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The Suitability of Lightfield Camera Depth Maps for Coordinate Measurement Applications

Shreedhar Rangappa, Mitul Tailor, Jon Petzing, Peter Kinnell, Michael Jackson
EPSRC Centre for Innovative Manufacturing in Intelligent Automation
Loughborough University, UK
S.Rangappa@lboro.ac.uk

ABSTRACT

Plenoptic cameras can capture 3D information in one exposure without the need for structured illumination, allowing grey scale depth maps of the captured image to be created. The Lytro, a consumer grade plenoptic camera, provides a cost effective method of measuring depth of multiple objects under controlled lighting conditions. In this research, camera control variables, environmental sensitivity, image distortion characteristics, and the effective working range of two Lytro first generation cameras were evaluated. In addition, a calibration process has been created, for the Lytro cameras, to deliver three dimensional output depth maps represented in SI units (metre). The novel results show depth accuracy and repeatability of +10.0 mm to -20.0 mm, and 0.5 mm respectively. For the lateral X and Y coordinates, the accuracy was +1.56 μm to -2.59 μm and the repeatability was 0.25 μm .

Keywords: Machine vision, lightfield camera, depth map, plenoptic camera.

1. INTRODUCTION

3D vision cameras are finding many applications in robotics and manufacturing, and new camera technologies are constantly being developed. Recently, lightfield or plenoptic cameras have been gaining popularity as devices that can produce additional Z coordinate data when compared to normal cameras which record X and Y coordinate data. In lightfield cameras, a microlens array is placed in between the lens and the imaging sensor, each small micro lens system is of shorter focal length compared to the focal length of main lens, which acts as multiplicity of individual cameras capturing angular data of light rays [1]. This technique was initiated by Lippmann with his findings related to integral photography [2]. This was further developed to parallax stereograms by Ives [2, 3], continued to plenoptic camera by Adelson [2, 4] and hand-held plenoptic cameras by Ren Ng [1, 2, and 5].

Lytro and Raytrix are well known commercial manufacturers producing microlens based lightfield cameras. The Raytrix cameras are more industrially orientated, whereas the Lytro cameras are significantly low cost consumer grade products. Both of these cameras have the capability of generating depth information of the scene with a single operation. The Raytrix devices use three different focal length microlens groups embedded in a single microlens array and allows for a degree of image triangulation [6], but Lytro cameras use single focal length microlens arrays [7] and generate grey scale depth values which are not in SI units. Recently, significant research has been completed and published describing different numerical methods to improve the quality of depth maps obtained by lightfield cameras. These have clearly shown that with the use of advanced algorithms and imaging manipulation techniques, better quality depth maps can be generated. Further work has also compared depth estimation techniques with Lytro camera generated depth maps [8-12]. In this research reported here, we have explored the ability of Lytro first generation camera to measure 3D depth space.

2. EXPERIMENTS TO ASSESS LYTRO CAMERA CAPABILITY

During initial experimentation measuring depths of objects placed at different distances from the cameras, it was identified that depth map generation primarily depends on external factors such as lighting conditions, object colour, size and distance from the camera. It has been observed that a Lytro camera has different response characteristics to colours, especially combinations of colours with high-low contrast. This response is demonstrated in Figure 1a, where the camera generated depth map for black and white region of a checker board being defined at different depths. Similar results can be seen with the RGB checker board image (Figure 1b), where the blue and green coloured areas are shown at

different depths when compared with red alone. But when using similar or uniform colour objects as shown in Figure1c and Figure1d, the camera can distinguish between several similar plastic bricks (Lego™ bricks), and each brick is represented with different depth values (dark and white region in depth map represents near and far regions respectively). This behavior potentially makes it interesting to explore for technical applications.

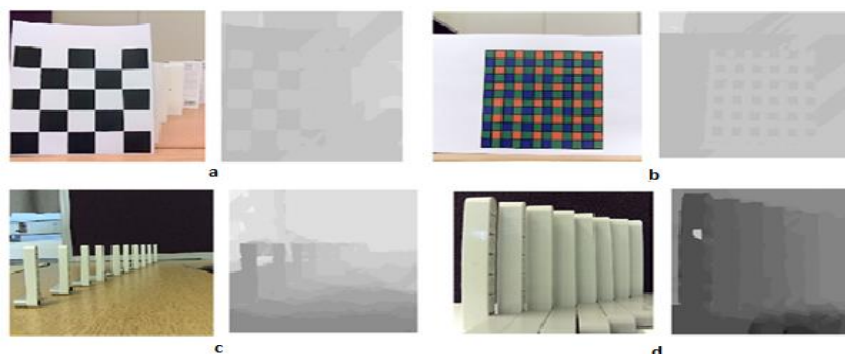


Figure 1: Raw images and corresponding depth maps

Figure1 illustrates the potential effects of external factors (object color and distance from camera) on depth values. However, the depth values remain consistent when images are taken with constant lightning conditions at a fixed distance from the camera. This provides potential evidence for repeatability, which is a basic requirement of many metrology instruments.

Analysis of existing work related to Lytro generated depth maps, identified that very little research has been published concerning matching or comparing depth values obtained from these light field cameras, or with different imaging pipelines to match with real world distances and coordinates. As a consequence, this research has specifically considered identifying if a working measurement volume can be defined in SI units for a Lytro camera, with initial statements of accuracy and repeatability.

3. CALIBRATION EXPERIMENTS

3.1 Calibration of depth map

Experiments were conducted in a stable laboratory environment under controlled lighting and temperature conditions. The main theme of the work was to measure distance related depth values which range from 0 to 255 for 8 bit depth map data. The camera was located in the same position and orientation, for all change of object distance. The accurate positional information of distance between the camera and object was recorded using a motorized positional encoder unit (accuracy of $\pm 10 \mu\text{m}$). A uniform diffuse lighting system was used to avoid directional and specular light. In this experiment the camera image plane and the object plane were set to be parallel with respect to each other, in order to obtain uniform depth value for any given distance from camera.

Two Lytro cameras, with slight differences with respect to microlens array alignment to image sensor, were used in the experimentation to determine imaging sensor response of both cameras to changing distances. Camera-1 microlens array was found to be rotated by 0.35° whilst Camera-2 microlens array was rotated by -0.5° to the respective image arrays. All other features on these two cameras were set to be automatic mode, with shutter speed, ISO and neutral density filter values noted as being 1/40 of a second, 400, and -0.4 respectively, at 120 mm object distance from the camera. All experiments were carried out, one camera at a time, by varying only the object distance from camera whilst all other factors (lightning and object) remained constant. For each positional value of the object, five images were acquired with subsequent processing of the average depth value being completed using the Lytro desktop software tool and Matlab R2014a. The cameras were treated as 'Black-box' depth sensors, as such, the working principles of the camera were not analysed in detail.

3.1.1 Experiment-1 with light intensity of 1400 cd

Relationship between real world measurements to Lytro grey scale 8 bit defined depth values are represented in the Figure 2. The depth results are not linear, but can be seen that map exponentially varies to distance and reach

constant value at approximately 280 mm object distance. The initial measurements for close range depth detection is very limited because 0 mm is represented by 0 grey scale depth value and rapidly increases to 85 grey scale depth value for 10 mm measurement on both cameras. Similarly depth values after 280 mm in both cameras reach an “Inactive zone (IAZ)” whereby many hundreds of millimetres will be compressed into a narrow range of grey scale values. Key points are the starting point of maximum depth value after which large distances are compressed within few depth values (Figure 2). Also, 70 mm to 280 mm is considered as “Active Zone (AZ)” as depth values and distance varies linearly, which is good for measurements.

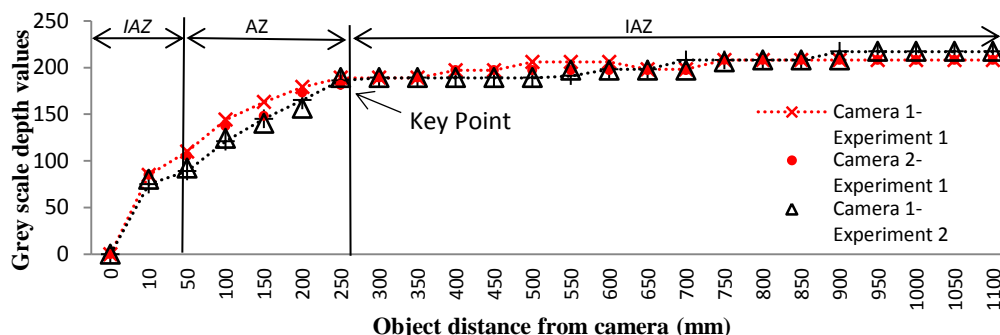


Figure 2: Lytro response curve of Camera-I & Camera-II for 1400 cd and 1600 cd

3.1.2 Experiment-2 with light intensity of 1600 cd

With changed light intensity from 1400 cd to 1600 cd, an experiment was conducted to access behavioral changes of Lytro camera to changing lighting conditions, which was similar to Experiment-1. From the Figure 2, it can be seen that response curve for changed lighting intensity for both camera has same exponential response. Again the regions are categorised as Active Region (70 mm -280 mm) and Inactive Region (0 mm -70 mm and 280 mm -1250 mm).

3.2 Experiment-3 with changed light intensity (920 cd), light sources and direction

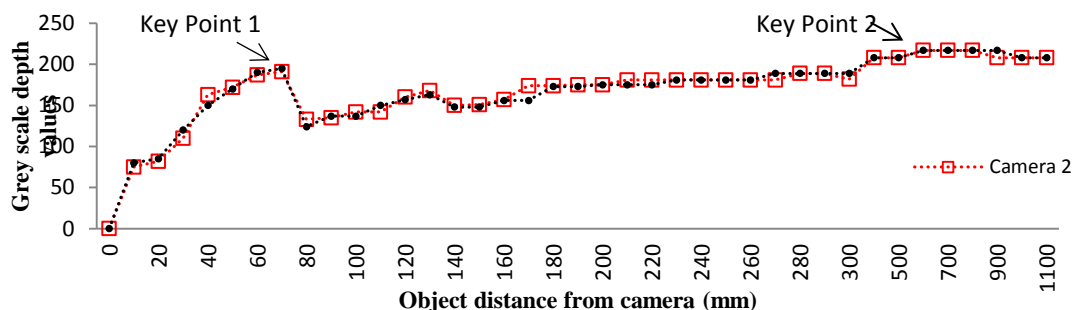


Figure 3: Lytro response curve of Camera-I & Camera-II with changed light intensity

A separate experiment was carried out to understand the effect of directional light source on depth values generated from a Lytro camera and the response is illustrated in the Figure 3. The response curve clearly indicates exponential behavior once again but with two key points at distance 70 mm and 700 mm, when compared to single key point points in other two experiments. In Experiments 1 and 2 light was uniformly distributed where as in Experiment 3, light source was split into two and object was illuminated from top and no other light illuminated object surface.

3.3 Experiment to measure pixel resolution

For complete 3D analysis of an object or scene, it is important to measure Z coordinates (depth) as well as X and Y coordinates. In machine vision, it is important to calculate the size of an object by counting the number of pixels accommodated in the region of interest (ROI) and hence pixel resolution. For such calculations the final image from the camera should be free from unwanted distortions and blur free. Radial distortion will reduce accuracy of any measurement application using camera by disrupting final image by Barrel distortion or Pincushion distortion or Mustache distortion effects. Also, blur causes problems in identifying the exact number of pixels in the ROI.

One of the advantages of using the Lytro camera is that, it generates grey scale depth map as well as all-in-focus RGB image of scene. With the help of all-in-focus image it is possible to obtain blur free RGB image and measure size of objects. Both Lytro first gen cameras used in this experiment suffer from radial distortion, hence distortion coefficients were found using Matlab software. A regular pattern checkerboard was used as an object to measure pixel resolution of the cameras. Raw images of the checker board were taken at different distances, ranging from 0 m to 1 m with an increment of 50 mm in steps, using both Lytro cameras. Pixel resolution was measured after applying correction factor to the raw images. Figure 4 represents Pixel resolution of Lytro cameras to distance (mm).

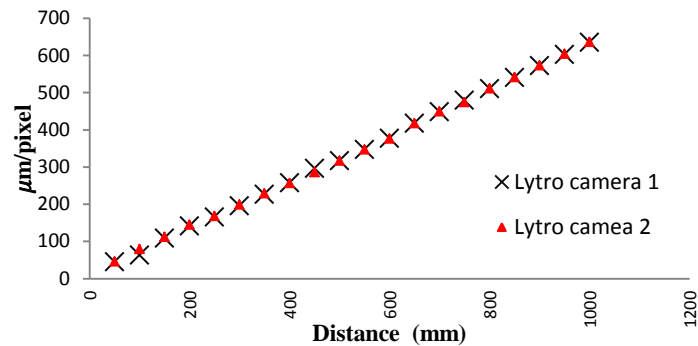


Figure 4: Pixel resolution of Lytro first Gen cameras

3.4 Measurement verification

Test were conducted to verify the 3D measuring capability of Lytro camera by measuring depth value of randomly placed square objects with in active zone of individual camera. Depth values in SI units were generated by comparing depth values generated by cameras with response curve data and hence matching up pixel resolution data with depth values to developing complete 3D analysis of the objects in scene. Figure 5 show the error (%) in measuring depth for both cameras used in Experiment 1 and 2. While, Figure 6 represent error (%) in measuring lateral X and Y coordinates.

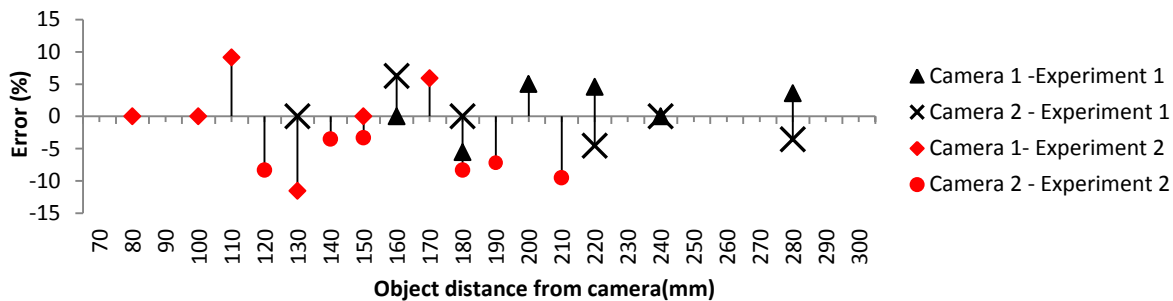


Figure 5: Percentage of error in depth measurement

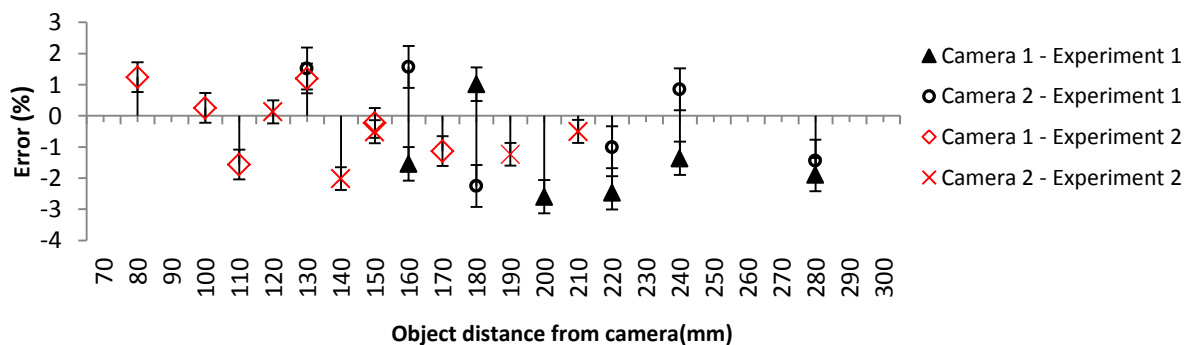


Figure 6: Percentage of error in lateral X and Y coordinates

Overall result of all experiments is shown in Figure 7, where four objects in the scene, placed within active zone of camera, are represented by calibrated depth map in SI unit (mm).

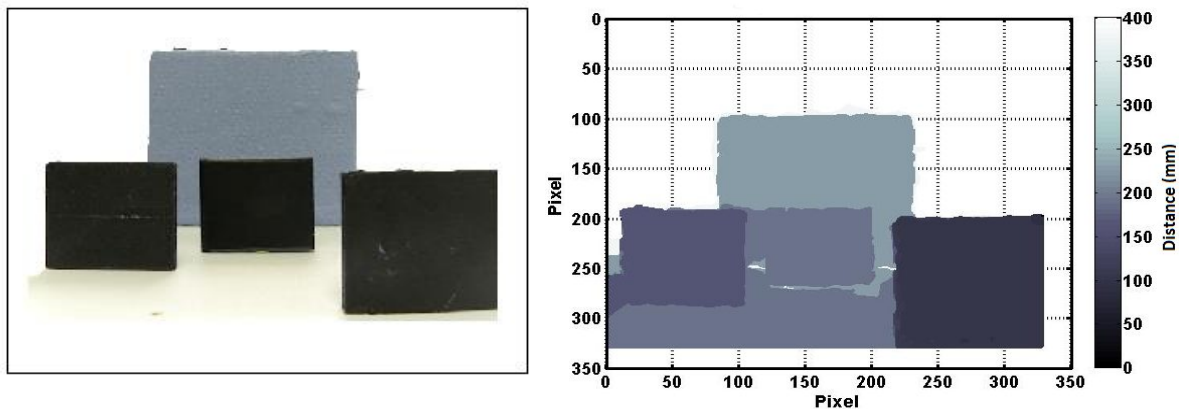


Figure 7: Objects in the scene (left) and calibrated depth map in millimetre (right)

4. CONCLUSIONS

This novel research has investigated the depth measuring capabilities of two Lytro lightfield (plenoptic) cameras, and methods to determine working volume where the quality of measurements can be achieved and assessed. As a result of this research, for the first time calibrated depth maps from the Lytro lightfield were produced in SI units. The investigation has yielded a number of novel and interesting results:

- The Lytro cameras have an active measurement zone of 210mm, between 70 mm and 280 mm from camera.
- It has been demonstrated that changing light conditions can change camera response to depth and hence the response curve.
- It should also be noted that both cameras behaved in a similar and consistent manner in different light conditions, indicating errors are systematic and repeatable.
- It was found that overall measured values were accurate by +10.0 mm to -20.0 mm in Z coordinate (depth) and +1.56 μm to -2.59 μm in lateral X and Y coordinate measurement, under the experimental conditions used. In addition, it was found that the repeatability of measurements achieved were good (typically 0.5 mm) although worst case values could be cited as 5.5 mm in Z coordinate and 0.25 μm in X and Y coordinates.

Further work is now considering the response of the camera technology to surface reflections, surface diffusivity, changing lighting types, and object colour, in the context of the camera calibration response curves, repeatability and accuracy of SI based depth values. In addition, comparability studies with other low cost and high cost 3D measuring systems are being completed.

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