

# The Impact of Dense Range Data on Computer Graphics

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## Abstract

In this paper, we discuss the impact of *dense* range data of real scenes on a variety of graphics applications, where dense is defined to be at least one sample per milliradian. We have built a prototype range collection system based on a scanning laser rangefinder, and combined the range data with high-resolution panoramic color photographs to give each pixel an accurate range value. The acquisition process is repeated from multiple locations and the results are registered with software. We discuss the acquisition system and review how the data from this prototype system has been used in existing graphics projects. We speculate about future improvements and what those improvements mean to additional graphics applications. We feel that the data we are producing is just a hint of what will be available in the future and conclude with speculation about the impact of such data on graphics hardware and algorithms, since prevailing graphics hardware and software do not support this data well.

## 1. Introduction

Dense range data, where dense means at least one range sample per milliradian, has the potential to change our view of 3D computer graphics. Our particular area of interest has been in enhancing image-based rendering by providing color images of real scenes where each pixel has accurate range information. Thus, in addition to range image acquisition, we have also collected high-resolution color images from the same point-of-view, and built a prototype software system that, through a series of processing steps, builds high-resolution color photographs suitable for image warping.

The availability of range data collection has also been useful in advancing a variety of other graphics and geometry projects in our lab. For example, the collection of range data in the "Office of the Future" gives static information about the geometry of projection surfaces for immersive telecollaboration. As range image acquisition systems improve, dynamic range data will allow the collaborators to walk about, viewing the collaboration scene in true 3D.

A well-established research area is building models from range data (point clouds and range images), and we have some new algorithms that quickly consume the range data, simplifying it to only a few percent of its original complexity.

Two additional image-based rendering applications use the dense range data. The first is our multi-center-of-projection images where, potentially, each range sample is taken from a different, but known, location. This allows us to acquire data in and around an environment, substantially reducing occluded areas in a single data set, producing distorted images that are correctly reprojected.

The second is our work on Image-Based Objects. Range data of an object is acquired from several locations, the images are then registered and warped to a single point-of-view. This representation has the advantage that occluded areas are drastically reduced while preserving properties of single image warping, such as occlusion compatible ordering of rendering to preserve proper occlusion.

The final area discussed is registration of range images. We have user-assisted and automatic registration of range images. One automatic technique improves upon the iterated-closest-point method [Besl 1992] by taking into account the presence of shadows (or occlusion volumes). A separate method for exploring automatic registration looks at 3D Hough transformations of separate range images, where the high-density of our data creates unmistakable peaks for detection of large planar areas.

The hardware system we have assembled is a proof-of-concept, and as such, it allows us to speculate about the future impact of high-density range images. Current hardware and algorithms in computer graphics have not considered the existence of high-density range images, and with the growing availability of similar commercial devices, new methods of handling such data need to be considered. For instance, what can be done with 100 million color samples that have positions in three dimensions? Currently, not much more than simplification, but perhaps it is time to think about new trends in rendering hardware, rendering algorithms, model-building and illumination based on high-density color and range data.

Consider a range image acquisition system that can acquire panoramic range and color data in only a few seconds. Remote walk-throughs in real-time would be facilitated by providing an initial data set in which the viewer could walk through for a short period of time. As the viewer moves further and further from the original acquisition point, much of the scene is not possible to render, but the acquisition device could move to a new point near the viewer and reacquire range and color information. An excellent

application for this might be examination of hazardous environments where it is too dangerous (radioactive, hot or cold, toxic, lack of oxygen, etc.) to send a human.

As range imaging systems develop, we can speculate that not only will the acquisition time improve, but the accuracy as well. Current systems, ours included, yield data with only a few millimeters of RMS error or better. As the error is reduced to 0.1 or 0.01 mm, applications such as remanufacturing of components becomes viable. In fact, systems currently exist with very small scan areas that have measuring capabilities in the micron range. In these applications, associated color may not be as important.

Other industrial applications are the measurement and visualization of “as-built” environments. It is often the case that complex engineering environments, such as ships, submarines, or industrial facilities, are built with variations from the original plans. If quick acquisition and presentation of color and range data were available for such environments, subsequent renovation and improvement work could be greatly enhanced.

This paper describes our prototype range acquisition system, the calibration procedures, the specifics of the data collected, registration of multiple range images, the process of matching range data with color images, and the impact that it has had on local research projects. We conclude with goals for future acquisition systems, citing potential impact on graphics research.

## 2. Hardware System

Our prototype data collection system consists of a commercial laser rangefinder, a high-resolution digital camera, a panning unit, with a PC to control the devices and collect the color and range data. The components are each described.

### *Scanning, Laser Rangefinder*

Our rangefinder is a commercially available scanning laser rangefinder from Acuity Research [Acuity Research 1998]. It is a time-of-flight rangefinder that can acquire range data at up to 50k samples/sec. It can accurately determine range from 0 to 15 meters, having better accuracy at closer ranges.

We typically limit our sample rate to 25k samples/sec., and limit our maximum distance to 6 – 8m. These two restrictions improve the quality of the range data significantly without hampering our ability to acquire useful range data.

The scanning mirror sweeps the laser beam in a vertical plane with a 60° occlusion (aimed downward). The scanning mirror has a 2000-position shaft encoder to aid in determining where the laser is aimed.

### *Pan-Tilt Unit*

We have placed the laser rangefinder on a pan-tilt unit built by Directed Perception [Directed Perception 1998]. The rangefinder is placed on the pan-tilt unit such that the position

where the laser reflects off the scanning mirror is on the panning axis. We use only the panning operation since the laser is sweeping a vertical plane. The step size of the panning motor yields 14,000 steps in 180°, thus, to acquire samples every milliradian (or better), we typically move 3 or 4 positions between each successive scan.

### *The Color Camera*

To collect color data, we have chosen the Canon/Kodak EOS D2000 digital camera for its high resolution (1728x1152 pixels), accessibility of actual data, and FireWire communication speed. The attached lens is the Canon 14mm flat-field lens, chosen to acquire a wide field-of-view, considering that the camera’s digital CCD is smaller than 35mm film (it is the equivalent of a 24mm lens if film were used). We’re considering the 15mm fish-eye lens as a replacement, since the distortion is more predictable.

During acquisition, we disable automatic exposure and focus, setting the aperture at f/11 to get a depth-of-field from .5m to infinity, and setting the exposure time as necessary to accommodate the aperture. The fixed setting of exposure for such a wide field of view (typically 8-12 photos spaced 24° apart) often requires additional lighting to more evenly illuminate the scene.

### *The Entire Collection System*

In combination with the above hardware, we have a PC, a deep-cycle 12v marine battery and inverter all placed on a rolling cart. The system can run free of connections for about 3 hours, but we are typically indoors, thus we can not only use power, but establish a network presence as well.

## 3. Calibration

Since the system is a prototype cobbled together from many parts, substantial calibration procedures were necessary, specifically in the realm of knowing where the laser beam is actually (vs. theoretically) aiming. These include calibration of the mirror’s angle, the scanning motor’s position, and the panning device’s positioning. The camera also required calibration to determine lens distortion. Each is described.

### *Calibrating the Range*

The rangefinder is well calibrated by the manufacturer to return accurate measurements over a wide range of values (0 to 15m). Still, there are a few steps a user can take to improve the range values read. First, the rangefinder can return a more confident value if it has a longer period to make a measurement. Knowing this, we typically set the collection rate to 1/2 to 1/3 of the peak rate, and have seen dramatic improvements in the data.

The second setting that can be controlled is the maximum range value that the rangefinder will return. The rangefinder modulates the laser light to create a destructive interference pattern, so to avoid harmonics, it must look at the longest

possible distances first. If this distance is set to be shorter than the maximum, the device can settle on a modulation frequency more quickly, returning a better indication of the range.

### **Calibrating the Latitudinal Angle**

The scanning mirror controls the latitudinal angle ( $\phi$ ), and we read its position from the attached 2000-position shaft encoder. Since we are typically taking 5000 – 10,000 samples per revolution, it is clear that we must interpolate the shaft position, since several subsequent readings all report identical shaft positions.

We assume constant motor speed over the time required to collect a 1k buffer of samples (typically 1/16 – 1/25 second). To perform proper interpolation, it is important to consider sampling theory, since it is not possible to know exactly when the encoder moves from one position to the next. But in having a large number of samples, we can determine where all the transitions occur and perform a least-squares line fit using the points around the transition.

Another calibration procedure that affects the longitude is the deviation in the mirror from its supposed 45° angle. This calibration procedure was done as part of the latitude calibration, and is discussed in the next section.

### **Calibrating the Longitudinal Angle**

Determining the actual angle around the polar axis relies not only upon the panning motor position, but on the angle of the 45° mirror as well. We devised a simple experiment to determine both at the same time.

In a room, we set the pan-position to  $-90^\circ$ , aim the laser horizontally ( $\phi = 0$ ), and mark where it lands on the wall. We then move the scanning mirror over the pole  $180^\circ$ , with the laser aiming at the opposite wall, and mark that position. We then pan the device  $180^\circ$  to  $+90^\circ$ , and make similar marks. If all the hardware were perfect, the two dots on each wall would be coincident, but due to errors, they are not. From the separation of the points and knowing the distance from the rangefinder to the points, the panning error and mirror error are both determined. The values we found are 14,039 steps in  $180^\circ$ , and  $44.89^\circ$ .

## **4. Data Collected**

The range data collected consist of quad-tuples of range, longitude and latitude angles ( $\theta$  and  $\phi$ ), and the intensity of the reflected laser light. Two visualizations of the data are shown in figure 1, which are spherical images showing the range and intensity values at regular latitude-longitude positions. After the data is collected, it can be processed to correct for the calibration values found, rewriting the quad-tuples with their new values.

The color data simply consists of a panoramic set of images taken with the camera's nodal point coincident with that of the rangefinder's (a custom mounting bracket ensures this).

The camera is rotated on the same plane (using the pan-tilt unit) stopping every  $24^\circ$  to acquire a  $55^\circ \times 77^\circ$  image with our 14mm lens. This step size was chosen so that every location in the scene would be photographed twice, and as a reasonable divisor of 360.

## **5. Combining Range and Color Data**

Substantial processing is required in our current system to combine range data with color information, but the result is a color image with accurate range information for every pixel in an image.

### **Undistorting**

All camera lenses have distortions from the pinhole model they are designed to emulate. The distortions typically get worse with wide-angle lenses, as more engineering is required to ensure flat focus, even illumination, and planar projection properties. Fortunately, lens distortion is well studied, and free software exists to determine parameters that aid in undistorting an image. We acquired hundreds of photographs and performed the analysis, using the values determined to resample the images into an undistorted form. This is necessary, as the distortion from our lens placed some pixels 30 pixels away from their proper position.

### **Regularization, Error Reduction and Hole Filling**

The data from the rangefinder is not on a regular grid, as there is no control between the scanning motor and the sampling hardware. We reproject all of the range samples onto a spherical grid, apply some error removal and hole filling heuristics, and then produce a spherical image of the range and intensity values. An example is shown in figure 1.

If the laser beam spans two disparate surfaces during a sampling period, the resulting range is usually between the two surfaces (though not always). We use a voting scheme on our reprojection grid that looks the range of the 8 nearest neighbors. If at least 4 are within some tolerance, the value is deemed to be valid, otherwise it is removed. This has the effect of removing all floating samples.

Since the rangefinder's ability to determine distance depends on the amount of light reflected, we cannot acquire range information for very dark or specular objects. Objects such as glossy (or even semi-glossy) furniture, dark metal, rubber or plastic objects (wall trim, electronic equipment, plastic trim on furniture), or metallic frames and light fixtures all cause problems.

We use a variation of the Splat-Pull-Push algorithm described in [Gortler 1996] to fill in the holes. This algorithm was designed to perform well on sparse data, but also works very well on dense data like that from the laser rangefinder. We use a bilinear basis function for the interpolation. The splat portion of the algorithm performs most of the work since the samples are about as dense as the image pixels. The pull and push phases interpolate the samples to fill in places that were not scanned well by the laser. We output two images from

this process—a range image and an infrared laser intensity image. These images are used to align the color camera images with the range data.

### **Alignment**

We use image processing techniques to register each color image with the spherical range image. Simply, we want to find the orientation of the camera image that best correlates with the rangefinder image. Since we have the infrared intensity image, it would seem that we could correlate this directly with the color image (or perhaps with a grayscale representation or just the red channel of the color image). But the illumination of the two images is so different that simple image correlation gives poor results. Specifically, the laser image is illuminated directly by the laser itself. The laser image has no shadows, the entire scene is equally illuminated, and specularities occur in different places than in the normally lit scene.

Instead, we perform the alignment on the edges in the images. Edge-detection algorithms work well on the data from the laser rangefinder, but tend to show the high frequency noise in the color images. To solve this problem, we use a *variable conductance diffusion* operation [Yoo 1993] on the color images to yield edge images with only the salient edges found. The VCD operation changes the size of the gaussian depending on the coloring of the surrounding neighborhood. Edges act as insulators for the blurring operation, leading to its name. The VCD operation is applied to the original color images, and then the edge pixels are undistorted according to the distortion parameters found in the camera calibration.

Edge detection is performed on both the range and intensity images from the rangefinder. The edges in these images are then blurred by convolving them with a kernel that has wide support, but whose gradient increase near the center of the kernel. This enhances the search by giving nearby solutions a small error value, but not nearly as small as an exact solution.

The search strategy varies the three angles of registration between the spherical range image and planar color image. The error value is computed as the degree of edgeness from the rangefinder image that corresponds with the edges in the color image. This works, conceptually, by using the planar image as a stencil, where the edges are transparent, and looking for edge values in the further range image. The search strategy is similar to simulated annealing, and seems to work well when presented with a reasonable starting point.

Having found values for the 3 angles, we return to the original color images, correct for distortion, and determine the proper distance information. To do so, we project the range information onto the planar grid, making a list of range values for each pixel. Resampling range data is a difficult problem, so we perform a clustering algorithm on the range values for each pixel, choosing the range from the largest cluster. This method avoids blending samples across multiple surfaces, which is a feature we were seeking.

### **Result**

The output of this process is a variation of TIFF images with 2 additional layers. The first is a generalized disparity layer (related to inverse depth), while the second, smaller layer contains sufficient information (a 3x4 matrix) that allows the 3D positions of each pixel to be calculated. This is our standard file format for image-based warping reference data [Oliveira 1997].

## **6. Use in Graphics Projects**

This section describes how the color and range data is used in current graphics projects in our lab.

### **Image-Based Rendering**

The field of image-based rendering is new and rapidly growing. It holds the promise of realistic rendering, since the source images can be from real scenes. It may also be simpler, in some situations, to use image-based rendering as opposed to rendering conventional geometry.

The primary motivation in producing the data described here is to support our image-based rendering project, based on work described in [McMillan 1995, McMillan 1997]. Many different aspects of IBR are being studied, such as representation, reconstruction, hardware acceleration, and hybrid CG systems, but all require source images to render.

Given that we've produced the registered color and range images, we now describe a warping walk-through application that renders them with as few artifacts as possible.

If the images were rendered as triangle meshes, most of the rendered output image would be acceptable. Errors would occur at silhouettes such as table edges, doorways, and other spatial discontinuities. The improper result is the stretching of the mesh between two discontinuous surfaces, which, besides looking bad, may occlude what should be visible.

One of the first steps is to perform silhouette edge detection. While many sophisticated methods for performing this can be imagined, especially with multiple views, it turns out that simple heuristics perform nearly as well and are extremely easy to compute. One common method is to compute the dot product of the viewing ray with the normal vector of the triangles in the mesh. Silhouettes (and badly sampled surfaces) will have values close to 0, and thus the mesh can be broken at these locations.

We have developed a simple application that uses OpenGL and runs on our Onyx2 hardware as well as the custom PixelFlow hardware [Eyles 1997]. The interface allows the user to move around the environment arbitrarily, using multiple panoramic source inputs.

The effect is very real, and we've tried to convey the realism presented on a large-screen monitor with the images from a walk-through sequence shown in figure 2. The performance is near real-time, but as more panoramas are added, the expected result is slower rendering.

Optimizations have been made to improve performance by using the PixelFlow graphics hardware. For instance, it is possible to perform incremental warping calculations where the warping arithmetic that applies to groups of pixels is performed once and only the pixel-specific arithmetic is performed for every pixel.

We also developed an image tile, a subsection of the input image that has associated silhouette information. We can cull at the image tile level, providing a dramatic improvement in rendering. The rendering of an image tile is also where the incremental arithmetic is performed.

As a further extension, we have developed a new point primitive for rendering, which we call the Voronoi-region primitive. It is basically a cone-shaped point rather than a flat disc, aimed at the viewer and falling off in Z as its radius increases. When several of these primitives are displayed from a planar surface, they implicitly compute the Voronoi regions of the samples. Not only is this our best rendering method, it is also the fastest.

### ***Immersive, 3D Telecollaboration: the Office of the Future***

An immersive, telecollaboration project is underway that seeks to share workspaces by projecting images of remote locations onto nearly every surface possible [Raskar 1998]. It builds upon display ideas such as the CAVE, but enhances it by making every possible surface in an office into a projection surface, including irregular and dynamic surfaces. The ceiling of the office is populated with projectors, and cameras are strategically placed in unobtrusive locations for two-way interaction. An artist's conception of the workspace is shown in figure 3.

Currently, range information provided by the system described here could be used to provide the range of the static structures in the shared environment. This information is used to not only locate all the projection surfaces but to locate the projectors as well, so that the position of each pixel from each projector in the room can be computed.

Multiple range acquisition techniques are used in the office of the future, and it is clear that as range acquisition becomes quicker, dynamic objects such as people, computer monitors, and coffee carafes can be located properly so that proper 3D projection can be achieved. Slower but more exact ranging technologies may also be used to refine range information acquired through quicker, less exact methods (structured light, vision techniques, etc.).

### ***Image-Based Objects***

Image-based objects [Oliveira 1999] are composed of six layered-depth images [Shade 1998] of an object properly registered. An IBO can be displayed from an arbitrary viewpoint where it will be rendered correctly. Applications of image-based objects include virtual museums, web-based catalogs and computer games. They can also be composed together and still be properly rendered, and all of McMillan's

results about occlusion compatible ordering [McMillan 1997] for rendering still apply.

One benefit of image-based objects is that of bandwidth. Sending an IBO to a web-browser is not much more costly than sending an animated GIF, yet with an IBO, the user can move the viewpoint arbitrarily. Additionally, an IBO can be rendered interactively, giving the user instant feedback.

Real data for an IBO can be obtained with our system, and an example of 4 of the images and their rendering are shown in figure 4. The images shown only use the laser light, but future objects will also have color.

### ***Reconstruction of Geometry***

A fast, memory efficient, linear time algorithm that generates a manifold triangular mesh has been developed [Meenakshisundaram 1999]. It has been used on standard point cloud data sets as well as the data sets acquired by our prototype range system. The speed of the algorithm is derived from a projection-based approach used to determine the incident faces on a point.

An example of the output from this algorithm is shown in figure 5. The original input has 6.5 million samples, while the result has only ~140k points. The processing time taken to build the mesh was 88 seconds on an Oynx2.

The rendering of the reconstructed geometric model is made by applying the intensity image as a texture map onto the created triangle mesh. Despite the drastic reduction in complexity, the model retains the important features of the collected data set.

### ***Registration of Multiple Range Images***

Multiple methods exist for registering range image data. One is user-assisted, and was used for all the warped data sets described in this paper. The other two are automatic.

In the user-assisted process, the user selects points from 3 corresponding planes in each data set. The data is shown in a 3D reprojection that can be translated and rotated for easy selection of the points. Once the 3 planes are selected, the fundamental matrix can be found, with the 2 models displayed in a single coordinate system. Error metrics are given, and the process can be repeated as needed.

Other selection techniques have been suggested for plane selection, including using ordinary box, lasso, and spray paint selection methods on the 2D display of the range images. This method may be quicker, as it is simple to interact with 2D data displayed on a monitor and manipulated with a mouse.

One automatic method is called the *Empty Space Registration Method*, which is a variant of the Iterated Closest Point Algorithm. In ICP, the data being registered is assumed to be "full," that is, there are no shadows or occlusions and the data is sampled similarly in each data set. In data sets of real environments, there are bound to be occlusions, regardless of the type of range collection hardware. The empty space

registration method considers the shadow volumes as special, and when points fall in a shadow, they are treated differently than visible points. Results of the search are shown in figure 6, where 2 source views of a computer on a table are shown. The merging shows their almost-correct registration, despite the fact that very little of the scene is shared between the views.

The second automatic registration method is under development, and is based on a 3D Hough transform of the range data. In performing a standard Hough transform, there is a step for edge-detection. This step is not necessary with the rangefinder data, as the data collected represents the first "edge" in 3D (surface, really). Skipping the edge detection step, this method takes each sample and performs the standard Hough transform voting operation by incrementing all possible buckets of  $r$ ,  $\theta$ , and  $\phi$  for each sample. The high density of the range data clearly separates the planar surfaces from the incorrect guesses, providing a starting point for a plane-matching algorithm. The high density also increases the runtime significantly.

### **Multi-Center-of-Projection Images**

In their paper on Multi-Center-of-Projection images [Rademacher 1998], Rademacher and Bishop show that it is possible to correctly reconstruct images where every pixel was acquired from a different, but known, position. The advantage of MCOP images is that they are still single images, yet the path of the camera can be controlled to uncover occlusions in the scene. They simplify the collection to that of a strip camera, thus only the position of each column of pixels in an image requires pose information.

The MCOP work was the first client of the ranging system described here. We attached the UNC Hi-Ball tracking system to the rangefinder, made the acquisition software network-aware, and slowly rolled the range acquisition cart in the tracked environment.

In figure 7, we show a photo of our lab environment with the camera's path superimposed. We then show the resulting image that was collected, colored by hand to distinguish the important parts of the scene. Finally, we show the reconstructed image.

## **7. External and Future Applications of Range Data**

Our data collection system is by no means unique; at least two commercial systems exist [Cyra 1999, K2T 1999] for acquiring dense range information. Clearly, their marketing strategy is to build models that fit into existing software, but certainly, they have explored the idea of keeping the data closer to its raw form.

### **As-Built Models**

Both scanners cited have described projects to create as-built models from range data. In one, an Atlas launch tower was

scanned from several locations, all images were interregistered, and a model was produced where subsequent renovations could be applied. The areas scanned were difficult to reach, apparently, as the scanning hardware was held hundreds of feet of the ground by a crane.

Another example of acquiring as-built models is that of sets for Hollywood movies. The Cyrax scanner was used to scan a cave set from the movie "Stormship Troopers" and a tree from the set of "Jack." 3D CAD models were produced, which allowed computer graphics artists to superimpose animations in the proper locations in Stormship Troopers, while carpenters built a replica of the tree in Jack.

These examples just two of many that demonstrate that the acquisition of dense range data for computer graphics is a growing field.

### **Remanufacturing**

A range scanner from the Canadian National Research Council has a high accuracy and real-time acquisition rates device that captures range over a limited volume [Beraldin 1992]. The error in range is in 10 – 100 microns, the maximum scanning rate is 10 million samples per second, and the volume is a cube several centimeters on a side at a distance of some tens of centimeters. Still, this system is useful in that it demonstrates a manufacturing application of dense range data.

The high-accuracy of such a system makes it ideal for scanning an existing part with the goal of reproducing that part. It is a well-known problem that many mechanical systems outlive their producers, especially systems built for the military, thus there is a big need for being able to remanufacture parts as they fail.

This system allows the remanufacturing of small parts, and can also be used in conjunction with a CCM milling device to accurately place it for scanning larger parts. Advances in speed, accuracy, and range volume will only make this process faster, simpler and less costly.

### **Remote Walk-Through**

The  $K^2T$  company has demonstrated, in conjunction with the Robotics Institute at CMU, the ability to build remote walk-throughs [K2T 1999]. They scanned an abandoned research facility with their SceneModeler ranging system, collected color images, and also videotaped a helicopter fly-over of the site to reconstruct the surrounding topology. The result is a model that can be viewed from arbitrary locations. Again, the acquisition of dense range data by other researchers shows that range images are being used for important calculations.

### **3D Movies and Television**

An extremely futuristic use of dense range data is the exciting and obvious application of range images to create true 3D movies and television where a viewer could presumably assume any position desired to view the movie. This is in contrast to the so-called 3D movies that are stereo projections

that give the user a 3D view from the camera's location. This application requires real-time range acquisition as well as hardware acceleration to display the images in real-time.

In its fullest form, a viewer could walk anywhere and look in any direction, viewing a properly reconstructed scene. For sports broadcasts, the freedom of motion holds immense appeal, in that a viewer could be on the field or court with the players.

Of course, movie and television directors have made their careers choosing the best presentation for the viewers, and are bestowed with awards when they do this well. In addition, current movies show far less than a 90-degree view, thus allowing the viewer to be anywhere would require the non-set areas to be substantially reduced. A lesser form of 3D movies can be imagined might be more like viewing a play, opera or ballet performance where the viewer is the only member of the audience and is free to move anywhere, including into free space above the floor, to view the action on stage. As such, the position and gaze direction of the viewer is restrained, but allows them to move about, getting a true sense of the 3D nature of the movie.

## 8. Conclusions

We are excited about building a successful range acquisition system, and the success of our system has been shown by the desire of others to use the data in their projects. As a custom system, we are able to quickly adapt our data collection methods to that required by different projects, an advantage not found in commercial systems. We feel in our own work and in the work of others that there is a large future for dense range data.

The ability to match color data with range data has also been rewarding, if not fraught with significant processing requirements. The combined data enables realistic walk-throughs of real environments that would be far too complex (or impossible) to model. Images generated from data similar to ours are showing up in television advertisements, despite the differences in achieving color and range data.

## 9. Future Work

Our immediate goals for the future have to do with reliable automatic registration methods, and better calibration of the rangefinder system. We are also exploring the development of hardware devices that will allow the simultaneous collection of range and color data.

Our future work is narrow compared to all the work that could be done to provide better support for dense range images with color. Obviously, real-time acquisition hardware from multiple locations would increase the demand for real-time rendering, so hardware acceleration both in acquisition and rendering are important areas to explore, despite the difficulty involved. The large number of points is, in itself, a demand for faster rendering hardware. In addition, dealing with view-dependent artifacts such as specular highlights

could be explored, where some sort of interpolation could be performed to more realistically yield the artifacts. Along the same thrust, exploration of reillumination, by first removing the illumination, would allow scenes to be rendered under a variety of lighting conditions.

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