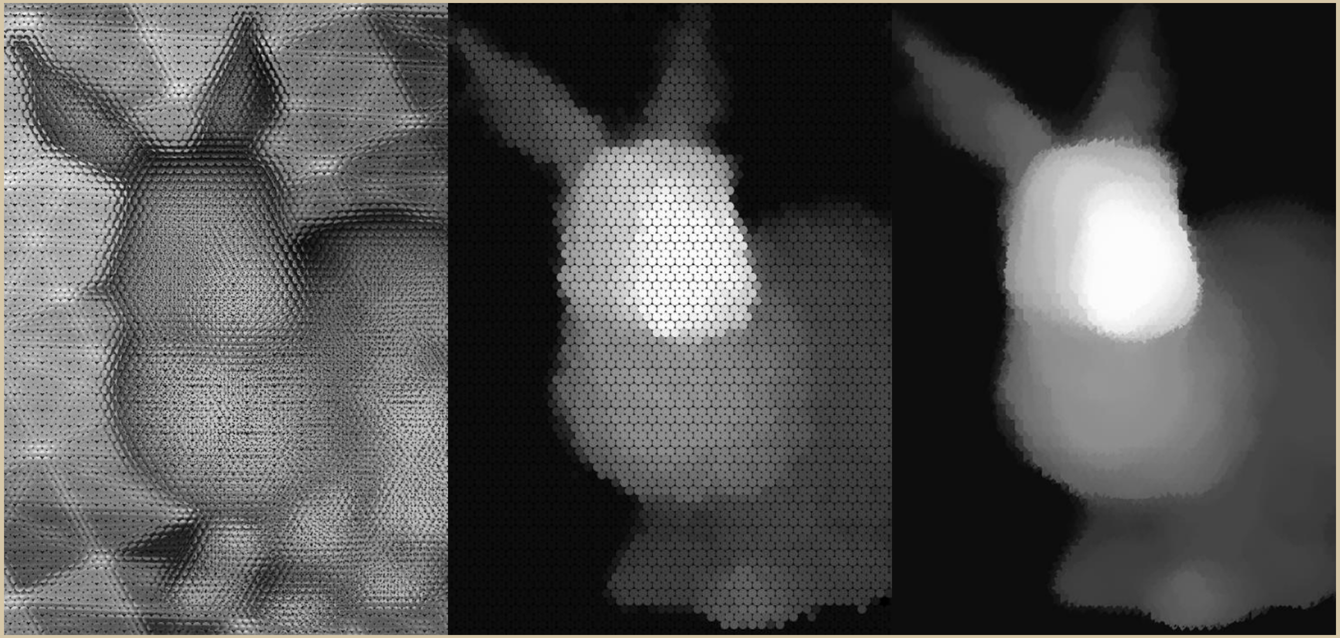

Rodrigo Miguel Belo Leal Toste Ferreira

A fully automatic depth estimation algorithm for multi-focus plenoptic cameras: coarse and dense approaches

Jury:
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February 2016

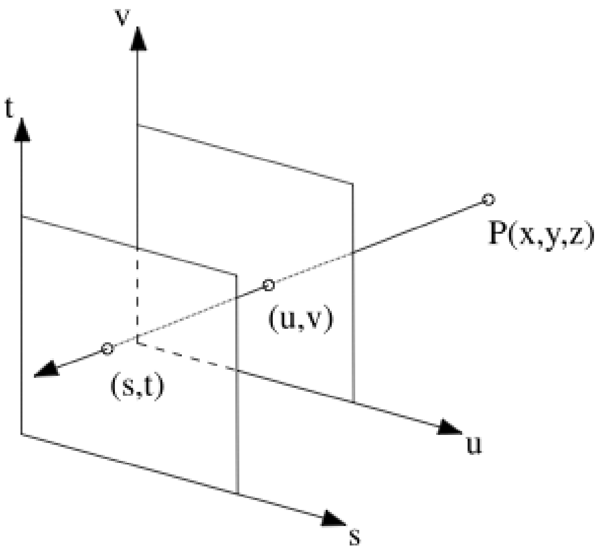
Contributions

- Depth estimation from improved point set;
- Merging of multiple depth maps to produce a more accurate depth estimation;
- Detection and correction of highly blurred areas;
- Coarse depth map with multiple depths on each micro-lens;
- Fully automatic algorithm;
- Improved performance.

Light Fields

The light field is given by all the light rays that flow from a scene, These light rays flow on all directions through time.

$$l = l(\theta, \phi, \lambda, t, V_x, V_y, V_z)$$

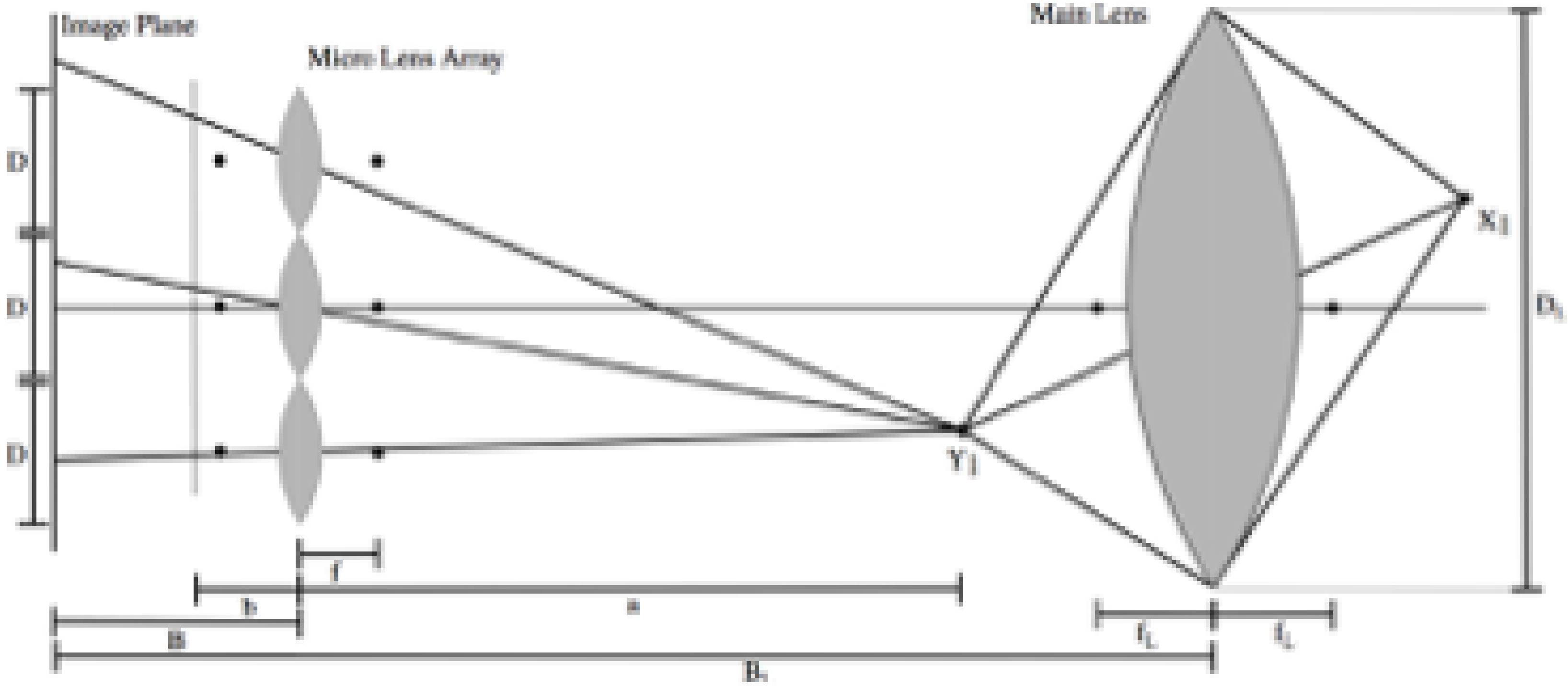


$$\longrightarrow \quad l = l(s, t, u, v)$$

two-plane parameterization

Plenoptic Cameras

What differs a plenoptic camera from a conventional camera is the placing of a micro-lens array between the image sensor and the camera’s main lens.



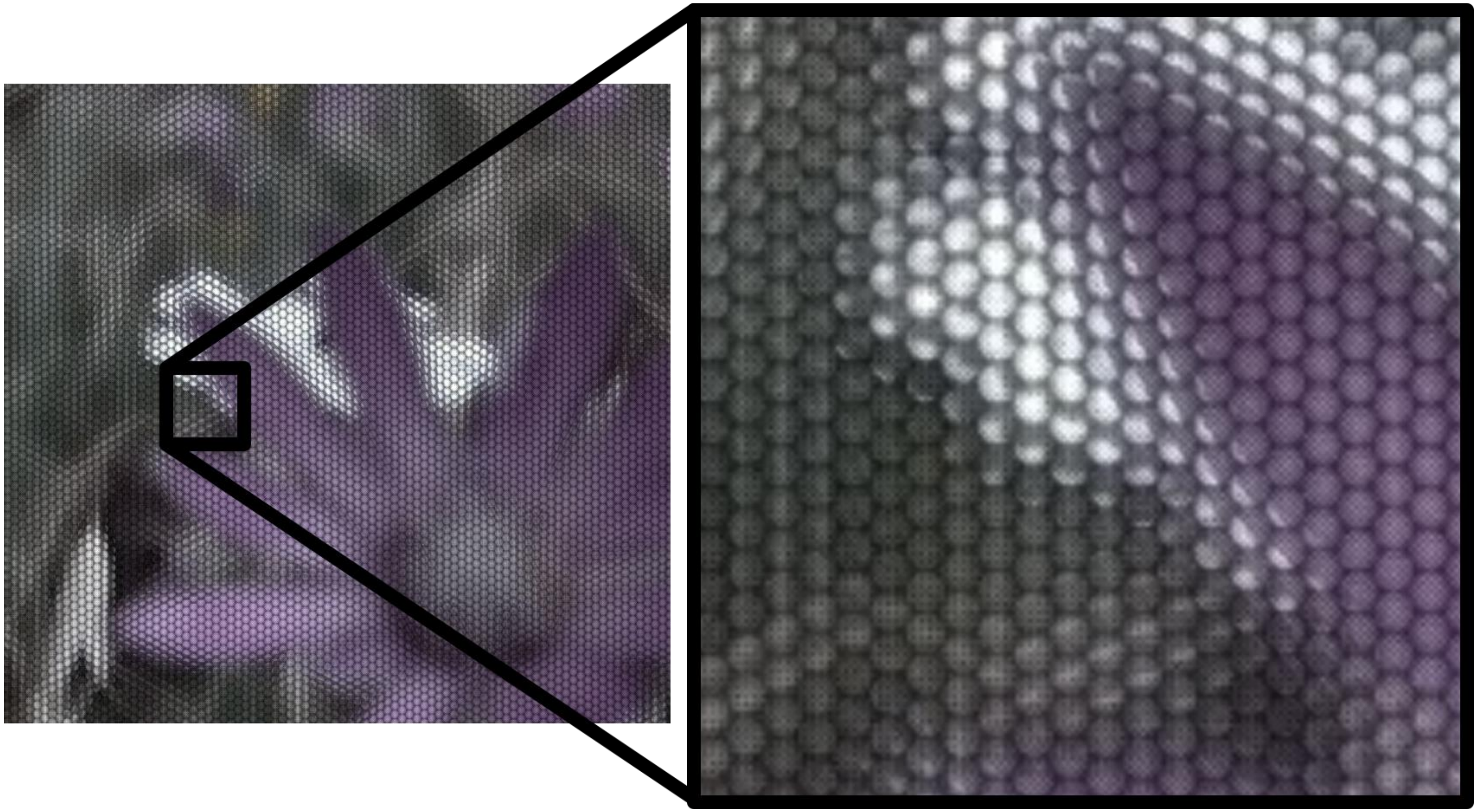
Plenoptic Cameras

Standard plenoptic camera
(first Lytro)

Multi-focus plenoptic camera
(Raytrix’s R8)

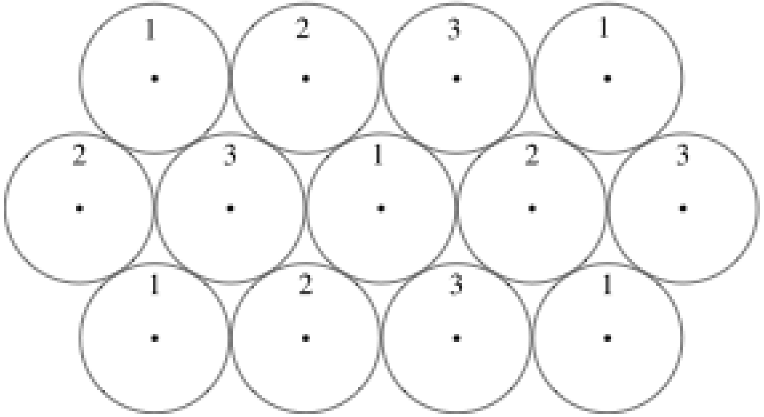
Standard Plenoptic Cameras

Lytro plenoptic image

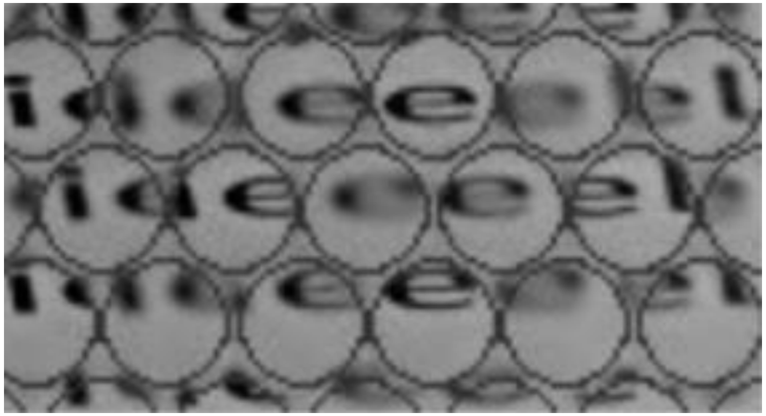


Multi-focus Plenoptic Cameras

Multi-focus micro-lens types and plenoptic image:

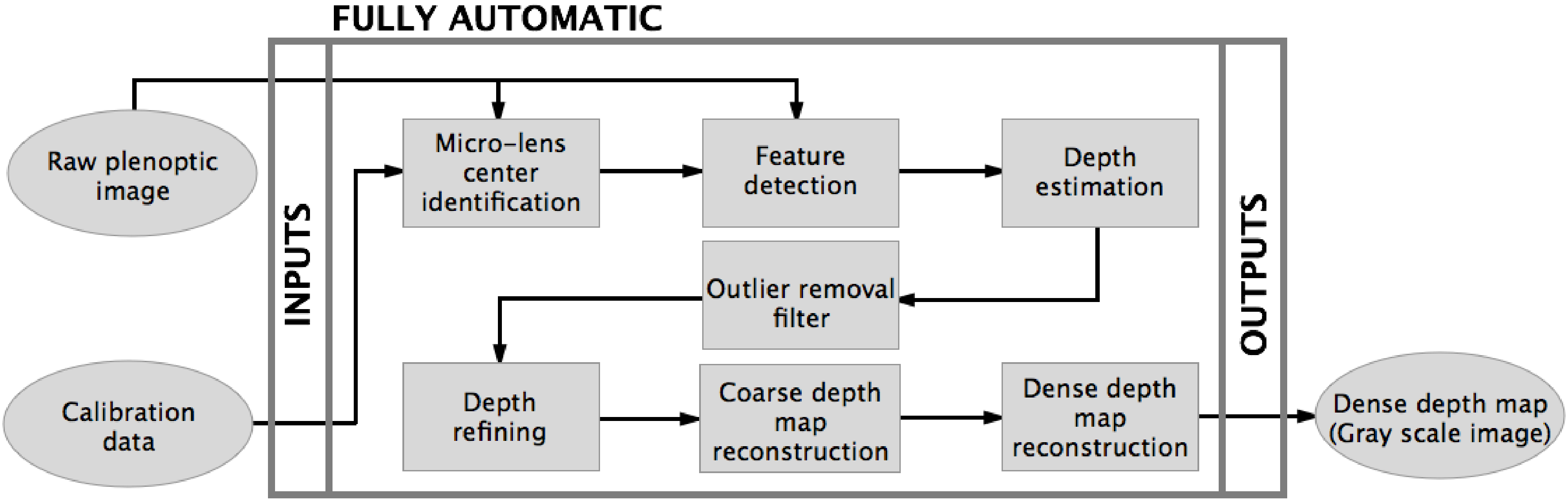


Micro-lens hexagonal configuration numbered by type (focal length).



Raytrix plenoptic image

Pipeline of the Algorithm



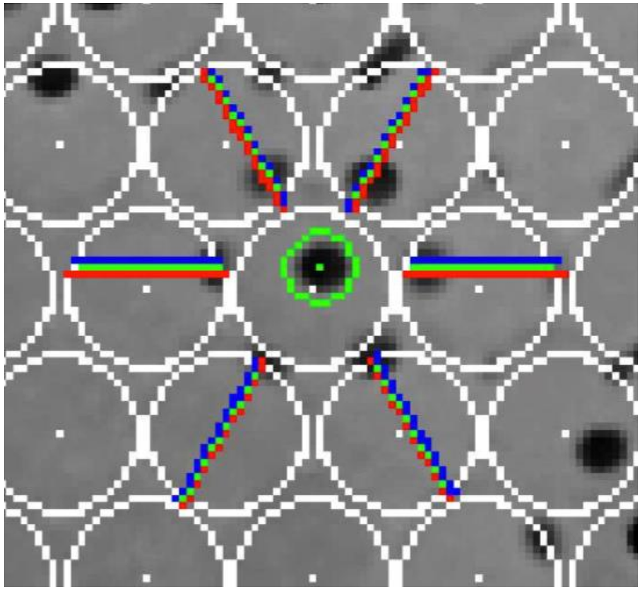
Previous Work

(developed by Joel Cunha)

Depth Estimation

The depth estimation is based on texture detail matching (photometric similarity)[1]. We use SIFT descriptor to search for salient points and then we apply a RANSAC- like method based on photometric similarities to obtain the best 3D point cloud:

- **Step 1 -** Selection of an epipolar line;
- **Step 2 -** Estimation of the 3D virtual points;
- **Step 3 -** Testing the model;
- **Step 4 -** Assessment of the model;
- **Step 5 -** Re-estimation of the 3D virtual point;
- **Step 6 -** Error metrics;
- **Step 7 -** repeat steps 1-6 for every correspondence.



Salient point and respective epipolar bands (one for each neighbor lens).

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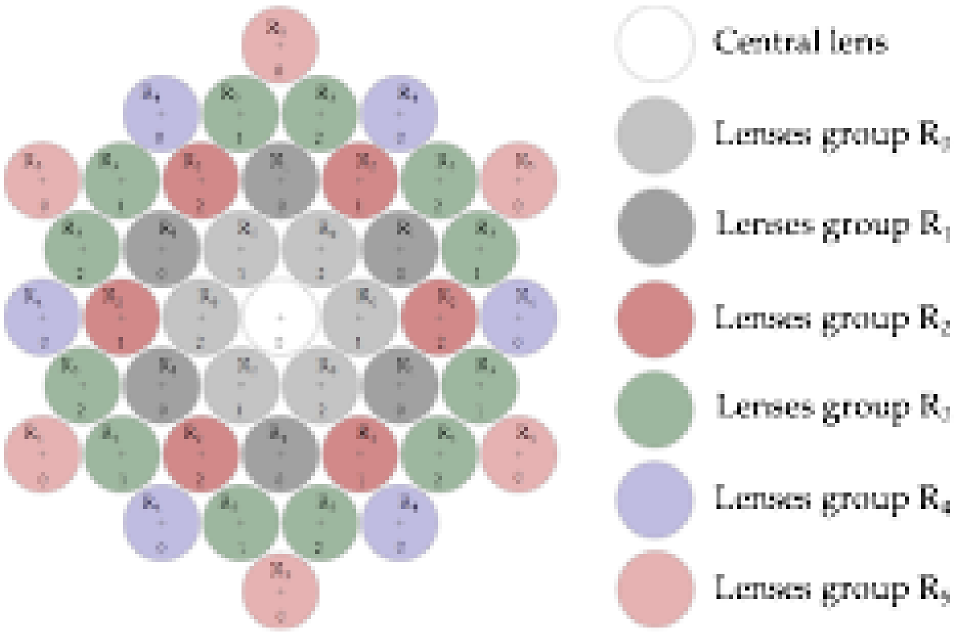
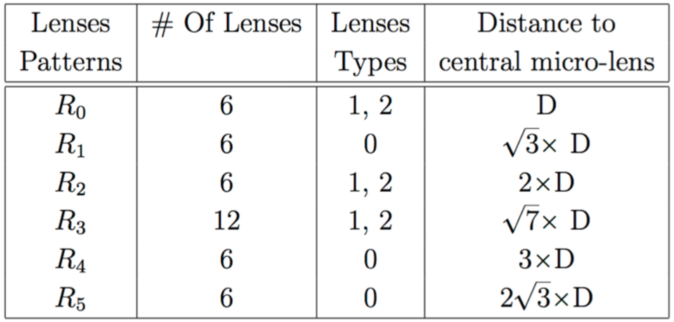
[1] - Christian Perwass and Lennart Wietzke. Single lens 3d-camera with extended depht-of-field. *SPIE Human Vision and Electronic Imaging*, 2012.

Micro-lens Patterns



Micro-lens groups representation.



Lenses Patterns	# Of Lenses	Lenses Types	Distance to central micro-lens
R_0	6	1, 2	D
R_1	6	0	$\sqrt{3}\times$ D
R_2	6	1, 2	$2\times$D
R_3	12	1, 2	$\sqrt{7}\times$ D
R_4	6	0	$3\times$D
R_5	6	0	$2\sqrt{3}\times$D

Parameters of the micro-lens groups.

Outlier Elimination

To detect outliers in the point cloud, all distances of pairs of points are computed and a threshold is establish based on the distribution of distances in a given vicinity[2].

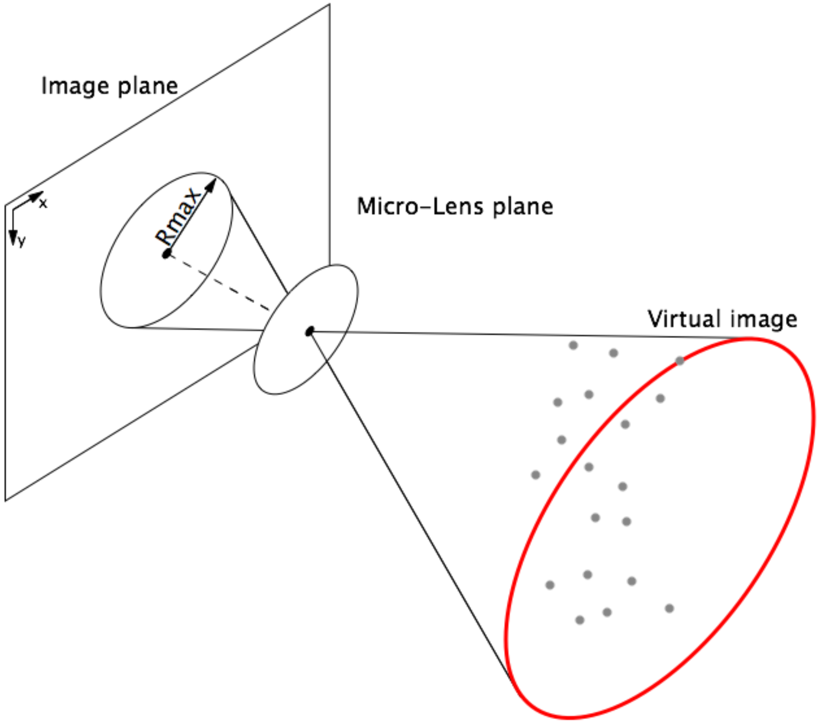
Every point that falls outside of the threshold is considered an outlier. All the outliers are removed.

---

[2] - Radu Bogdan Rusu, Zoltan Csaba Marton, Nico Blodow, Mihai Dolha, and Michael Beetz. Towards 3d point cloud based object maps for household enviroments. *Robotics and Autonomous Systems*, 56(11):927–941, 2008.

Coarse Depth Map

For the reconstruction of the coarse map, each point is projected into the image plane through the micro-lens array.

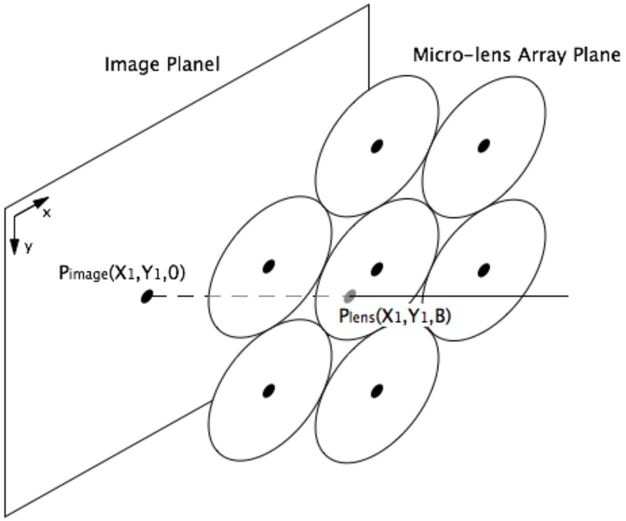


- **Step 1** - determine which points fall inside the projection cone with Rmax radius.
- **Step 2** - project those points into the image plane through the micro-lens. A color intensity is assigned to each projected point with the same value as its virtual depth.
- **Step 3** - Average every point’s color intensity.

Dense Depth Map

The creation of the dense depth map follows a group of steps. The final depth map is reconstructed on the image plane, with a depth value per pixel.

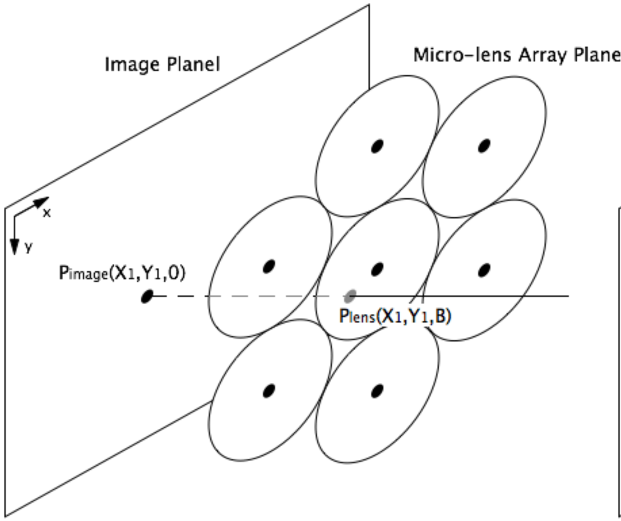
- **Step 1 -** Determine the central lens;

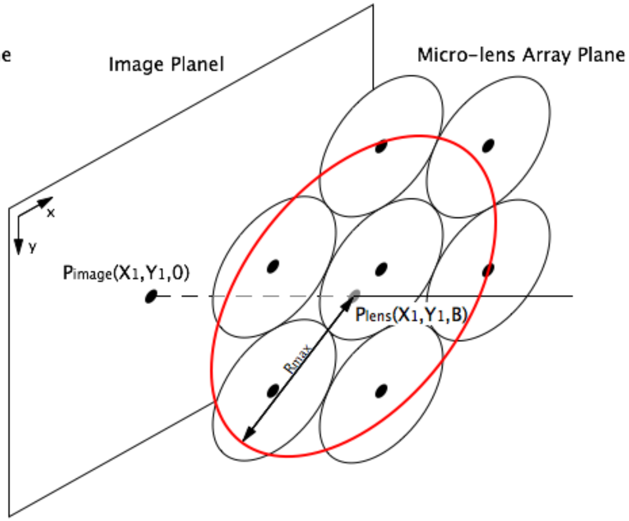


Dense Depth Map

The creation of the dense depth map follows a group of steps. The final depth map is reconstructed on the image plane, with a depth value per pixel.

- **Step 1 -** Determine the central lens;
- **Step 2 -** Determine which lenses belong to the radius Rmax;

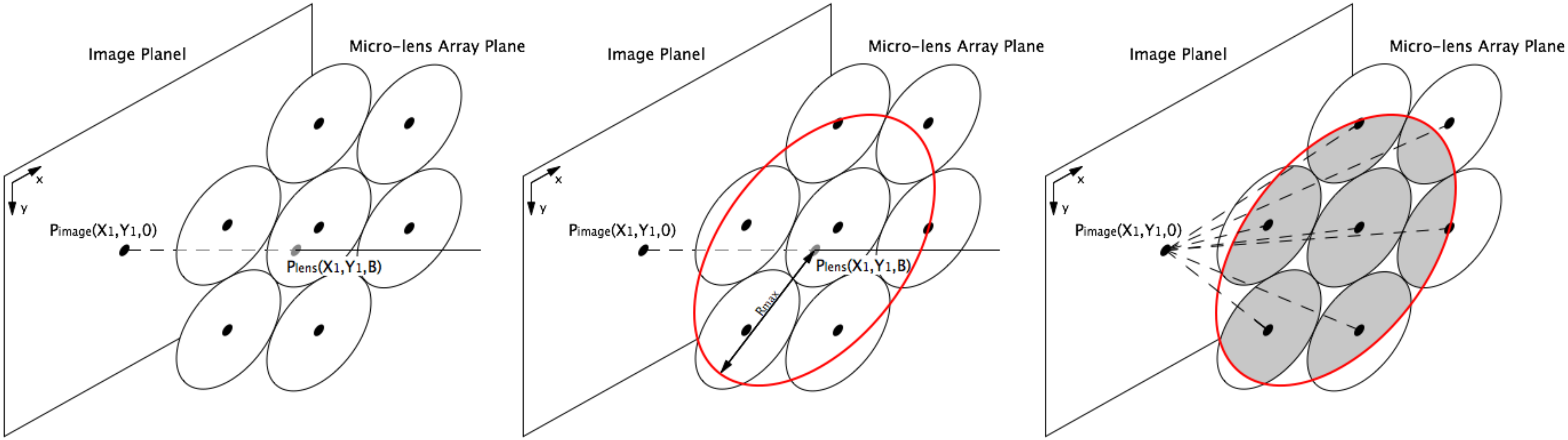




Dense Depth Map

The creation of the dense depth map follows a group of steps. The final depth map is reconstructed on the image plane, with a depth value per pixel.

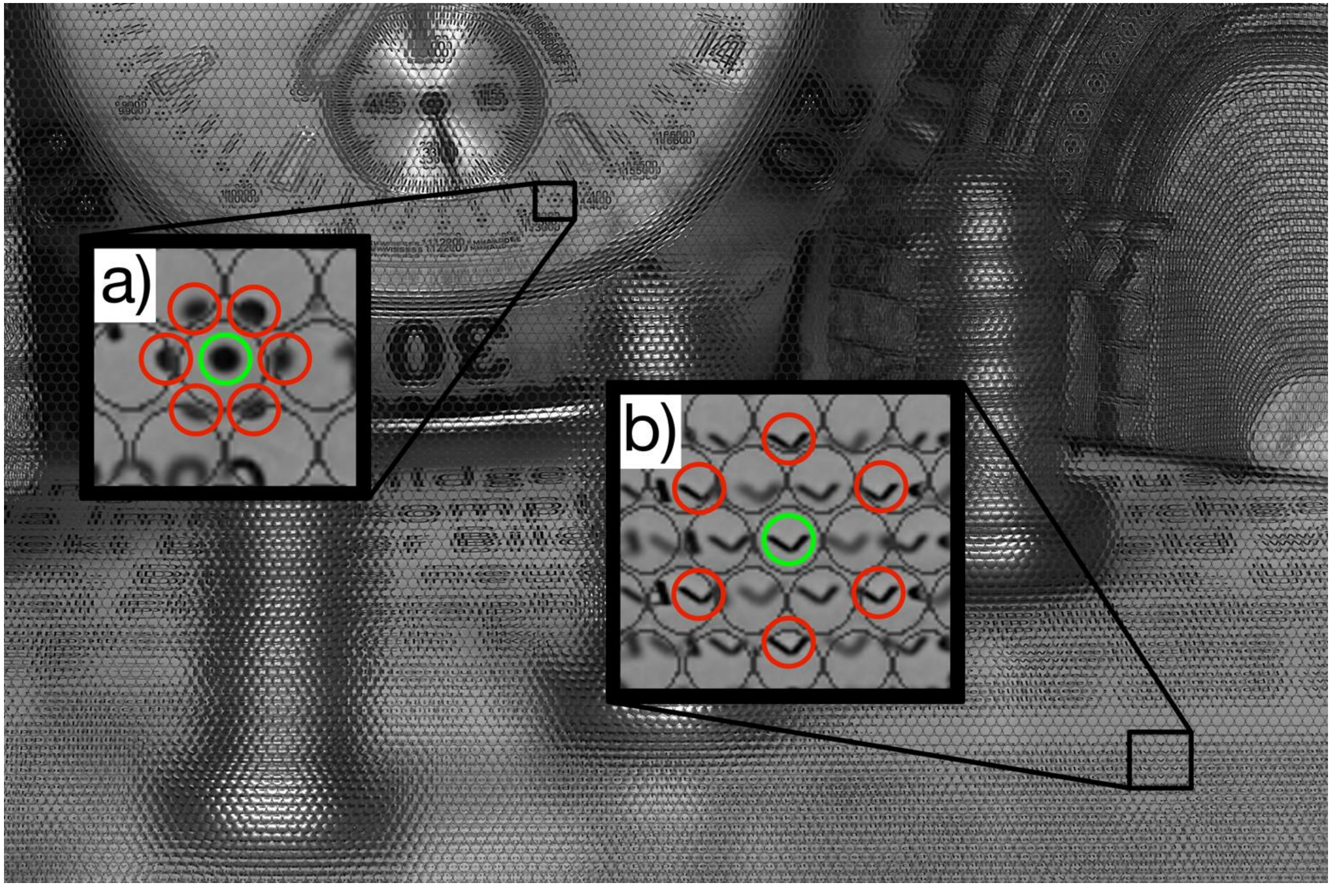
- **Step 1 -** Determine the central lens;
- **Step 2 -** Determine which lenses belong to the radius Rmax;
- **Step 3 -** Estimate pixel's depth value (averaging the depth values of all the lenses within Rmax).



Improved Work

Depth Refining (multiple depth map merging)

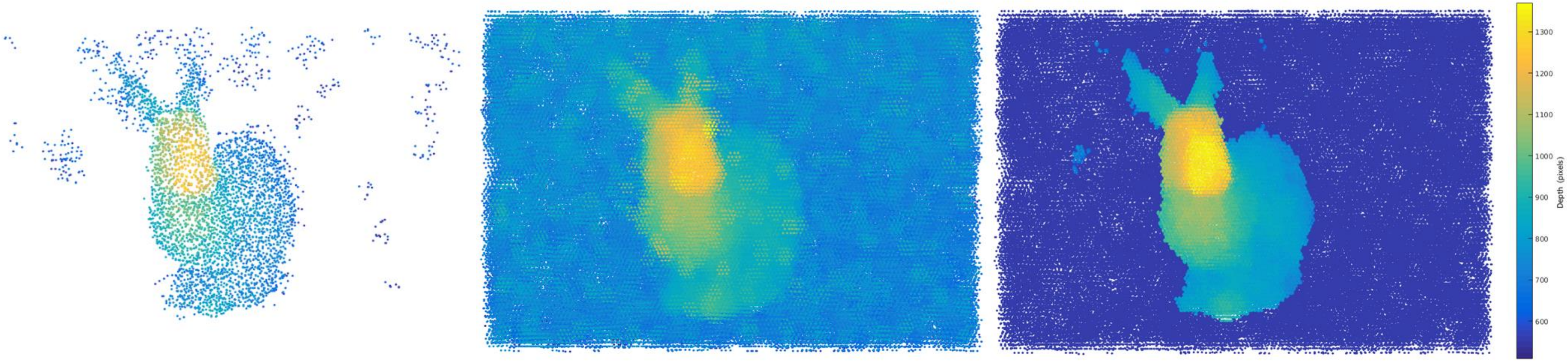
The closer a point is to the camera, the more lenses will replicate it.



Depth Refining (highly blurred areas)

We generate a point set for 2 or more correspondences and we cross it with a generated point set for 5 or more correspondences of the same plenoptic image.

- **Step 1-** Section labeling of the depth map with stable estimations **-** 5 or more correspondences;
- **Step 2 -** Reject all correspondences outside the inlier label area from the point set with 2 or more correspondences;
- **Step 3 -** Analyze the rejected points depth.



Coarse Depth Map (outlier elimination)

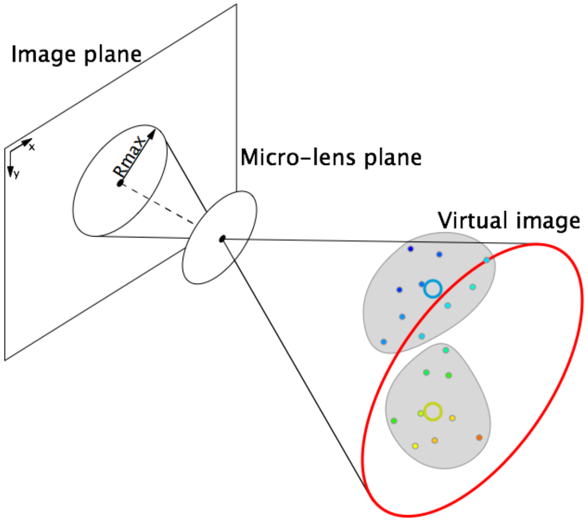
As we project the virtual points to each micro-lens for the coarse depth estimation, we apply a fine filter for each local point cloud.

This filter is based on a median $\tilde{p}$ and standard deviation σ_p of each local point cloud $P(n)$ (local point set with n points).

Coarse Depth Map (micro-lens sectioning)

We section the micro-lens into two depths using a clusterization algorithm called k-means.

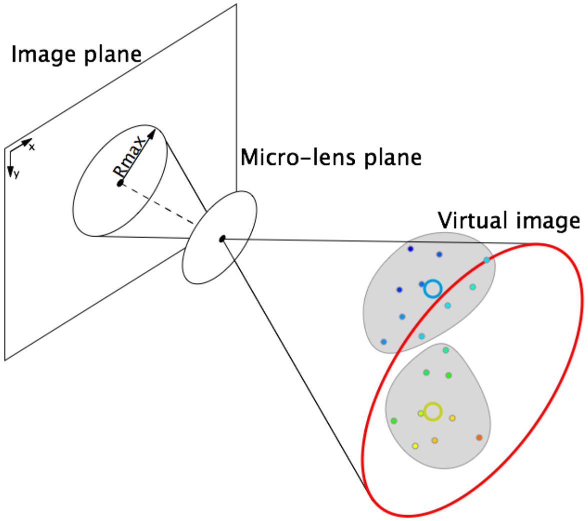
- **Step 1-** determine which points fall inside the Rmax radius cone and calculate 2 clusters;

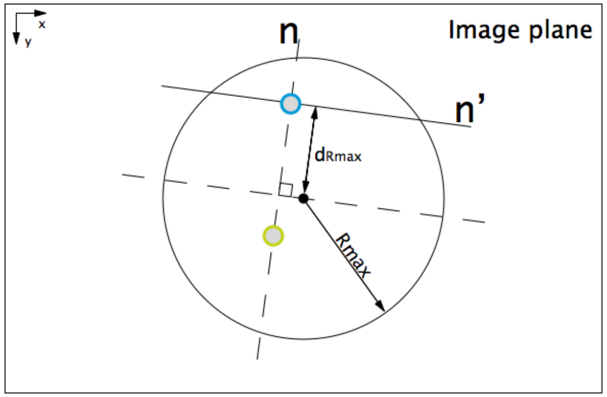


Coarse Depth Map (micro-lens sectioning)

We section the micro-lens into two depths using a clusterization algorithm called k-means.

- **Step 1-** determine which points fall inside the Rmax radius cone and calculate 2 clusters;
- **Step 2-** project the clusters centers into the image plane and divide the micro-lens;

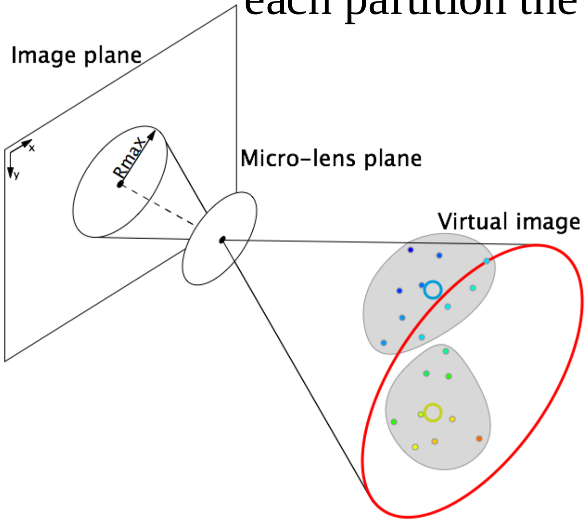


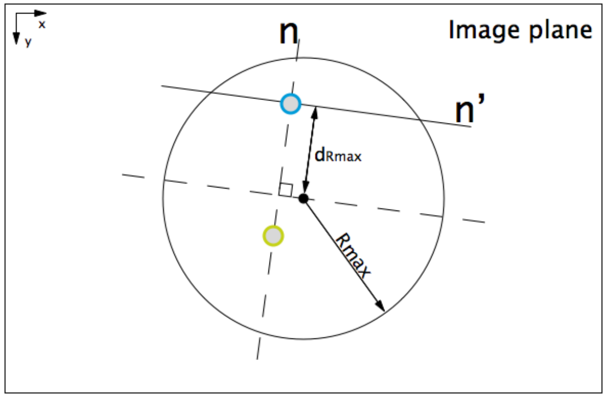


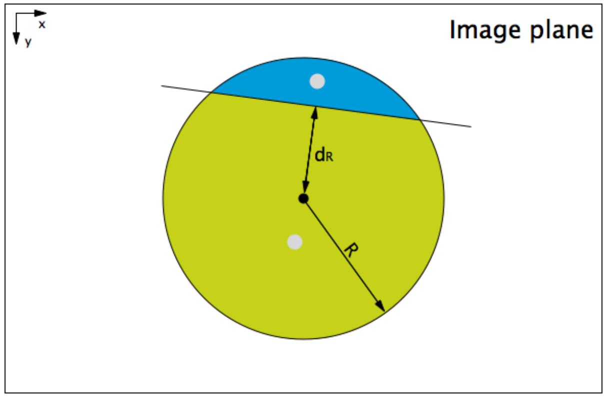
Coarse Depth Map (micro-lens sectioning)

We section the micro-lens into two depths using a clusterization algorithm called k-means.

- **Step 1-** determine which points fall inside the Rmax radius cone and calculate 2 clusters;
- **Step 2-** project the clusters centers into the image plane and divide the micro-lens;
- **Step 3-** Normalize and scale the partition to the micro-lens R radius, assigning each partition the intensity value of the corresponding cluster center.

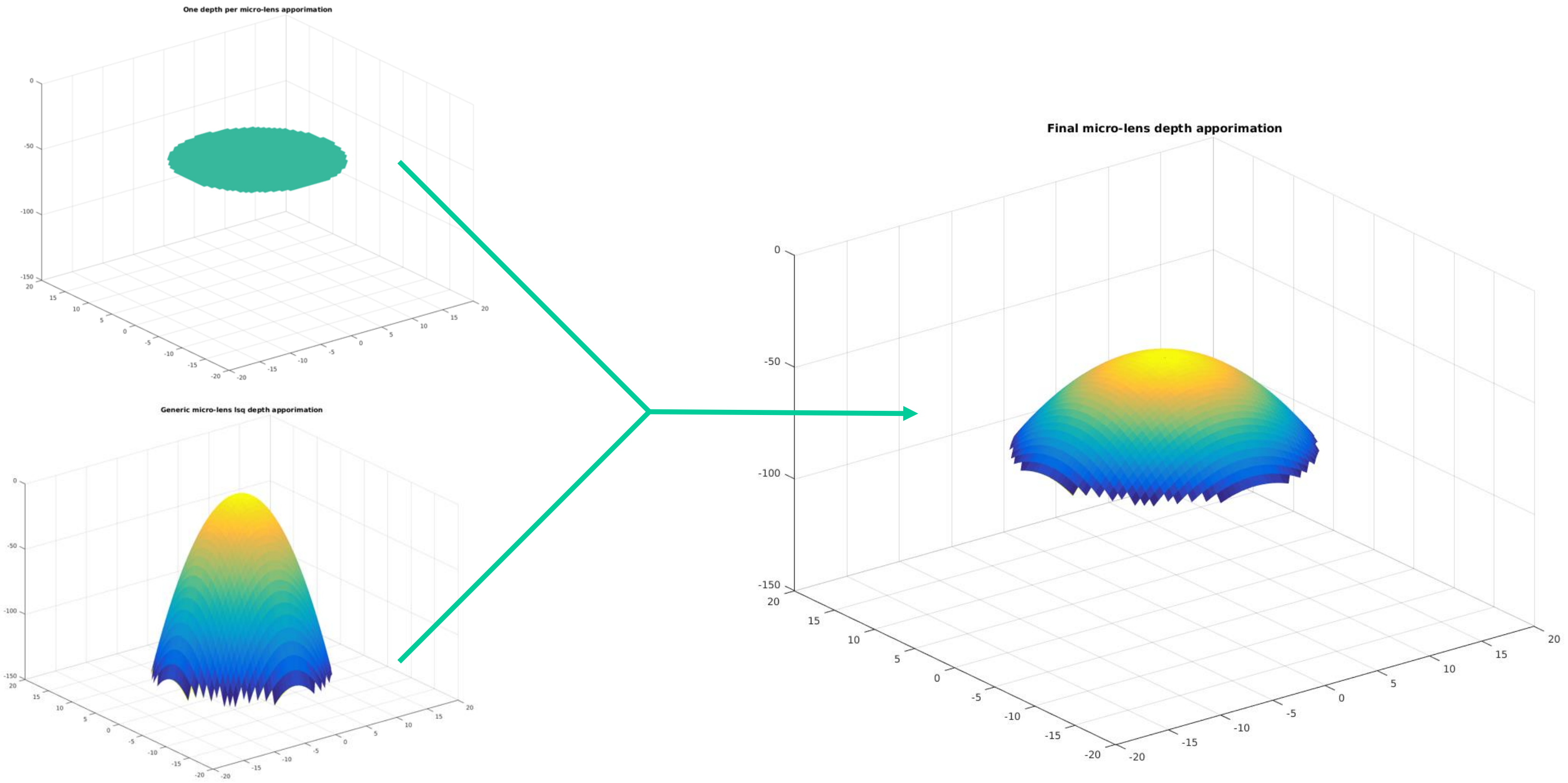






Coarse Depth Map (second order fitting)

We integrate the single depth per micro-lens with a multiple-depth per micro-lens generated with the least squares method.



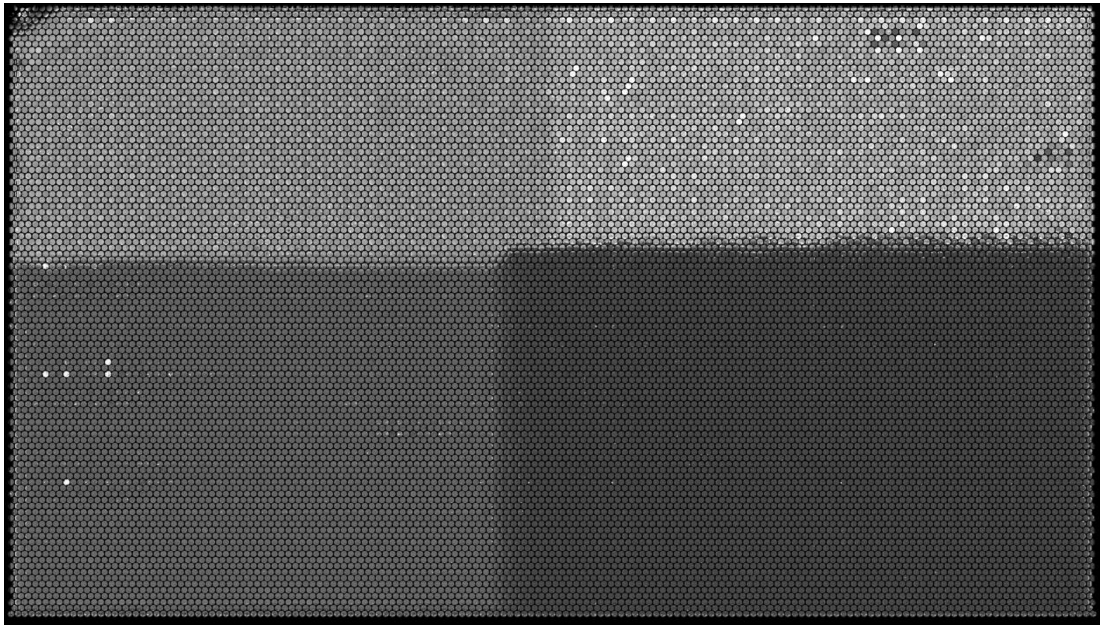
Dense Depth Map

To improve the dense depth map synthesization, similarly to the fine filter of the outlier removal, we calculate the median and standard deviation for all the lenses within Rmax radius.

The final P_{image} depth value is the average of the filtered depth values of all lenses within the Rmax radius.

Fleischmann & Koch (disparity map)

We replicated Fleischmann and Koch[3] for a direct comparison, which is actually the state of the art for multi-focus plenoptic cameras. It is based on photometric similarities, generating a disparity map per micro-lens image.



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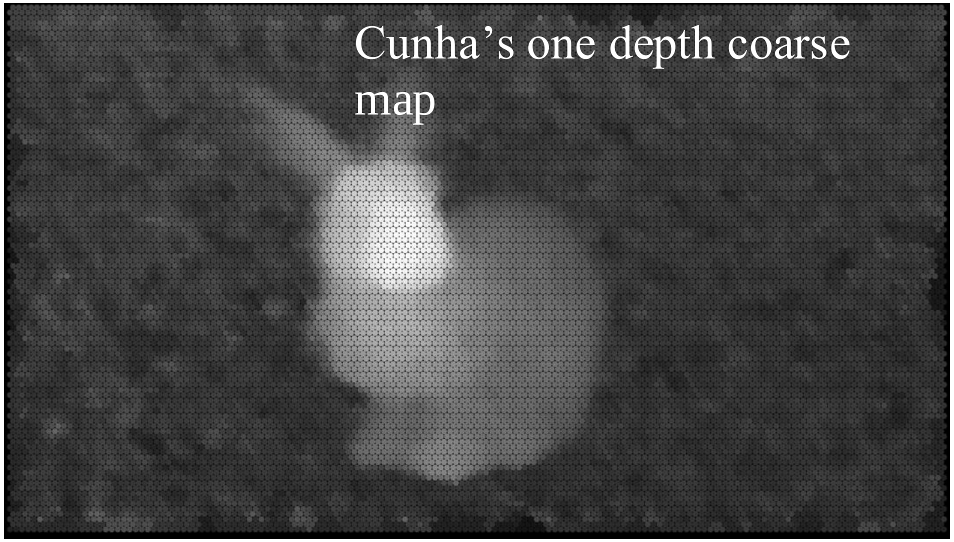
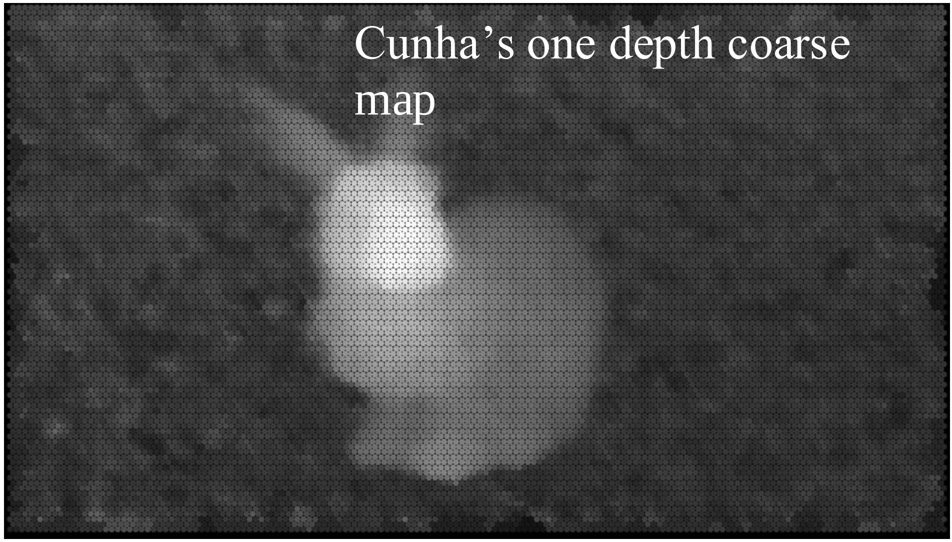
[3] - Oliver Fleischmann and Reinhard Koch. Lens-based depth estimation for multi-focus plenoptic cameras. *36th German Conference on Pattern Recognition*, 8753:410–420, October 2014.

Experimental Results (synthetic data)

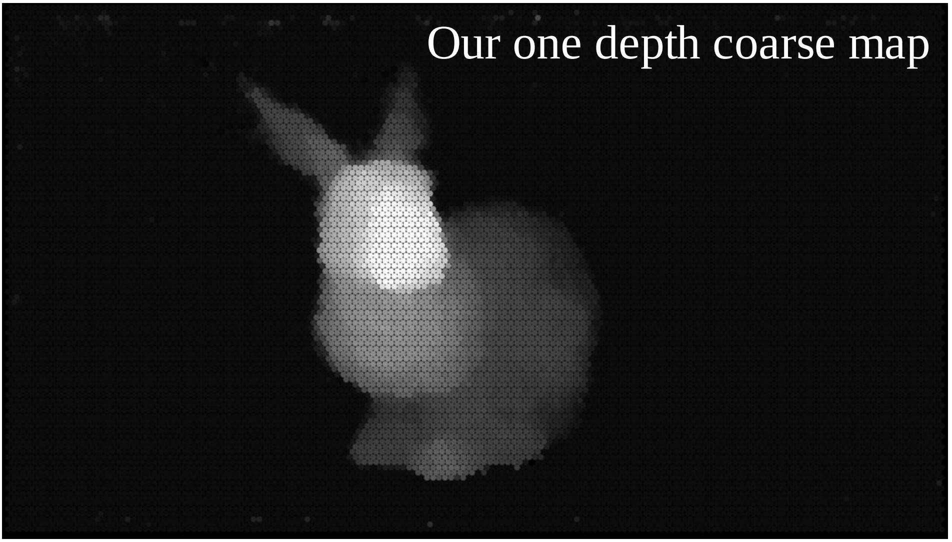


Cunha's one depth coarse map

Experimental Results (synthetic data)

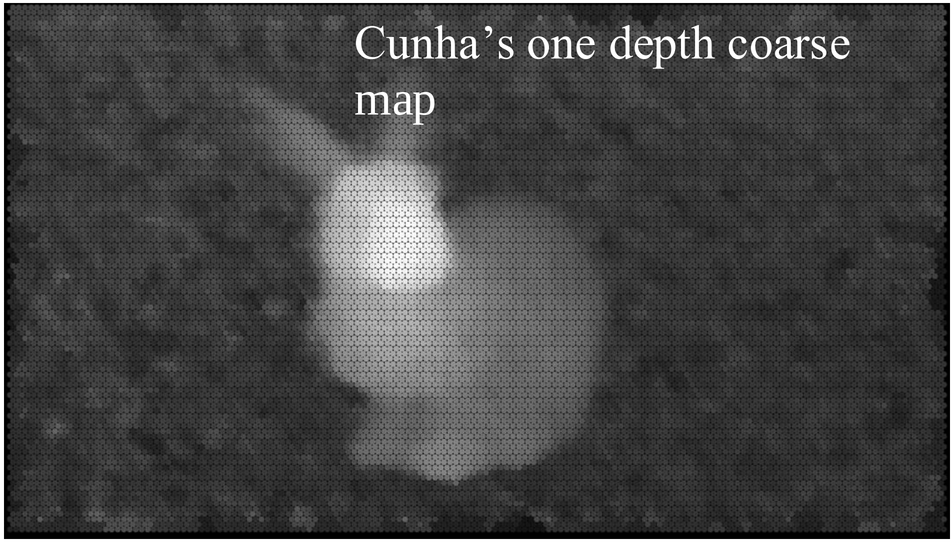


Cunha’s one depth coarse map

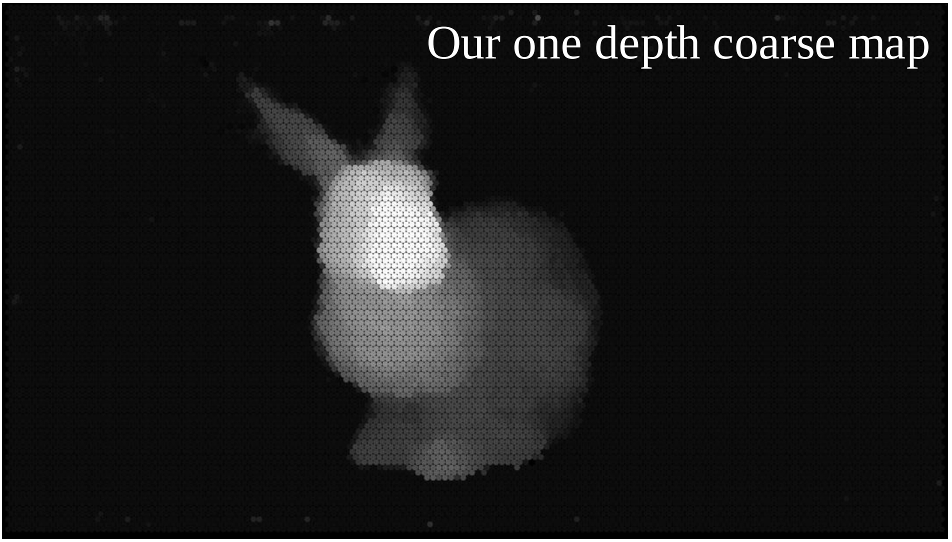


Our one depth coarse map

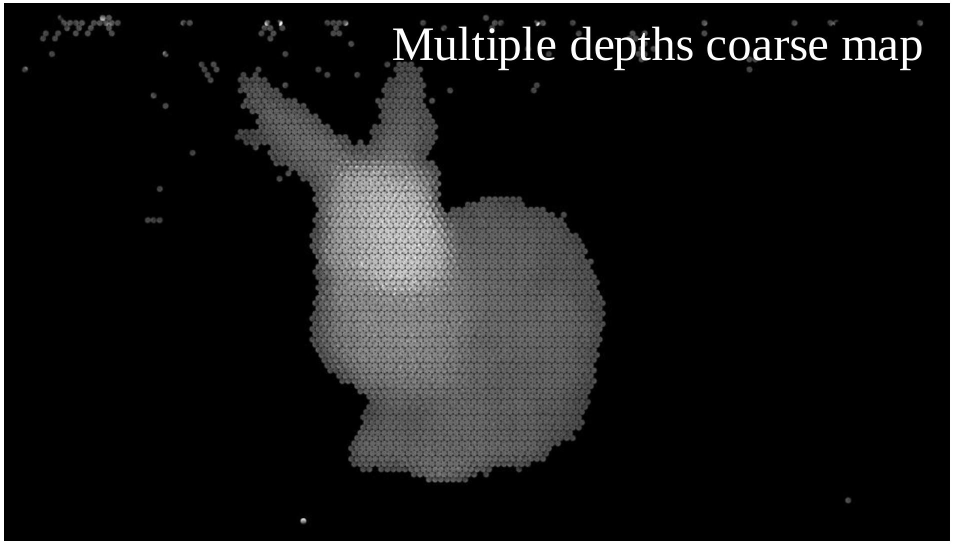
Experimental Results (synthetic data)



Cunha’s one depth coarse map

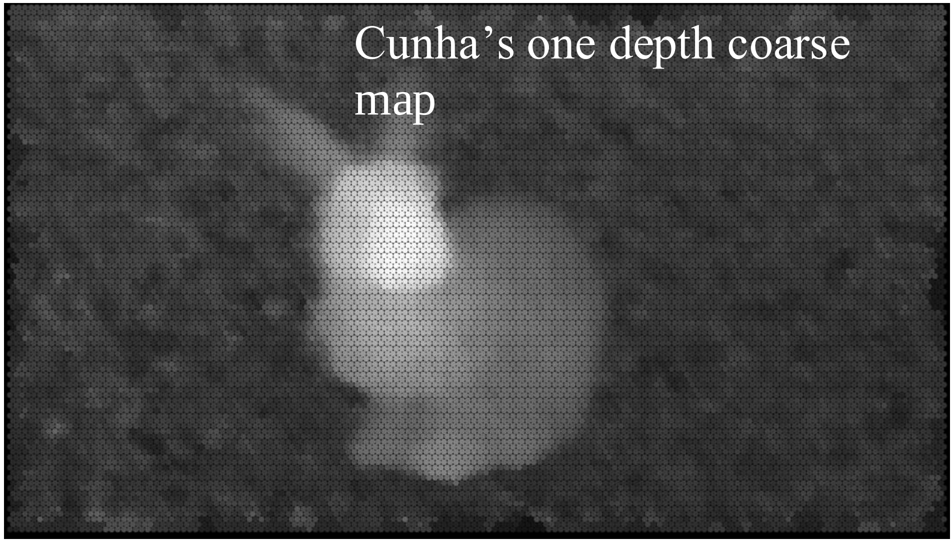


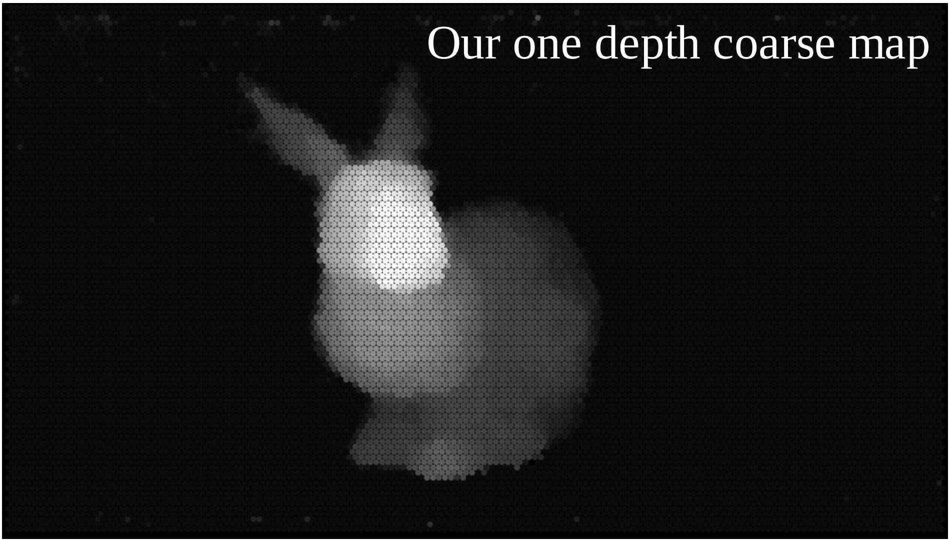
Our one depth coarse map

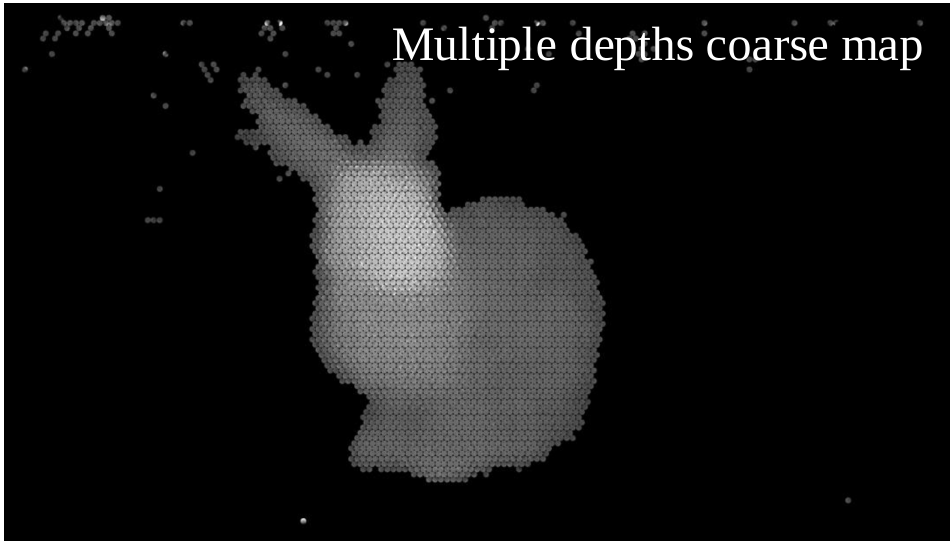


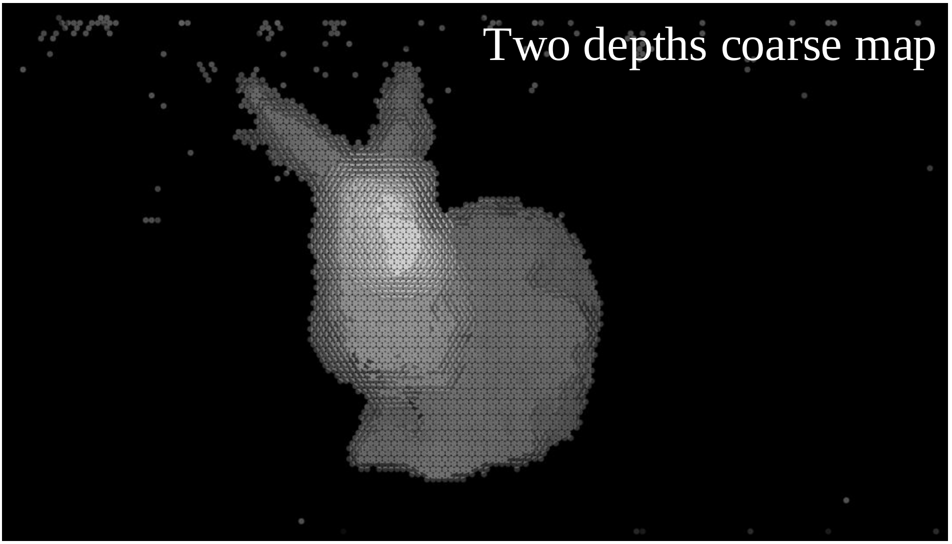
Multiple depths coarse map

Experimental Results (synthetic data)

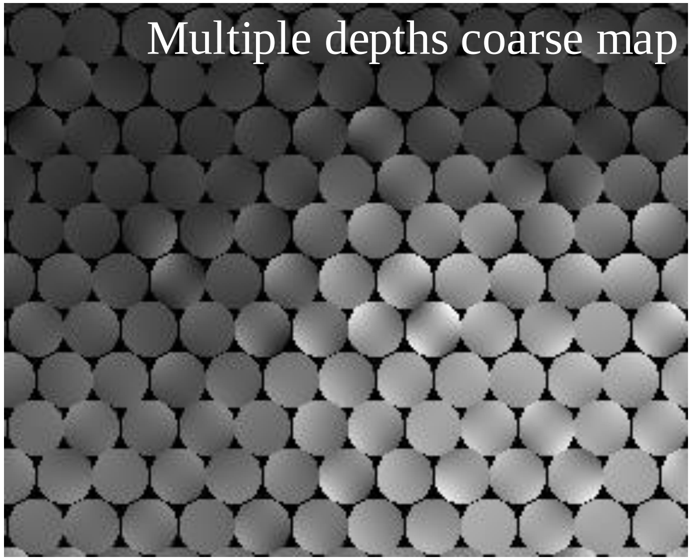

Cunha’s one depth coarse map

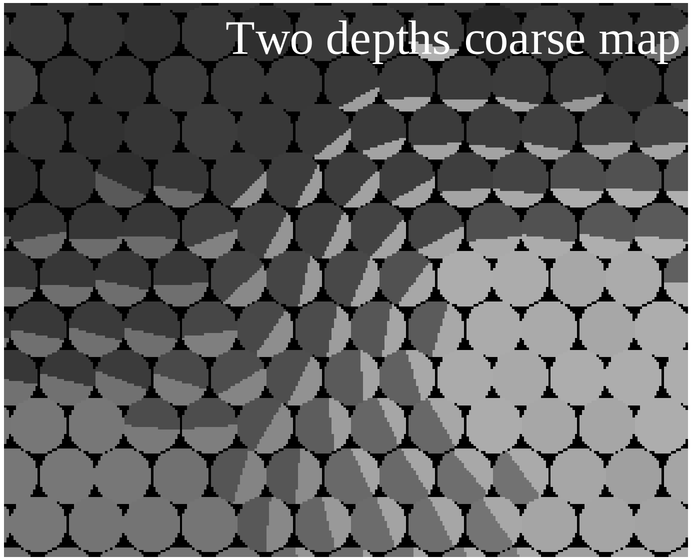

Our one depth coarse map

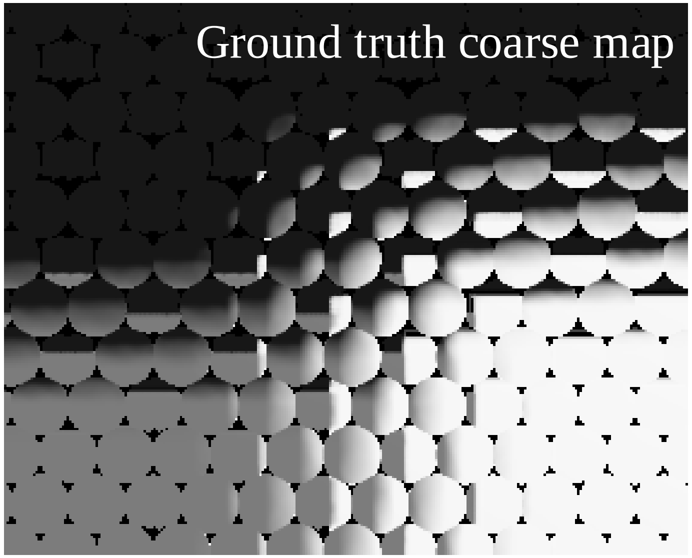

Multiple depths coarse map


Two depths coarse map

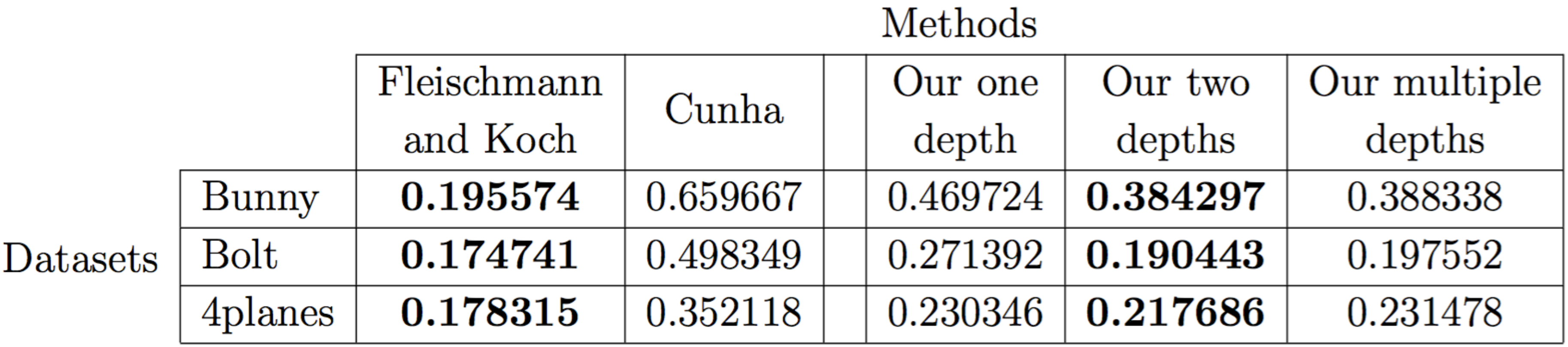
Experimental Results (synthetic data)


Multiple depths coarse map


Two depths coarse map


Ground truth coarse map

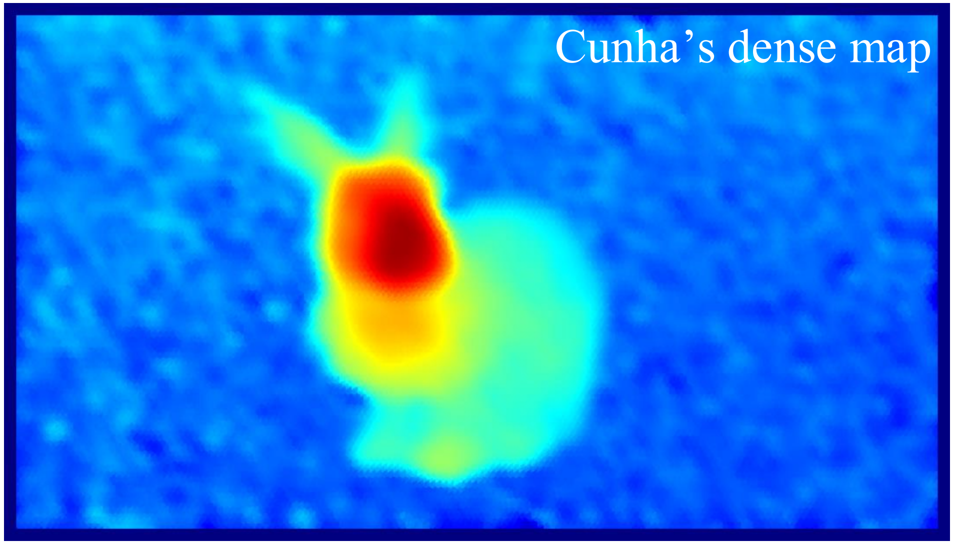
Experimental Results (synthetic data)



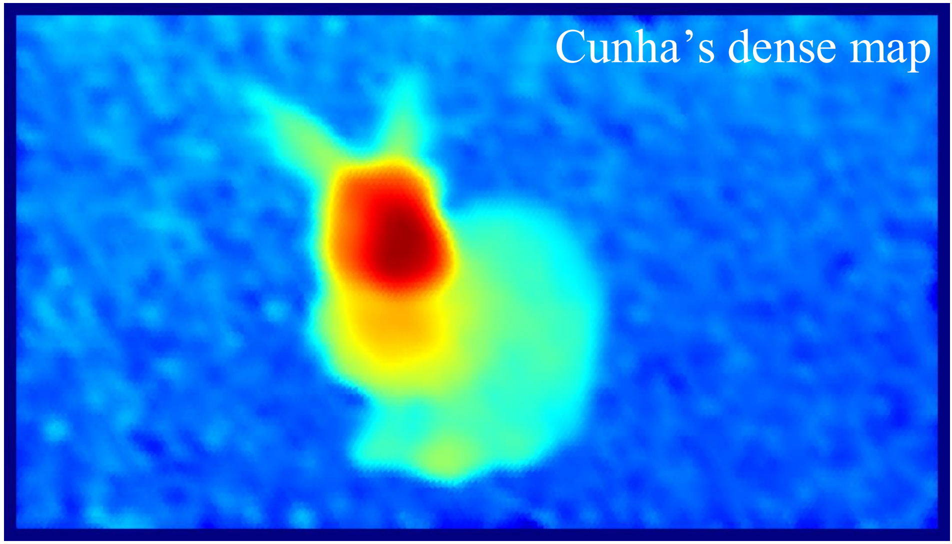
		Methods					
		Fleischmann and Koch	Cunha		Our one depth	Our two depths	Our multiple depths
Datasets	Bunny	**0.195574**	0.659667		0.469724	**0.384297**	0.388338
	Bolt	**0.174741**	0.498349		0.271392	**0.190443**	0.197552
	4planes	**0.178315**	0.352118		0.230346	**0.217686**	0.231478

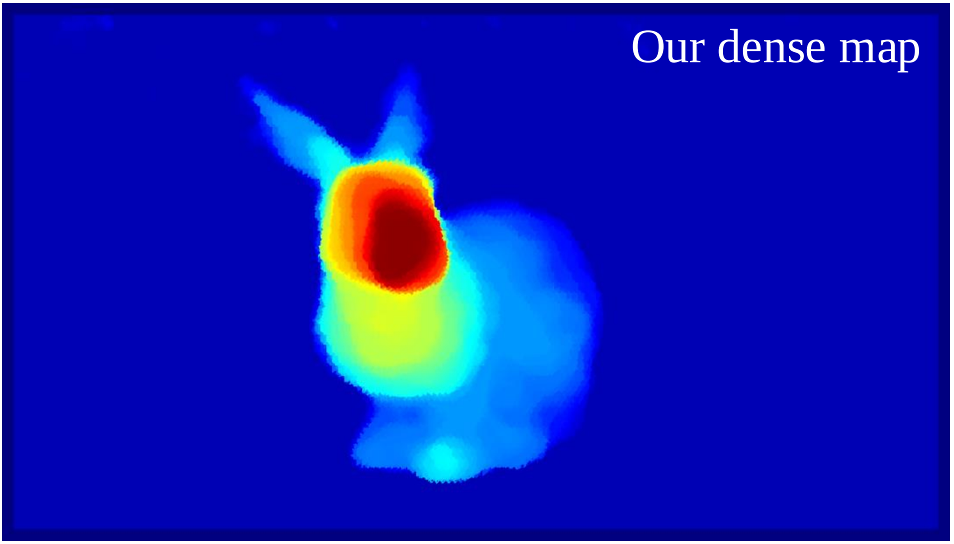
Mean absolute disparity error (in pixels) for all studied coarse maps.

Experimental Results (synthetic data)

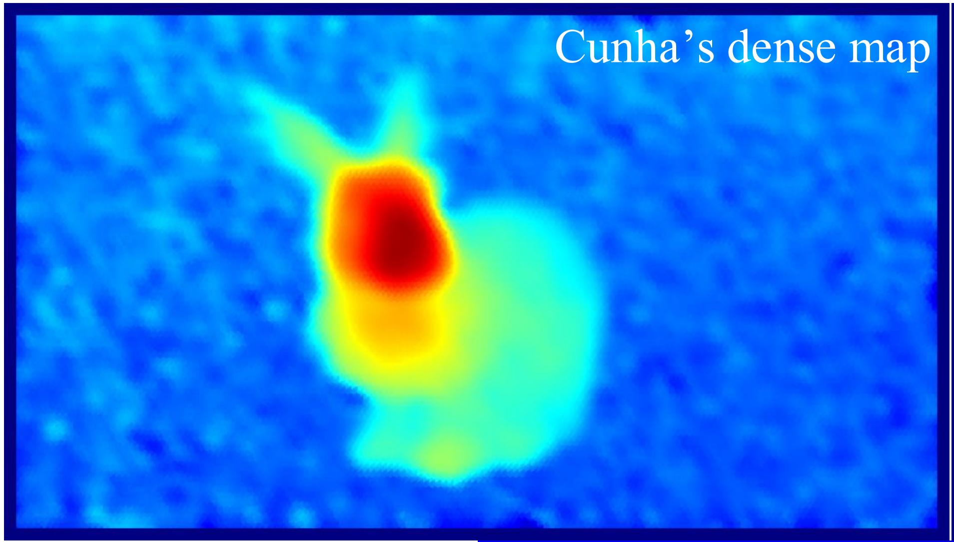


Experimental Results (synthetic data)

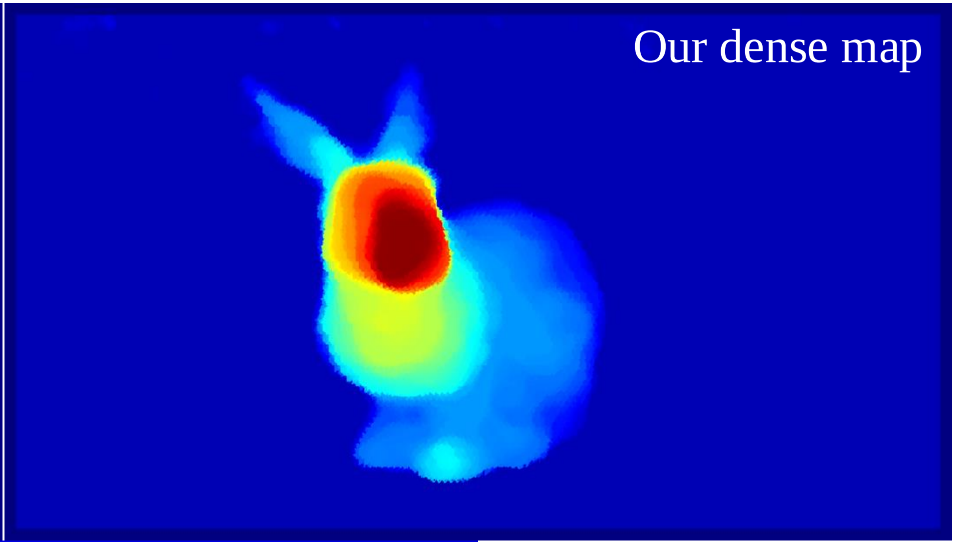




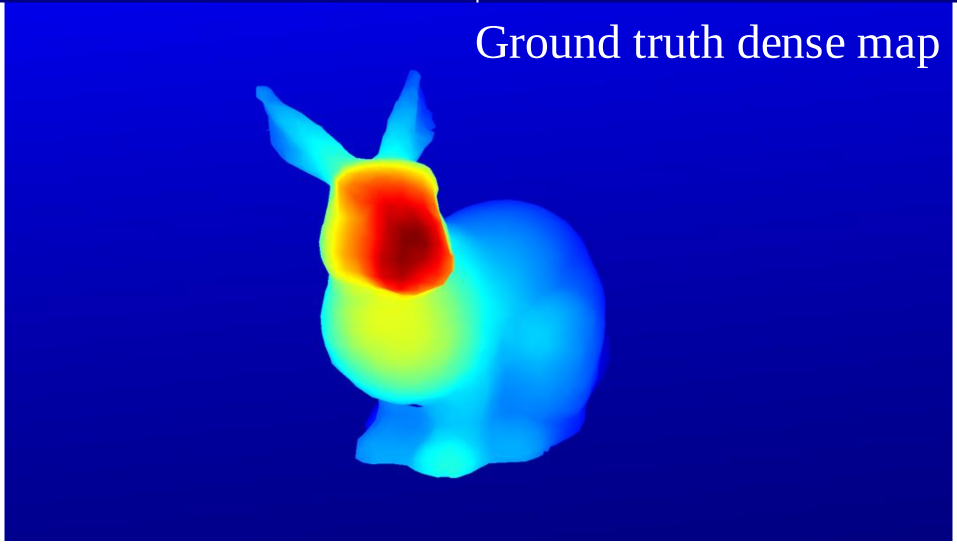
Experimental Results (synthetic data)



Cunha’s dense map

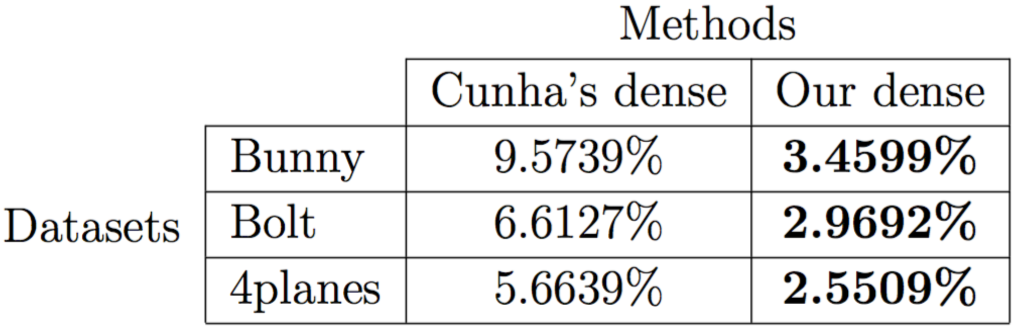


Our dense map



Ground truth dense map

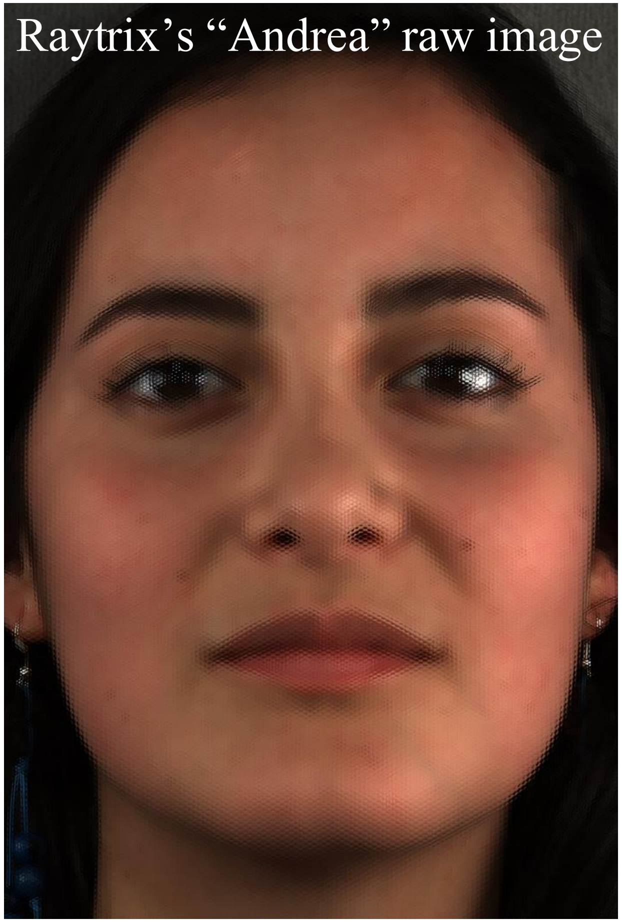
Experimental Results (synthetic data)



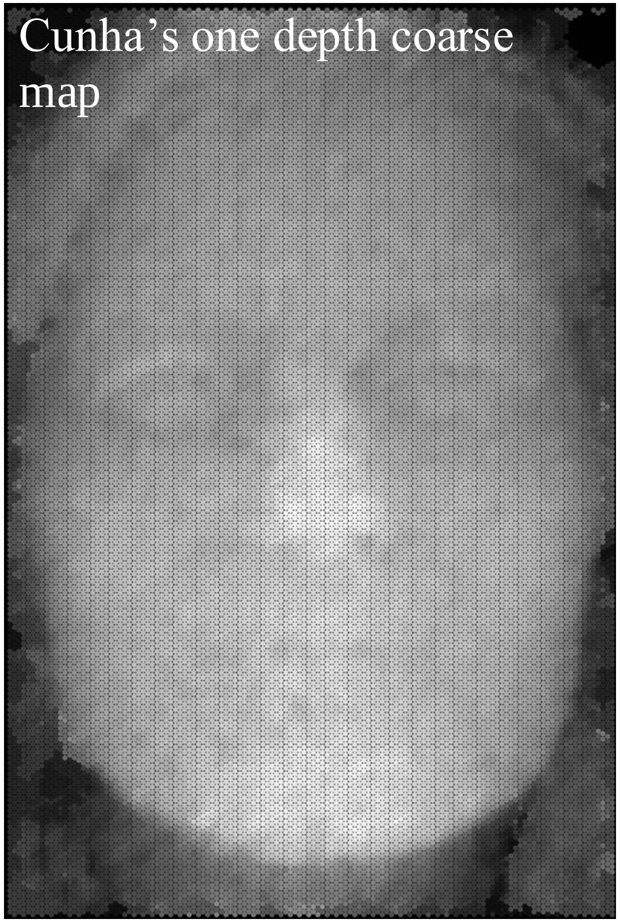
		Methods	
		Cunha's dense	Our dense
Datasets	Bunny	9.5739%	**3.4599%**
	Bolt	6.6127%	**2.9692%**
	4planes	5.6639%	**2.5509%**

Root mean squared error comparison.

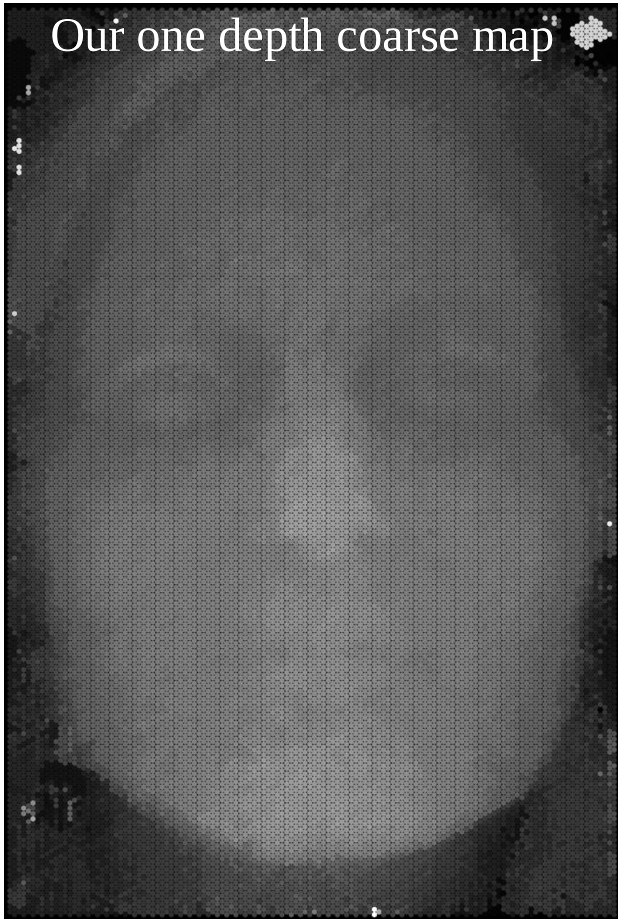
Experimental Results (real images)



Raytrix's "Andrea" raw image

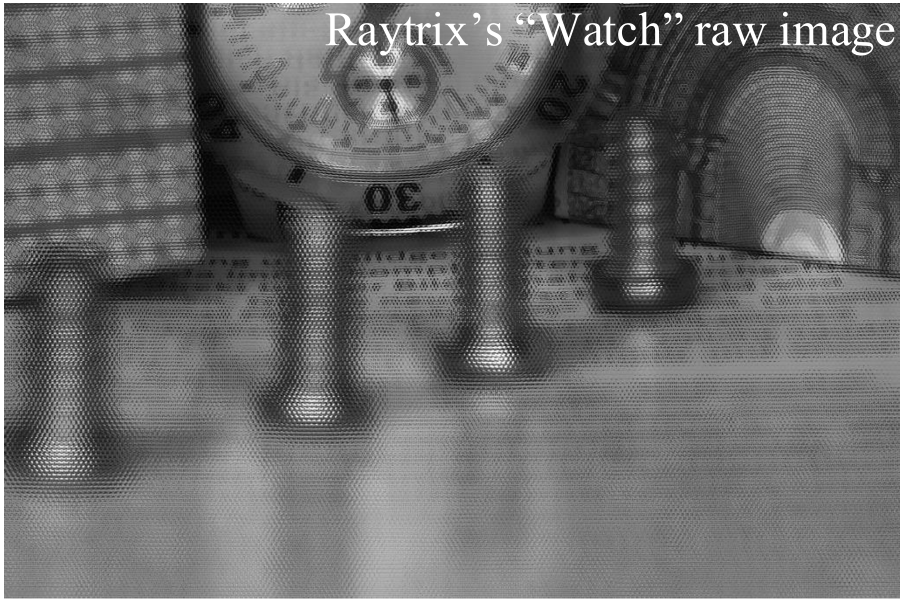


Cunha's one depth coarse map

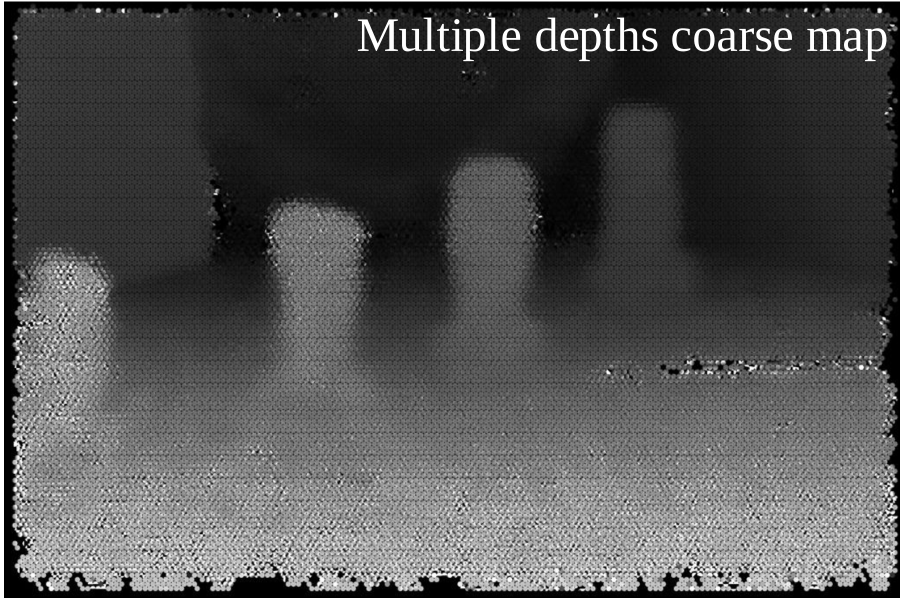


Our one depth coarse map

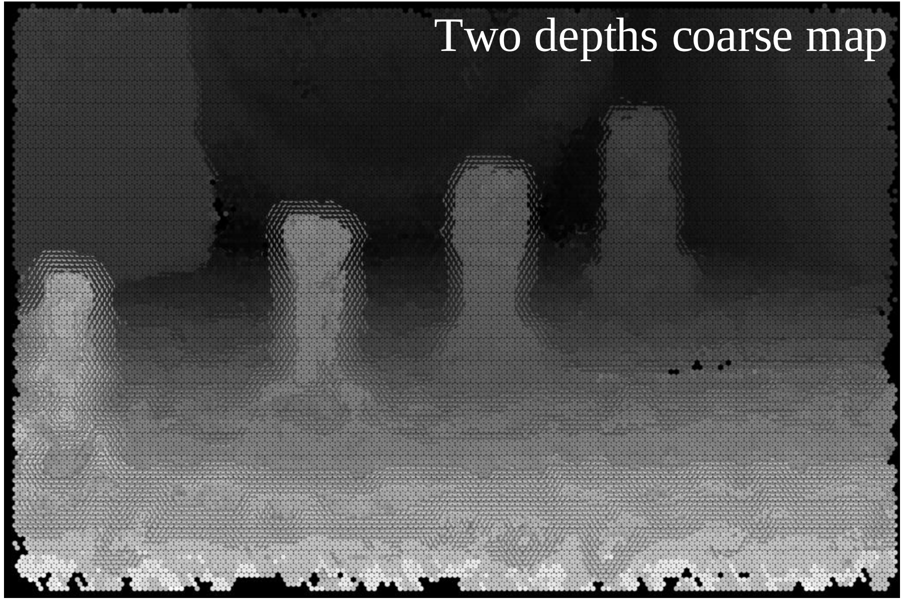
Experimental Results (real images)



Raytrix's "Watch" raw image

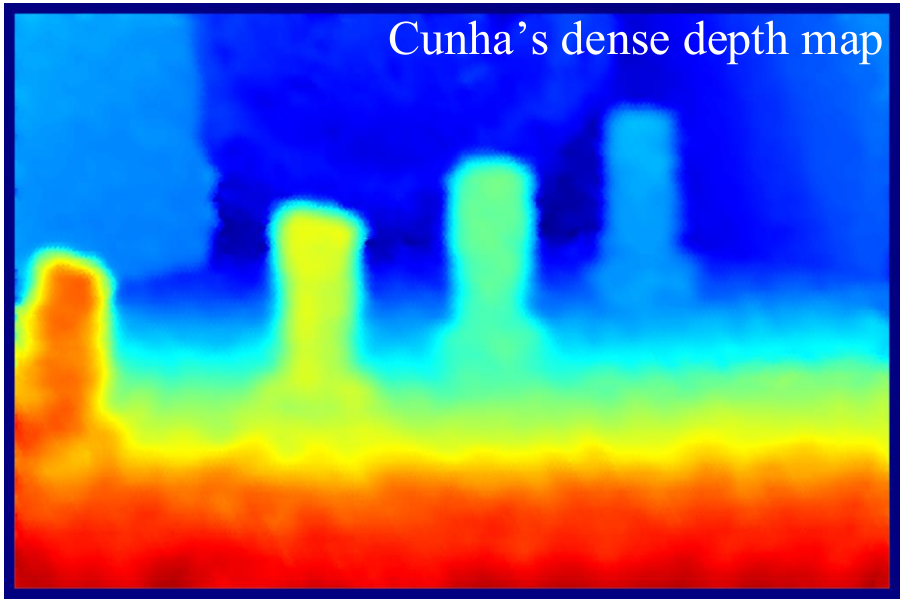


Multiple depths coarse map

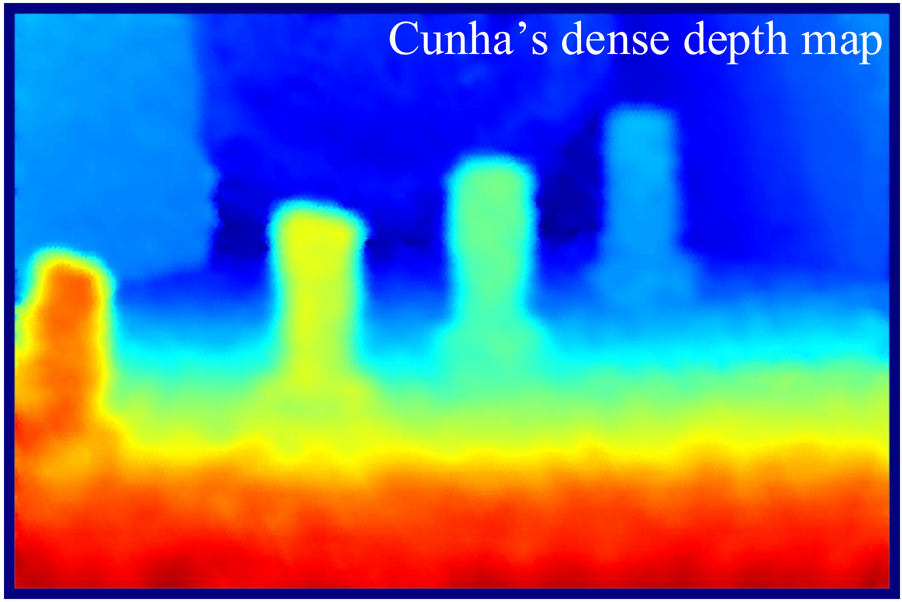


Two depths coarse map

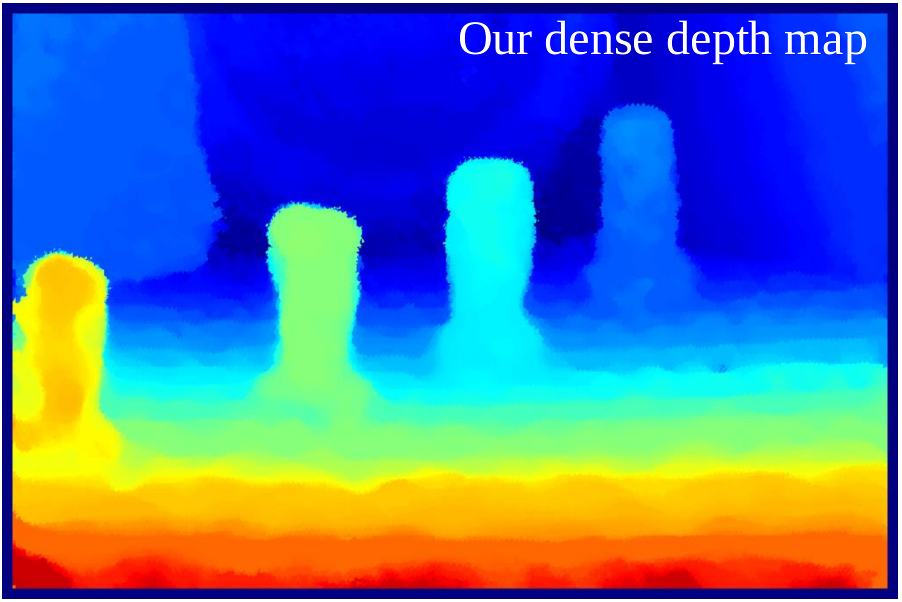
Experimental Results (real images)



Experimental Results (real images)

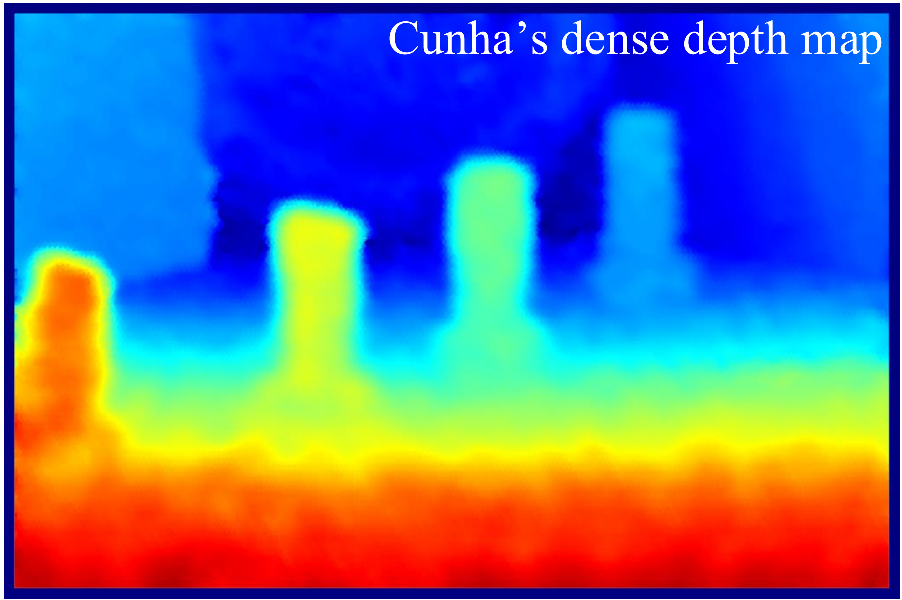


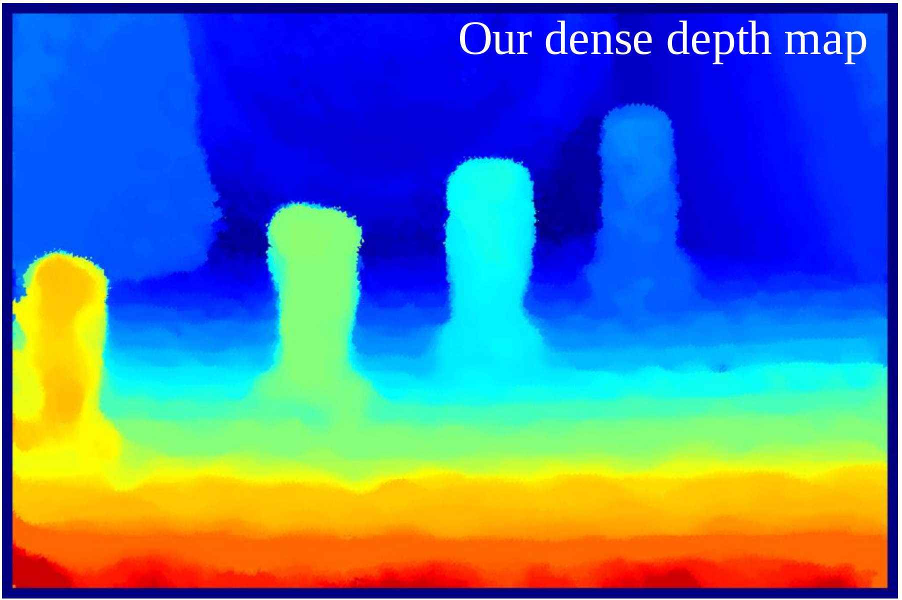
Cunha’s dense depth map

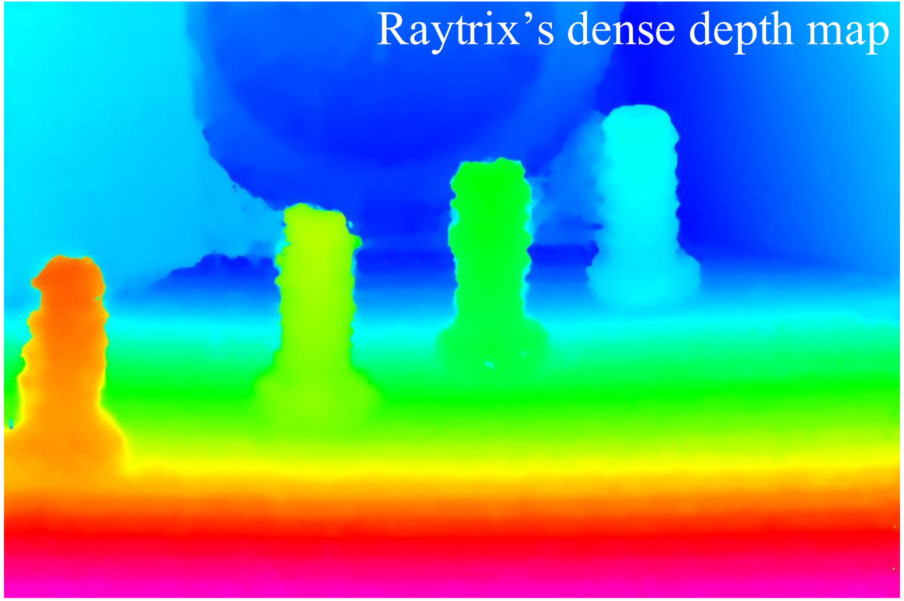


Our dense depth map

Experimental Results (real images)


Cunha’s dense depth map


Our dense depth map


Raytrix’s dense depth map

Improvements

- **Improved point set -** merging of multiple depth map, detection and correction of blurred areas, local outlier filter;
- **Two new and improved coarse depth maps -** improved one depth per micro-lens coarse map, two and multiple depths per micro-lens coarse maps;
- **Improved estimation for the dense depth map**;
- **Improved performance -** 3 times faster that Fleischmann and Koch with comparable results

Future Work

- Improve the new methods to estimate the coarse depth map;
- Dense depth map estimation for the new methods to estimate the coarse depth map;
- Estimate the micro-lenses calibration parameters, such as the focal-length of each micro-lens;
- Correct the micro-lenses distortion[4].

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[4] - O. Johannsen, C. Heinze, B. Goldluecke, and C. Perwass. On the calibration of focused plenoptic cameras. In *German Conference on Pattern Recognition Workshop on Imaging New Modalities*, volume 8200, pages 302–317, 2013.