The Parabolic Multi-Mirror Camera

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Abstract

Conventional multi-view camera setups are typically bulky, difficult to handle and not affordable for the average consumer. We present a one-piece single-camera multi-mirror imaging system made of low-cost off-the-shelf components. The system is relatively easy to set up and use while producing imagery similar to the output of a conventional multi-camera array. In addition to deriving the elementary theoretical foundations of our approach, we present a working prototype and captured footage and demonstrate the practical usability of the system with results for geometry reconstruction and view interpolation applications.

1. Introduction

Multi-view imagery is useful for a wide range of applications, from 3D reconstruction over free-viewpoint video to digital refocusing. Traditionally, there are three field-tested ways to obtain multi-view footage: multiple images taken with a single camera, camera arrays, and light field cameras that employ a lenslet array and a single sensor. However, a single camera with conventional optics cannot capture multiple views of dynamic scenes simultaneously. Camera arrays, on the other hand, are not affordable for the average consumer, and synchronized capture and storage of multiple streams of data poses a challenging problem [9]. These problems become even more apparent when non-conventional imaging devices such as high-speed or infrared cameras are used. Light field cameras [6] do not suffer from these issues, but the baseline between views is limited by the size of the lenslet array, making them unsuitable for many applications unless the lenslet array is very large (and therefore costly and difficult to handle).

Since a single camera with high resolution is both cheaper and easier to handle than an array of multiple medium resolution cameras, a promising approach is to use mirrors to create several virtual cameras from a single physical camera. Compared to lenses, mirrors are inexpensive, and they are not limited in size so that arbitrary baselines can be realized. This combination of mirrors and refractive imaging elements is commonly called catadioptric imaging.

2. Related Work

Some existing approaches employ catadioptric imaging systems to capture some kind of multi-view footage. Gluckman and Nayar [2] describe the advantages of catadioptric stereo systems and present a prototype with two mirrors. A laboratory setup of Levoy et al. [4] uses an array of planar mirrors to capture sixteen views of an object, but is limited to small scenes on an optical bench. A setup by Kuthirummal and Nayar [3] uses a truncated cone mirror to capture a distorted wraparound view of a small object in addition to a conventional photograph. Finally, Reshetouski et al. [7] have developed a kaleidoscopic imaging system that captures multiple reflections of a small object surrounded by mirrors, thereby obtaining views from all sides.

The aforementioned systems are limited to small scenes, typically in a laboratory environment. The proposed parabolic multi-mirror camera, while similar in concept to the
setup of Levoy et al., extends the range of applicability of the aforementioned approaches to large outdoor scenes.

3. Hardware Setup

Our hardware setup, Figure 1 and Figure 3, consists of a commercially available satellite dish to which 31 round, planar glass mirrors are affixed. The original antenna fixture is used to fasten a conventional digital SLR camera close to the focus of the parabolic dish. Because the position of the focus is slightly off-axis, the camera itself does not obstruct its view of the scene situated behind the camera. The size of the dish allows for a baseline of about 90 cm between the most distant mirrors. In our setup, the mirror dish is captured by a full-frame digital SLR camera using a 28 mm wide-angle lens. In this configuration, the entire field of view is filled by the dish, so that no sensor resolution is wasted. Figure 2 shows a typical raw camera image taken using this setup.

Figure 3 illustrates the geometric properties of the setup. Rays from the focus of the parabola become parallel rays when they are reflected on the surface of the parabola. Since each planar mirror is a secant to the off-axis parabolic dish, its normal approximately coincides with the normal of the parabola below the center of the mirror, such that rays from the focus become approximately parallel when reflected in the center of a mirror. Because the mirrors are planar, each mirror effectively creates a virtual camera behind the dish. Although the virtual cameras are approximately parallel, their respective centers of projection do not necessarily coincide with the center of the image of the corresponding mirror, a fact that has to be taken into account during calibration of the virtual cameras.

The proposed setup is adequate for the capture of large outdoor scenes at a distance of several meters. For smaller scenes, a modified setup can be used where the positions of camera and scene are switched. The dish is then imaged through a telephoto lens that captures approximately parallel rays from the planar mirrors. This allows to capture several views of the object with large baseline and large overlap between the views similar to a multi-camera dome. An image of this setup is shown in Figure 5.

4. View Segmentation and Calibration

After an image has been captured as with a conventional camera, the individual views have to be segmented from the raw camera image. Due to perspective, the circular mirrors appear as ellipses in the photograph. These can be located automatically [11] when the distinctive color of the dish is dissimilar enough to the colors of the scene. However, since the camera is typically focused on the scene and not on the mirrors, defocus blur can make automatic detection difficult. In this case, the result of the automatic ellipse fitting is manually improved using a simple graphical user interface. Additionally, since the dish is captured using a wide-angle lens with noticeable vignetting, the intensity values are divided by $f / \sqrt{x^2 + y^2 + f^2}$, where $f$ is the focal length and $(x, y)$ are the pixel coordinates on the chip, to achieve a more even brightness distribution.

For many applications, the relative locations and orientations of the virtual cameras need to be known, and potential lens distortions have to be removed. While this is typically achieved using multiple exposures of a known calibration pattern, a simpler approach is possible when high accuracy is not required. In this case, we first detect a large number of SIFT features in the raw camera image [10]. The set of features is then split according to the mirror that the respective feature point falls into. On these feature sets, we perform sparse bundle adjustment [8] to simultaneously compute the extrinsic parameters of the virtual cameras, the intrinsic parameters of the physical camera and a sparse representation of the scene geometry. Because the feature points are given in the image coordinate system of the physical camera, the
Results

To demonstrate the practical usability of the multi-mirror camera system, we have captured a snapshot of a dynamic outdoor scene, Figure 2. Such dynamic, large-baseline footage can not easily be captured with any other method except a well-synchronized camera array. The image was segmented as described in section 4, and the virtual cameras were calibrated accordingly, generating a sparse point cloud of the scene. This point cloud was subsequently enhanced using PMVS2 [1]. The result, Figure 4, is a reasonably complete 3D reconstruction of the object of interest.

Another possible application of multi-view footage is view interpolation, for example in the context of free view-point video. To demonstrate the usability of our system in this context, we apply a recent feature-based algorithm for correspondence estimation and image interpolation [5] to our footage of another large outdoor scene, Figure 6. By exploiting the large number of intermediate views that the proposed system captures, we are able to simulate a smooth camera movement across the entire dish, Figure 7.

Conclusion

We have shown that the proposed low-cost multi-mirror camera system is able to capture multi-view footage of sufficient quality for typical applications such as 3D reconstruction and view interpolation with minimal effort and monetary expense. The design of the system is simple enough to be rebuilt without specialized tools or extensive technical knowledge.

While the characteristics of the camera system are adequate for many applications, some trade-offs have to be
resolved. As in light field cameras, there is a conflict of aims concerning the number of views versus the resolution of each individual view. Also, as the number of views increases, the field of view of the virtual cameras decreases. The distance between camera and scene controls the trade-off between a large amount of overlap between the images for a distant scene and larger parallax at the expense of reduced overlap for a close scene. While the distance to the scene can be varied flexibly at any time, we have chosen the size of the individual views to be just large enough to encompass typical subjects, such as a human actor.

One obvious limitation of the system in its current form is the circular shape of the mirrors. A redesign would probably comprise a mirror shape that produces a more conventional rectangular field of view. Additionally, using an elliptic geometry instead of a parabolic dish would allow to create larger overlap between the views but would require a custom-made support. We also aim to combine the multi-mirror dish with a high-resolution video camera to allow for the time-resolved capture of dynamic scenes, thereby exploiting the full benefits of the implicit synchronization between the views.

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References