Computational Cameras:

Approaches, Benefits and Limits

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Abstract

A computational camera uses a combination of optics and software to produce images that cannot be taken with traditional cameras. In the last decade, computational imaging has emerged as a vibrant field of research. A wide variety of computational cameras have been demonstrated - some designed to achieve new imaging functionalities, and others to reduce the complexity of traditional imaging.

In this article, we describe how computational cameras have evolved and present a taxonomy for the technical approaches they use. We explore the benefits and limits of computational imaging, and discuss how it is related to the adjacent and overlapping fields of digital imaging, computational photography and computational image sensors.

1. Evolution of the Camera Model

1.1. The Traditional Camera

Over the last century, the evolution of the camera has been truly remarkable. However, through this evolution the basic model underlying the camera has remained essentially the same, namely, the *camera obscura* (Figure 1(a)). The traditional camera has a detector and a standard lens which captures only those principal rays that pass through its center of projection, or effective pinhole, to produce the familiar linear perspective image. In other words, the traditional camera performs a very simple and restrictive sampling of the complete set of rays, or the light field, that resides in any real scene.

1.2. Computational Cameras

A computational camera (Figure 1(b)) uses a combination of novel optics and computations to produce the final image [Nayar 2006a]. The novel optics is used to map rays in the light field of the scene to pixels on the detector in some unconventional fashion. For instance, the ray shown in Figure 1(b) has been geometrically redirected by the optics to a different pixel from the one it would have arrived at in the case of a traditional camera. As illustrated by the change in color from yellow to red, the ray could also be photometrically altered by the optics. In all cases, the captured image is optically coded and may not be meaningful in its raw form. The computational module has a model of the optics, which it uses to decode the captured image to produce a new type of image that could benefit a vision system. The vision system could either be a human observing the image or a computer vision system that uses the image to interpret the scene it represents.

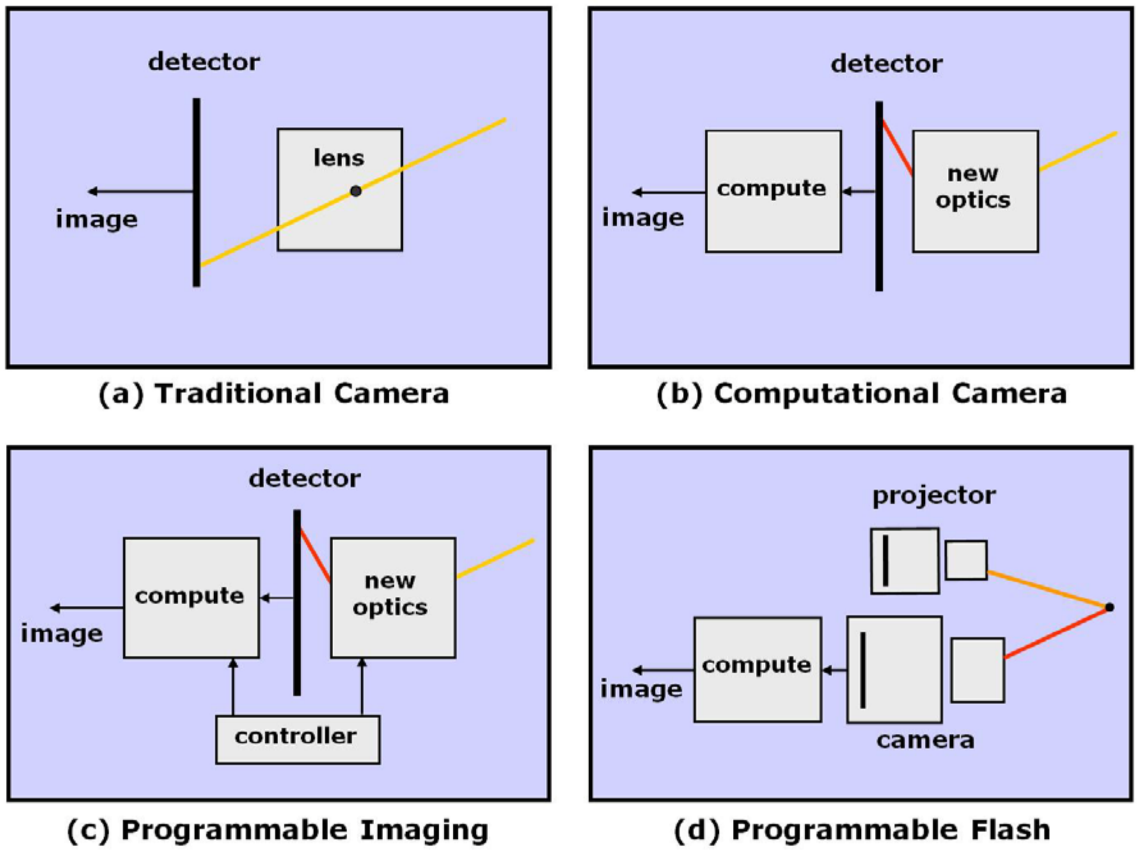


Figure 1: (a) The traditional camera model, which is based on the *camera obscura.* (b) A computational camera uses optical coding followed by computational decoding to produce new types of images. (c) A programmable imaging system is a computational camera whose optics and software can be varied/controlled. (d) The optical coding can also be done via illumination by means of a programmable flash.

1.3. Programmable Computational Cameras

Computational cameras produce images that are fundamentally different from the traditional linear perspective image. However, the hardware and software of each computational camera are typically designed to produce a particular type of image. The nature of this image cannot be altered without significant redesign of the imaging system. A programmable imaging system [Nayar 2006b] uses an optical system for forming the image that can be varied by a controller (Figure 1(c)) in terms of its radiometric and/or geometric properties (also see [Christensen 2002]). When such a change is applied to the optics, the controller also changes the decoding software in the computational module. The result is a single imaging system that can emulate the functionalities of several specialized ones. Such a flexible camera has two major benefits. First, a user is free to change the role of the camera based on his or her needs. Second, it allows us to explore the notion of a *purposive camera* that, as time progresses, automatically produces the visual information that is most pertinent to the task. In order to give its end-user true flexibility, a programmable imaging system must have an open hardware and software architecture (see [Adams 2010] for an initial step in this direction).

1.4. Programmable Illumination

The basic function of the camera flash has remained the same since it first became commercially available in the 1930s. It is used to brightly illuminate the camera's field of view during the exposure time of the image detector. It essentially serves as a point light source. Due to the significant technological advances made with respect to digital projectors, the time has arrived for the flash to play a more sophisticated role in the capture of images. The use of a projector-like source as a camera flash is powerful as it provides full brightness and color control over time of each of the 2D set of rays it emits (a projector with a finite aperture actually projects a 4D set of rays but only permits control over two of the dimensions). It enables the camera to project arbitrarily complex illumination patterns onto the scene, capture the corresponding images, and compute information regarding the scene that is not possible to obtain with the traditional flash. In this case, the complete imaging system can still be thought of as a computational camera where captured images are optically coded due to the patterned illumination of the scene (Figure 1(d)).

An array of cameras and an array of projectors can be used simultaneously to capture coded measurements of the light field of a scene. Computational decoding of such measurements can facilitate post-capture control of a variety of imaging parameters, including, viewpoint, resolution (spatial, temporal, angular and spectral), depth of field and lighting.

2. Coding Approaches

The design space for the optics of computational cameras is large. It would be desirable to have a single design methodology that produces an optimized optical system for any given set of imaging specifications. The optimization criterion could incorporate a variety of factors, including performance and complexity. At this point in time, however, such a systematic design approach does not exist. Consequently, as with traditional optics, the design of computational cameras remains part science and part art.

The coding methods used in today's computational cameras can be broadly classified into the six approaches shown in Figure 2. The first four of these can be viewed as modifications to the traditional camera model. We use examples of existing computational cameras to describe each of the six approaches. These examples are chosen mainly to convey the diversity of work in the field - they do not include all the important results in the field.

2.1. Object Side Coding

This is the most convenient way to implement a computational camera, as it only requires optics to be externally attached to a traditional camera (Figure 2(a)). Examples of this approach include catadioptric (lens + mirror) wide angle imaging [Yamazawa 1993][Chahl 1997][Baker 1999]; catadioptric [Gluckman 2002][Kuthirummal 2006], omnidirectional [Peleg 2001][Yi 2006], and biprism [Lee 1998] stereo; generalized mosaicing [Schechner 2001][Aggarwal 2001]; diffusion coding for depth estimation [Zhou 2010]; reflection/scattering separation using polarization filters [Wolff 1991][Nayar 1997][Schechner 2004]; illumination measurement using a light probe [Debevec 1998]; veiling glare removal using a structured occlusion mask [Talvala 2007]; motion deblurring using a fluttering shutter [Raskar 2006]; integral imaging using an externally attached lens or prism array [Georgiev 2006]; and multispectral imaging using an externally attached prism and occlusion mask [Du 2009].

Object side coding has also been used to develop a variety of "non-central" cameras that do not have a single effective viewpoint but rather a locus of viewpoints. In some cases, the locus of viewpoints is a necessary compromise made to achieve a particular type of image projection [Hicks 2000] [Swaminathan 2001], and in other cases it is a desirable attribute [Peleg 2001]. Non-central cameras can be represented compactly using the concept of caustics [Grossberg 2001].

2.2. Pupil Plane Coding

In this case, an optical element is placed at, or close to, the pupil plane of a traditional lens (Figure 2(b)). Examples include depth of field extension using Fresnel zone pupil masks [Indebetouw 1984], cubic phase plates [Dowski 1995], focal lattices [Levin 2009], and diffusers [Cossairt 2010]; the use of coded apertures for improved signal-to-noise ratio (SNR) [Fenimore 1978], super-resolution imaging [Neifeld 2007], compressive multispectral imaging [Brady 2006], and defocus deblurring [Zhou 2009a]; depth estimation using coded apertures [Levin 2007][Zhou 2009b], differential masks [Farid 1998], and phase plates [Greengard 2006]; aperture size control for depth from defocus [Pentland 1987][Subbarao 1995]; aperture and focus control for high resolution 3d reconstruction [Hasinoff 2009]; aperture splitting for dynamic range extension [Aggarwal 2004] and image replication [Green 2007]; the use of a spectral filter at the aperture for image matting [Bando 2008]; and the use of programmable apertures for viewpoint control and light field capture [Liang 2008].

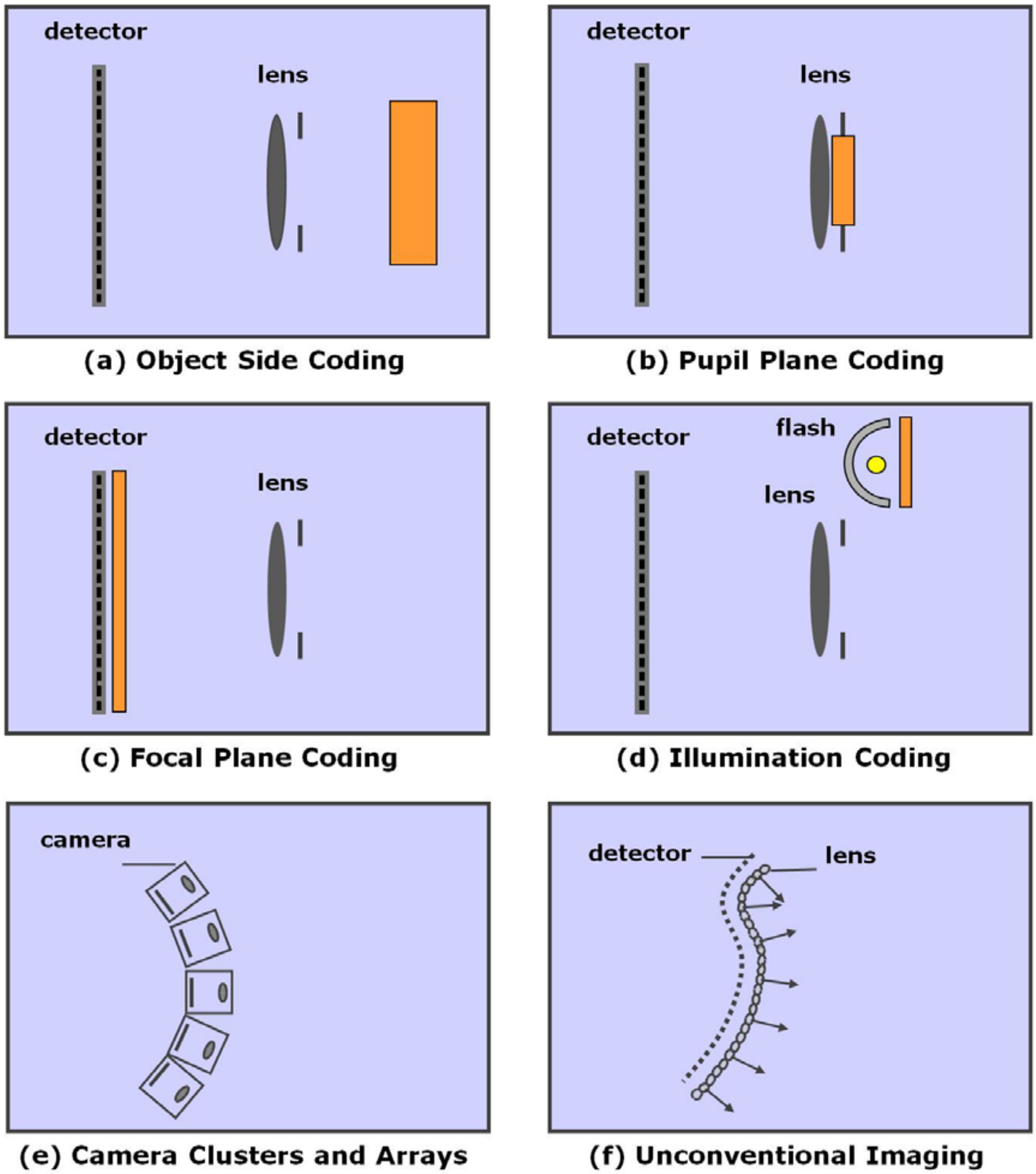


Figure 2: Optical coding approaches used in computational cameras. The first four of these are shown as modifications made to a traditional camera. (a) Object side coding, where an optical element is attached externally to a conventional lens. (b) Pupil plane coding, where an optical element is placed at, or close to, the aperture of the lens. (c) Focal plane coding, where an optical element is placed at, or close to, the detector plane. (d) Illumination coding, where coding is achieved by projecting complex illumination patterns onto the scene. (e) The imaging system is made up of a cluster or array of traditional camera modules. (f) A radically different camera design that cannot be described as a modification to a traditional camera or a collection of traditional cameras.

2.3. Focal Plane Coding

Here, an optical element is placed on, or close to, the image detector (Figure 2(c)). In this approach, we also include the use of small physical motions of the image sensor or pixel-wise control of exposure. Examples include the use of lens arrays [Adelson 1992][Naemura 2001][Ng 2005] and attenuation masks [Veeraraghavan 2007] for light field imaging; assorted pixel filters for multispectral and high dynamic range imaging [Narasimhan 2005][Yasuma 2010]; photonic crystals for multiplexed spectroscopy [Xu 2003]; sensor motion for extended depth of field imaging [Hausler 1972][Nagahara 2008], super-resolution imaging [Ben-Ezra 2005], gigapixel resolution imaging [Ben-Ezra 2010], and motion deblurring [Levin 2008]; pixel-wise exposure control for adaptive dynamic range [Nayar 2003][Gu 2010], high speed video capture [Bub 2010][Gupta 2010], skew removal [Gu 2010], and high speed imaging of periodic phenomena [Veeraraghavan 2010]. In [Horstmeyer 2009], coding is done both at the pupil plane (with a filter array) and the focal plane (with a lens array) to achieve multimodal imaging.

2.4. Illumination Coding

As mentioned earlier, by using a spatially and/or temporally controllable flash, captured images can be coded using illumination patterns. This approach enables image coding in ways that are not possible by only altering the imaging optics (Figure 2(d)). Illumination coding has a long history in the field of computer vision. Virtually any structured light method (see [Salvi 2004] for a survey) or variant of photometric stereo [Woodham 1980] is based on the notion of illumination coding.

Recent examples of illumination coding include the use of structured illumination to overcome the resolution limits of microscopy [Gustaffson 2000][Gustaffson 2005] and volume density estimation using diffuse optical tomography [Horn 1978][Lee 1995]; the use of multiplexed illumination for improving SNR in the case of weak sources [Schechner 2003], object relighting [Wenger 2005], and multispectral imaging [Park 2007]; the measurement of light transport in a scene [Seitz 2005][Sen 2005][Garg 2006][O'Toole 2010]; the separation of direct and global illumination [Nayar 2006c]; recovering depth from illumination defocus [Zhang 2006][Gupta 2009]; recovery of refractive and specular shapes by light path triangulation [Steger 2008]; measuring the depths of points outside the camera's field of view using echoes of pulsed illumination [Kirmani 2009]; image enhancement using flash and no-flash images [Petschnigg 2004][Eisemann 2004][Agrawal 2005]; depth edge measurement using multiple flashes [Raskar 2004]; BRDF invariant surface reconstruction using Helmholtz stereopsis [Zickler 2002]; estimation of specular and diffuse normals using gradient illumination [Ma 2007]; robust 3d reconstruction using space-time stereo [Zhang 2003]; and high speed 3d reconstruction using structured light [Gong 2010][Narasimhan 2008].

2.5. Camera Clusters and Arrays

A number of traditional cameras can be spatially arranged to capture different types of images (Figure 2(e)). In this case, these is no explicit optical coding involved. One can view this approach as increasing (in space and/or time) the sampling of the light field. While camera clusters seek to capture wide fields of view with minimal overlap between the fields of view of adjacent cameras, camera arrays capture multiple perspectives of the same scene with large overlap between fields of view. Outward looking camera clusters have been used for wide angle imaging [McCutchen 1991][Nalwa 1996], while inward looking clusters have been used to facilitate fly arounds [Taylor 1996]. Camera arrays have been used for multi-baseline stereo [Okutomi 1993] and virtualized reality applications [Randar 1997]; light field imaging [Levoy 1996]; synthetic aperture imaging [Levoy 2004]; spatio-temporal super-resolution [Schechtman 2005]; capture of high quality video [Wilburn 2004][Wilburn 2005]; and capture of dynamic scene collages using flexible camera arrays [Nomura 2007].

If we further relax the definition of a computational camera, we may also include methods that use camera motion to capture information from multiple viewpoints, but sequentially in time. Examples include the creation of panoramas and environment maps by stitching or mosaicing [Szeliski 1997][Peleg 1997][Rousso 1999]; all-focus and depth panoramas using a non-frontal imaging system [Krishnan 1996a][Krishnan 1996b]; stereo mosaics [Ishiguro 1992][Peleg 1999][Shum 1999] [Karmarkar 2000][Seitz 2002]; route panoramas [Zheng 1992]; pushbroom panoramas [Gupta 1997]; and multiperspective images [Seitz 2003][Zomet 2003].

2.6. Unconventional Imaging Systems

These are optical designs that cannot be easily described as modifications to, or collections of, traditional cameras (Figure 2(f)). While we have not seen many well-tested examples of such systems, one can expect novel designs in the decades to come. Examples may include flexible cameras that can be wrapped around objects or incorporated into clothing, networked dust cameras that can be scattered to produce images of volumes of space, and surfaces made of pixels that can both measure and radiate light.

Figure 3 shows a way to characterize computational cameras based on three factors: (a) the technical approach used for coding, (b) the number of images that need to be captured, and (c) the type of information produced.

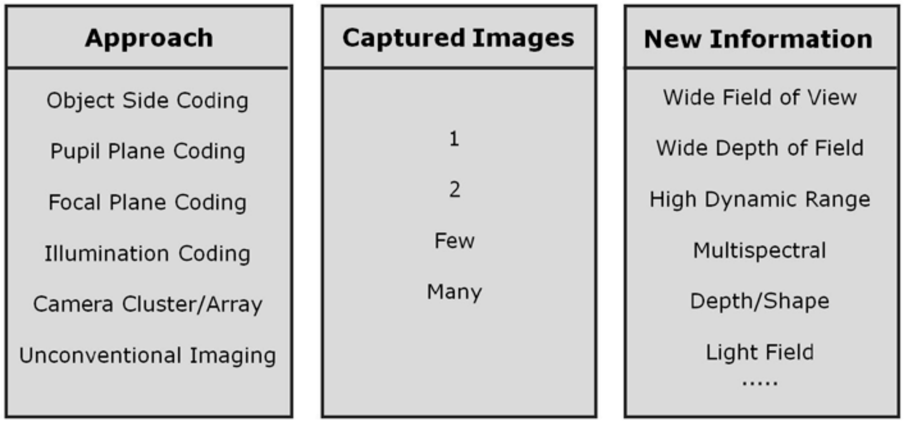


Figure 3: Computational cameras can be characterized based on the coding approach they use, the number images they need as input, and the type of information they produce.

3. Benefits of Computational Cameras

3.1. New Imaging Functionalities

One motivation for developing computational cameras is to create new imaging functionalities that would be difficult, if not impossible, to achieve using the traditional camera model. The new functionality may come in the form of images with enhanced field of view, spectral resolution, dynamic range, temporal resolution, etc. The new functionality can also manifest in terms of flexibility – the ability to manipulate the optical settings of an image (focus, depth of field, viewpoint, resolution, lighting, etc.) after the image has been captured. A few examples of new imaging functionalities that were mentioned in Section 2 are omnidirectional imaging using catadioptrics [Baker 1999]; high dynamic range imaging using assorted pixels [Narasimhan 2005]; refocusing using integral imaging [Ng 2005]; post-capture control of spatial/temporal/angular resolution [Agrawal 2010] and spectral resolution [Yasuma 2010]; and plenoptic imaging for recovering scene structure [Adelson 1992].

3.2 Improved Performance-to-Complexity Ratio

Another major benefit of computational imaging is that it enables the development of cameras with higher performance-to-complexity ratio than traditional imaging. Camera complexity has yet to be defined in concrete terms. However, one can formulate it as some function of size, weight and cost. In imaging, it is generally accepted that higher performance comes at the cost of complexity. For instance, to increase the resolution of a camera, one needs to increase the number of elements in its lens. In traditional imaging, this is the only way to combat the aberrations that limit resolution. In contrast, computational imaging allows a designer to shift complexity from hardware to computations. For instance, high image resolution can be achieved by post-processing an image captured with very simple optics. A few examples of computational imaging systems that achieve high performance-to-complexity ratio are multiplexed multispectral imaging [Brady 2009], extended depth of field using chromatic aberrations [Guichard 2009][Cossairt 2010a], and gigapixel imaging using a single optical element [Cossairt 2011].

4. Limits of Computational Cameras

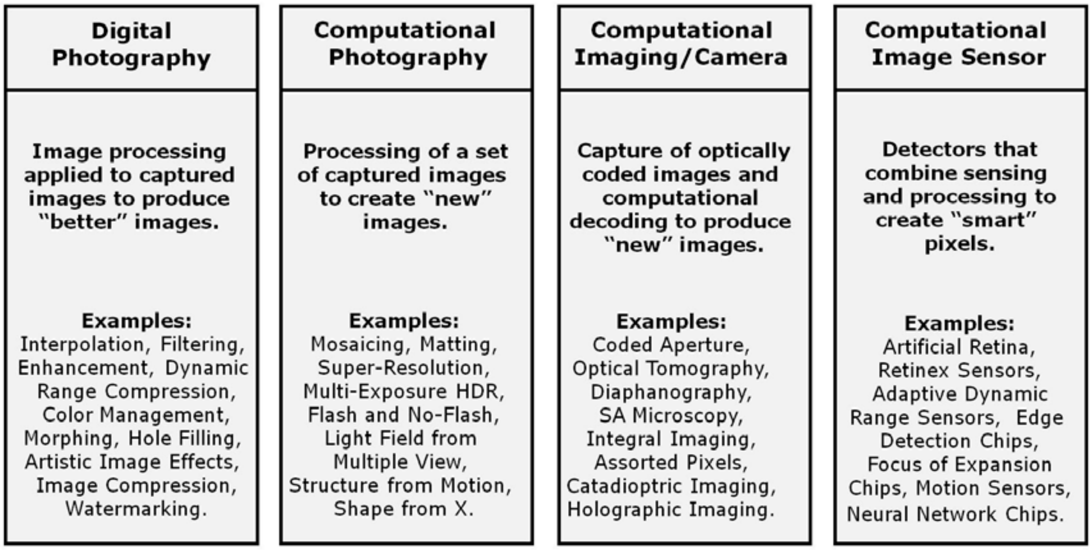
The design of computational cameras may be viewed as choosing an appropriate operating point within a high dimensional parameter space. Some of the parameters are photometric resolution, spatial resolution, temporal resolution, angular resolution, spectral resolution, field of view and F-number. The space could include additional parameters related to the "cost" of the design, such as, size, weight and expense. In general, while making a final design choice to achieve a desired functionality, one is forced to trade-off between the various parameters. In short, as with traditional imaging, there is no "free lunch" with computational cameras. For instance, in the cases of omnidirectional imaging and integral imaging, resolution is traded-off for wider field of view and viewpoint (or focus) control, respectively. Generally, the trade-off made with any given computational camera is straightforward to analyze and quantify.

While computational cameras have been shown to enable new imaging functionalities and achieve high performance-to-complexity ratios, it is not known whether computational imaging can be used to break fundamental limits of imaging. For instance, it is not clear that the hard resolution limits imposed by diffraction can be overcome using computations. This is an open question that deserves closer attention.

5. Related Fields

The development of computational cameras lies within the larger field of computational imaging. One can trace the basic philosophy underlying computational imaging all the way back to the initial work on integral imaging [Lippman 1908][Ives 1930]. While computational imaging encompasses a wide range of imaging modalities and applications, computational cameras seek to overcome the limits of the traditional camera and impact all fields that use the camera as a source of information. Examples of such fields include photography, computer vision, computer graphics, biometrics, remote sensing and robotics.

Figure 4 shows one possible way to define and relate the terms digital photography, computational photography, computational imaging/cameras and computational image sensors. The field of computational cameras naturally overlaps the areas of computational



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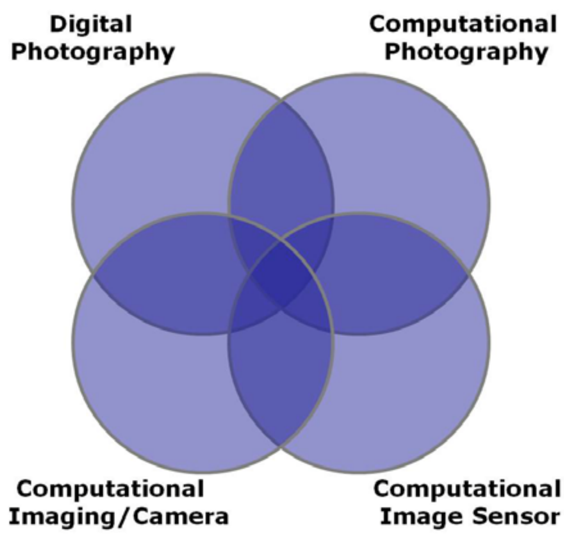

Figure 5: The four fields defined in Figure 4 are closely related to each other and overlap significantly in terms of the types of methods they encompass.

photography and computational image sensors (Figure 5). Computational photography includes the development of purely software based methods that seek to process multiple images (which could be taken with even a traditional camera) to produce a new type of image or scene representation. With respect to the computational image sensors, several research teams are developing detectors that can perform image sensing as well as early visual processing. Some early examples of this line of work are described in [Mead 1989][Wyatt 1992][Kanade 1993].

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This reference list represents a sampling of work in the area of computational cameras and is by no means a complete list.

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