Holodeck: Telepresence Dome Visualization System Simulations

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Abstract

This paper explores the simulation and consideration of different image-projection strategies for the Holodeck, a dome that will be used for highly immersive telepresence operations in future endeavors of the National Aeronautics and Space Administration (NASA). Its visualization system will include a full 360 degree projection onto the dome's interior walls in order to display video streams from both simulations and recorded video.

Because humans innately trust their vision to precisely report their surroundings, the Holodeck's visualization system is crucial to its realism. This system will be rigged with an integrated hardware and software infrastructure—namely, a system of projectors that will relay with a Graphics Processing Unit (GPU) and computer to both project images onto the dome and correct warping in those projections in real-time. Using both Computer-Aided Design (CAD) and ray-tracing software, virtual models of various dome/projector geometries were created and simulated via tracking and analysis of virtual light sources, leading to the selection of two possible configurations for installation.

Research into image warping and the generation of dome-ready video content was also conducted, including generation of fisheye images, distortion correction, and the generation of a reliable content-generation pipeline.

Nomenclature

CAD = Computer-Aid Design
DOUG = Dynamic On-board Ubiquitous Graphics
EDGE = Engineering Doug Graphics for Exploration
F.F = Flight Deck of the Future
GPU = Graphics Processing Unit
iPAS = Integrated Power, Avionics, and Software
NTPSM = Normal-Throw Projector and Spherical Mirror
STP = Short-Throw Projector

I. Introduction

The Holodeck is a confined telepresence dome—a twelve-foot-diameter hollow fiberglass sphere that can be entered through a latch-style door on its side. In this dome NASA's Flight Deck of the Future (F.F) crew aims to create a unique telepresence experience for both ground crew and astronauts. *Telepresence* is simply the notion of fabricating the experience of being "elsewhere," of existing and interacting realistically with a manipulable virtual environment. Through appeals to *visual, auditory, tactile*, and even *olfactory* technologies, the Holodeck will be able to provide a level of immersion that is both groundbreaking and unprecedented. Each of these sensory technologies will be developed independently and integrated into the dome as they are completed—ideas include three-dimensional surround sound, gesture and voice recognition, haptic feedback from wearable technology, and emitted smells. This paper, however, will focus solely on the ideation and development of the dome's visualization system.

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The choice of the dome shape was chosen particularly to enhance the visual aspect of telepresence. It is generally accepted in both the gaming industry and the virtual reality community that the inclusion of peripheral vision leads to a heightened sense of immersion in any simulation.[1] Existing visualization systems that engage peripheral vision include planetariums and the iDome system of specialist Paul Bourke, from whom many of this paper's sources are drawn.[1] Still, these systems utilize hemisphere-based systems, which engage a visual range of only 180 degrees. Though this range is acceptable for a stationary subject, anyone who is free to rotate demands a more complete virtual environment.

Figure 1. The iDome. *Paul Bourke's standing hemispherical system, using a single projector for gaming and education visualizations.*

The Holodeck will be just that—a complete dome, two hemispheres, which together create a 360 degree range of vision all around the subject. Enclosed in such a full dome, a user will be able to freely rotate and simply see different views of a complete virtual environment. This, combined with other sensory technologies, create a very powerful telepresence experience that NASA can use for *tele-operation of ground crews, mission planning,* and *training programs for astronauts*, as well as *recreation to improve crew morale.*

Figure 2. The Holodeck. *The double-hinge-style door is visible, as is its magnitude and composition. Technically considered a confined space until the ventilation system is installed, it has the capacity to fit two or three adults comfortably. The floor is modular, and the whole dome has been placed on an 80/20-style raised floor and added supports.*

The Holodeck's superior immersion comes with the cost of a necessarily more complex projection technique. Since the projected images must cover the entire inner surface, there is no "blind spot" at which all the projection equipment can be harmlessly placed; indeed, any possibly location within the dome is a possible obstruction for light travelling across it. Light also cannot be shot from wall to wall, as the user standing inside will also throw large shadows, ruining the immersion.

Because of these added complications, a standard equidistant-fisheye-lens projection will not work. A Normal-Throw Projector—that is, a standard image projector—will not provide adequate dome coverage on its own. Also, since multiple projectors would be necessary to cover 360 degrees, a single image would have to be divided onto the projectors with the edges of each projection blended together in a convincing way. Thus, strategies were chosen that:

1. Maximized dome coverage
2. Minimized shadows
3. Minimized overlap to ease edge blending

With these considerations in mind, two strategies were chosen to pursue.

1. Normal-Throw Projector and Spherical Mirror (NTPSM)[2]

This system implements a normal-throw projector and widens the image range by bouncing the light off of a section of spherical mirror that is placed in front of it. The light reflects, and different rays reflect at different angles off of the curvature of the mirror, as explained in Fig. 3. This magnifies the projected images such that a single projector can fill a hemisphere, *if* the mirror is placed at the hemisphere's center However, the dome's

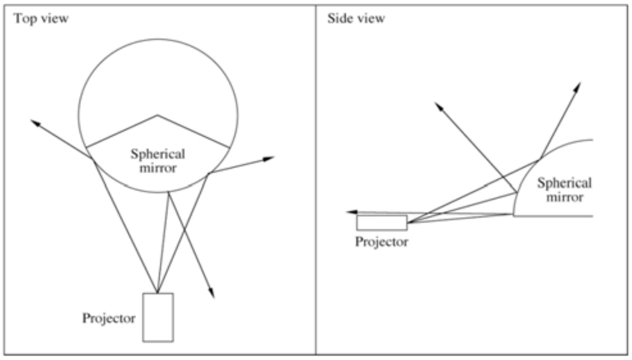

Figure 3. Top and side view of an STPSM system.[2]

effective two hemispheres will have the user standing at the origin, necessitating a more creative solution and more projectors.

2. Short-Throw Projectors (STP)

This system implements a special type of projector—the STP. An STP is a projector with a low throw ratio; as explained in Fig. 4, a projector's throw ratio is given by

$$TR = \frac{D}{W}$$

Where *TR* is the throw ratio, *D* is the distance from the projector to the screen or surface, and *W* is the width (non-diagonal) of the projected image. The higher the value of *TR*, the further away from the surface the projector must be to throw the same-size image. Most projectors have a small range of throw ratios that can be adjusted. Projectors with very low throw ratios (usually between 0.38 and 0.75) are considered STPs—these projectors are commonly used in presentation settings where, mounted from the ceiling, the can cast an image onto a screen while behind the presenter, removing any worry of shadows cast by the presenter's gesticulation.

Such a projection system can also be invaluable in settings like the Holodeck, where coverage is crucial but space is limited.

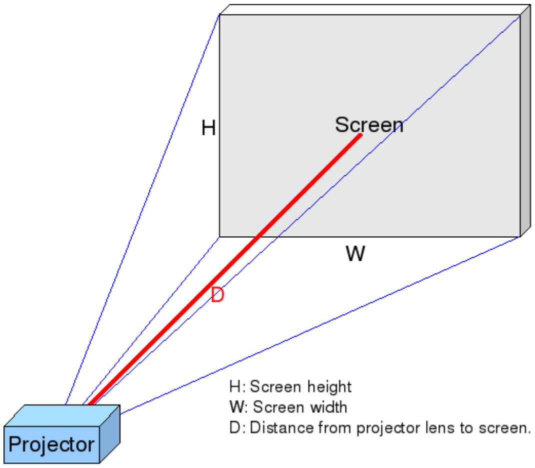

Figure 4. Throw Ratio. *A projector's throw ratio is given by the projector-screen distance* D *divided by the image width* W*. Projectors with lower throw ratios can "throw," or project, a larger image from the same distance.*

II. Simulation Technique

Since the simulations were to be of a visual system and the most important considerations of the simulations were to be dome coverage, shadows thrown by users, and projector overlap, it was decided that a very visual representation of simulation data would be the most intuitive information to use to decide feasible projection strategies. The simulations would be 3D models of the dome/projector system while the projected light would be viewed as colored and traced rays. *Ray tracing* is a computational technique of tracing virtual rays on their paths through a fabricated 3D scene as they reflect and are absorbed by objects with differently specified material properties.[3] Typically this is used for high-quality image generation by placing a virtual image plane at any arbitrary location in the scene, but it can be used for simulation as well.

After much research the software TracePro[4] was selected to perform the simulation. TracePro is a software that can generate hundreds of thousands of virtual rays, colored by frequency or by light source, as they travel through a scene full of objects that can be important from a CAD software such as Pro/Engineer.[5] Once generated, the surfaces of each object can be analyzed with different visual tools, including illuminance maps and Candela plots, which analyze the intensity of light as a function of 3-dimensional position across the surface.

Using imported CAD models along with TracePro's support for customizable, optics-accurate lenses, *any type of projector's thrown image can be accurately modeled if its image specifications are known.* It is in this manner that both the NTP and STP can be modeled, as shown in Fig 5. Along with a to-scale representation of the dome (Fig. 6) and the spherical mirror (Fig. 7), the entire dome/projector system can be modeled accurately. Ray-tracing simulations were conducted using two types of projectors: an NTP (Optoma HD25-LV) and an STP (Mitsubishi WED390U-EST) whose relevant specifications are contained in Fig. 8.

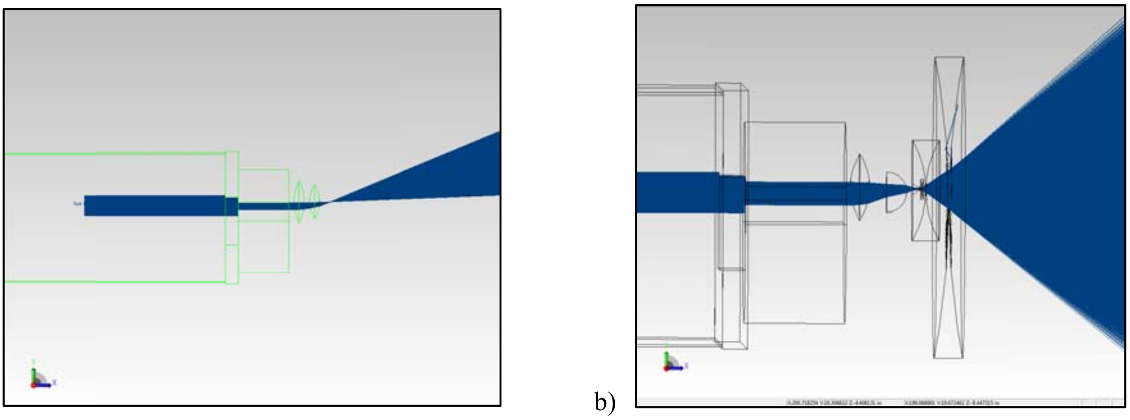
a) b)

Figure 5. Simulated projectors. *Shown above are the TracePro-simulated projectors for both a) the NTP, an Optoma HD25-LV, and b) the STP, a Mitsubishi WED390U-EST. Note the different spread of the projected beams due to the different throw ratios of each projector.*

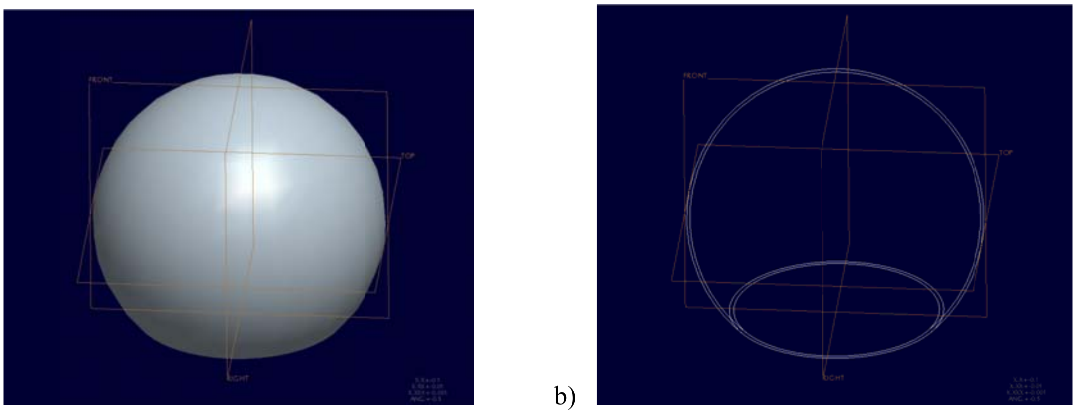
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Figure 6. CAD model of the dome. *The dome has a 12' diameter and is 1.5'' thick.*

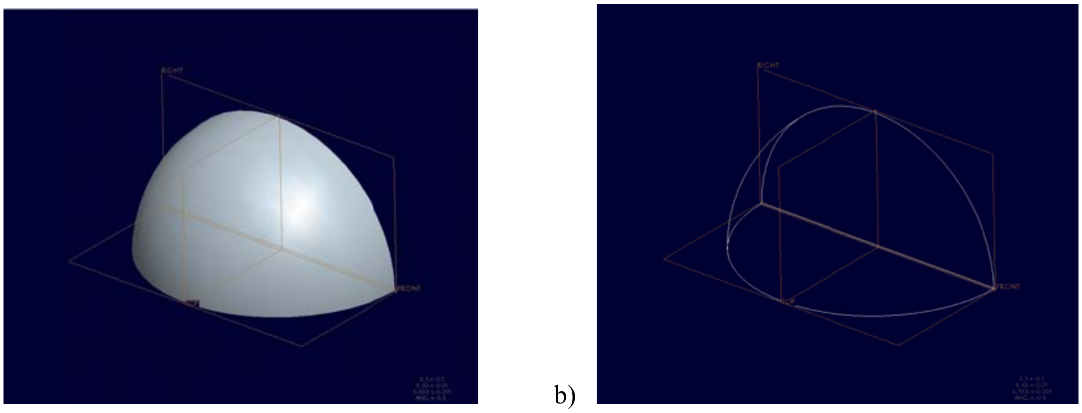
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Figure 7. CAD model of the mirror. *The spherical mirror is a quarter-section of a 9''-diameter sphere.*

	Throw Ratio	Aspect Ratio	Dim. (W x H x D)
NTP	1.5	16:9	12.7″ x 3.8″ x 9.2″
STP	0.378	16:10	12.8″ x 4.5″ x 10.2″

Figure 8. Projector Specifications. *The NTP and STP specifications for simulation-relevant fields such as throw ratio, aspect ratio, and projector dimensions.*

Using the information from Figs. 5-8, accurate virtual representations of various dome/projector geometries were explored and simulated. Simulations were conducted using light sources containing rays in a rectangular grid of *400x400* rays, or *160,000 simulated rays per projector*. A rudimentary representation of a 5’9’’ user (a user for which the dome was optimized) was constructed from primitive solids and placed in the center of the dome to accurately cast shadows from any thrown projector.

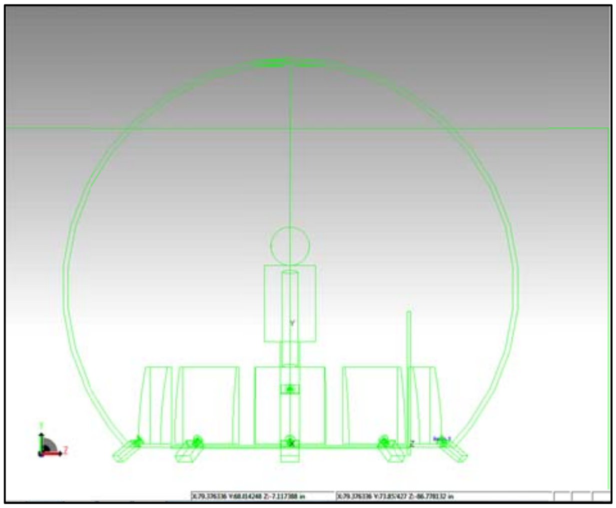


Figure 9. Simulation Setup. *This image displays the system of dome, projector(s), and user all in a virtual environment.*

III. NTPSM Simulations

The simulations for the Holodeck’s visualization system will be explored categorically, first for the NTPSM system and then for the STP system. In order to establish a logical progression of ideas and advancements for feasible geometries, several discarded possibilities will be shown to discuss their flaws and set the background for their descendants.

1. NTPSM Simulation Series 1: Pivoting

The NTPSM system was explored before the notion of the STP system was conceived. The initial idea was to have three or four projectors and the same number of mirrors, pivoted about 90 degrees from the center. In this way the images could be thrown onto the dome without interfering too much with the user inside. The image would hit the dome’s inner surface at varying path lengths, providing a sloping contact.

Fig. 11 shows the data from the pivoted-style NTPSM trials. *The beam from each projector is represented by rays of a different color.* An unexpected artifact from pivoting the NTPSM was that distortion from both the mirror and the differing path lengths rendered the image into extreme curved and spiked shapes. This would render an accurate post-processing such as edge-blending between projectors and distortion correction of those images extremely difficult to perform. A system with three projectors gave the most distortion, and the attempts to correct with a fourth projector rendered the coverage inadequate.

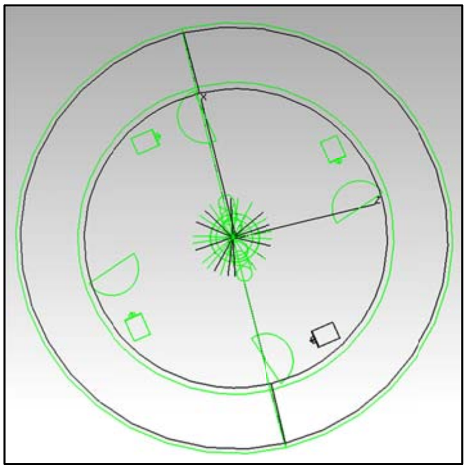
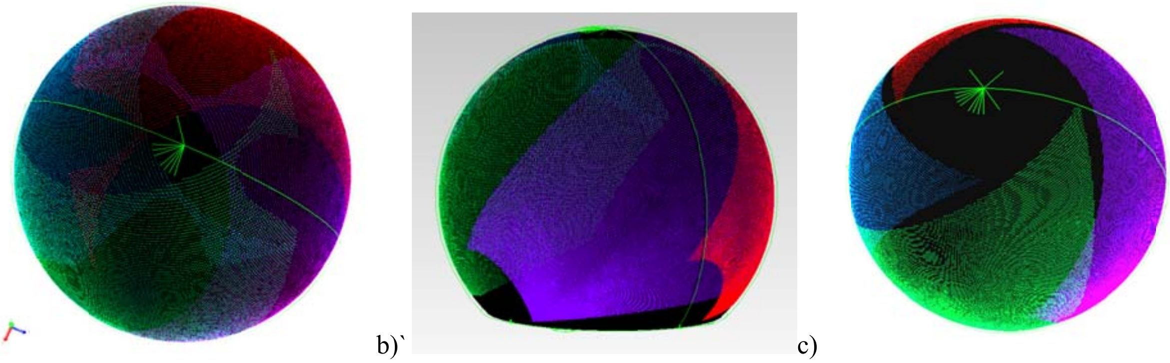


Figure 10. Top view of the first STPSM attempt with four projectors.

It was decided that a *radially symmetric* image would be the best option for later post-processing.



a) b)` c)

Figure 11. Discarded NTPSM attempts. *The notion of placing pivoted projector/mirror systems in the dome was ruled unacceptable due to a) large semicircular shadows cast by the user, b) extreme curvature and distortion of the rectangular projection, and c) general image sloping and inadequate coverage.*

2. NTPSM Simulation Series 2: Radial Symmetry

Once it was agreed that a NTPSM system with radial symmetry was the best option, the remaining questions were

1. How few projectors could be used and still retain full dome coverage?
2. How could the mirrors be arranged to prevent shadows cast by the user?

It was determined that by radially arranging the projectors below the floor of the dome, pointed directly in toward the center, and then placing mirrors radially along a smaller radius, pointing out, the images could be projected upward and inward *through cutouts in the floor* and reflected outward before ever crossing the center of the dome, eliminating all shadows. This strategy was tested for various numbers of projectors.

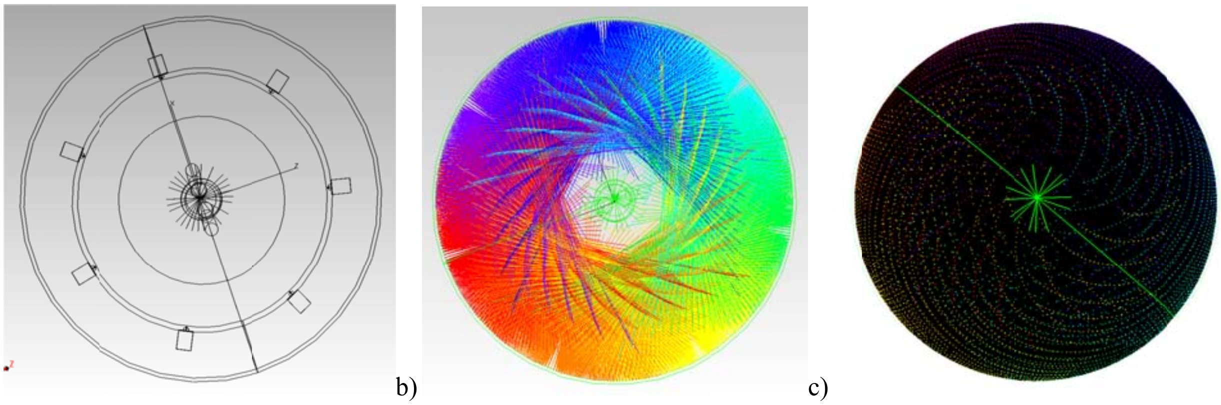

a) b) c)

Figure 12. Radially symmetric NTPSM with seven projectors. *The radial symmetry provided a much more feasible outcome than pivoting. By lowering the projectors below the floor and placing them radially outside the outer edge of the dome as in a), a much more even coverage can be obtained. Note how, as shown in b), the light reflects back away from the dome's center and avoids ever crossing the path of the user, preventing shadows. Part c) shows the much more complete overhead coverage provided by seven projectors.*

However, a system of seven projectors was not economically feasible. A new system containing only five projectors was subsequently modeled and simulated, leading to the results in Fig. 13. As with the seven-projector system, dome coverage was adequate with overlap and distortion that was not overly extreme. As shown in part c), there was a hole in the projected image at the top of the dome. However, we know that although peripheral vision is key to immersion in the Holodeck, for the purposes of the virtual reality, left-to-right periphery is much more vital than being able to look straight up. *The five-projector NTPSM system was chosen as a feasible dome geometry.*

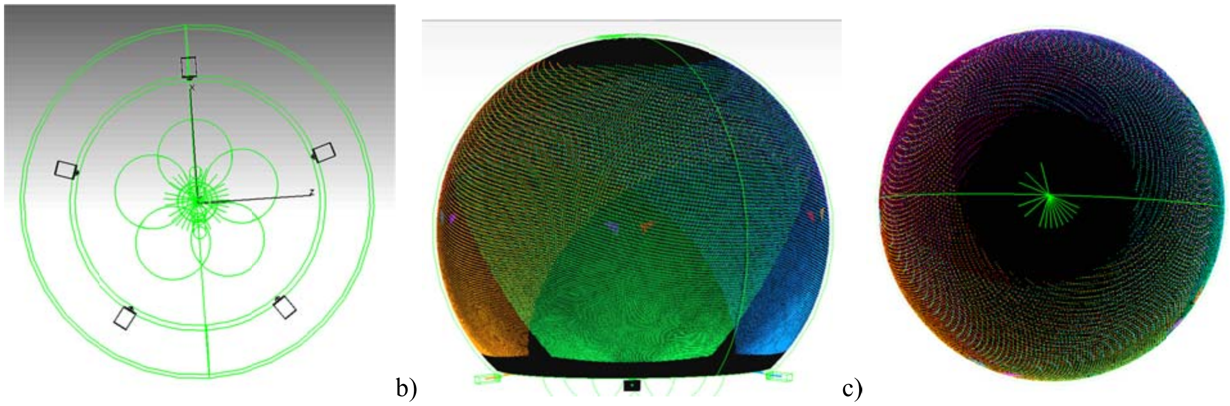
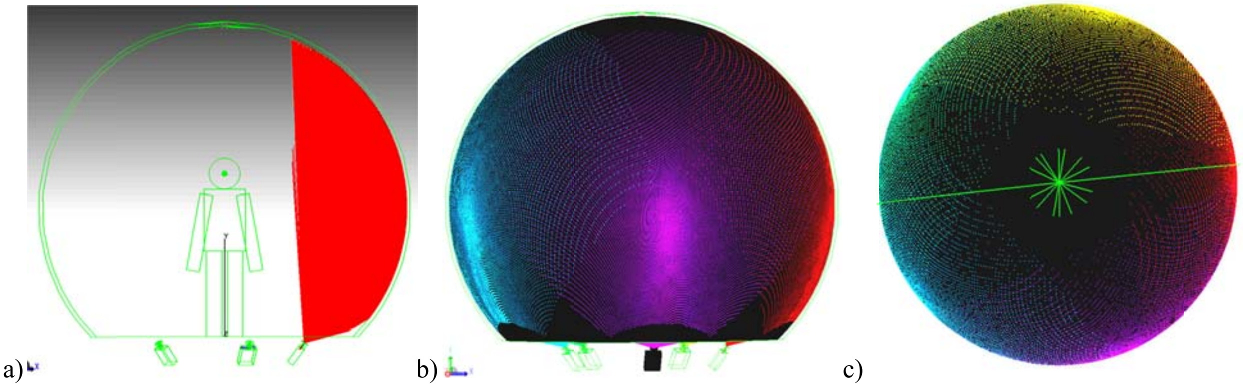

a) b) c)

Figure 13. Radially symmetric NTPSM with five projectors. *Part a) shows the new setup with larger mirrors. The overlap was plentiful but acceptable, and spherical distortion led to some image curvature, as shown in b). The missing hole of coverage in c) is straight up and therefore not significant.*

IV. STP Simulations

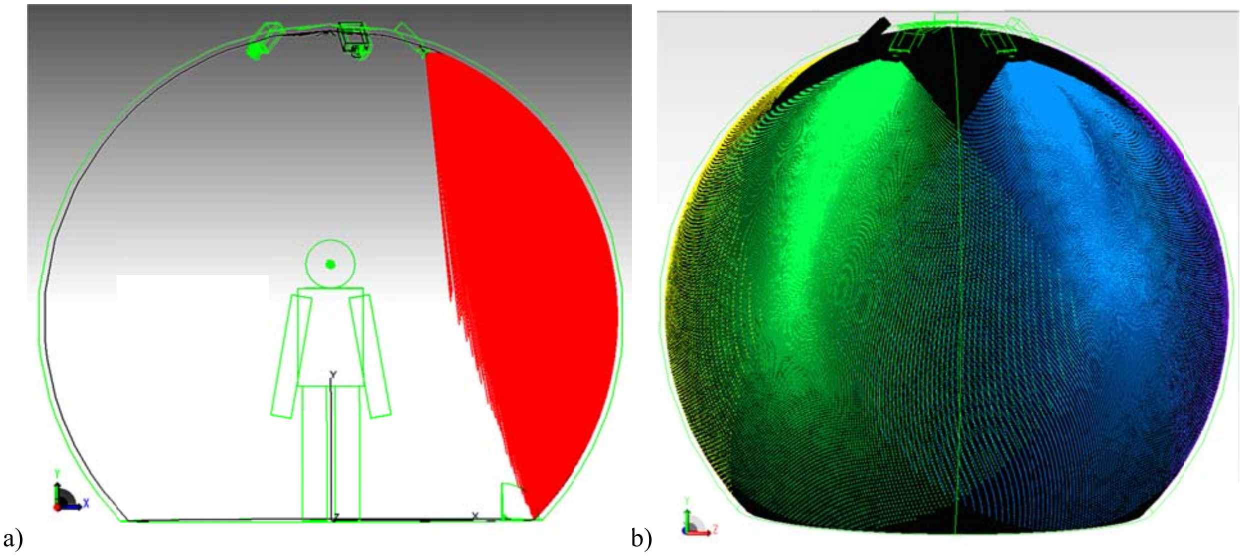
Since the notion of radially-symmetric, inward-pointing projectors was posited, tested, and confirmed to be feasible, the task of finding short-throw geometry was made much simpler. Instead of being arranged around the edge of the dome pointed inward, the STPs were arranged near the center of the dome, pointing out. This was tested at two elevations. First was a simulation run with projectors below the floor (Fig. 14).



a) b) c)

Figure 14. STP system from under dome. *Part a) shows the projector arrangement, with one active. Parts b) and c) speak to the lateral and vertical coverage, respectively. Note the fairly geometric overlap and lack of image curvature and distortion.*

However, recall that the NTPs were able to shoot a beam through cutouts in the floor because of their relatively narrow beams. Since the STP have such wide, diverging beams, the necessary areas of the floor cutouts reach prohibitively large sizes. A more feasible approach would be to hang the projectors on a support structure on the inside of the dome, near the top (Fig. 15). Though the projectors appear to be intersecting the dome, they are actually completely contained with it (projectors were tilted to more accurately portray projector image overlap).



a) b)

Figure 15. STP system from inside dome. *In this system the projectors are suspended on the inside of the dome near the top, as in a). The coverage is comparable if not more complete than the under-dome STP system, and overlap and curved distortion are also similar.*

As shown from Fig. 14 a) and 15a), a cross-section of these projection systems reveals that they too completely avoid intersecting the user and throwing shadows. In either STP system a 5’9’’ user has a 5’-5.5’ diameter circle in which they can walk without obstructing any ray’s path. This is slightly larger than the NTPSM system, which gave a walkable circle of around 4.5’. They also provide nearly equal (slightly superior) dome coverage as well as less overlap and curvature. Since the above-head STP system gave equal results without requiring extremely large floor cutouts, it was chosen as the viable STP solution.

V. Comparing Solutions

Both the NTPSM and STP projection systems show full telepresence dome coverage. To choose a solution, a close comparison is justified. *The NTPSM solution:*

- Requires no support structure, which would require drilling holes in the dome
- Houses projectors completely outside the dome, making wiring and ventilation easier

The STP solution:

- Gives slightly better dome coverage
- Is all internal, requiring no cutouts
- Gives less image overlap and distortion—easier to warp to correct later
- More walkable area for user without casting shadow
- No added convolution of sphere placement/geometry/trip hazard

While neither solution has yet been chosen, *the STP solution appears to be the more viable approach.*

VI. Future Work

1. Creating Fisheye Images

Whatever the solution and number of projectors, as well as whatever the content that is going to be projected, the pipeline of image distortion, slicing, and blending demands a consistent image input—this is commonly a fisheye image, since they contain a whole hemisphere or more of image data in one image, to be expanded later. If the video stream input is not natively in a fisheye projection, one can be created simply. *Cubemapping* is the process of taking four, five, or different planes of view of an environment (or a “cube” of images) and inflating them into a fisheye shape (Fig. 16). There are many software packages that can perform cubemapping, such as those in Unity[6], software in which many simulated dome-content environments may be created as well.

Some software, such as the Fulldome[7] plugin of Adobe After Effects, has support for images that extend past 180 degrees of altitude, or in other words, more than a hemisphere. Such software would be required for the telepresence dome as it is a sphere more complete than a hemisphere or planetarium dome—called a *hyperdome*—and any image would similarly need to also extend past a hemisphere’s data to cover it.

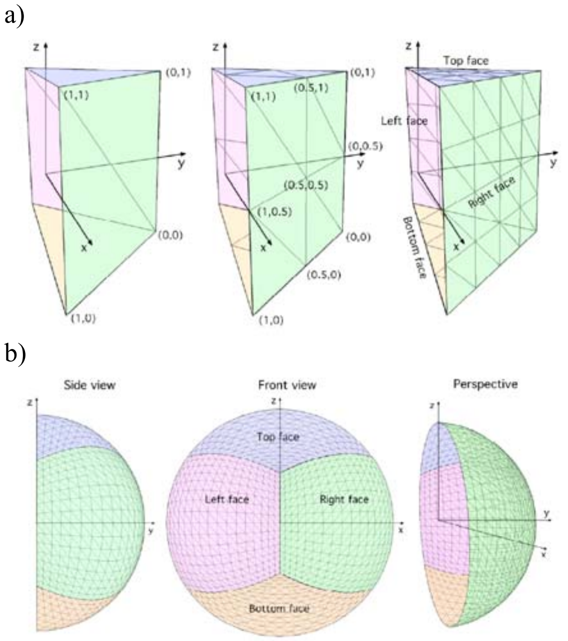


Figure 16. Cubemapping. *The top, left, right, and bottom faces of a cube in a) are inflated into the artificial fisheye image of b) using software. The transformation is relatively simple and computationally inexpensive.*

2. Image Warping

Once the input is standardized to a fisheye image, it must be warped to the specific configuration of the dome/projector solution. Since no two systems on the planet are exactly alike, each warp must be custom. Software that can aid is Paul Bourke's MeshMapper[8]. The software functions by taking in a mesh input, usually one created in a computer graphics environment such as OpenGL. Images are parametrized and each pixel is processed as a set of texture coordinates, which are preserved when the mesh is read into the software. Those coordinates are matched, and the image is effectively "wrapped" onto the mesh, providing a custom distortion; indeed, with MeshMapper any image projection can be warped into any desired shape. *Each coordinate on the mesh should also contain a variable for intensity to correct for the difference in brightness due to different light-path lengths.* All of the research concerning this software and its capabilities has been completed; the only remaining task is to get into OpenGL and actually create the warp meshes for the dome.

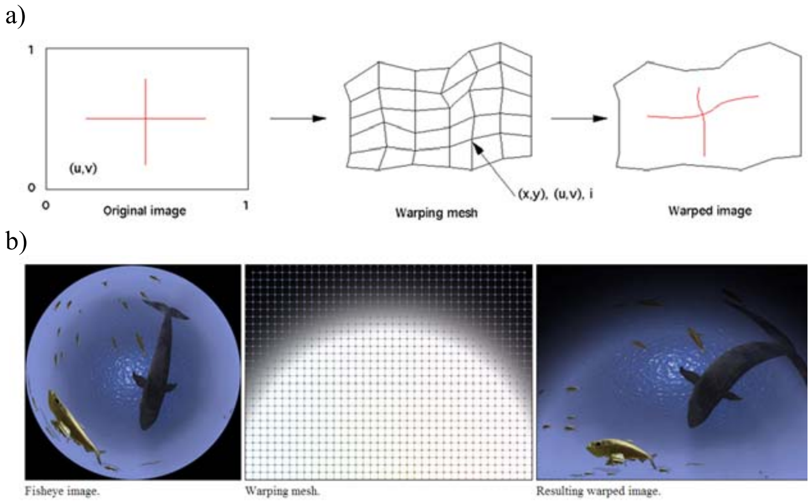


Figure 17. MeshMapper.[2] *Part a) shows how images are processed as texture coordinates and wrapped to a custom-built mesh to be warped. Part b) shows a fisheye image being warped via mesh to a projection suitable to be reflected off a spherical mirror.*

3. Image splitting

After the image is warped for the specific dome/projector geometry, the image must be chopped and fed to each of the five projectors. The exact methodology to perform such image splitting is not yet exactly known, unlike the image warping. However, initial research has shown that certain NVIDIA Graphics Processing Units (GPUs) can interact and feed graphical information to all five projectors at once, relaying that information from a master computer.

Edge blending is more of an artistic process that involves tapering the edge brightness of each overlapping projector image in order to "stitch together" a single realistic, seemingly unified image. Luckily, the supplied intensity mapping of the warp meshes will make edge blending easily, as the programmer can arbitrarily set the intensity variable of each node to a lower value along the edges of each image until the desired effect is created. This, once again, is a more artistic sort of process and will involve trial and error until a convincing edge-blending technique is created.

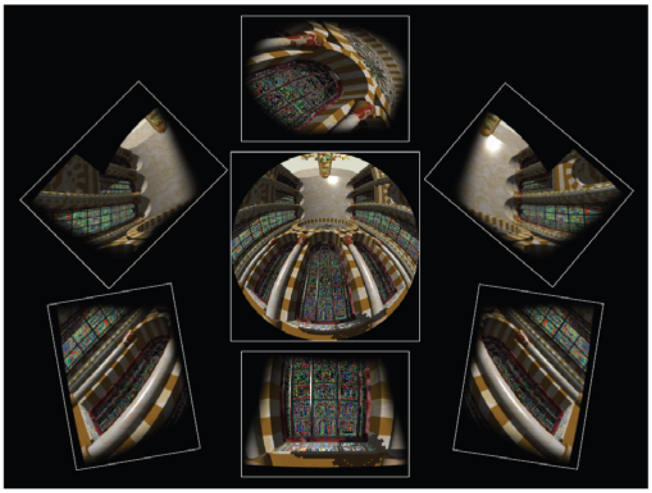


Figure 18. Image splitting. *The process of splitting an image, as shown above, is not always uniform or geometrical. Processes like edge blending are more artistic than scientific.*

4. Content Generation Pipeline

As shown in VI subsections 1-3, much of the research for the video stream post-processing has already been completed. What remains is to configure all those pieces together into one unified pipeline from raw video input to a completed, polished output on the dome walls.

Fig. 19 proposes one simple way to view the stream of connections and transformations that manipulate the video stream on its path to becoming finalized dome output. However, much of the technology has only been researched and not implemented, so much of the logistics of hardware-software interactions and transmitting data still needs to be further explored.

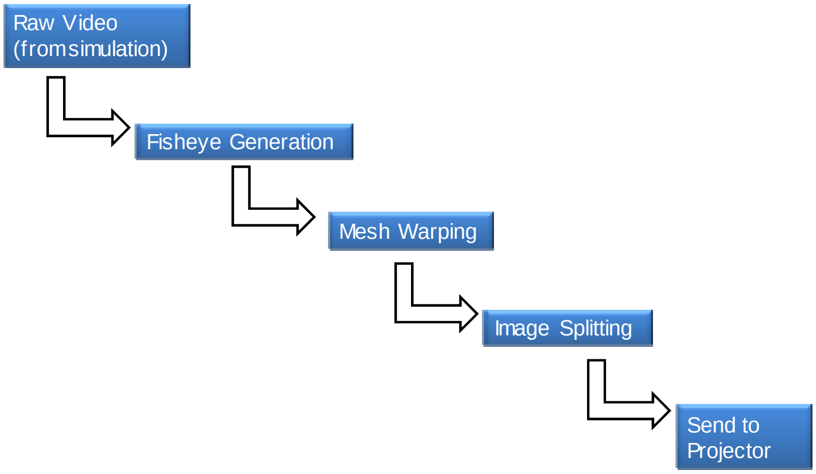


Figure 19. Proposed pipeline for content creation. *Additional research must be performed; this is only a cursory suggestion.*

VII. Conclusion

While ideating the Holodeck, engineers at NASA remained unsure as to the possibility of even attaining a full 360 degree projection system, as such ground remained unbroken and was by a wide margin more complex than existing dome visualization technology. The CAD modeling and ray-tracing simulation provided accurate representations of new and different projection strategies before any installation actually had to be done.

Furthermore, these ray-tracing simulations showed a multitude of different options for projections, leaving the F.F crew with a decision regarding their strategy. They can choose to opt for the NTPSM setup, which despite slight disadvantages such as added distortion and additional objects to consider has more support in the telepresence community. The other choice is, of course, the STP setup, which boasts an easier post-processing pipeline but has very little support as to projection on curved surfaces. This engineer notes that if ST projections onto a curved dome are only slightly different than ST projections on a flat screen (as opposed to a NT projection involving the added element of the sphere being much more complex than its flat-screen counterpart), the additional worldwide support may not be necessary to achieve stunning telepresence visualizations in the Holodeck.

According to the results of the ray-tracing analysis, *the notion of a hyperdome projector-based visualization system is indeed feasible in multiple techniques. The confirmation of such possibility allows the NASA engineers at the Flight Deck of the Future to continue in their development of sensory technologies to install and integrate into the Holodeck.*

Acknowledgments

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