

Capturing wide field of view light fields using spherical mirrors

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Abstract

This project idea is motivated from the image based lighting technique presented in the class, where a single spherical mirror is used as a light probe for image based lighting. The project used an array of spherical mirrors arranged in a fixed pattern to capture the light field of the surrounding. The main steps in the project involved construction of a spherical mirror array of a fixed pattern, taking pictures using a high resolution camera and recreating the light field by processing the data obtained using axial cone modeling.

1. Introduction

A light field can be essentially viewed as a collection of images taken from different perspectives. This idea can be used to capture a light field by using an array of cameras. However such a system would be very expensive and the field of view will be limited (if using an array of narrow FOV cameras). This project involves creating a light field from a single DSLR camera by using an array of spherical mirrors. Unlike in class, where the light field was represented using a two-plane parameterization, this project uses texture mapping to represent light fields[3]. Not only does this require a single camera, but it also has a wide FOV thanks to the spherical mirrors. This study falls under the category of Catadioptric Imaging System(CIS), which is a well studied branch in literature [4]. CIS comprises of camera systems consisting on mirrors and lenses for increasing the effective field of view. A number of studies which uses spherical mirrors used as lighting probes for image based lighting [8] or as multi-perspective cameras for triangulation and 3D reconstruction[5] [1][2] and for the construction of light fields [7] [6].

2. Mechanical Construction

The system is composed of the following components (Figure 1):

1. **Plywood base** : For providing a stable platform, with L-bracket attachments so that the foam boards containing mirrors can be propped up
2. **Spherical mirrors** : Due to the low cost and availability, I used Christmas decoration balls of different sizes for this project. The sizes considered were $5in$, $3\frac{1}{3}in$ and $2in$.
3. **Foam board** : The spherical mirrors were arranged in a square grid(2×2 , 3×3 , 5×5) in the foam board. A mounting tape was used to secure the mirrors onto the foam board. Care was taken to ensure that the spacing between adjacent spheres in minimized.
4. **Binder clip** : To attach the foam boards to the base. For additional rigidity, a wooden scale was inserted between the clips and the foam board.

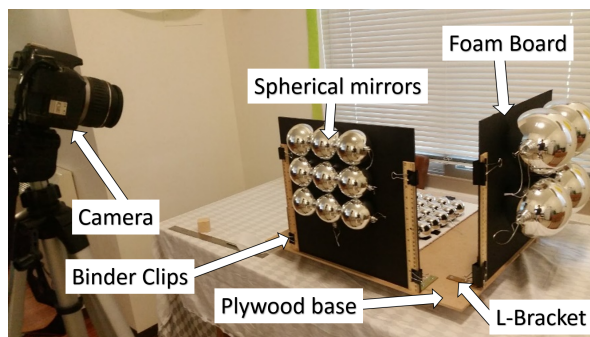


Figure 1. Parts of the system

3. Calibration

The system calibration involves identifying the exact location of the camera with respect to the spherical mirror array. It is necessary to know the distance of the camera from the center of each spherical mirror and also the pixel in the image which corresponds to the reflection of the camera itself in each spherical mirror. Although one could use an



Figure 2. Spherical mirrors arranged in grids (2in diameter spherical mirrors arranged in a 5×5 grid, $3\frac{1}{3}$ in diameter spherical mirrors arranged in 3×3 grid and 5in diameter spherical mirrors arranged in 2×2 grid)

automated image processing technique to achieve this (for example, using a checkerboard pattern or a light source attached to the periphery of the camera lens), due to lack of time and the inferior quality of the reflections from the mirrors, I chose to do this manually. The calibration proceeds as follows

1. **Manually mark camera reflections :** From the captured image manually find the reflection of the center of the camera in all the spherical mirrors. A simple MATLAB script was used that allows the user to click on such locations. Note that this step needs to be done only once per setting.
2. **Absolute position of mirrors :** Let $(p_{i,j}^{(x)}, p_{i,j}^{(y)})$ denote the normalized pixel corresponding to the spherical mirror (i, j) normalized between $(-1, 1)$ marked in the last step. Let the field of view of the camera be $(\alpha^{(x)}, \alpha^{(y)})$, then in the coordinate system centered at the camera with Z-axis pointing into the scene and X, Y in the image plane, the position vector of the center of the mirror (i, j) can be written as

$$\vec{r}_{i,j} = \lambda_{i,j} \left(\tan(\theta_{i,j}^{(x)}), \tan(\theta_{i,j}^{(y)}), 1 \right)$$

where

$$\tan(\theta_{i,j}^{(x)}) = p_{i,j}^{(x)} \tan(\alpha^{(x)}/2)$$

$$\tan(\theta_{i,j}^{(y)}) = p_{i,j}^{(y)} \tan(\alpha^{(y)}/2)$$

with unknown $\lambda_{i,j}$. In order to estimate $\lambda_{i,j}$, I solve the following optimization problem

$$\begin{aligned} & \underset{\lambda_{i,j}}{\text{minimize}} && \sum_{i_1,j_1,i_2,j_2} (|\vec{r}_{i_1,j_1} - \vec{r}_{i_2,j_2}| - \\ & && 2r(|i_1 - i_2| + |j_1 - j_2|))^2 \\ & \text{subject to} && \lambda_{i,j} \geq 0, \quad i = 1, \dots, m. \end{aligned}$$

In the above equations r is the radius of the spherical mirror. Essentially it tries to find a distance that explains the fact that the spheres are arranged in a grid.

The optimization problem was solved using *fmincon* in MATLAB. At the end of this step we know the position vectors of the centers of each spherical mirror. Moreover we can also obtain an equation for the plane containing the center of the spheres in the camera coordinates by a simple least square plane fit of the position vectors. These calibrations will be used in the light field reconstruction

4. Reconstructing light fields and Refocusing

The light fields are reconstructed using axial cone modeling introduced in Taguchi *et al.* [7], which is an accurate geometric modeling of the multi-perspective photo captured with a spherical catadioptric imaging system. The basic idea is to use multiple perspective cameras lying on an axis each with a different viewpoint and a different cone of rays. thereby avoiding geometric approximations. The light field reconstruction is done in the following steps :

1. **Projection to virtual image plane :** If we imagine a pinhole camera placed on the axis of a spherical mirror, rays at an angle θ from the axis passing through the pinhole, after reflection will intersect at a virtual viewpoint inside the mirror, subtending an angle θ_v . The locus of virtual viewpoints for a given θ is a single point on the mirror axis and can be treated as a virtual camera with a peripheral cone of rays. For each sphere, given a value of θ , the intersection of virtual image plane corresponding to θ and the mirror surface is computed, which is a circle with out of plane normal pointing along the position vector of the mirror center. This circle is projected to the image plane, resulting in an ellipse. A number of discrete pixel samples (1000) are taken along this ellipse and the resulting image (a circle of pixels) is the image as seen from the virtual camera inside the sphere. This procedure is repeated for multiple values(1000) of θ for each spherical mirror, resulting in a virtual image collection. This step is labeled in the Figure 3
2. **Projection to refocusing geometry :** In this step we can compute the light field and the refocused image by texture mapping all the virtual camera images to the desired refocusing geometry using a refocus viewpoint(Figure 3). For simplicity I have assumed that the refocusing geometry is a plane parallel to the plane of the spherical mirrors, which is a natural choice. This restriction can however be easily relaxed. The projection to the refocusing geometry is done as follows. For each virtual camera pixel, extend the ray from the virtual viewpoint along the virtual image plane and find the intersection with the refocusing geometry. The refocusing geometry is discretized into pixels, and each

valid intersecting ray's pixel is added to the pixel value. To account for finite sampling, a small random noise (inversely proportional to the sampling size) is added to the path of the light rays while performing this projection and about 10 such rays are shot from each pixel in the virtual camera to obtain a smooth image. From this we can get a light field from each mirror, which is the projection of all virtual images corresponding to that mirror onto the refocusing geometry, and the refocused image itself, which is the sum of all the Light fields.

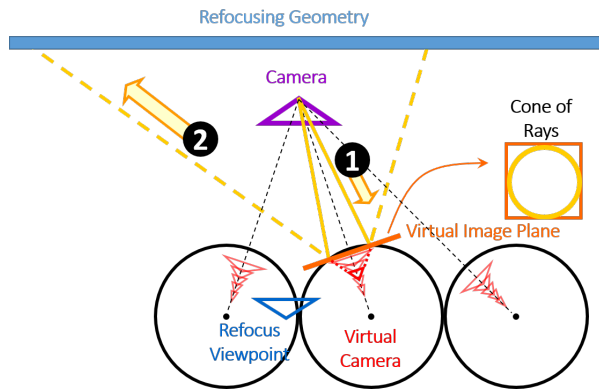


Figure 3. Schematic for axial cone modeling based on Taguchi *et al.* [7]. The steps are described in detail in Section 4

The above logic is implemented in *C++*. Figure 4-6 shows the different light fields reconstructed from the image of spherical array. Figure 7-9 shows the refocusing output using this algorithm. It is clear that the image is blurry. This is attributed primarily to the roughness of the mirror surface, so that the base image itself is blurry and all calculations are based on an infinitely smooth sphere surface. One could in theory estimate the PSF and deblur this prior to processing, however it was not attempted in this project.

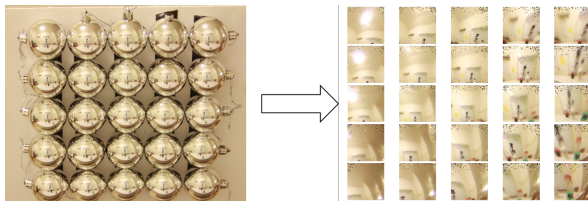


Figure 4. Light field for 5×5 grid

5. Conclusion

A wide FOV Light field was reconstructed from a single image of an array of spherical mirrors using axial-cone modeling. The scheme requires a simple calibration step.

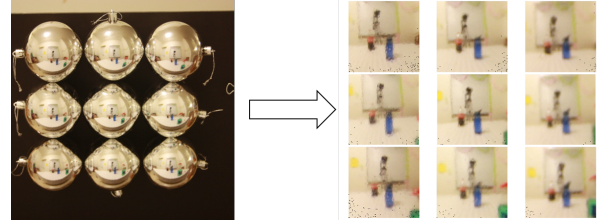


Figure 5. Light field for 3×3 grid

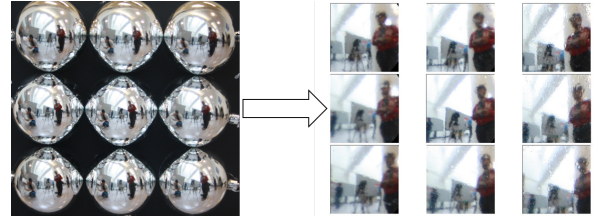


Figure 6. Light field for 3×3 grid



Figure 7. Refocusing using the 3×3 light field showing the focal plane swept from close to far as you move down in the row or across columns.



Figure 8. Focusing close from light field

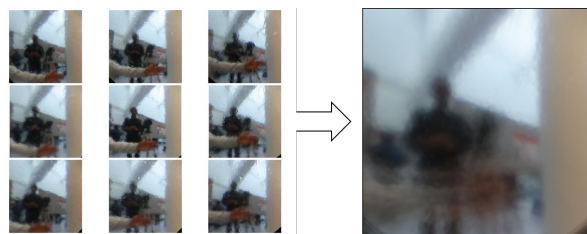


Figure 9. Focusing far from light field

Light fields were constructed for various grid sizes revealing spatio angular trade-off. The effective FOV of the light field was around 90 degrees, which is about four times the FOV of the camera used. With lower number of spheres, we get better quality image, but lesser light field samples. The sphere surfaces considered here were not smooth enough, and this surface imperfection was the bottleneck of this study, which inherently makes the image blurry. Despite a blurry image the defocus deblur was evident particularly for the 3×3 grid. Better results can be obtained by using stainless steel polished spheres.

References

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