Catadioptric Video Sensors *

Shree K. Nayar, Joshua Gluckman, Rahul Swaminathan, Simon Lok, Terry Boult[†]

Department of Computer Science
Columbia University
New York, NY 10027

Abstract

Conventional video cameras have limited fields of view which make them restrictive in a variety of applications. A catadioptric sensor uses a combination of lenses and mirrors placed in a carefully arranged configuration to capture a much wider field of view. At Columbia University, we have developed a wide range of catadioptric sensors. Some of these sensors have been designed to produce unusually large fields of view. Others have been constructed for the purpose of depth computation. All our sensors perform in real time using just a PC.

1 Catadioptric Vision Sensors

In many vision applications a large field of view is highly desirable. Examples include surveillance, teleconferencing, model acquisition for virtual reality, and autonomous navigation. A number of other applications, such as ego-motion estimation and tracking, could also benefit from enhanced fields of view. Unfortunately, conventional imaging systems are severely limited in their fields of view and so both researchers and practitioners have had to resort to using either multiple cameras or rotating cameras in order to image the entire scene of interest.

One effective way to enhance the field of view is to use mirrors in conjunction with lenses. The general approach of using mirrors in combination with conventional imaging systems is referred to as *catadioptric*[1] image formation. Several references to previous work in this area can be found in [Nayar, 1997][Baker and Nayar, 1998].

At Columbia University, we have developed an array of catadioptric video cameras with fields of view equal to, or larger than, a hemisphere [Nayar, 1997]. We have also developed a software system that is able to compute several perspective and panoramic video streams from a single omnidirectional one [Peri and Nayar, 1997]. More recently, we have derived the entire class of wide-angle imaging systems that can be constructed from a single mirror and a single lens [Baker and Nayar, 1998]. The point blur function and resolution of any such catadioptric system has also been studied [Baker and Nayar, 1998]. In addition, the use of omnidirectional cameras for egomotion estimation has been investigated [Gluckman and Nayar, 1998a].

Based on this technology, we have recently developed a variety of video and depth cameras. All of these sensors are based on catadioptrics and perform in real time. Here, we will briefly describe each of these systems.

2 Real-Time Planar Catadioptric Stereo

We have developed a compact stereo system that uses two planar mirrors and a single camera [Gluckman and Nayar, 1998b]. Catadioptric stereo has several advantages over conventional (two camera) stereo. The use of a single camera obviates synchronization issues and guarantees that the two views have the same intrinsic calibration parameters and radiometric properties (those of the camera). We have found these factors to greatly enhance the quality of stereo matching, and hence the computed depth maps. In addition, conventional methods

*This work was supported in parts by the DARPA VSAM program, DARPA/ONR MURI Grant N00014-95-1-0601, an NSF National Young Investigator Award, and a David and Lucile Packard Fellowship.

[†]Terry Boult is with the Electrical Engineering and Computer Science Department at Lehigh University.

[1]*Dioptrics* is the optics of refracting elements (lenses) whereas *catoptrics* is the optics of reflecting surfaces (mirrors). The combination of refracting and reflecting elements is therefore referred to as *catadioptrics*.

0-8186-8606-5/98 $10.00 © 1998 IEEE

for extrinsic calibration and rectification based on the fundamental matrix are easily applied to the two views embedded in each image captured by the stereo camera. We have implemented a simple stereo algorithm that produces a (320x240 pixel) depth video stream using just a PC for all computations. This system is presently being used to develop a robust depth-based man-machine interface.

3 Real-Time Panoramic Stereo

We have developed a real time stereo sensor that produces panoramic depth video [Gluckman *et al.*, 1998]. Such a sensor has several applications in video surveillance, virtual reality (games) and autonomous navigation [Nayar, 1988]. The sensor uses two omnidirectional cameras, each with a field of view that is larger than a hemisphere. Each camera includes a parabolic mirror, an objective lens, a relay lens, and a video detector. The two cameras are optically aligned so that epipolar lines are radial lines. Once the omnidirectional images are mapped to panoramas (cylinders), the epipolar lines become vertical and hence efficient to search along. With this sensor we are able to produce panoramic depth maps in real time.

4 Remote Controlled OmniRover

A remote controlled car has been mounted with an omnidirectional camera, a microphone, and speakers. Using wireless communication, this compact vehicle enables a user to visually and acoustically interact with a remote location. The user can drive the car with a joystick, using the omnidirectional video produced by the on-board camera as visual feedback. The omnidirectional data is mapped to panoramic video for ease of visual interaction. The user may also use a head-mounted display and the remote reality system developed by Terry Boult's group at Lehigh University to "look around" the remote location. The on-board microphone and speakers are used to communicate with people located in the remote location.

5 Distortion Free Wide-Angle Video

Wide angle lenses are commonly employed in security applications. However, such lenses suffer from severe radial and tangential distortions that make it hard to recognize people and objects in some parts of the image. The distortion parameters can vary substantially from one lens to the next (of the same lens model). We have developed an accurate and efficient algorithm for non-metric calibration of wide angle lenses [Swaminathan and Nayar, 1998]. Our algorithm uses images of straight lines (in the scene) and a carefully derived objective function to robustly recover the lens distortion parameters. These parameters are used to generate a look-up table that maps distorted images to pure perspective or pure panoramic ones. This permits real-time mapping of wide-angle video to distortion-free video for either human monitoring or further visual processing.

References

[Baker and Nayar, 1998] S. Baker and S.K. Nayar. A theory of catadioptric image formation. In *Proceedings of the 6th Internation Conference on Computer Vision*, Bombay, India, January 1998. IEEE Computer Society.

[Gluckman and Nayar, 1998a] J. Gluckman and S.K. Nayar. Egomotion and omnidirectional cameras. In *Proceedings of the 6th Internation Conference on Computer Vision*, Bombay, India, January 1998. IEEE Computer Society.

[Gluckman and Nayar, 1998b] J. Gluckman and S.K. Nayar. Real-time planar catadioptric stereo. In *Proceedings of the 1998 DARPA Image Understanding Workshop*, Monterey, California, November 1998. DARPA.

[Gluckman *et al.*, 1998] J. Gluckman, S.K. Nayar, and K. Thorek. Real-time omnidirectional and panoramic stereo. In *Proceedings of the 1998 DARPA Image Understanding Workshop*, Monterey, California, November 1998. DARPA.

[Nayar, 1988] S.K. Nayar. Sphereo: Recovering depth using a single camera and two specular spheres. In *Proceedings of SPIE: Optics, Illumination, and Image Sensing for Machine Vision II*, November 1988.

[Nayar, 1997] S.K. Nayar. Catadioptric omnidirectional camera. In *Proceedings of the 1997 Conference on Computer Vision and Pattern Recognition*, pages 482–488, June 1997.

[Peri and Nayar, 1997] V. Peri and S.K. Nayar. Generation of perspective and panoramic video from omnidirectional video. In *Proceedings of the 1997 DARPA Image Understanding Workshop*, New Orleans, May 1997.

[Swaminathan and Nayar, 1998] R. Swaminathan and S.K. Nayar. Non-metric calibration of wide angle lenses. In *Proceedings of the 1998 DARPA Image Understanding Workshop*, Monterey, California, November 1998. DARPA.