Refocusing the photography industry

Two firms hope that pioneering imaging technology that lets images be refocused after having been taken will lighten up photography, as **David Appell** reports

The problem of correctly focusing on a subject when taking photographs has bedevilled photographers ever since the first photographic processes became available in the early 1800s with the then-revolutionary daguerreotype. Shooting sharp portraits with this invention, which consisted of a positive image on a silver-plated copper sheet, required subjects to place their head in a fixed iron collar to ensure immobility. Modern photography has of course moved on since then, helped in part by physicist Gabriel Lippman, who won the 1908 Nobel Prize for Physics for the invention of colour photography.

Yet, as photographers know all too well, what looks right to the eye does not always appear the same on film or screen. This is because conventional photography discards most of a scene's information and only records the summed intensity and primary-colour wavelengths of all the light striking each point of the image. Indeed, capturing all light from a particular view has been a dream of photographers for more than a century.

Now, a camera that lets users refocus pictures after they have been taken is exciting photography enthusiasts as it promises a new revolution of the kind brought about by the daguerreotype. Called a "light-field camera", it uses optical principles that are more than a century old but that have only recently been put into a hand-held package thanks to digital technology and insights into the imaging process. Blurry pictures and missed moments could well be a thing of the past.

Two companies are putting the light-field camera's capabilities into the hands of both professional and amateur photographers. Raytrix of Kiel, Germany, has been offering a light-field camera since 2010, aimed at serious photographers as well as industrial users for applications in quality control, research and development, and security and surveillance. The new entrant in the field – Lytro of Mountain View, California – has recently attracted copious attention with its announcement in October 2011 of a light-field camera aimed at mainstream consumers. Backed by $50m from the likes of venture-capital firm Andreessen Horowitz and Mike Ramsay, who co-founded the digital-video-recorder firm TiVo, Lytro even boasts physics Nobel laureate Douglas Osheroff from Stanford University as a member of its technical advisory board.

Flash in the pan? Lytro, a firm based in Mountain View, California, has released a $400 "light-field camera" that allows users to easily refocus images.

Lytro

Apart from being a boon to consumers, light-field cameras could also be used in science. Raytrix's cameras, for example, have been attached to microscopes for various biological applications such as deep-tissue focusing of tumours, and could be useful in medical situations where a single exposure must suffice or a procedure is especially invasive. Proponents also suggest that astronomers might someday be able to correct for atmospheric distortions, eliminating the real-time deformable mirrors used in modern adaptive-optics telescopes.

Apart from being a boon to consumers, light-field cameras could also be used in science

Enter the light field

The modern effort to make light-field cameras began in the 1990s when researchers in vision and computer graphics, including Edward Adelson and John Wang from the Massachusetts Institute of Technology (MIT), began to think about the total field of light emanating from an object: the wavelength, intensity and direction of every abstract light ray that passes through a space. Traditional cameras capture only a limited range of the first two parameters – namely the wavelength and intensity – of this multidimensional function, and only for an instant in time. Although an array of cameras around an object could, in principle, capture more of the light field, doing so has only become practical with digital technology.

The light-field camera is similar to a "plenoptic camera" (from the Latin *plenus* for complete or full), first designed by Adelson and Wang in 1992 and built by Adelson later that year. It builds on Adelson and fellow MIT researcher James Bergen's definition of a "plenoptic function", which provided an abstract, systematic method for extracting directional information from the light field by mathematically tracking each individual (abstract) light ray.

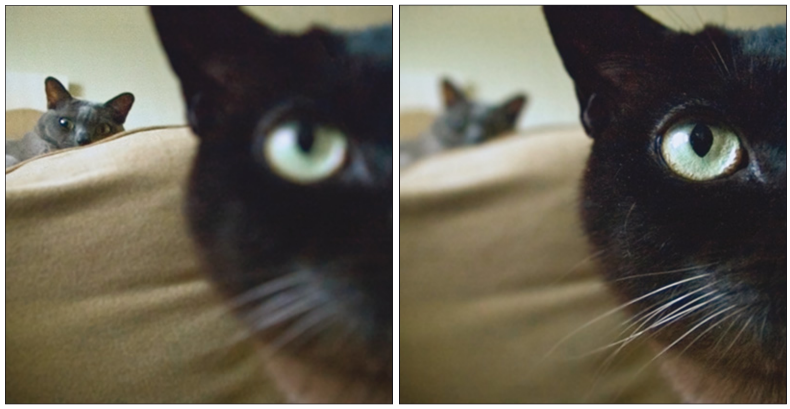
A light-field camera works by capturing the entire "light field" before it – all light rays entering the camera's aperture. Here "light ray" means all photons from a given angle – not only the light intensity as a function of wavelength but also where it lands on the aperture inside the initial lens and the photosensor. These additional data allow a complete reconstruction of the photographed scene, which lets the spot be refocused afterwards using software or changed at will. The processing even allows all different areas of a picture to be in focus, regardless of their depth in the field.

Adelson and Wang's design involved focusing light from a 50 mm main lens (taken from a single-lens reflex camera) onto an array of small, individual microlenses, which then are focused onto a photosensor. Knowing the positions of the main lens and the microlens array, and the known distance between the array and photosensor, it is possible to determine which direction the light rays that produce an image came from. To get a high-resolution image, however, the distance between the microlens and photosensor needs to be tens of microns, but it is difficult for the microlens to focus at this length. Adelson built the first plenoptic camera by putting additional lenses in the system to combat this effect, but it was too large to ever be made portable.

Then in 2005 a team of engineers at Stanford University led by Marc Levoy shrunk this system, eliminating the need for the extra lenses by finding a way to put the photosensor exactly at the focal plane of the microlenses. Ren Ng, a PhD student in Stanford's computer-science department, used this principle to build a prototype light-field camera in an existing digital camera body. Ng's prototype is the basis for Lytro's recently introduced consumer camera.

Although Lytro has been extremely tight-lipped about its technology or plans, Ng's PhD thesis lays out the prototype's design. In his graduate work, Ng used a Kodak colour photosensor with 4096 × 4096 pixels – each 9.25 μm wide. The microlens array was 500 μm in front of the photosensor's surface and consisted of 296 × 296 square-shaped lenslets, each 125 μm wide. As the focal length of each lenslet is then 500 μm, the lenslets have an *f*-number – a measure of the focal length divided by the "effective" aperture diameter – of *f*/4, which is typical of many cameras. Beneath each lenslet was a 12 × 12 array of pixels, meaning the camera collected 144 times the information of a conventional camera – this extra information being the "secret ingredient". (Conventional digital cameras waste a large amount of sensor capability – even sensors of more than 2 megapixels offer very little improvement on standard prints.) Whereas conventional digital cameras use photosensors with about 10 megapixels, photosensors for light-field cameras need to be as large as 100 megapixels to exploit the extra information in the light field. Although such chips are possible with today's technology, they have not – until now – been in high demand.

Once the light-field photograph is taken, software can then refocus a picture. Computations create a 2D photograph by projecting the 4D space of light rays (two dimensions on the aperture lens plane and two dimensions on the film plane), with the projection direction determined by the depth of focus. This is what allows users to refocus the image after it has been taken, which can be done by brute force computation or more elegantly by the "Fourier slice theorem" as explained by Ng in his thesis.



Lytro

Coming into focus The photograph as taken (left) results in an out-of-focus image of the cat in the foreground, but with just a click on the cat, the image refocuses to produce a much sharper picture (right).

The biggest challenge in creating the camera was miniaturizing the light-field technology

"Living pictures"

The Lytro consumer camera is surprisingly small and extremely simple to use, with only a button for power and another for the shutter. Its "living pictures" can be viewed, and focused, on the camera's touchscreen, or on any computer, since each picture file carries a copy of the software that allows the image to be refocused. The camera comes in two sizes: 8 GB and 16 GB, holding 350 and 750 pictures, respectively, priced at $399 and $499. For now Lytro is only selling them in the US.

Raytrix's camera, like Lytro's, comes in a simple package, but instead requires a connection to a PC or laptop to do the post-shot processing. It is also more expensive – Raytrix's lowest price camera is currently €1490. "We concentrate on the people who really want to make money using our camera," says Raytrix's chief executive Lennart Wietzke. A computer scientist by training, he co-founded Raytrix in 2009 with camera engineer Christian Perwass, having spent the 2000s developing image-processing software for a light-field camera's picture files, to be run on a PC. He adds that business is "very good, because of the light-field hype" associated with Lytro's new product.

"The biggest challenge in creating the camera was miniaturizing the light-field technology," says Ng, who founded Lytro in 2006 and is its chief executive. But picture resolution is something Lytro has been unwilling to specify, saying only that it consists of "11 Megarays", without defining this new unit. It is not obvious if Lytro processes its images in the spatial domain or the Fourier domain. "I wouldn't assume either one," says Levoy, Ng's PhD supervisor, who is still at Stanford but is also a technical advisor to Lytro. Raytrix computes its images in the spatial domain for patent reasons.

Lytro's picture resolution is not, however, good enough for its images to be printed. As US nature photographer Jason Bradley, who has been testing the new cameras for the firm, puts it, the images are "not something you could put on a wall". Lytro is therefore aiming for the huge market of consumers who view and share pictures online via social media: *Facebook* users now upload about 250 million pictures a day, and Loren Appin, director of marketing for the photo-aggregation company Pixable, estimates that *Facebook* has more than 150 billion pictures on its servers.

However, Appin is unsure about the utility of light-field pictures for online social media. "Social photosharing is more about communicating or sharing an event, emotion or thought than making sure the photo is focused on the correct part of the shot," he says. "In my opinion, it is not a technology that will seem to have an immediate direct impact on social photosharing." But photographers see a new world opening up before them – one they are anxious to explore. "I didn't get it at first," says Bradley, "not until I played with the camera. It's a different type of photography – a different way of telling a story."

As with all new technologies, unanticipated applications for light-field cameras may emerge as the concept spreads. Future possibilities include flash-free photography in low-light conditions, digital correction of aberrations, automatic focusing on all faces in a picture and light-field videography. "I am certain that once it is in the hands of creative photographers, its advantages will multiply rapidly," says Osheroff, who knows Ng from his student days at Stanford. "Suffice to say that the light-field camera represents a remarkable leap forward in technology."