 2 dimensions (2D), the attempts to fake 3 dimensions (3D) with stereoscopic glasses have been less impactful. The next step to revolutionize electronic displays is to feature a complete 3D image visible to the naked eye, colloquially called a “hologram.” Ironically, holograms are frequently featured in science fiction content for 2D screens, as if they are seeking to usher in the next wave to replace themselves. While in theory, a bunch of microscopic lights could be suspended in a glass container to form a volumetric image, the cost of such an item would be impossible to reach for most markets. However, with recent advances in persistence-of-vision displays because of extreme refresh rates, a hologram may be both viable and possibly affordable.

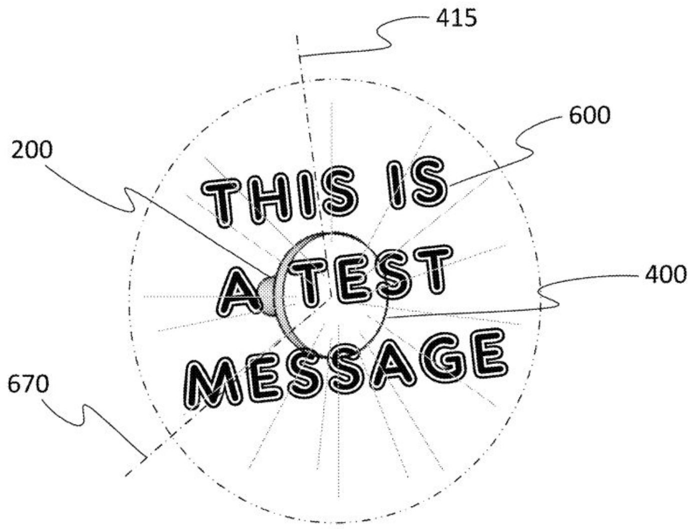
Concepts

Persistence-of-vision (POV) is the phenomenon that if an image is refreshed quickly enough, it will appear as if it is in motion. Typically, this refreshing happens 60 times per second (60 Hz), which is used as the refresh rate of many electronic displays. Experiments in the past have shown that a refresh rate below 48 Hz (the typical refresh rate in cinemas) can cause strain on the human eye. As a result, a hologram implementation must attempt to refresh at least 48 times per second in order to be viewable by the majority of the human subjects. The hologram technology to be implemented relies on the transparent nature of objects while in motion [4], such as a fan. In fact, some POV displays have been implemented in this fashion as shown by the patented design in Figure 1 [12]. The way that these displays work is by having a strip of spinning light-emitting diodes (LED) being refreshed every small bit of rotation. The entire image is refreshed at a near 60Hz, but the LEDs mounted onto the fan are refreshed for the desired radial resolution [12] (for example, slicing a pie into 500 pieces). For the hologram implementation, a similar approach could be used but with a rotating helix-like structure to have minimal blocking of the image drawn to the viewer's eyes.

Figure 1

Diagrams of the Persistence of Vision Rotary Display Device. Weihui Ted Meng, US 10410559 B2.





Unlike the design shown, LED bulbs will not be mounted on the rotating apparatus. If a bulb were to slip off during operation it could potentially inflict an injury.

Instead, laser diodes (LD) from a stationary position project light onto the helix structure, which is composed of lightweight brushes. LDs are very similar to LEDs but are engineered in a way to form a beam of light as opposed to a diffused light. Electric current when passed through the diode causes light to be produced. It also is worth mentioning that LDs and LEDs both have very minimal power consumption, making this a practical design for the average consumer. The tradeoff of this design is that since the helix structure is rotating, it needs a motor that will consume a significant amount of power. Future implementations of this hologram design could mount LEDs onto the structure itself perhaps with more mechanical expertise, but this experimental prototype is more of a proof-of-concept to see how visible the 3D image can be as opposed to designing a retail product.

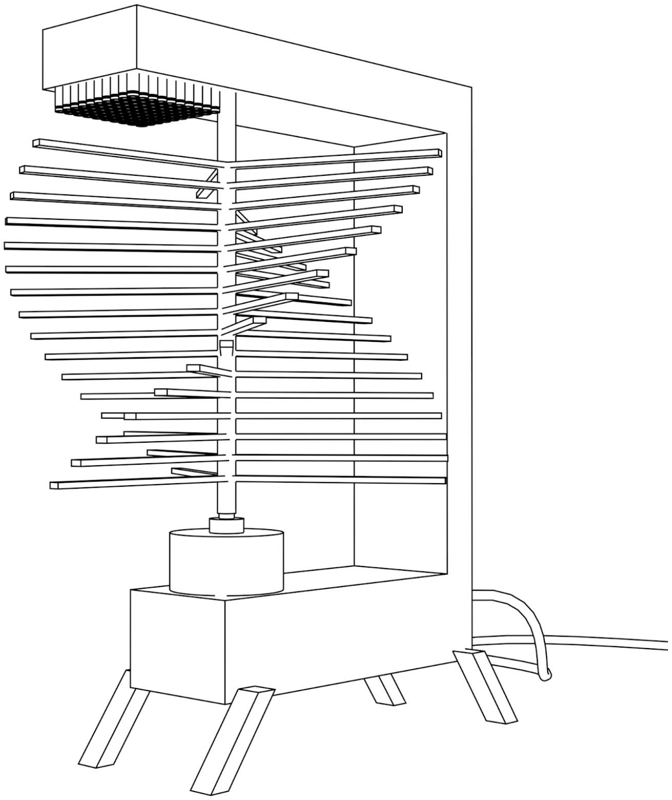
CHAPTER II: DESIGN

In 2 dimensions, a display is made up of individual squares known as “pixels” which produce unique colors/brightness to make up part of an entire image. In a similar way, a volumetric pixel or “voxel” is an individual cube to form part of a larger volumetric image. The number of pixels required to make a modern display is 3840 × 2160 = 8,294,400 pixels. A third dimension added to this means that billions of voxels are needed to achieve a similar fidelity in 3D. The advantage of projecting from a 2D grid of LDs is that it keeps costs relatively low and makes the controller refreshing the grid do the heavy lifting of the third dimension rather than an extreme number of voxels.

The design of the “Rotary Volumetric Helical Display” (RVHD) prototype is quite elegant and simple. A series of light “catchers” are arranged in 3 spiral staircases or helixes. This allows for 3 refreshes of an image per revolution of the motor. Thus, in order to achieve 48 Hz, the motor required only needs to spin at 16 Hz, or 960 revolutions per minute (rpm). However, the most ideal amount would be a single helix for optimal viewing and completeness of an image, but this comes at the potential safety hazard of an apparatus spinning at 48 Hz or 2880 rpm. A series of LDs need to be refreshed in sequence with the spinning of the helix. Essentially, a 2-D image is drawn on the diagonal plane of the helix as it is rotating, creating as many unique layers of an image as possible. Since these 2-D images are being drawn and layered roughly 48 × the number of desired layers per second, the POV will occur to the human eye for a volumetric image. The helical arrangement of the apparatus allows for near-perfect viewing angles of the apparatus. The viewer is guaranteed to see nearly every voxel once per rotation.

Figure 2

The RVHD prototype 3D previewed model



As seen in Figure 2, the group of LDs is suspended from the top of the structure pointing downward towards the helical apparatus. Since the budget of this prototype is limited, the helix is not semi-transparent. Thus for easy viewership, the image will only be on top so that viewers can look down at it. Ideally for the reserving space and overall image “freedom,” the LDs would be placed on the bottom facing up towards the helix with some sort of illuminating material like fiber optics making up the strands of it. As seen in Figure 3, the LDs intended for the prototype are quite small and low power, but they also produce a slightly diffuse light as opposed to a straight atom-like beam. This allows for more soft “form-painting” similar to technology in classic cathode-ray tube

(CRT) televisions [6]. Also for the constraint of time and lack of technical expertise in multiplexing, the image drawn by the RVHD will be a static cube. Dynamic images could be drawn but would require a significant level of effort to calculate and encode (see Appendix B for an example 3D rendering engine to support the RVHD).

Figure 3

A laser diode sample used in the prototype for the Rotary Volumetric Helical Display

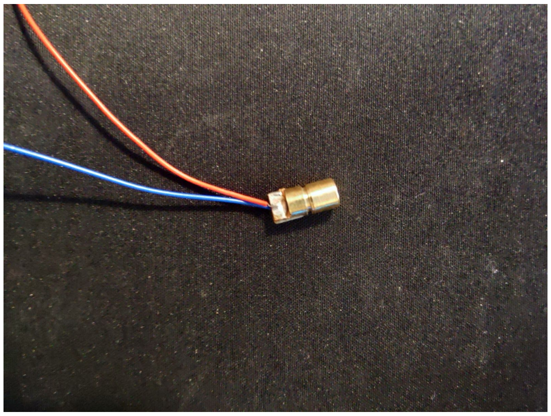
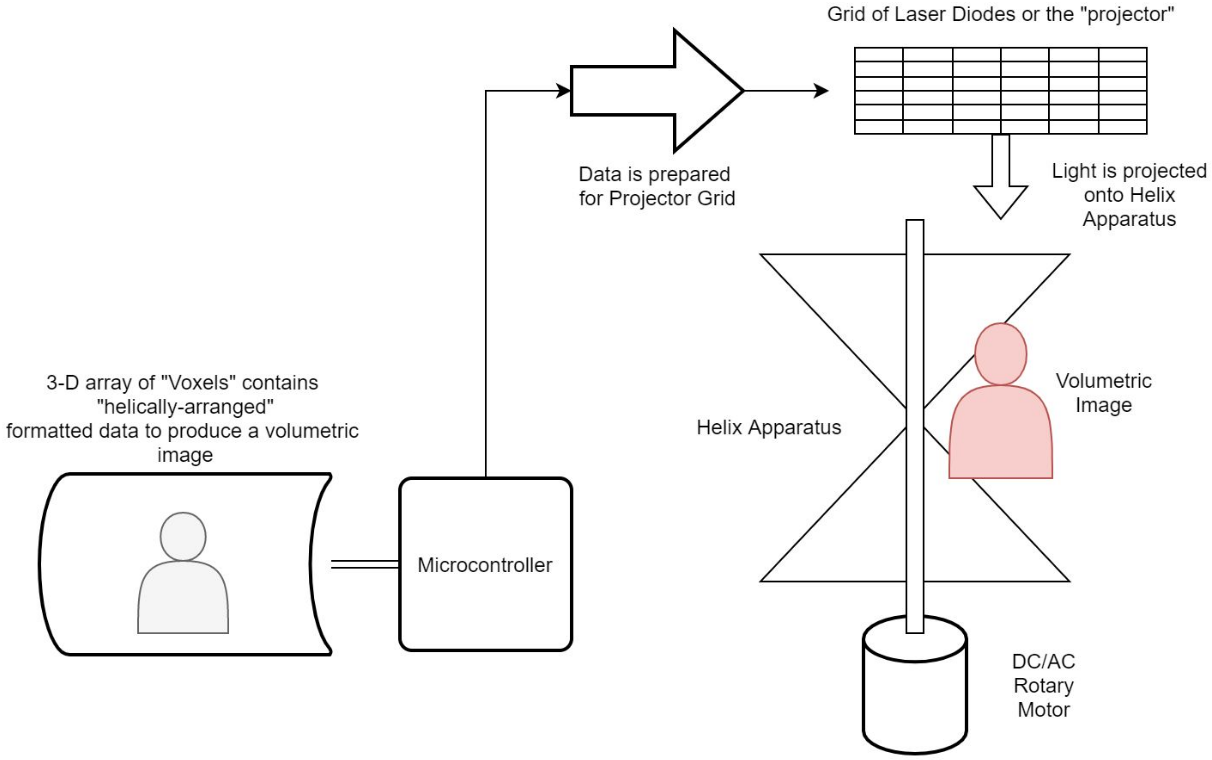


Figure 4 illustrates the flowchart of operation in the prototype. All "helically-arranged" data is stored in memory on a microcontroller. For the prototype, this is a static cube to be drawn. Data must be streamed extremely fast onto the LD grid labeled as the "projector". To support a large number of diodes, multiplexing should be used to control the LDs. However, for the sake of simplicity in getting a functioning prototype, each LD is wired directly to an IO pin on the microcontroller, as outlined in Figure 5. Another important thing to note is that a non-multiplexed array is capable of being refreshed much faster than multiplexed laser diodes. Multiplexing requires each diode to be controlled individually [5]. Thus, in order to keep the laser diodes on longer, they would need to be latched, meaning that they keep their charge when set to high or low. Likely because of the speed of the refresh rate required for a complex image, several multiplexors would drive portions of the diodes.

Figure 4

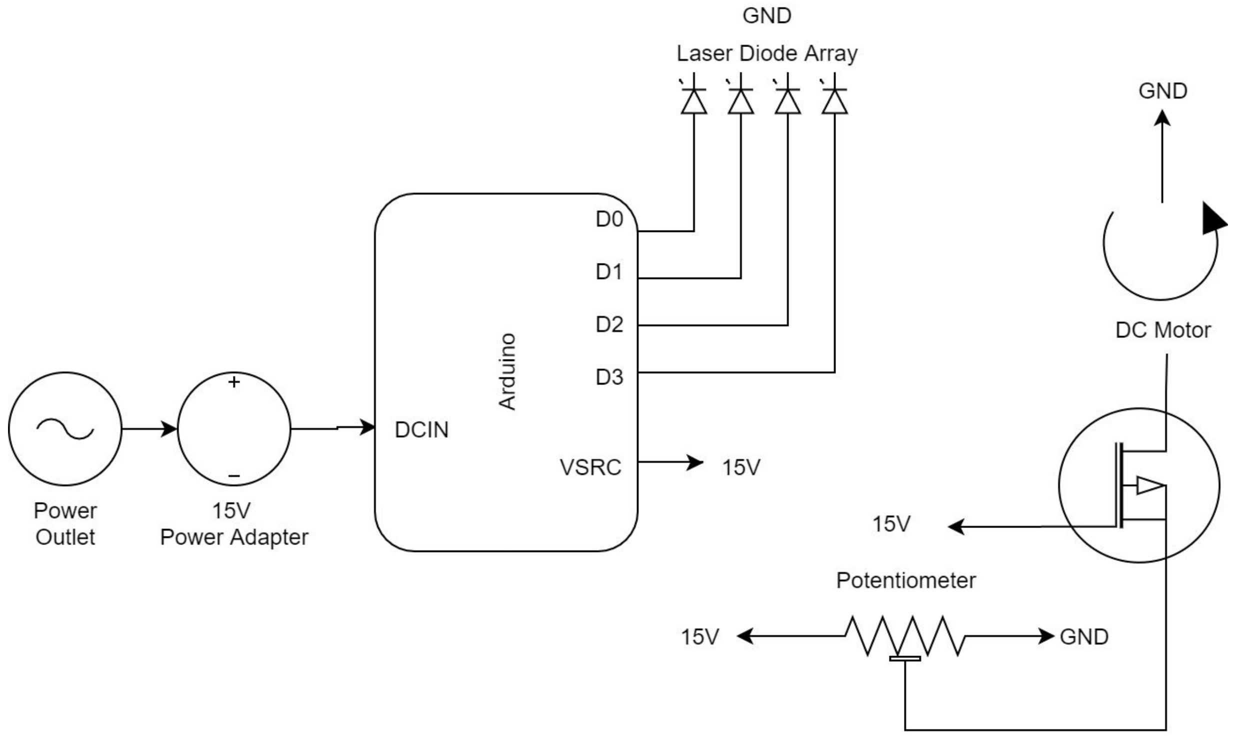
The generic operation of the RVHD prototype



The motor must spin the helix apparatus and match the speed. For simplicity, a Direct Current (DC) motor is used for the basic prototype. The speed of a DC motor is directly dependent on how much current passes through it. This speed can be adjusted slightly with a potentiometer and a high-power transistor, producing a variable current. Figure 5 shows the wiring required for the prototype. Many microcontrollers are able to drive all the required components. If a larger DC motor (>20 V) is needed for a higher rotational force, a voltage divider would likely need to be used so that the microcontroller would not malfunction or be damaged.

Figure 5

The wiring diagram of the prototype



CHAPTER III: IMPLEMENTATION

Equipment and Materials

The following equipment and materials were used in the construction of the prototype.

- XLX Wyhp Mini 3V 5mW Laser Diodes
- GQ30-150180-AX 15V 1.8A Switching Adapter
- Arduino Zero

- Bimior B10K Potentiometer
- Slide switch
- T3AN70OUG3 LM2937ET Power MOSFET
- Greartisan ZGA37RG9i 550 RPM 12V DC Motor
- Dusting bristles
- Mechanical pencil body
- LEGO System A/S various components

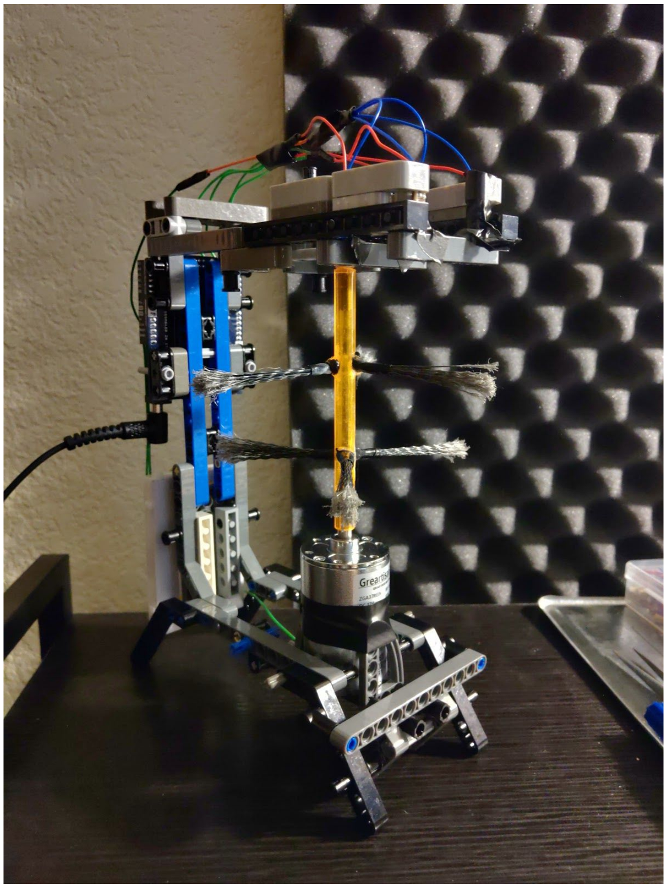
The Arduino Zero provides the primary driving force for the system since it provides easy access to control other parts of the system. The simple code ran on this microcontroller is provided in Appendix A. The 12V DC motor provides enough torque to turn the lightweight helical apparatus at its highest possible angular velocity. The laser diodes were bought in bulk for a discounted rate. The Bimior B10K Potentiometer was also bought in a similar fashion to the laser diodes. Every other material was extracted from preowned household and lab items. The estimated total cost of this prototype is $96.47 United States currency. Considering the limited number of laser diodes purchased, a more sophisticated prototype with the same materials would likely double this price.

Construction

As shown in Figure 6, the structural basis of the prototype is constructed from LEGO system parts, due to limited budget and time restrictions. This allows for rapid iteration while keeping tight tolerances for distance measurements and alignment, as well as excellent references for LD placement. The Arduino Zero features mounting holes that happen to snuggly fit certain LEGO system parts, making future disassembly or reworks clean and simple. For future builds, this would likely be done with computer drafting and 3D printing the structure, enabling much tighter precision and purpose. The central pillar of the helical structure is made from the malleable plastic from a mechanical pencil body so that holes for the bristles and the fitting to the motor could be finely formed. Electric tape is used for additional support and convenience where needed. A small breadboard is used to mount the potentiometer and power MOSFET components. The LDs used have resistors soldered into them which allows their ground wires to be combined, saving some work on the top of the prototype.

Figure 6

The constructed prototype for the RVHD



Results

The prototype successfully produces a volumetric image that is visible in moderately dark conditions. The laser diodes produce red light which is caught by the rotating structure, and, since it stays consistent, the stationary image is visible. The bristles of the helix aperture are able to reflect the light, but they do seem to limit the potential brightness of the image. The structure is stable enough to hold steady while the motor is in use. Using a microphone, the motor produces about 36 decibels of sound, which could potentially be a detractor of the experience if higher RPM was achieved. Another limitation of the RVHD is that the light from the LDs is visible below the apparatus. See Figure 8 for the first image taken of the RVHD. Figure 9 also shows the image but in more moderate lighting conditions.

Figure 8

The first image of a cube produced by the Rotary Volumetric Helical Display in near-darkness (October 4, 2020)

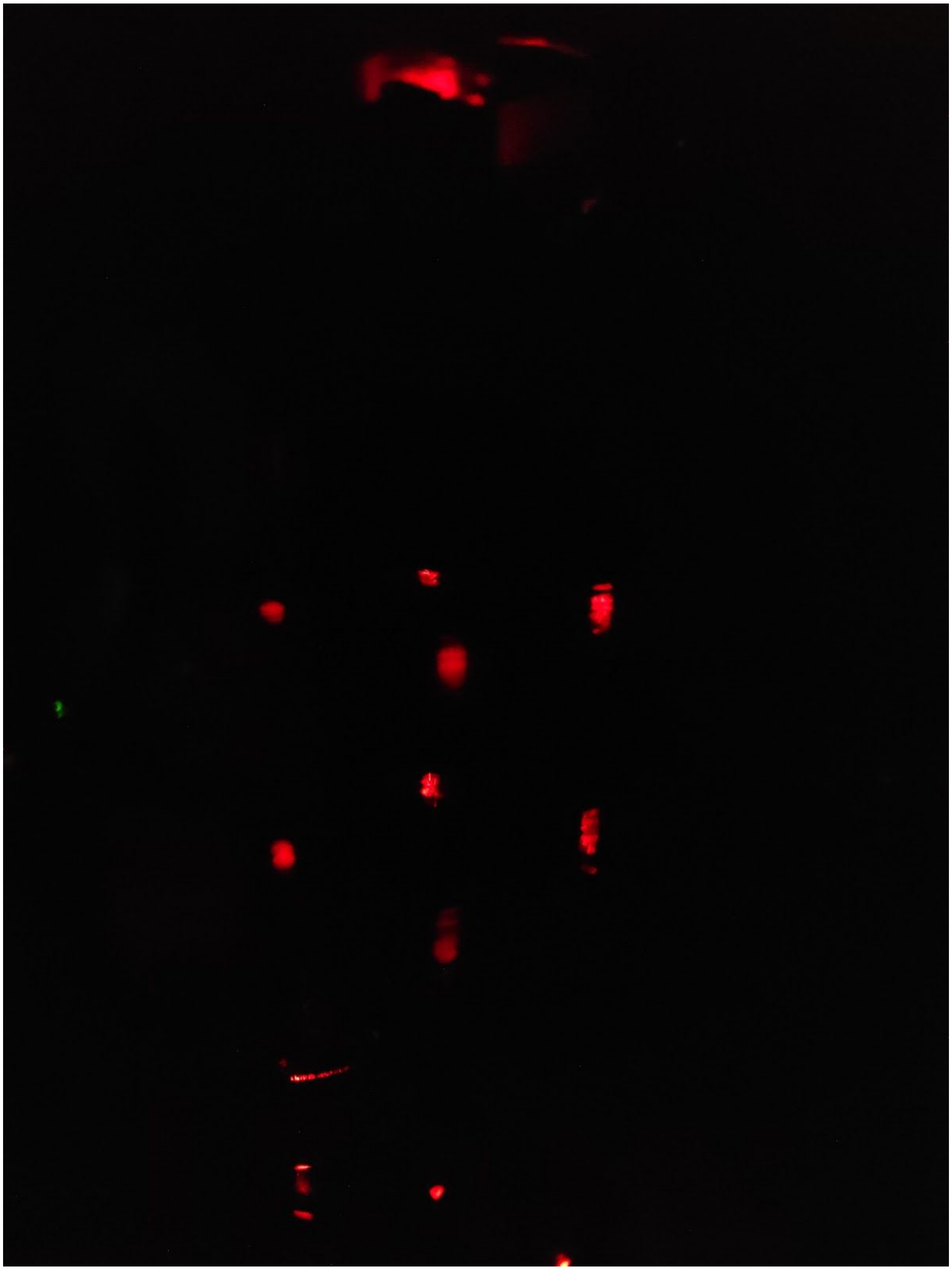
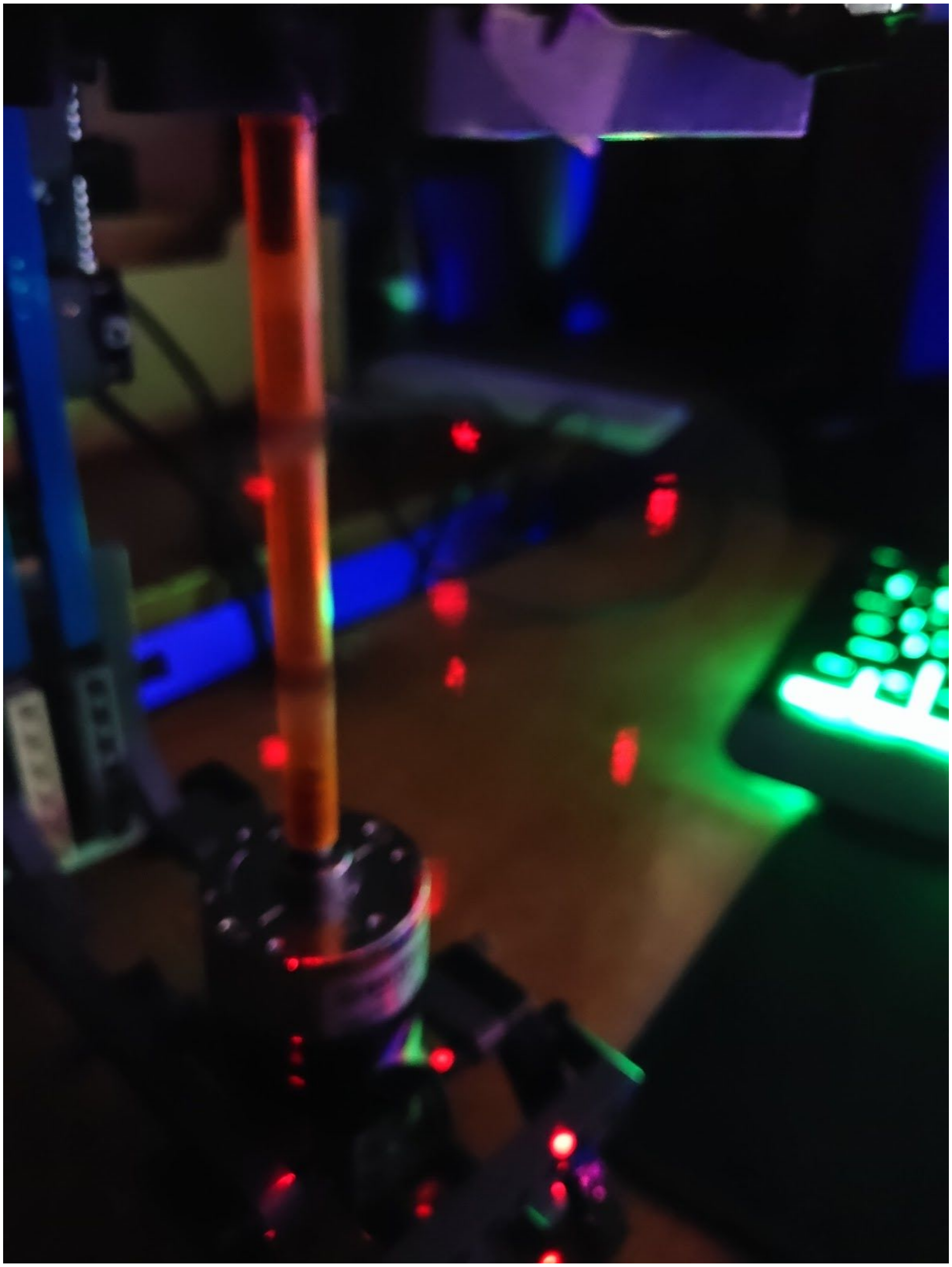


Figure 9

The Rotary Volumetric Helical Display in moderately brighter lighting conditions

(October 6, 2020)



CHAPTER IV: LIMITATIONS AND IMPROVEMENTS

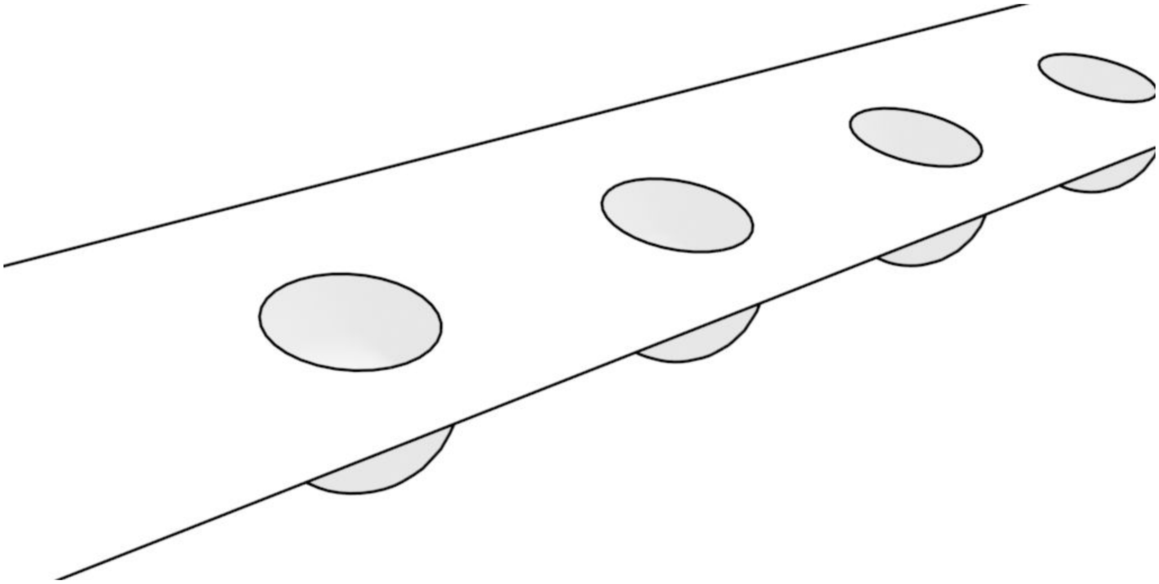
Brightness and Visibility

Although this design successfully gives a complete volumetric image, it only works in dark conditions, similar to low-power projectors. This is likely because of the minimal amount of light exposure per voxel. In a 2-dimensional display, each pixel is visible for almost the entire refresh rate, making the screen able to be consistently bright. However, with this design, the number of vertical layers reduced the exposure of each voxel to a small portion of that refresh rate. In order to have an optimal display outdoors or in daylight, a brightness of approximately 4000 nits [8]. Further experiments with higher-power laser diodes need to be conducted to see if the design is viable outdoors. Another approach to expose the image would be to have a dark apparatus to create a “shadow” effect which would still reflect the lasers to the point that the contrast is great enough for the image to be visible even in daylight.

Additionally, using other materials could help with the visibility of the display in darkness. In brighter areas, overly reflective materials would likely show what is located adjacent to it, acting like a warped mirror of the ambient environment. Other special materials incorporating fiber optics could be explored to allow the illumination of the underside of the helix structure. Another clever way to accomplish this dual illumination, since the helix is already in motion, is to have different passes per vertical step as pictured in Figure 10. On one pass, a flat reflective part shows the light on one side, and then, as the apparatus rotates, the bulbous refractive part is able to catch and display the light on the opposite side. This would allow for better viewing from more perspectives of the apparatus.

Figure 10

A solution for displaying light on both sides of the helix apparatus using one diffuse portion and a refractive bulbous portion



Another improvement could be made by using laser diodes that emit ultraviolet (UV) light for the projector. UV light is invisible to the human eye and thus would not illuminate anything except the apparatus. UV light is able to react with certain phosphors, a term for photosensitive compounds, and illuminate what is not illuminated by visible light. This effect can be seen in the ocean where several hundred meters below sea level, there exists a noticeable glow on certain bioluminescent sea life [23]. As noted before, having a black apparatus that only reacts to the lasers would create a shadow-like effect, allowing for higher contrast. This could be implemented by having UV-reactive phosphors on the apparatus which is mostly black in visible light. This would allow indoor viewing to be possible with lights on, but may not work in direct sunlight since UV light is present outdoors.

Currently, this implementation only produces a monochrome image. A full-color image could potentially be produced by having each pass of the helix reflect a different color channel. For example, as with the prototype, there are 3 “staircases” which make 3 passes per rotation. Certain televisions such as the JVC LCCS monitor would do 3 separate color passes for red, green, and blue (RGB) flashing each image separately and then the POV would combine the result in full color [19]. One pass of the helix can reflect red, the next green, and then blue. The LD array would need to know which color pass it is drawing at a given time and produce a different brightness for each color channel. Also, a higher refresh rate may be required to reduce color flickering.

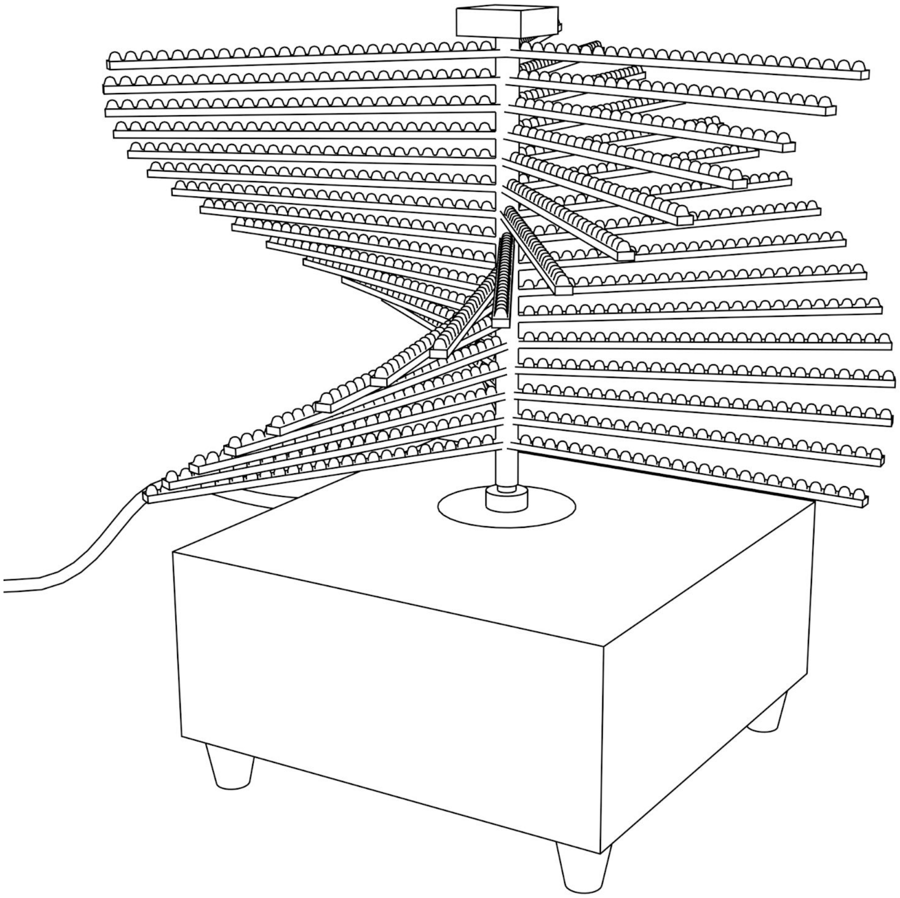
Alternatives to Projection with Laser Diodes

Figure 11 shows a version that is very closely related to the first patent shown in the introduction. LEDs are mounted directly onto the display and have to feature complex wiring and circuitry to operate. This would likely work, but may also prove far more expensive because of the nature of having to secure more volatile components. Each iteration of this type has required a microcontroller to be mounted on the rotating portion and power with a battery, not making it ideal for a household product, but great for mobile iterations. This alone would increase the cost of manufacturing and components to likely be more expensive than modern flat displays today. Additionally, it would be prone to breaking and potentially presenting safety hazards should electrical components be launched during operation. The tangential velocity with a motor spinning at 3000 RPM and a 20 cm apparatus is 60.3 meters per second or 134 miles per hour. This is definitely a harmful speed for any object but especially an electrical component.

Thus, not only would it be expensive because of the circuit design but also testing and reinforcement for the helical apparatus.

Figure 11

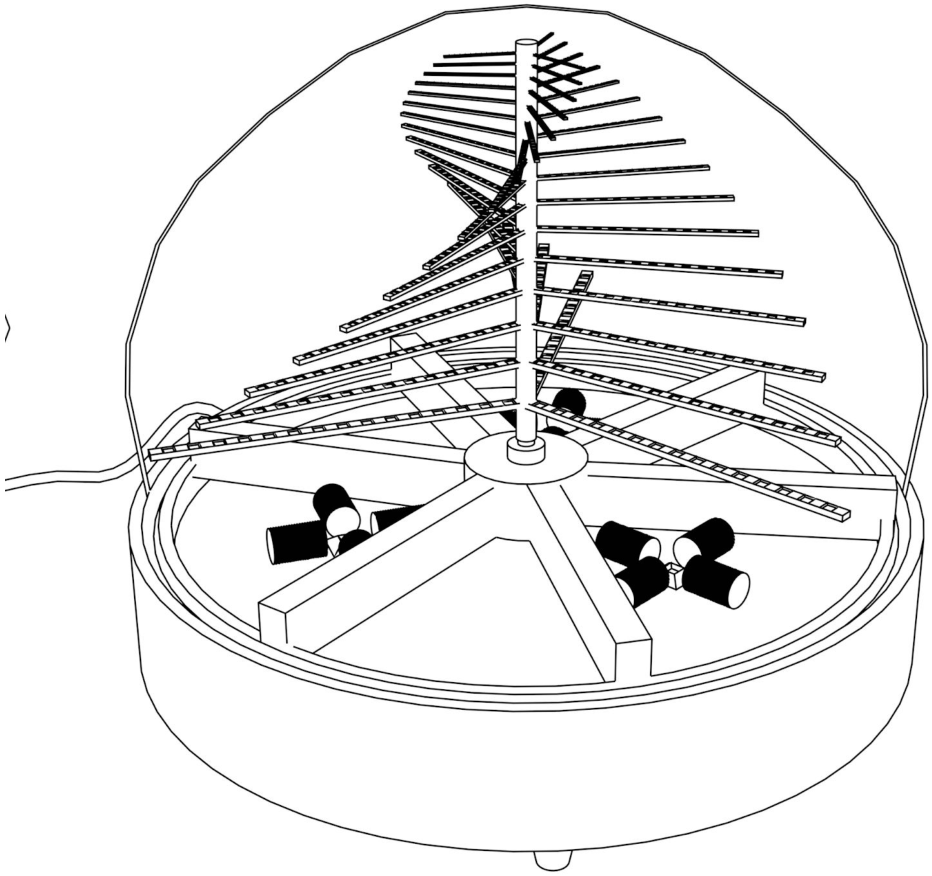
An iteration of the RVHD with mounted LEDs



Another far more outlandish and likely impractical solution would be to use CRT technology to project to the helical apparatus. Multiple cathodes could launch electrons and small electromagnets can direct them to hit their destinations. See Figure 12 for a potential look at how this could be implemented. A large vacuum-sealed glass container holds the spinning apparatus and several cathodes with surrounding electromagnets can steer electrons to the appropriate part of the apparatus. Another important thing to note is that a more hemispherical version of the hologram could make viewing from above far clearer and without view obstruction of details behind any portion of the helix apparatus. Notice that at the given angle, the back of the apparatus is still largely visible even with the more front-facing portion. The major problem with this idea is that electrons can potentially influence each other's position with their equal charges. Investigating this would require some electromagnetic simulations and experiments.

Figure 12

A cathode-ray tube implementation of the Rotary Volumetric Helical Display

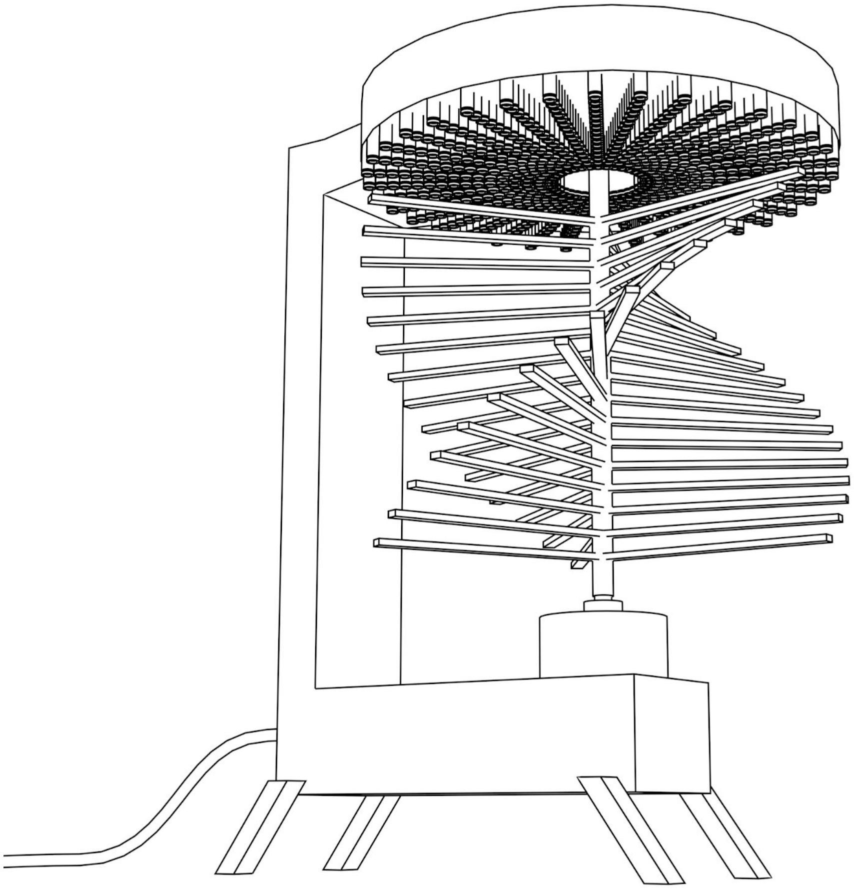


Cylindrical Form

The ideal implementation of the RVHD is to use cylindrically-arrayed LDs as shown in Figure 13. This will minimize any aliasing that would result from having traditionally cartesian-arrayed LDs. Additionally, this maximizes the space to be used by the RVHD. This will also provide more predictability from a calculations standpoint of what should be displayed in the LD array. Appendix B has some example code to raster 3D data into individual voxels.

Figure 13

A cylindrical iteration of the Rotary Volumetric Helical Display



The most optimized way to convert cartesian 3D data into cylindrical voxels is to first figure out what lines need to connect the vertices of a shape in cartesian coordinates. Then these lines can be converted into a voxelated 3D space. Each of these voxel points can then be easily converted as referenced below.

$$\text{cart} \leftrightarrow \text{cyl} \qquad \begin{cases} x = r\cos\theta, \\ y = r\sin\theta, \end{cases} \qquad \begin{cases} r = \sqrt{x^2 + y^2}, \\ \theta = \arctan\dfrac{y}{x}, \end{cases} \qquad \begin{cases} \sin\theta = \dfrac{y}{\sqrt{x^2 + y^2}}, \\ \cos\theta = \dfrac{x}{\sqrt{x^2 + y^2}}. \end{cases}$$

[9]

A custom arctangent function which would give exact rotational coordinates from a dictionary lookup with respect to the LD array resolution makes the calculation even faster. Straight lines in cylindrical coordinates feature division which is not ideal for computing power.

Vertical Layer Limitations

The major limitation for vertical layers is an LED’s response time, which by most manufacturing standards is 30 nanoseconds. Recently, computer monitors have been able to achieve 360 Hz, which should be feasible by properly multiplexed laser diodes. Thus, a reasonable level of vertical resolution assuming that the multiplexed array is refreshed within 5 microseconds would be around 300-500 voxels high, since it needs to refresh all layers within a 48th of a second. This is comparable to a low-quality YouTube video which, although not ideal, should produce a fine enough image for visibility. At a certain point, the amount of volumetric data is simply too much to handle for traditional computing power.

CHAPTER V: CONCLUSION

Volumetric displays are on the brink of becoming a reality for consumer electronics. Flat panels are close to maximizing their potential and entertainment is pursuing new attractions for consumers. Holograms will enable interaction and images that have not been seen by the masses, except in the science fiction media that is displayed on flat panels. Likely this technology in its infancy will mimic that of 80s electronics. Low resolutions will be great for basic text and blocky images as found in retro arcade machines. With photogrammetry being able to produce 3D models from surrounding images of a focused subject, films could potentially be done by having multiple perspectives being filmed and then parsed into 3D data (CITATION). It is unlikely that flat panel displays will be replaced, since they typically take up minimal space, but it will present a new medium akin to how radios are still in use.

The design of the Rotary Volumetric Helical Display is simple and intuitive, as well as easily manufacturable. The helical shape is central to the design, allowing for multiple viewing angles while retaining consistency. The phenomenon of persistence of vision is used to fool the human eye into seeing the constantly refreshed image over several layers as one form. Laser diodes are an easy way to project voxels onto the helical apparatus. A microcontroller is used to refresh the LD array. Ideally, each LD would be latched and keep its charge for the longest period possible during refresh because of the limitations of multiplexing. With the refreshing of the image for every slice during the rotation of the helical apparatus, a volumetric illusion occurs.

The implementation of the device featured very affordable parts making the prototype under $100. The framework used reliable plastic parts and an Arduino to drive the electronic components. The laser diode array is simplified to only draw the 8 corners of a cube, given time and budget constraints. The resulting cubic image produced from the prototype indicates that this technology is not only possible but very simple. The prototype is viewable only in dark conditions but still, the resulting image is clear and quantifiably volumetric.

With the success of this prototype, improvements and experimentation can be accomplished. Using photosensitive materials a darkened apparatus could increase contrast to produce a more distinct image to be visible in indoor lighting. Having a more uniquely manufactured helical apparatus could allow for a light pass both on top and below the apparatus, making voxels visible from more angles. Ultraviolet light can also be used with phosphoric materials to illuminate otherwise unlit material on the helical apparatus, similar to a blacklight. Another improvement would be employing multiple RGB passes using the threefold-shaped helical apparatus. Another way that could improve image quality would be mounting LEDs onto the apparatus. However, this comes at the cost of safety and complex circuitry. The cylindrical coordinate system is necessary for the implementation of the RVHD to be fully utilized. Encoding 3D graphics in this format is less math-heavy when converting between cartesian voxels to cylindrical voxels as opposed to drawing lines in cylindrical format.

Volumetric displays will be the largest jump in household entertainment since the first home television. Images in 3D enable new user interactions and experiences. Video games in the RVHD will be a unique opportunity for innovation and competition with current market leaders. Films with 3D characters can enable a sense of scale and scope which traditional cinema has already accomplished so much within 2D. Video calls with family and friends will be completely revolutionized by a true face-to-face experience. New 3D graphics engines will need to be made to properly raster voxels and anti-alias volumetric images. The holographic revolution is within reach.

REFERENCES

[1] Al-Natsheh, W. H., Hammad, B. K., & Abu Zaid, M. A. (2019, August 12). Design and Implementation of a Cylindrical Persistence of Vision Display [Scholarly project]. In IEEE Xplore. Retrieved February 10, 2020, from https://ieeexplore.ieee.org/document/8792555

[2] Allen, F. (1902). Some Phenomena of the Persistence of Vision. Harvard University. pp. 45-56.

[3] Calvez, S., & Adams, M. J. (2012). Semiconductor lasers: The first fifty years [Editorial]. Semiconductor Science and Technology.

[4] Dai, S., & Wu, Y. (2008). Motion from blur [Scholarly project]. IEEE Conference on Computer Vision and Pattern Recognition. Anchorage, AK, 2008, pp. 1-8. doi: 10.1109/CVPR.2008.4587582.

[5] Forbes, M. & Brey, B. (1985). Digital Electronics. The Bobbs-Merrill Company Inc. pp. 235-237.

[6] Goldsmith, T. et. al. (1948). Cathode-Ray Tube Amusement Device. U.S. Patent No. 2,455,992. Washington, DC: U.S. Patent and Trademark Office.

[7] Greenwald, W. (2020, September 22). What is 8K? Should you buy a new TV or wait? PC Magazine.

[8] Hatchett, J., Toffoli, D., Melo, M., Bessa, M., Debattista, K., & Chalmers, A. (2019, April 26). Displaying detail in bright environments: A 10,000 nit display and its evaluation. Retrieved October 16, 2020, from https://www.sciencedirect.com/science/article/pii/S0923596518307859

[9] Igarashi A. (2018). Liquid Crystal Display. U.S. Patent No. 10,025,150. Washington, DC: U.S. Patent and Trademark Office.

[10] Levanto, L. (1991). Matrix Display. U.S. Patent No. 5,016,002. Washington, DC: U.S. Patent and Trademark Office.

[11] Levy, S. (1995, October 14). Relations between Cartesian, Cylindrical, and Spherical Coordinates. Retrieved October 17, 2020, from http://www.geom.uiuc.edu/docs/reference/CRC-formulas/node42.html

[12] Meng, W. T., & Zhou, Q. (2019). Persistence of Vision Rotary Display Device. U.S. Patent No. 10,410,559. Washington, DC: U.S. Patent and Trademark Office.

[13] Molina, E. (2014). IEEE Annals of the History of Computing. IEEE Annals of the History of Computing, 36(3), 30-41. doi:10.1109/MAHC.2014.47

[14] Popov, A. D. (2000). Team working of AC electronic motor and inverter. Proceedings of the 6th International Scientific and Practical Conference of Students, Post-graduates and Young Scientists. Modern Techniques and Technology. MTT'2000 (Cat. No.00EX369), Tomsk, Russia, 2000, pp. 186-188. doi: 10.1109/SPCMTT.2000.896111.

[15] Richardson, M., & Wiltshire, J. D. (2018). A Personal View of the History of Holography. In The hologram: Principles and techniques. Hoboken, NJ: Wiley.

[16] Russo, A., & Russo, J. (Directors). (2019). Avengers: Endgame [Motion picture]. United States: Marvel Studios.

[17] Sprague, J. L. (2016). Frank J. Sprague Invents: The Constant-Speed dc Electric Motor [History], in IEEE Power and Energy Magazine, vol. 14, no. 2, pp. 80-96, March-April 2016, doi: 10.1109/MPE.2015.2501085.

[18] Technology Connections. (2017). How Analog Color TV Works: The Beginnings [Video]. YouTube. https://www.youtube.com/watch?v=dX649lnKAU0&list=PLv0jwu7G_DFUGEfwEl0uWduXGcRbT7Ran

[19] Technology Connections. (2017). LCCS: The LCD / CRT Hybrid from JVC [Video]. YouTube. https://www.youtube.com/watch?v=z-q8ehzHeQQ&t=593s&ab_channel=TechnologyConnections

[20] Technology Connections. (2017). Lines of Light: How Analog Television Works [Video]. YouTube. https://www.youtube.com/watch?v=l4UgZBs7ZGo&list=PLv0jwu7G_DFUGEfwEl0uWduXGcRbT7Ranctions

[21] Technology Connections. (2017). Trinitron: Sony’s Once Unbeatable Product [Video]. YouTube. https://www.youtube.com/watch?v=l4UgZBs7ZGo&list=PLv0jwu7G_DFUGEfwEl0uWduXGcRbT7Ranctions

[22] The University of Washington (1994). The History of Motion Pictures. Retrieved October 16, 2020, from https://faculty.washington.edu/baldasty/JAN13.htm

[23] Underwater Kinetics (2014). Ultraviolet Diving with Underwater Kinetics UV Lights [Video]. YouTube. https://www.youtube.com/watch?v=E56IuJumLAE&ab_channel=UnderwaterKinetics

APPENDIX A

The prototype code that is executed on the microcontroller for the Rotary Volumetric Helical Display.

```
/**
 * hologram.ino
 *
 * Seth Barger
 * 10-4-2020
 *
 * Mississippi State University
 * Electrical and Computer Engineering
 *
 * A program to control a laser diode array for the
 * Rotary Volumetric Helical Display prototype.
 */

/**
 * Initializes and configures the controller.
 */
void setup() {
  // this code executes first
  delay(1000);
  Serial.begin(115200);
  Serial.println("Rotary Volumetric display program");

  // configure I/O pins appropriately
  pinMode(0, OUTPUT);
  pinMode(1, OUTPUT);
  pinMode(2, OUTPUT);
  pinMode(4, OUTPUT);
  digitalWrite(0, HIGH);
  digitalWrite(1, HIGH);
  digitalWrite(2, HIGH);
  digitalWrite(4, HIGH);
}

/**
```

```
 * Refreshes the laser diode array repeatedly. (not necessary for final prototype form)
 */
void loop() {

  digitalWrite(0, HIGH);
  digitalWrite(1, HIGH);
  digitalWrite(2, HIGH);
  digitalWrite(4, HIGH);
  digitalWrite(0, LOW);
  digitalWrite(1, LOW);
  digitalWrite(2, LOW);
  digitalWrite(4, LOW);

  delay(1);
}
```

APPENDIX B

An example 3D voxel rasterizer for the RVHD format written in pseudocode

```
/**
* voxel_raster.x
*
* Seth Barger
*
* This is an example realtime rasterizer for the Rotary Helical
* Volumetric Display. This rendering engine assumes that the RVHD
* has a cylindrically-aligned set of laser diodes/projection to draw.
* This program will only draw lines provided by input of vertices.
* Another improvement would be to vertically offset the data before
* sending it out to the hardware which is in helix form.
**/

// main program
int main() {

    // vertices groups are grouped by count, x, y, and z
    vertex_groups = float[][][][]

    // the number of individual rows (the resolution of 2PI represented)
    num_rows = 30

    // the number of individual rows (the resolution of phi represented)
    num_phi = 20

    // the number of slices of the volumetric image (the vertical resolution)
    num_slices = 20

    /*
     * This is the pre-final data.
     * It is arranged as phi, theta, and layer.
     * Assumed only "ON" or "OFF" for laser diodes.
     */
    volume_cyl_data = boolean[num_rows][num_phi][num_slices]
```

```
    /*
     * This is the final helix-shifted buffer to be given to the RVHD.
     * It is arranged as phi, theta, and layer.
     * Assumed only "ON" or "OFF" for laser diodes.
     */
    volume_data = boolean[num_rows][num_phi][num_slices]

    // the refresh-image loop
    while (refresh)
    {

        // this assumes that a generic 3D engine is giving a new set of vertices
        update_from_engine(vertex_groups)

        for (vertex_group in vertex_groups)
        {
// assumes that line segments will connect all vertices in a group consecutively
            for (pair in vertex_group)
            {
                voxels_of_line = draw_cylindrical_line(pair)
                for (voxel in voxels_of_line)
                {
                    // add voxels to the RVHD pre-buffer
                    volume_cyl_data[voxel.x][voxel.y][voxel.z] = true
                }
            }
        }

        // update the physical hardware from the cylindrical voxel data
        send_buffer_to_RVHD(volume_cyl_data);

    }

    return
}

// converts a cartesian point into cylindrical point
float[][][] convert_cartesian_to_cylindrical(float[][][] input)
{
```

```
    // the output array
    output = float[][][][]

    // translate each vertex into a cylindrical coordinate
    for(vertex_group in input)
    {
        for (vertex in vertex_group)
        {
            phi = sqrt(input.x^2 + input.y^2)
            theta = atan(input.y/input.x)
            output.put([phi][theta][input.z])
        }
    }

    return output

}

// returns a set of voxels along a line from two cartesian points
[[][][]] draw_cylindrical_line_from_cart(float[][][] point_a, float[][][] point_b)
{

    // first, draw the line as standard xyz coordinates

    // get direction vector from difference
    slope = float[point_a.x - point_b.x][point_a.y - point_b.y][point_a.z\ point_b.z]

    // offset is provided by point_a, resulting in line functions

    // determine distance
    distance = sqrt(slope.x^2 + slope.y^2 + slope.z^2)

    // set of voxels as described by voxels in xyz
    line_of_voxels_xyz = [float[][][]]

    // x(t) = point_a.x + slope.x*t
    // y(t) = point_a.y + slope.y*t
    // z(t) = point_a.z + slope.z*t
    // iterate over distance and add voxels to group
```

```
    for (t ; t < distance ; t++)
    {
        // since t from 0 to 1 traverses the whole line,
        // we want to find function at int(distance) increments

        x_t = point_a.x + slope.x * t / distance
        y_t = point_a.y + slope.y * t / distance
        z_t = point_a.z + slope.z * t / distance

        line_of_voxels_xyz.put([x_t][y_t][z_t])
    }

    // set of voxels as described by voxels in cylindrical coordinates
    line_of_voxels_cyl = [float[][][]]
    voxels_cyl_discrete = [[][][]]

    // now, we convert these points into cylindrical voxels
    for (voxel in line_of_voxels_xyz)
    {
        voxel_cylinder = convert_cartesian_to_cylindrical(voxel)

        // round values to integers to properly display on laser diode array
        voxels_cyl_discrete[index] = [int(voxel_cylinder.x)]        \
                                     [int(voxel_cylinder.y)]     \
                                     [int(voxel_cylinder.z)]
    }

    return voxels_cyl_discrete

}
```