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Focused light field camera for depth reconstruction model

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Abstract

The light field camera with spatial multiplexing configuration enables to capture 4-dimensional data on 2-dimensional sensor. It creates 2D array of 2D images on a single sensor. Once certain conditions are fulfilled, it is possible to reconstruct the depth with single light field camera. Such measurement method has several advantages as well as several disadvantages. Currently, the most important problems are narrow measurement area and low light intensities.

To overcome these obstacles, we propose augmented focused light field camera model which contains vignetting and image overlapping features included. The model is based on 2D ray tracing technique with first order optics and thin lens approximation. In this article, we state several properties which should be sufficient for the light field optical system design for depth reconstruction. This allows to describe every light field system configuration containing main lens, microlens arrays, stops and a sensor.

Introduction

Within last few decades the light field (LF) camera concept has been studied in plenty areas [1] and many of its features have been elaborated. Both optical design and image processing has been examined, which lead to the effects, such as digital refocusing, view shifting, depth reconstruction, synthetic aperture imaging and others. Although there were some attempts to use LF cameras in photography [2], there was no anticipated response in the market. Another area of LF cameras that was more interested in its possibilities was science and industry. Much has been done with depth reconstruction and it brought valuable results [3]. Especially focused light fields (FLF) [4] with microlens array are widely used for this purpose. Since Raytrix [5] released their first plenoptic cameras in 2010, there is no commercial alternative for them. These cameras are all based on f-number matching rule [6] which ensures maximum sensor resolution usage. Despite its many advantages, there are still some limitations, especially narrow measurement area. To generalize the description of LF cameras, Debis Mignard et al. proposed Equivalent Camera Array model [7] which describes every possible LF camera model. However, it does not include vignetting and image overlapping. In order to augment FLF description we propose a light field camera model which contains vignetting, image overlapping and useful field of view for each image description that can compute any focused light field camera configuration.

The model is based on 2D ray tracing technique and enables rays propagation through optical systems containing lens, lens arrays, stops and sensors. It takes FLF camera configuration as input arguments and calculates some of its properties. Camera configuration in this case shall be understood as a sensor, microlens and main lens properties and their relative positions. The LF camera properties were chosen in order to describe camera's abilities to reconstruct depth. All calculations are limited to first order optics with thin lens approximation and no aberrations are taken into account. The model is implemented in Matlab R2018a.

At first, we consider every main lens-microlens pair (which can be referred as Single Main lens - Microlens System (SMMS)) as an individual optical system. The model calculates its properties separately, in the same way as for conventional cameras. Secondly, it designates LF camera as a sum of single SMMS-s and computes additional properties. In this paper, the model describes FLF camera configuration, which is the most promising for depth reconstruction purposes. However, in the future it can be easily extended to a afocal light field (ALF) case. Figure 1 depicts an example light field system generated by our model.

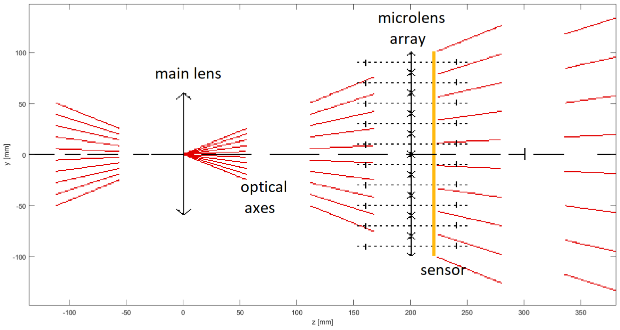

Figure 1: Example LF system containig main lens, microlens array and sensor.

LF camera configuration variables:

- main lens
  - aperture
  - focal
- microlens array
  - apertures
  - focals
  - relative to main lens position
- sensor
  - aperture
  - resolution
  - relative to main lens position

In the paper, we do not consider configurations with different microlens in the array. We examine only the offset equal to microlens apertures where they touch each other. Still, the model can compute LF configurations without those limitations.

Light Field Camera properties

The main goal of the paper is to describe the LF camera quality in function of depth reconstruction. For this purpose, we propose a set of properties and methods of their calculation that should be sufficient to achieve this goal. In general, these are stated as measurement area and measurement quality.

LF camera properties:

- measurement area
  - useful chief rays
  - stereo-vision condition
  - depth of field
- measurement quality
  - MTF function
  - marginal angles
  - effective lateral resolution

Measurement area

The measurement area of light field camera is limited by each SMMS field of view, its depth of field and stereo vision condition, necessary for depth reconstruction. Moreover once overlapping occurs, regions on which more than one image is projected cannot be used for depth reconstruction. Therefore, we propose method of useful chief rays designation.

Chief rays and useful chief rays

Classic definition of chief rays divides the situation depending on aperture and field stop positions. Chief rays propagate through apertures center and edges of field stop [8]. It designates the case with approximately 50% vignetting and doesn't provide full information about energy distribution through optical system. However, another approach is required in order to include vignetting effect and neighbor images overlapping.

In two aperture system, boundary rays can be designated. Parallel ones propagate through same side edges (both bottom or both upper) of main lens and microlens, while the diagonal ones propagate through opposite edges (bottom and upper). Once boundary chief rays are defined, they can be categorized into outside and inside rays. For some regions inside rays are defined by the parallel boundary rays, whereas for others by diagonal boundary rays. It is analogical for outside rays. Figure 2 presents the scheme of these rays in a single SMMS system with main lens, one microlens and a sensor.

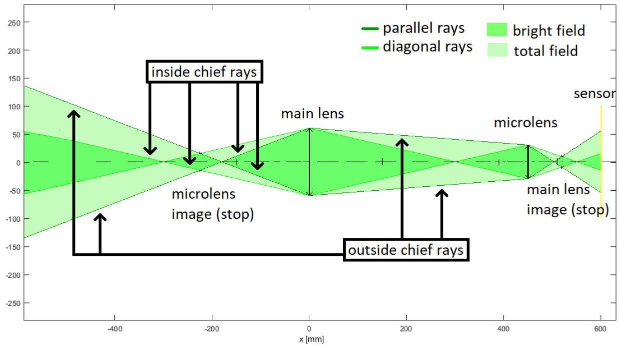

Figure 2: Boundary chief rays for single SMMS.

Inside rays mark the bright field and outside rays the total field. In the area limited by bright field, the light intensity is constant and equivalent to the brightness defined by marginal rays. Outside the edges of the total field, no light can propagate through the system. Between the bright and the total field there is vignetting. Simulations carried in our model have shown that the decrease of light intensity between inside and outside rays is linear in plane perpendicular to the LF system main optical axis.

F-number matching rule fixes sensor's position in the exit pupil. In Fig. 2 it is shown, that in the pupil both, inside and outside chief rays cross. Therefore, no vignetting occurs. However, when considering FLF camera general case outside f-number matching rule, it is possible that adjacent images do not touch. Once the images are smaller than microlens apertures, not whole sensors' surface is used. In this case, boundary chief rays are the same as described above and there are gaps between the images. However, if images are bigger, they overlap each other and it is not possible to use overlapped regions for depth reconstruction. Such an instance is presented in Fig. 3.

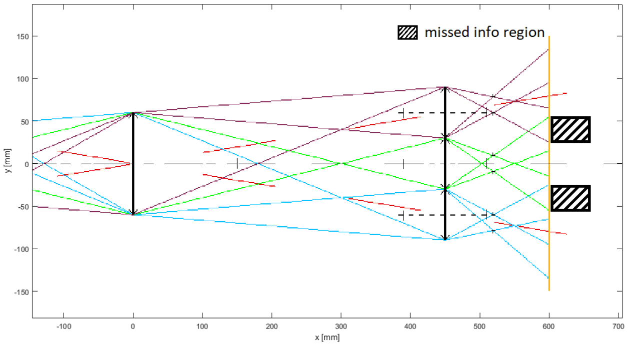

Figure 3: Image overlapping example of LF camera with three SMMS's.

Once the overlapping takes place, new chief rays must be designated. These are called useful chief rays and can also be described by parallel and diagonal (and by inside and outside) rays. This situation could be interpreted if the third aperture in the system appears. Therefore, useful boundary chief rays must cross the edges of useful areas on the sensor and the edges of main lens or microlens. Outside useful chief rays do mark total field, however unlike boundary chief rays, inside useful chief rays do not mark bright field. Energy distribution character does not change within the system, only some part of a sensor is not being used. Therefore, the bright field is limited by inside chief rays and the total field is limited by outside useful chief rays (Fig. 4).

An analogous situation of designating useful chief rays is when the images are not limited by overlapping and the sensor is not placed in exit pupils plane (thus vignetting occurs). It was mentioned that one of the LF cameras problems is low light passing through the system. Therefore, for a given illumination conditions a minimum vignetting must be defined. It limits each SMMS field of view in the same way as overlapping does.

Stereo and multistereovision

Depth reconstruction via stereo vision imposes condition of viewing each measured point from at least two perspectives. Therefore, areas viewed by only one SMMS cannot be measured. It limits the area of measurement as presented in Fig. 5 (on the figure useful chief rays are used). This restraint is defined by

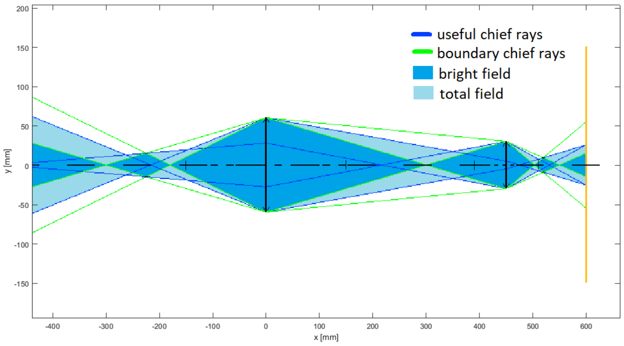

Figure 4: Boundary chief rasy and useful chief rays for single SMMS with inoperative part of the sensor's area.

stereo-vision angle and minimal stereo-vision distance.

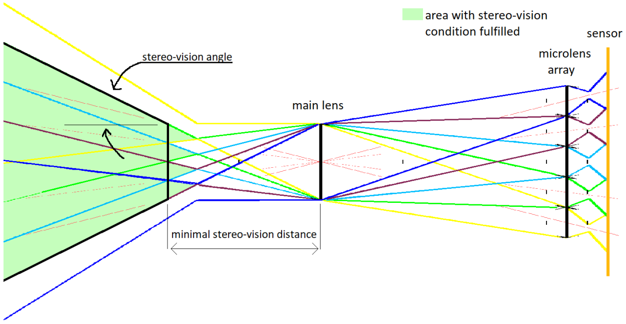

Figure 5: The LF camera measurement area designated by stereovision condition.

Depth of field

Another limitation of optical imaging is placing the object inside depth of field. Front and back depth of field planes limit measurement area. The same condition must be fulfilled for LF cameras. If the object is not in focus, the depth reconstruction is not possible. Example LF camera measurement are limited by useful chief rays, stereo-vision condition and depth of field is presented in Fig. 6.

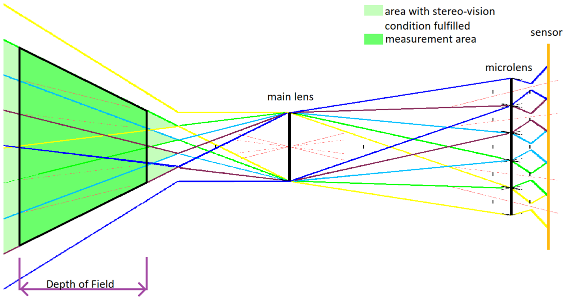

Figure 6: The example LF camera measurement area limited by useful chief rays, stereo-vision condition and depth of field.

Measurement quality

The light field depth reconstruction quality can be stated as an ability to distinguish object structure's details and its' lateral resolution. The first one can be described by the MTF function and theoretically, it would be sufficient for almost every type of camera. However, considering our model's approximations, it is not. Therefore, for the LF camera design purposes, it is more efficient to describe image quality by including also light intensity passing to the sensor. For optical system design purposes it can be described by marginal angles. The second LF depth reconstruction quality parameter is its' final lateral resolution. It is dependent on single views resolution and number of views imaging single object's point.

MTF function

It is acceptable to use MTF function [9] for the optical system resolution description. Though, the LF cameras resolution should also be characterized this way. Because in the model thin lens approximation is used, the MTF will be dependent only on SMMS's magnification and sensor's resolution. Thus, MTF function can be calculated only by resizing bar pattern considering SMMS's magnification and sensor's spatial resolution (equation 1). Only maximal contrast pattern would be examined in the model. For resized output image (Fig. 7), MTF function is calculated with equation 2. This method does not include raytracing, however is sufficient regarding presented model's approximations.

$$r_{out} = \frac{h'}{p} = \frac{m*h}{p} \tag{1}$$

where:

r_{out}	bar pattern's image resolution
h	bar pattern's height
h'	bar pattern image height
m	SMMS's magnification
p	sensor's pixel size

$$MTF = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{2}$$

where:

$I_{max/min}$	max/min image intensity

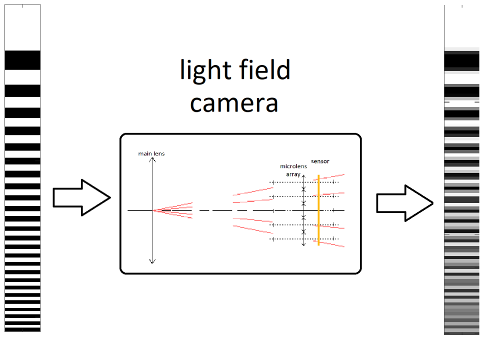

Figure 7: MTF function scheme. Original bar pattern with lineary changing frequency (on the left) and simulated output image of the bar (on the right).

Marginal angles

One of the LF cameras' main disadvantage is low light intensity propagating to the sensor. It is caused by small apertures and results in low dynamic range. This affects cameras' ability to distinguish details and decrease measurement quality. Especially, it can be cumbersome with darkened scenes and high frequency measurements. Therefore, LF cameras require high sensitivity and quality sensors. Nevertheless, for a given illumination conditions, an optical system output can be calculated using radiometry. Such parameters as scene illumination and optical system including sensors' properties need to be considered. However, due to complexity of such approach, for the design process of LF cameras, we can limit this description only to marginal angles (Fig. 8) values.

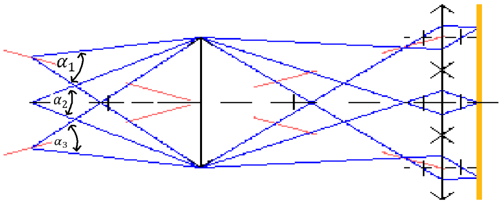

Figure 8: Marginal rays for example LF system with aperture on microlens.

Marginal angles define cones of light transmitted through the system to the sensor and are calculated for on-axis objects. However, as mentioned above, every SMMS can be affected by vignetting. Thus, the marginal angles are valid only on the bright field area. For total field, the cone of light also can be calculated by multiplying marginal angle value by vignetting ratio (for 2D system).

Using proposed model example LF camera system marginal angles simulations were carried. For every microlens and for different sensors' positions, marginal angles were calculated. In Fig. 9 a 3d plot of those angles is presented. For a given sensor position, marginal angles of subsequent microlens create curve with classical cos^4 vignetting associated with the main lens.

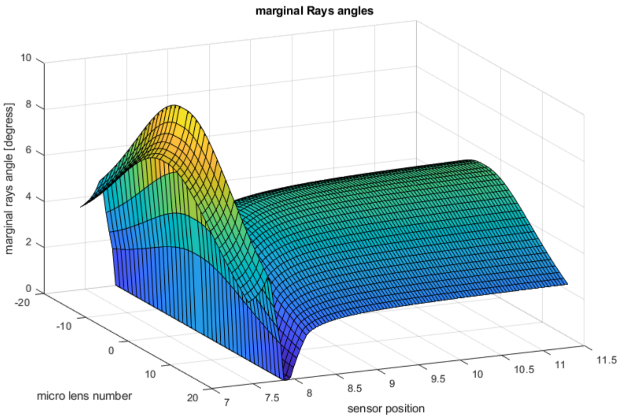

Figure 9: Marginal angles for example LF system with different sensors' positions. Microlens number represents microlens position (0 is on axis microlens), sensor position represents sensor distance from the main lens and on Z axis - marginal angle values in degrees are presented.

Effective lateral resolution

The number of points that can be measured using LF camera is determined by useful sensor resolution divided by a number of images containing single object's point. As stated before, it is necessary to see every measured single point by at least two cameras. However, depending on camera configuration and object's position, different number of views can see each objects' point. Thus, effective LF camera resolution for depth reconstruction equals useful sensor resolution divided by number of pixels seeing the same point (equation 3). In paper [6] this property was defined as virtual depth.

$$ELR = \frac{R_u}{v} \tag{3}$$

where:

ELR is Effective Lateral Resolution

R_u is useful sensor resolution

v is virtual depth

Laboratory setup

Light field camera laboratory setup has been built and is presented in Fig. 10. It allows to set up every LF camera configuration containing sensor, main lens and microlens array. Provides an ability to adjust microlens array in two axis precise (with a rotation stage and a goniometer) and coarse in the main system axis with a rotation ring. Furthermore, every element can be adjusted linearly in the system symmetry axis direction with linear stages.

For the paper purposes following elements has been used:

- main lens
  - F = 50mm
  - F/# 1.6 - 16
- microlens array
  - ROC = 422 μ m
  - NA = 0.18
  - pitch = 400 μ m
- sensor
  - resolution 3664x2748
  - pixel size = 1.66 μ m

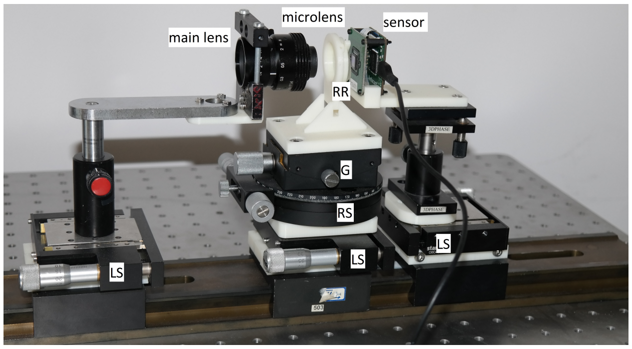

Figure 10: LF camera measurement system scheme. G - goniometer, LS - linear stage, RT - rotation stage, RR - rotation ring.

Below in Fig. 11 an example RAW image captured with LF system of 4 dots pattern is presented. The system was set with f-number matching rule and thus, there is no vignetting. Each dot is imaged on several views, which means the depth can be reconstructed.

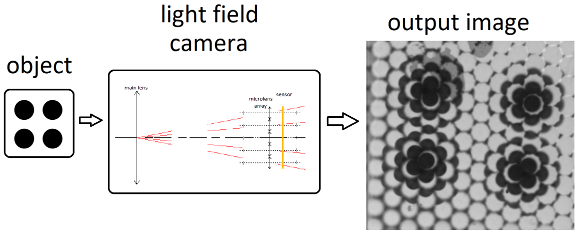

Figure 11: Example 4 dot pattern imaged by laboratory light field camera setup.

Conclusion

The proposed LF camera model extends current LF description state of the art. In this paper, we have demonstrated several properties that are essential for depth reconstruction and which we believe are sufficient for this aim. With our model it is possible to designate every FLF camera configurations' properties. When designing the FLF camera optical system, it is possible to improve some properties at the expense of others. Usually, there must be a compromise between the measurement area and the measurement quality. The number of variables in the proposed model leads to a great number of possible configurations. Thus the process of finding optimal configuration implies performing many iterations. Once the FLF camera configuration is stated for a given requirements and conditions, an optical system must be analyzed in terms of aberrations. The proposed model is not valid for this objective, however it can be done with commercially available software. Finally, it can be extended to configurations with microlens array with different than its apertures pitch.

At the moment the model lacks validation. Although it would be difficult to measure each property for several LF camera configurations, the authors intend to propose model validation. The idea is to compare the difference of the LF camera properties' between few configurations calculated with the model and acquired with experimental setup. This will allow to eliminate several unknown factors such as illumination conditions or quality of the workmanship of optical elements or the object. The model does not include the impact of the algorithm on depth reconstruction and is limited to first order optics with no aberrations considered.

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References

[1] Gaochang Wu, Belen Masia, Adrian Jarabo, Yuchen Zhang, Liangyong Wang, Qionghai Dai, Tianyou Chai, and Yebin Liu. Light field image processing: An overview. *IEEE Journal of Selected Topics in Signal Processing*, 11(7):926–954, 2017.

[2] Lytro Inc., 2006.

[3] Niclas Zeller, Franz Quint, and Uwe Stilla. Depth estimation and camera calibration of a focused plenoptic camera for visual odometry. *ISPRS Journal of Photogrammetry and Remote Sensing*, 118:83–100, 2016.

[4] A. Lumsdaine and T. Georgiev. The focused plenoptic camera. In *2009 IEEE International Conference on Computational Photography (ICCP)*, pages 1–8, April 2009.

[5] Raytrix GmbH, 2009.

[6] Christian Perwass and Lennart Wietzke. Single lens 3d-camera with extended depth-of-field. In *Human Vision and Electronic Imaging XVII*, volume 8291, page 829108. International Society for Optics and Photonics, 2012.

[7] Lois Mignard-Debise, John Restrepo, and Ivo Ihrke. A unifying first-order model for light-field cameras: The equivalent camera array. *IEEE Transactions on Computational Imaging*, 3(4):798–810, 2017.

[8] Michael J Kidger. *Fundamental optical design*, volume 92. SPIE press Bellingham, 2002.

[9] Glenn D Boreman. *Modulation transfer function in optical and electro-optical systems*, volume 21. SPIE press Bellingham, WA, 2001.

Author Biography

Piotr Osinski received B. Eng. in 2016 and MSc in 2018 degree in mechatronics with photonics specialty at Warsaw University of Technology, Poland. Since 2018 he is PHD student and employee at WUT. His current interests include design of optical measurement systems and 2D and 3D image processing. Since the end of 2017 mostly light field cameras.

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Marcin Malesa is working at the Institute of Micromechanics and Photonics, Warsaw University of Technology. He received his PhD in 2014 in the discipline of Building and Maintenance of Machines. His scientific interests include applications of non-coherent optical methods of displacements, strains and shape measurements as well as data science and machine learning techniques. He focus on industrial applications of the results of the research works.

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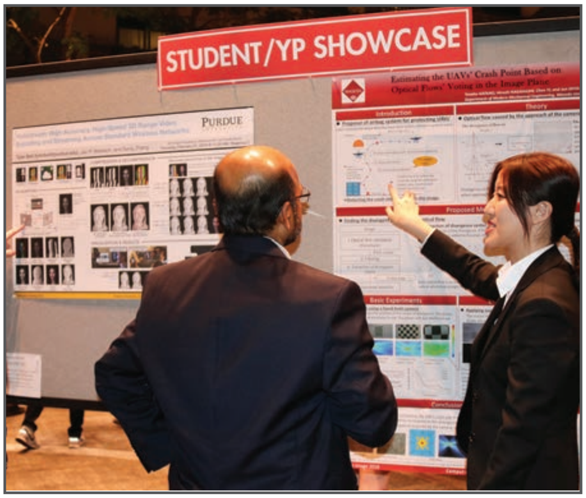

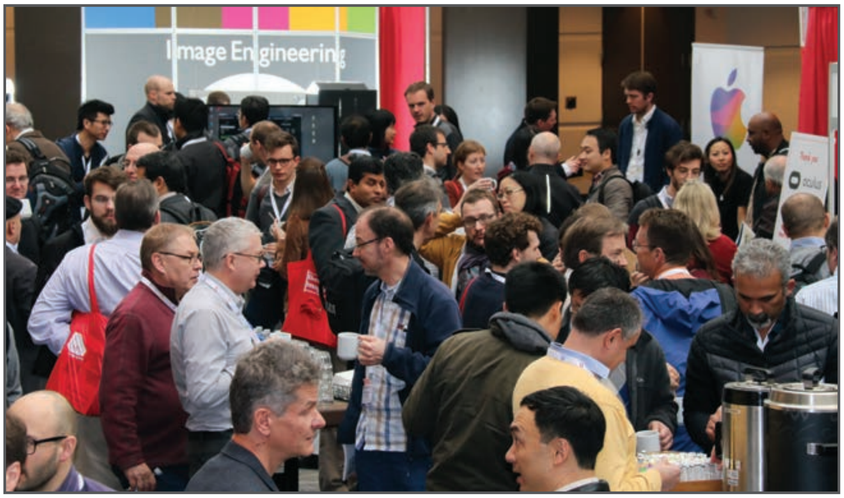

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