Architectural Daylighting Validation

Bill Davey*
Rensselaer Polytechnic Institute
Computer Graphics Group
Computer Science Department

Figure 1: *Example of Un-Distorted Image*

Abstract

Accurately simulating the effects of daylighting has numerous benefits. It allows building planners to take into account how bright a room will naturally be and estimate how warm the room will get due to the daylight. A system has been created by another research group which can simulate daylighting in a digitally-designed room. The system is known as LightSolve Viewer (LSV).

This paper will present the ongoing project of validating LSV's results. This validation is completed by comparing rendered images from LSV to actual photographs of a room which LSV is attempting to model.

Keywords: validation, radiosity, image manipulation, fisheye distortion

1 Motivation

The Architectural Daylighting Simulation program LightSolve Viewer (LSV) has been working well for some time now. It has been used by RPI architecture students to test their designs and by students at MIT to determine how warm a room will get based on the effects of daylighting.

LSV has previously been compared to the Radiance [Ward 1994] rendering system [Cutler et al. 2008]. While this comparison was useful a system examining LSV's results was needed. As such, this project was created.

2 Background

Before going into further detail about the validation project it is neccessary to explain what exactly it is validating. LSV is a program which accepts a model created using the Google SketchUp [Google 2008] program. This model represents a room or floor of a building. After accepting the model, LSV will use a hybrid system involving radiosity and shadow volumes to simulate how daylight will enter the room or floor and illuminate it. There are several parameters which can be set in LSV such as the direction the room is facing, the diffuse properties of the materials, the camera properties and the exact date and time.

The model used for this validation project is based on a standard office. It has a tall south-facing window, a long desk, a circular table, a bookshelf and a file cabinet. See Figure 1 for a picture of the office the model used for this project is based on.

Once supplied with the model, date, time, material properties and camera properties LSV can create a rendering of the scene in the form of a PPM image.

This is one side of the *equation* so to speak. The other side involves actual photographs of the office shown in Figure 1. In order to capture photographs of the office a camera with a fisheye lens was mounted to one wall of the office and attached to a computer. The computer would have the camera take a photo of the office every minute between the hours of 9:00 AM and 10:00 PM. These photographs were taken at seven different exposure values and stored as PPM images. These photographs were taken every day for a six month period.

The purpose of these images is to show what the office actually looks like at any minute of the day in that six month span. These images were compared to matching renderings from LSV in order to see how accurate the program is. This is how the project will determine if LSV is validated or not.

The reason that the images were captured at seven different exposures is so that a High Dynamic Range image can be created which more accurately represents what LSV should be rendering. A High Dynamic Range image is one which has a large range of possible color intensities. So large, in fact, that modern monitors are unable to render most HDR images. However a technique known as Tone Mapping can shrink the large range of intensities allowing the images to be shown on a monitor. LSV can render the scene to any desired exposure. As such the images can be compared exposure to exposure or HDR image to HDR image.

A fisheye lens was used on the camera in order to capture the entire width of the office. However, this meant that all of the images had some fisheye distortion. A program called Ocam Calib [Scaramuzza et al. 2006] was used to remove the fisheye distortion.

Details on how the Ocam Calib program was used along with more information on how the renderings and captured images were compared will be discussed later.

3 Related Work

Several papers have been found which proved useful over the course of this project. Each paper either describes a useful technique or gives some background information which helps to better under-

*e-mail: daveyw@rpi.edu

stand the task at hand. These papers are summarized below and their individual applications in this project are also described.

3.1 Accurate Omni-Directional Camera Calibration

This paper is useful because it explains the theory behind the Ocam Calib program used in this project. The paper describes how a mathematical model can be created for a camera with a fisheye lens. The model will be able to translate points in an image captured by the camera to un-distorted locations in a new image.

The model requires a set of points to be gathered from images from the camera. The points need to be on the same plane in the 3D scene. These points are used to determine the intrinsic properties of the camera which are needed to calculate the mathematical model.

The authors of the paper developed the Ocam Calib program using the system described in the paper along with some enhancements. The program was used to remove the fisheye distortion from the raw images as will be further discussed later.

This paper was useful because it allowed for a better understanding of how the fisheye distortion was removed from the images.

3.2 High Dynamic Range Display Systems

This paper explains the main challenges in displaying an HDR image on modern monitors. The paper explains that modern monitors do not have the sufficient range of color intensities needed to render a High Dynamic Range image [Seetzen et al. 2004]. As such, images have to be scaled through a technique known as Tone Mapping which shortens the range of intensities allowing the image to be displayed.

The paper also explains two new monitor designs which could render HDR images at a much larger range then regular monitors. The first design is to combine a projector and an LCD screen to create a hybrid system with a much larger range. The LCD screen would effectively be a filter for the projector allowing the two to combine their intensity ranges into one larger range. The other design is to use small but intense LEDs in an array to generate the needed intensities.

These designs each have significant flaws. For instance the projector design has a high financial cost, a large electric cost and generates a large amount of heat. The second design avoids the electric and heating complications but is still not very financially feasible.

The main usefulness in this paper is its large amount of discussion on why displaying High Dynamic Range images is challenging. This knowledge will be useful in determining how to best compare the images from LSV and from the raw photographs.

3.3 High Dynamic Range Video

This paper was chosen because it outlines an optional extension for this project. The paper describes a system which can create a High Dynamic Range video [King et al. 2003]. This is accomplished through several steps briefly described as follows.

The system first captures raw video in a variety of exposures similar to the way the raw photographs for this project were captured. The best exposure setting for each frame is then chosen along with some neighboring exposures. The chosen exposures are used along with the other exposures to create a High Dynamic Range image for each frame. The individual exposures are weighted based on which were deemed more accurate. These HDR frames are then stitched together into a chain of images. Lastly, these images are tone mapped in order to shrink the dynamic range allowing the images to be viewed on a monitor.

The system for creating an HDR video could be used in this project to create an HDR video of a day in the office. Also, the tone mapping algorithm outlined in the paper may be useful for generating HDR images which can be viewed on a monitor.

4 The Process

This section will explain the details of the validation process. The process has involved overcoming a variety of challenges through the use of several different techniques.

4.1 Camera Calibration

As mentioned earlier the actual photographs had been taken by a camera with a fisheye lens. This meant that the images showed signs of fisheye distortion. See Figure 2 for an example of one of the phographs showing such distortion.

Figure 2: *Photograph showing fisheye distortion.*

The first step in this project was to find a way to remove the distortion. The program known as Ocam Calib [Scaramuzza et al. 2006] was used. This program is designed to determine the intrinsic properties of an omni-directional camera in order to create a function which can translate distorted points in one image into new, un-distorted locations.

In order to find the intrinsic properties of the camera Ocam Calib needed to create a mathematical model of the camera by examining images which show the distortion it creates. More specifically the program requires several pictures be taken of a checkerboard pattern using the camera. The program then needs the corners of each square of the checkerboard to be selected. The program will then use these coordinates in order to calculate the translation function.

Ten images were taken of the checkerboard, they are shown in Figure 3. In each image the corners used to determine the function are highlighted.

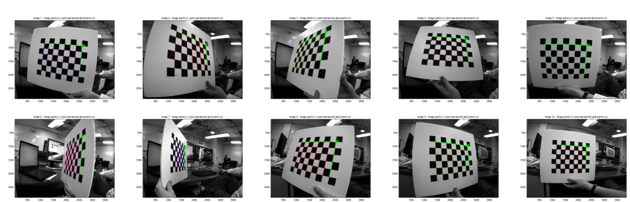

Figure 3: *Photographs used to determine the transition function.*

Once these images were captured and loaded into Ocam Calib the program created forward projection function and distance function graphs. These graphs are shown in Figure 4.

The intrinsic lens calibration results allowed us to create a tool to automate the removal of distortion from the images. We also created a tool to crop out the unnecessary data from the undistorted images. Images showing the results of using the tool to remove the fisheye distortion can be seen in Figure 5.

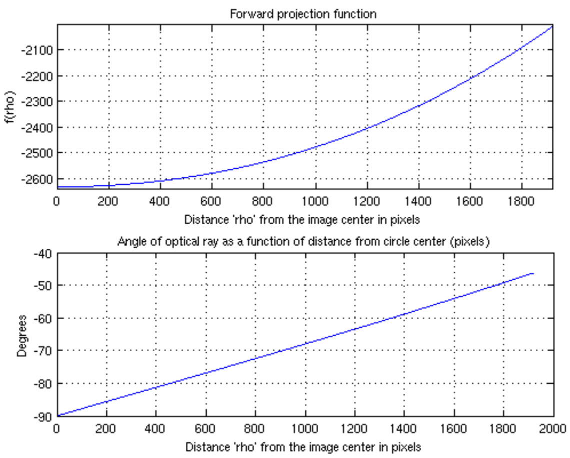

Figure 4: *Calibration Graphs.*

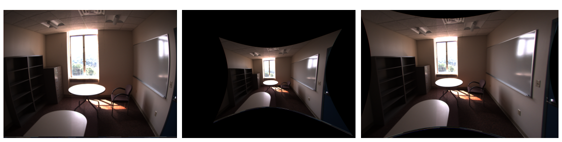

Figure 5: *From left to right: Orignal, Undistorted and Cropped photographs.*

4.2 Modeling the Office

Now that the images from the camera had been un-distorted, they were ready to be compared to renderings from LSV. As such the next step was to create the model in SketchUp [Google 2008] of the office.

Careful measurements were made of the dimensions of the office and the exact placement and orientation of the furniture and window within the office. Images of the model as seen in SketchUp are shown in Figure 6.

Figure 6: *Screenshots from the SketchUp modeling program.*

4.3 Measuring the Office Materials

In order to create a more accurate model of the office, each material in the office needed to be examined. Specifically the Diffuse Reflectancies of each surface along with the Specular Transmittance of the window needed to be measured in order to accurately simulate the scene using radiosity.

Material	Transmittance	Reflectance	Reflective Color		
Walls		76.1	205	182	157
Ceiling		80.1	211	215	203
Whiteboard		65.3	188	150	143
Door		13.1	16	22	33
Door Frame		16.1	29	30	33
Radiator		65.5	106	72	58
Window Frame		46.6	180	137	116
Floor		7.35	78	30	16
Shelves		20.8	100	77	66
Table and Desk		56.8	128	99	89
Base Trim		40.2	41	25	20
Window Glass	0.33				

Figure 7: *Real World Material Properties.*

The reflectivity of each surface was first measured with a reflectometer. Next the approximate ratio of Red to Green To Blue was found using Adobe Photoshop for each material's color. The color ratio was then adjusted to account for human's increased sensitivity to Green. Next the color ratio was combined with the reflectivity to calculate the Diffuse Reflectance value for each surface.

The specular transmittance of the window was calculated by using a Luxometer. The amount of light entering the luxometer was measured just inside the window and just outside the window. The ratio between these two readings is used as the Specular Transmittance of the window.

This portion of the project was revisited several times. The color ratios for each material were adjusted in order to better match the actual office. The changes affect more then just the base color of the materials in the scene. They define how the illumination of the room is displayed on each material. Making the diffuse settings too bright for instance causes the room to seem unnaturally bright while making them too dark causes the room to seem oddly gloomy.

These settings are also important for architects to consider. While the layout of a room can show where shadows will appear in a room, it is the colors and reflectances of the materials which show the actual look of a room. Without carefully setting these material properties an architect will not know how bright or colorful a room will be.

After several iterations of defining the material properties a final set of Diffuse Reflectances and Specular Transimttence was found. These material properties are shown in Figure 7.

4.4 Finding the Exposure Values

In order to accurately render the scene precise exposure values needed to be specified in LSV. Unfortunately the exposure values used to capture the original photographs are not known. The raw images were identified based on which of the seven exposure values was used to capture them however the actual value of the exposure was not identified. As such the correct LSV exposure values needed to be determined.

Several different techniques were tried however the one which proved most effective was a binary search program. The program would render a scene from LSV at a specific time and specific exposure. It would then examine a series of areas in the rendering and find the average greyscale color for each area. The program would then compare these averages to the average greyscale color for the corresponding areas in the undistorted photograph from the same date and time. The average difference between the greyscale values was used as the accuracy of the exposure value chosen. The program would use a binary search algorithm to find the exposure value in the range (0, 100) which results in a rendering from LSV which best matches an actual photograph.

Figure 8 shows which areas were selected in the photographs and in the rendered images. These areas were selected because they avoided the specular surfaces such as the whiteboard and the circular table. They also encapsulate a large percentage of the scene. Note that areas 4 and 8 were not used in the final version due to the chair appearing in the actual office but not in the rendered scene.

Figure 9 shows an example photograph, its best fit LSV exposure value calculated with this program and the rendering from LSV using this value. Eventually this system was adapted to create the validation portion of this project. Details of this adaptation will be discussed in the next section.

Figure 8: *Image showing the areas which were examined in the actual photographs (left) and in the rendered images (right).*

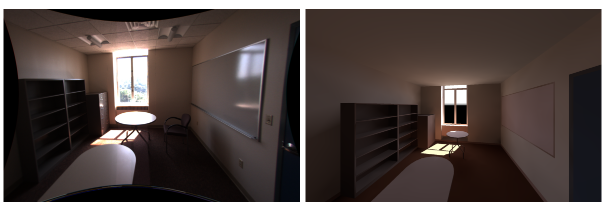

Figure 9: *Photograph from camera (left) and best-fit rendering (rigt). The exposure value chosen for this image was 1.169*

4.5 Validation

With the correct exposure values found, both sides of the equation mentioned earlier were ready. The photographs from the camera had been successfully un-distorted and LSV was prepared to accurately render the corresponding scenes. Now a system was needed to compare the photographs to the rendered scenes.

The program which found the best exposure for a given date and time was adapted to complete this task. The program would now be given a series of dates, times and exposures. The program would calculate the best LSV exposure for each day, time and camera exposure combination. Next the program would calculate the average best-fit exposure for each of the camera exposures. Finally, it would compare each of the average exposures to their corresponding best-fit exposures to calculate the percent error in the system.

More specifically, four clear sunny days were chosen along with six different times and the seven different camera exposures. This resulted in 168 different date, time and exposure combinations. The program found the best exposure for each combination and the average for each of the seven camera exposures. These seven exposures were then compared with their corresponding twenty date and time combinations to determine the percent error.

This program was by far the most time intensive portion of the project. The program was run repeatedly as the material values

Date	Average Error
08-04-2009	26.03%
09-25-2009	21.73%
10-16-2009	18.20%
01-09-2010	24.27%

Figure 10: *Average Error for each of the selected days.*

Time	Average Error
09:00 AM	52.93%
10:00 AM	26.33%
11:00 AM	16.70%
12:00 PM	16.26%
01:00 PM	12.82%
02:00 PM	11.29%

Figure 11: *Average Error for each of the selected times.*

were refined and the dates more carefully chosen. Unfortunately due to the amount of processing neccessary for each image, the program took approximately eleven hours to complete each time it was executed.

After running the program several times a very large percentage of error was reported for each exposure value. The average error was around 500%. This seemed innacurate as the renderings look very similar to the images from a visual comparison. The program was carefully examined and it was found that Dalylight Savings Time had not been handled correctly. As such the incorrect images were being compared to the renderings. Once this issue had been resolved the error was reduced to approximately 30%.

While this error value is acceptable, it still seemed innacurate. As such the data needed to be more carefully examined. First each day was examined. Figure 10 shows the average error for each of the four days chosen.

These errors were too close together to identify any obvious problems. As such another way to view the error was chosen; examining each selected time. Figure 11 shows the average error for each of the six selected times.

After reviewing this data it was discovered that there was much more error present in the earlier hours. The individual photographs for these times were reviewed and it was found that there were several clouds present in the sky on the selected sunny days but only during those early hours. After reviewing the data for 09:00 AM it was decided that the data for that time should be omitted since the sky is too cloudy at that point when compared to the rest of the times.

This time was omitted from the results and the error was recalculated. The average error for each of the camera exposures was examined and can be seen in Figure 12. The average error was reduced to 16.68%. This error is low enough to be acceptable. The sources of this error will be discussed in the next section.

Before the final conclusions were drawn for this project the best fit exposure values needed to be tested. It had been shown that the percentage error when using these exposure values is acceptably small however some visual confirmation was also needed.

High Dynamic Range images were created using the best-fit exposure values found. These images visually confirm the validity of the exposure values since they seem ”correct”. More specifically, detail in the trees can be seen through the office window along with details of the room itself. These two sets of details are not present in any of the individual exposures and as such have been composed

Camera Exposure	Best-Fit LSV Exposure	Average Error
0016	0.1005	0.0%
0031	0.1005	0.0%
0062	0.1030	3.49%
0125	2.1712	37.27%
0250	18.4780	34.95%
0500	63.5524	19.83%
1000	73.1520	21.21%

Average Error (All Exposures)
16.68%

Figure 12: *Validation Results.*

Figure 13: *HDR example, these images are the raw images used to create the HDR images shown in Figure 12.*

correctly. Figures 13 and 14 show examples of HDR images created using the best-fit exposure values found.

5 Results

After gathering the Validation Results shown in Figure 10 an analysis was done to determine what was causing the error values. Several sources were found which will be described in this section.

5.1 Finding a Clear day

After looking day by day through the six months of data it was found that *very* few of the days were clear for the entire day. It seems that Troy, NY is not exactly a sunny paradise.

Many days were bright and clear in the middle of the day but were at least partially overcast early or later in the day. This led to the error mentioned in an earlier section where a time was deemed invalid due to random patches of overcast sky.

This meant that the data available to work with was quite limited and potentially error prone.

5.2 Precise Material Properties

The material reflectancies were an approximation at best. The color ratios were gathered and estimated until they appeared correct. The carpet in the room, for instance, was troublesome since it is multicolored in the photographs but monotone in the renderings. Each slight modification to the material properties made large differences in the renderings and error values.

In addition, some material properties could not be properly rendered. For instance, the whiteboard, table and bookshelf all have some significant specular properties. These specular effects are quite prominent in the images but absent from the renderings as they are not yet supported by LSV. Due to these specular properties, the photographs will appear much brighter then the renderings when the light hits one of these specular surface.

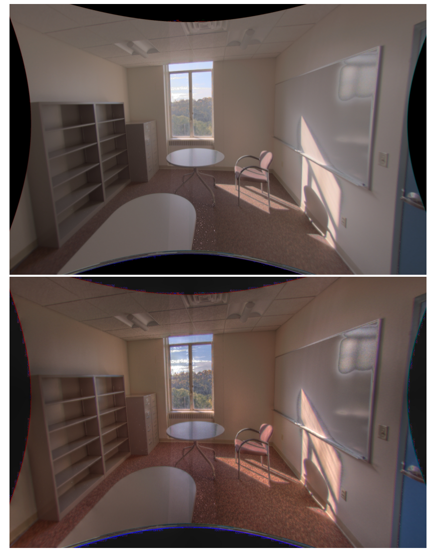

Figure 14: *Tone-Mapped HDR images using two different Tone-Mapping techniques.*

5.3 Exposure Values

Without knowing the exact exposure values used when capturing the raw images, an approximation had to be used. Hence why the best-fit program was created. This means that the project results involve more approximated data which could lead to more error.

6 Conclusion

The purpose of this project was to validate the program known as LSV. This was to be accomplished by proving that LSV could be set up to render scenes with a very good simulation of daylighting shown in several actual photographs. This was to be tested by finding an exposure value to match each of the exposure values used when taking the photographs. Renderings would be made using these exposure values in LSV and the percent error between the renderings and actual photographs would be determined.

This task was executed as designed and the resulting percentage error is low enough to be acceptable. However there is still room for improvement, for instance the sources of error discussed in the previous section could be reduced.

The result of the project at this point is that LSV has been validated however the sources of error still need to be reduced. The next section will explain where this project can go from here.

The other main purpose of this project was to gain experience with image manipulation, camera properties and tool development. This goal was certainly met. Over the course of this project dozens of small programs were created to facilitate data collection and automated processing. In addition experience with a variety of image manipulation techniques was gained such as distortion removal, sRGB conversion and HDR imaging just to name a few. This has been a very successful and productive project which will continue until the error is resolved as much as possible.

7 Future Work

Even though LSV has been validated, this project will continue. The sources of error were minimized as much as time would allow but far more work can be done to mimize them. Some possible ways to mimize the souces of error are described below though there are likely several more to be tried.

- A more careful examinination can be done of the raw images in order to pick the best possible dates and times
- The material properties can be further optimized perhaps with another search algorithm in order to best render the scene.
- The Best-Fit program can be optimized to shorten the running time allowing for faster iterations of testing.

Once the sources of error are reduced in the project it is very likely that the percentage of error will drop significantly allowing LSV to be validated more completely.

Acknowledgements

Special thaks to Professor Barbara Cutler, Yu Sheng and all of the members of the Computer Graphics Group without whom this project would not have been possible.

References

CUTLER, B., SHENG, Y., MARTIN, S., GLASER, D., AND ANDERSEN, M. 2008. Interactive selection of optimal fenestration materials for schematic architectural daylighting design. *Automation in Construction 17*, 7 (September), 809–823.

GOOGLE, 2008. SketchUp: 3D modeling software. http://www.sketchup.com.

KING, S. B., UYTTENDAELE, M., WINDER, S., AND SZELISKI, R. 2003. High dynamic range video. *ACM Transactions on Graphics 22*, 3 (July), 319–325.

SCARAMUZZA, D., MARTINELLI, A., AND SIEGWART, R. 2006. A flexible technique for accurate omnidirectional camera calibration and structure from motion. In *Proceedings of IEEE International Conference of Vision Systems (ICVS'06)*, 45. http://asl.epfl.ch/~scaramuz/research/Davide_Scaramuzza_files/Research/OcamCalib_Tutorial.htm.

SEETZEN, H., HEIDRICH, W., STUERZLINGER, W., WARD, G., WHITEHEAD, L., TRENTACOSTE, M., GHOSH, A., AND VOROZCOVS, A. 2004. High dynamic range display systems. *ACM Trans. Graph. 23*, 3, 760–768.

WARD, G. J. 1994. The radiance lighting simulation and rendering system. In *Proceedings of SIGGRAPH 94*, Computer Graphics Proceedings, Annual Conference Series, 459–472.