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Title On Light-field Cameras using the Example of Lytro Illum
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Abstract

Light-field or plenoptic cameras are able to capture the direction of light in addition to the position and intensity at the image sensor. The additional angular information of light rays allows changing the focus after image acquisition and even altering the depth of field during post-processing becomes possible. We present a comprehensive summary of the "light-field photography technique" as well as the currently available technology and consider the market potential. Finally, we conclude with a recommendation regarding the establishment of an MPEG standardization group.

1 Introduction

Light-field or plenoptic cameras are able to store the entire light-field of a scene. Based on the theoretical work of the French physicist Gabriel Lippmann from 1908 [1], they capture the direction of light in addition to the intensity for each image pixel position [2]. In contrast to conventional cameras, additional micro lenses on top of the sensor plane are used to separately store each light ray with the information captured by different pixels (Fig. 1, [3]). As a consequence, the effective resolution of a digital camera sensor (e.g. CMOS) is drastically reduced, i.e. a camera which stores 40 Megarays is able to generate images with 4 Megapixels.

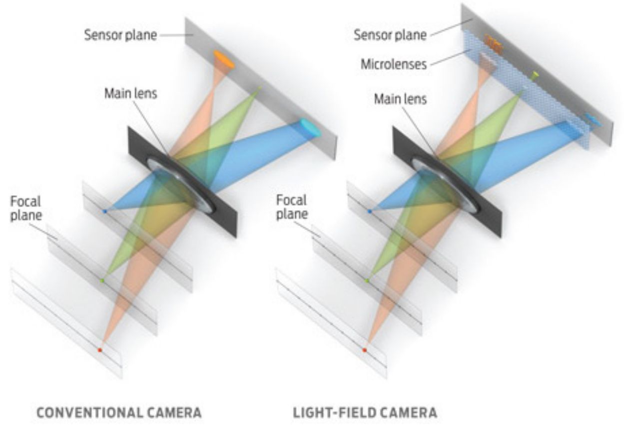

Figure 1: Basic principle of a light-field camera (Illustration by Emily Cooper [3]).

Figure 2: Lytro Illum light-field camera [4].

Light-field cameras got in the focus of commercial development in the last ten years. Consumer products like the *Lytro Illum* (Fig. 2, [4]) or the *Raytrix R11* [5] have been entering the market within the last five years and became affordable for end users with the intention to broadly revolutionize photography.

Based on the example of the Lytro Illum we performed a short field test. With respect to possible application scenarios and by considering the market potential, we give a final recommendation regarding possible standardization activities.

2 Example of Lytro Illum

As one of the leading commercial products, we investigated an *Illum Light Field Camera* which is manufactured by the company *Lytro*. We list the most important technical specifications first before we give an impression of the usability and finally conclude our findings.

2.1 Specifications of the Lytro Illum

The most important specifications (as provided by the manufacturer [4]) are listed below.

Light Focal Length	9.5 – 77.8 mm (30 – 250 mm equivalent)
Crop Factor	3.19
Lens Aperture	Constant *f/*2.0
Sensor	Light-field sensor based on CMOS technology
Macro	Focus to 0 mm from lens front (macro ratio 1:3)
Light Field Resolution	40 Megarays
Effective Resolution (2D still image export)	4 Megapixel (2450 x 1634 pixels)
Aspect Ratio	3:2
Sensor Format	1/1.2’’
Active Area	(10.82 x 7.52) mm^2
Shutter Type	Focal Plane
Shortest Shutter Speed	1/4000 s
Longest Shutter Speed	32 s
Continuous Drive (Shutter)	3 fps
ISO Range	80 – 3200
Focus Modes	Auto-focus Region AF
Touchscreen	Capacitive Multi-touch
Viewfinder	No
Life View	Yes (4’’ LCD, 480x800)
Recommended Retail Price	1299 USD

2.2 Usability Test

For gaining hands on experience and showing the potential of the light-field photography, we took several test images for different common scenes with the Lytro Illum. For post-processing we used the *Lytro Desktop* software (v4.2.1, build 150408.64, © 2015) as provided on the Lytro homepage on a Windows 8 platform. From the “raw” files (*.lfr format, approx. 53–103 MB each), we exported different output formats:

- JPEG images with different focus planes (Figures 1 to 3)
- Depth map (.png file format with .tiff original image and .txt support file) (Figure 4)
- Movie animations with sweeping focus (.mp4 video format)

Example images and a corresponding depth map are shown in the Figures 1–4:

Figure 1: Re-focussing of a scene with three target focus planes (front, middle, back).

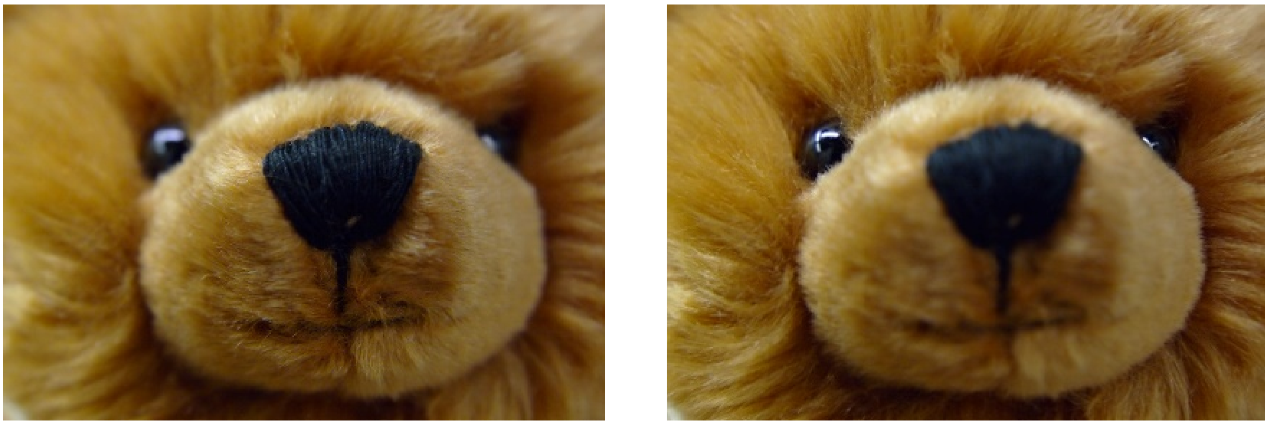

Figure 2: Re-focussing of portrait scene.

Figure 3: Re-focussing of outdoor scene and conversion to full depth of field (right).

Figure 4: Depth image and corresponding scene.

Figure 1 shows the example of a scene with three target focus planes. The distance between the test objects (trolls) is approximately 30 cm and the distance between the first object and the camera is also about 30 cm. Re-focussing either the green or the yellow troll is possible (Fig. 1, left and middle). However, focussing the red troll does not work perfectly (Fig. 1, right) because the object is close to the border of the re-focussing area, which leads to a not perfectly sharp result.

Figure 2 shows an example of a portrait scene. It was taken from about 10 cm distance (camera to the front of the bear). The Lytro Illum light-field camera allows to re-focus the eye (Fig. 2, left) or the nose respectively (Fig. 2, right) with a distance of 3 cm between them. Focussing the mouth does not differ from the nose although they are not located in the same focal plane (depth difference about 0.5 cm).

In Figure 3 the results of an outdoor scene with larger distances is shown. The distance between the camera and rock in the front was about 1 m and the depth of the scene is about 7 m. Re-focussing in the near field is possible at different focal planes located about 20 – 30 cm from each other (bumps on the front rock) or for the full depth of field (Fig. 3, right).

Figure 4 gives an impression of the depth map generated by the Lytro Desktop software and shows its limited accuracy. While the depth map of the right troll is highly accurate, the discrimination between the left and the middle troll is rather imprecise, e.g. at the hand of the red troll. The limited accuracy might affect Computer Vision tasks relying on this depth map.

Summarizing we experienced the following advantages and disadvantages of the Lytro Illum.

- Advantages:
  - Focus adjustment possible directly on camera (in post-processing)
  - Aperture ratio selection possible (in post-processing)
  - “Calibrated” depth image and 3D output formats available

- Disadvantages:
  - Rough focus preselection necessary before image acquisition in order to be able to re-focus image (not as easy as claimed by manufacturer)
  - Limited competition for post-processing solutions (e.g. Adobe Lightroom) due to proprietary file format, i.e image viewing, editing, exporting and publishing only possible with proprietary software provided by Lytro for selected Windows and Mac OS
  - Depth image accuracy limited (from Lytro software)

2.3 Limitations of the Current Light Field Technology

Image acquisition does not differ much from usual digital cameras. Nevertheless, without any experience it is rather challenging to find the right camera settings for a particular scene. Although Lytro provides several features for estimating the depth of field to be captured, these estimates tend to be inaccurate, especially for scenes with more than two distinct focus planes. Therefore at the moment it is not possible to re-focus to arbitrary focal planes.

One question that arose during the field test is, if light-field photography is able to replace common photography or like stereo video will become “only” an additional feature.

2.4 Conclusions of the Field Test

Even though the usability, image quality and resolution still needs some improvements, the Lytro Illum shows the potential of the light-field technology. Assuming that all the teething problems can be solved, there is a tremendous potential for wider use in all kinds of consumer and professional applications.

3 Application Scenarios

Our field test shows that light-field photography offers new possibilities for artistic or documentary still image acquisition and is already usable in non-laboratory environments. There are additional application scenarios which could benefit from this technology which are listed in the following.

3.1 Extension for Video

At the moment the continuous shutter drive for "high resolution video" is limited to 3 frames per second (fps) for the Lytro Illum or 10 fps for the Raytrix R11, respectively. It is expected that the series image rate can be highly increased for one of the next generations of (consumer) light-field cameras. Thus, the generation of light-field videos becomes realistic. Within the scope of a still image format standardization, the extension to light-field videos should be considered as well.

3.1.1 Movie and Commercial Production

There is an increasing integration of Digital Single Lens Reflection (DSLR) camera movies in the professional movie and commercial production. Therefore (consumer) light-field video cameras may also become of interest for stereo movie and commercial production ("3D cinema") as a low-cost alternative for professional stereo systems.

3.1.2 Teleconferencing

Taking into account the availability of affordable virtual reality systems (e.g. provided by smartphone based solutions like the Google card board), virtual reality teleconferences may become possible/accepted in near future. In this scenario image acquisition could be assisted by light-field video cameras (e.g. light-field webcams).

3.2 Computer Vision

From the image acquisition process with light-field cameras itself, depth information is available. This depth map can be exported to an editable depth map using the Lytro Desktop software. The information gained can be used for Computer Vision applications like 3D scene reconstruction or enhanced face detection which incorporates 3D information.

3.3 Professional Photographer Applications

For professional photographers the change of focus or the change of the depth of field in the post-processing provides additional possibilities.

- The principal character of an image can be changed afterwards. For instance, the development of several still images with different focus settings from one light-field photograph might be of interest, e.g. for photojournalism or wedding photographers.
- By changing the aperture in the post-processing, the same light-field photograph may be utilized for different purposes, e.g. one artistic and one commercial still image can be developed from only one image shot.

3.4 *Amateur Photographer Applications*

For amateur applications the correction of focus errors in the post-processing might be of high interest. Many pictures are captured as commemorative photographs and thus are taken without accurate image composition, e.g. holiday photographs, snapshots taken with compact cameras or smartphones and common “party pictures”. Current consumer cameras try to assist the user with automatic scene detection for aperture, focus, shutter and ISO setting selection. For those scenarios, sophisticated light-field cameras could be beneficial, providing more flexibility for corrections in the post-processing.

4 Conclusion and Recommendation

The light-field photography technique offers several interesting possibilities for still image photographs. In contrast to common photography, the focus as well as the aperture (i.e. the depth of field) can be altered for light-field photographs in the post-processing. Additionally, a calibrated depth map is provided by the desktop software. This enables a variety of Computer Vision applications (e.g. scene reconstruction, face recognition). Although the replacement of common photography by light-field photography is not expected, improvements in terms of the (effective) image resolution and usability of light-field cameras could speed up the market penetration in the near future. Progresses in CMOS technology and optics might enable the future integration of light-field cameras even in small devices like webcams, compact cameras or smartphones.

Nowadays proprietary solutions are used for saving the raw light-field data resulting in incompatible formats between different manufacturers and non-standard data compression methods. This obstructs data exchange and endangers long-term availability of decoder software. Consequently, it is advisable to create an MPEG standard for the output format of light-field photographs. We strongly advise to consider also an extension for light-field videos.

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