COVER FEATURE

Computational Cameras: Redefining the Image

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Computational cameras use unconventional optics and software to produce new forms of visual information, including wide field-of-view images, high dynamic range images, multispectral images, and depth images. Using a controllable optical system to form the image and a programmable light source as the camera's flash can further enhance the capabilities of these cameras.

The camera's evolution over the past century has been truly remarkable. Throughout this evolutionary process, however, the principle underlying the camera has remained the same—namely, the camera obscura,[1] Latin for "dark room." As Figure 1a shows, the *traditional camera* has a detector—either film or solid-state—and a lens that essentially captures the light rays that pass through its center of projection, or effective pinhole. In other words, the traditional camera performs a special and restrictive sampling of the complete set of rays, or the light field,[2] that resides in a real scene.

Computational cameras sample the light field in radically different ways to create new and useful forms of visual information. A computational camera embodies the convergence of the camera and the computer. As Figure 1b shows, it uses new optics to map rays in the light field to pixels on the detector in an unconventional fashion. For example, the computational camera assigns the yellow ray, which would travel straight through to the detector in a traditional camera, to a different pixel. In addition, it can alter the ray's brightness and spectrum before the pixel receives it, as illustrated by the change in its color from yellow to red.

In all cases, because the captured image is optically coded, interpreting it in its raw form might be difficult. However, the computational module knows everything it needs to know about the optics. Hence, it can decode the captured image to produce new types of images that could benefit a vision system—either a human observing the images or a computer that analyzes the images to interpret the scene.

COMPUTATIONAL CAMERAS

At Columbia University's Computer Vision Laboratory, we have developed several types of computational cameras. As the "Related Research" sidebar describes, several research groups around the world are working on the development of computational cameras and related technologies.

Imaging can be viewed as having several dimensions, including spatial resolution, temporal resolution, spectral resolution, field of view, dynamic range, and depth. Each of the cameras presented here can be viewed as exploring one of these dimensions.

Field of view

The first imaging dimension we will look at is field of view. Most imaging systems, both biological and artificial, are rather limited in their fields of view. They can only capture a small fraction of the complete sphere around their location in space. Clearly, if a camera could capture the complete sphere or even a hemisphere, it would profoundly impact the capability of the vision system that uses it. French philosopher Michel Foucault explored at great length the psychological implications

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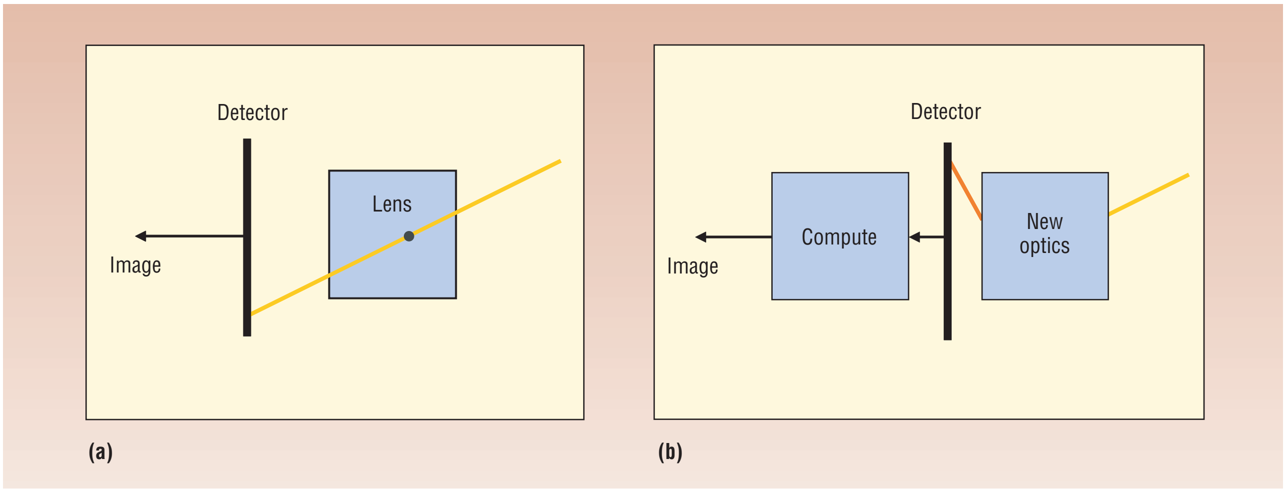

Figure 1. Traditional and computational cameras. (a) The traditional camera is based on the camera obscura principle and produces a linear perspective image. (b) A computational camera uses novel optics to capture a coded image and a computational module to decode the captured image to produce new types of visual information.

of being able to see everything at once in his discussion of the panopticon.[3]

First introduced about a century ago, the fish-eye lens[4] is a wide-angle imaging apparatus that uses meniscus (crescent-shaped) lenses to severely bend light rays into the camera—in particular, the rays that are in the periphery of the field of view. However, it is difficult to design a fish-eye lens with a field of view that is much larger than a hemisphere while maintaining high image quality. To address this limitation, we use *catadioptrics*, an approach that combines the use of lenses and mirrors. Catadioptrics has been used extensively to develop telescopes.[5] While a telescope captures a very small field of view, here we are interested in exactly the opposite: capturing an unusually large field of view.

In developing a wide-angle imaging system, ensuring that the camera captures principal rays of light that pass through a single viewpoint, or center of projection, is highly desirable. If the system meets this condition, regardless of how distorted the captured image is, software can map any part of it to a normal perspective image. For that matter, the user can emulate a rotating camera to freely explore the captured field of view. In our work, we have derived a complete class of mirror-lens combinations that capture wide-angle images while satisfying the single viewpoint constraint. This family of cameras uses ellipsoidal, hyperboloidal, or paraboloidal mirrors, some of which were implemented in the past. We have also shown that it is possible to use two mirrors to reduce the imaging system's packaging while maintaining a single viewpoint.

Related Research

Several academic and industrial research teams around the world are developing a variety of computational cameras. In addition, some well-established imaging techniques naturally fall within the definition of a computational camera. A few examples are integral imaging[1] for capturing a scene's 4D light field; coded aperture imaging[2] for enhancing an image's signal-to-noise ratio; and wavefront coded imaging[3] for increasing an imaging system's depth of field. Each of these techniques uses unconventional optics to capture a coded image of the scene, which is then computationally decoded to produce the final image. This approach is also used for medical and biological imaging, where it is referred to as *computational imaging*. Finally, significant technological advances are also being made with respect to image detectors.[4-6] In particular, several research teams are developing detectors that can perform image sensing as well as early visual processing.

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