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Full-parallax 3D display using time-multiplexing projection technology

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Abstract

We enhanced the resolution characteristics of a three-dimensional (3D) image using time-division multiplexing methods in a full-parallax multi-view 3D display. A time-division light-ray shifting (TDLS) method is proposed that uses two polarization gratings (PGs). As PG changes the diffraction direction of light rays according to the polarization state of the incident light, this method can shift light rays approximately 7 mm in a diagonal direction by switching the polarization state of incident light and adjusting the distance between the PGs. We verified the effect on the characteristics of 3D images based on the extent of the shift. As a result, the resolution of a 3D image with depth is improved by shifting half a pitch of a multi-view image using the TDLS method, and the resolution of the image displayed near the screen is improved by shifting half a pixel of each viewpoint image with a wobbling method. These methods can easily enhance 3D characteristics with a small number of projectors.

Introduction

Recently, attention has been focused on light field displays that reproduce numerous light rays to form an optical image in space. These displays are expected to be employed in applications in a wide range of industrial fields such as TVs, games, medicine, and education because natural 3D images can be expressed without using special glasses or headgear. In light field displays, there is a three-dimensional (3D) display that uses multi-view images [1–3]. This display superimposes multi-view images on a screen by projectors or similar devices to reproduce a 3D image in space. Because the resolution of the 3D image is equal to the resolution of each viewpoint image, the resolution of the 3D image can be enhanced by increasing the resolution of the multi-view images. However, conventional multi-view 3D displays can only reproduce 3D images with horizontal parallax, not with vertical parallax. Thus, a faithful optical image is not formed in space, and distortion might occur in the 3D image at places other than the predetermined observation position. Furthermore, as numerous projectors are used, and the scale of the system increases, the settings in which these displays can be used become limited.

Therefore, we have developed a system called *Aktina Vision*, which can be watched by multiple people and displays high-resolution 3D images with full-parallax for 3D TV broadcasting [4]. In this system, the number of projectors can be reduced because a multi-view image with both horizontal and vertical parallax is projected from each projector. However, each projector must have a high level of performance to display high-quality 3D images.

Several time-multiplexing methods are reported [5–7] to improve the quality of the 3D images. These methods improve the quality of the 3D images by controlling each LED of the backlight at a high frame rate or using a shutter. A potential drawback of these methods is the low brightness of the displayed 3D image. A method to control the direction of light by using an active slit [8] and a method for dynamically swinging the optical screen [9] are proposed. However, it is challenging to maintain the state because these methods require the optical elements to move mechanically.

In this research, we propose a time-division light-ray shifting (TDLS) method to enhance the 3D resolution characteristics. As the light rays projected from a projector are optically shifted, the number of light rays reproduced by the projector is increased by time division. Two polarization gratings (PGs) are used to perform the TDLS method. The PG selects the direction of the diffraction of the light rays according to the polarization state of the incident light. Hence, the optical axis of the incident light can be shifted in parallel by arranging two PGs in parallel and switching the polarization state of the light from the projectors. We also developed compact projectors with a wobbling device, which shift the light rays of a multi-view image by half a pixel. We performed analyses and experiments to verify the effect of the two proposed methods on the 3D image resolution characteristics.

Aktina Vision

Figure 1 shows the basic configuration of *Aktina Vision* [4]. A multi-view image, which has both horizontal and vertical parallaxes and arrayed in the prescribed plane, is projected from each projector and collimated by the collimator lens. Those same images are passed through the imaging lenses to divide them into viewpoint images. Then, each viewpoint image is condensed at Condenser lens 1 placed at the focal length of the imaging lenses. After the viewpoint images are diffracted, they are superimposed onto the 3D screen consisting of the condenser lens and the diffusing screen, which is placed at the focal length of Condenser lens

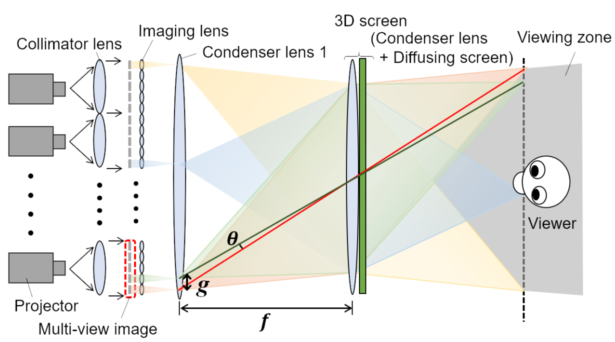

Figure 1. *Basic configuration of Aktina Vision.*

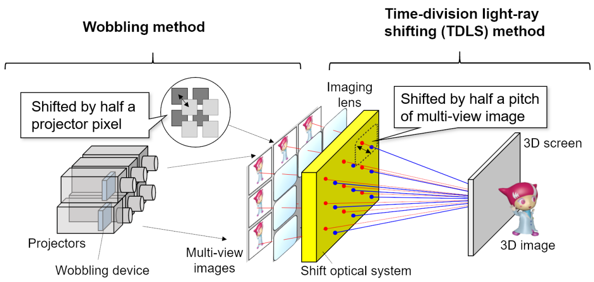

Figure 2. Overview of proposed methods in Aktina Vision.

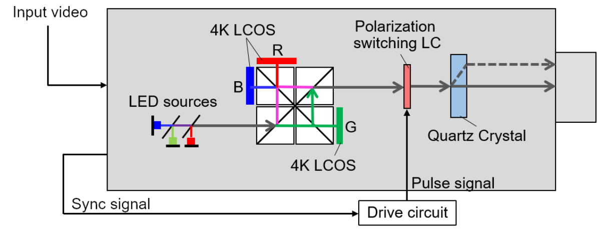

Figure 3. Developed 4K Projector with wobbling device.

1. The diffusing screen has narrow diffusion characteristics. Because the diffusing screen widens the light rays of each viewpoint image, the viewer can observe a 3D image with smooth motion parallax. In this system, the image of each viewpoint is displayed on the entire screen. Therefore, the number of pixels of the 3D image becomes equal to the number of pixels of each viewpoint image. Furthermore, the angular interval θ of the viewpoint images is determined by the focal length f of Condenser lens 1 and the pitch interval g of the viewpoint images, and it is expressed as

$$\theta \approx \frac{g}{f}. \tag{1}$$

Therefore, the angular interval θ can be reduced by increasing the focal length f of Condenser lens 1 or decreasing the pitch interval g of the viewpoint images. In this system, the angular interval in the horizontal direction is designed to be approximately one degree.

Time-division light rays multiplexing methods

Each projector must project numerous light rays to reproduce natural 3D images in *Aktina Vision*. In this research, we propose two time-division light rays multiplexing methods. The number of light rays from each projector is increased by shifting them by time division. Figure 2 shows an overview of these two methods. The first method, called the wobbling method, shifts light rays by half a pixel in the diagonal direction inside each projector. The other method, which is Time-division light-ray shifting (TDLS) method, is used to shift the multi-view image by half a pitch in the diagonal direction. As a result, the number of viewpoint images increases in time division by using the TDLS method.

Wobbling method

The wobbling method uses a Quartz crystal and a polarization switching liquid crystal (LC) using a drive circuit. The polarization state of lights is switched to orthogonal polarization directions by the LC. These elements are placed in the light path of the projector as shown in Fig. 3. As the control voltage of the drive circuit is switched, the incident light into the Quartz crystal is also switched as ordinary light rays or extraordinary light rays. In the Quartz crystal, the ordinary light rays go straight without reflection. However, the extraordinary light rays in the Quartz crystal are diffracted. Thus, the outgoing lights can be shifted by electrical switching of the LC via the drive circuit. The thickness of the Quartz crystal determines the amount of light shifting. The thickness of the Quartz crystal is adjusted to shift light rays by half a pixel in the diagonal direction. Therefore, the resolution of each viewpoint image of the multi-view images becomes double in time division.

Time-division light-ray shifting (TDLS) method

The TDLS method uses two polarization gratings (PGs). The PG is a diffractive optical element manufactured by combining a liquid crystal polymer, which is a birefringence and photo-alignment material in a diffraction grating shape achieved by irradiation of UV light [10, 11]. Its function is to select the diffraction direction according to the polarization state of the incident light, as shown in Fig. 4. When the incident light of horizontal polarization is input into the PG, it is diffracted in the 1st-order diffracted direction as shown in Fig. 4(a). However, when the incident light of the vertical polarization is input, it is diffracted in the −1st-order diffracted direction as shown in Fig. 4(b). The PG can achieve a diffraction efficiency of approximately 90 % by having a thickness that changes the phase of the light transmitted through the PG by 90 ° [10].

Therefore, the light rays can be shifted in parallel by using the optical shift system with the two PGs arranged in parallel. For example, the outgoing lights that is diffracted in the 1st-order diffracted direction by the 1st PG becomes vertically polarized, followed by the light diffracted in the −1st-order diffracted direction by the 2nd PG, as shown in Fig. 4(a). If the diffraction pitch Λ of the two PGs is the same, the diffraction angle is also the same. This means that the light rays are shifted in parallel by the amount of Δs. However, in the case of incident light with vertical polarization, the light rays are shifted by $-\Delta s$. Because the shift amount is determined by the distance l between the two PGs, the TDLS method makes it possible to shift light rays by any desired amount. The shift amount Δs is given as

$$|\Delta s| = \frac{\lambda}{\sqrt{\Lambda^2 - \lambda^2}} l, \tag{2}$$

where λ is the wavelength of the light and Λ is the diffraction pitch. In this research, the multi-view images are shifted by half a pitch using the TDLS method so that the angular interval of the multi-view image becomes half.

Analysis of 3D resolution characteristics

We analyzed which of the 3D image characteristics shows improvements by using the proposed methods. As shown in Fig. 5, we assume a spatial viewing frequency of a 3D image observed at a position D from the screen surface. When the 3D image is reproduced at a depth position z from the screen surface, the spatial

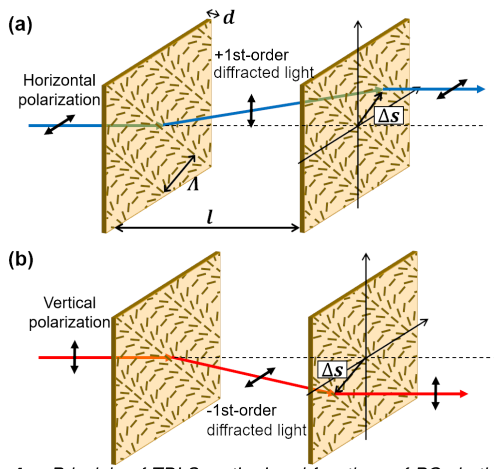

Figure 4. *Principle of TDLS method and functions of PGs in the case of input incident light of (a) horizontal polarization and (b) vertical polarization.*

viewing frequency β [cpr (cycles per radian)] is expressed [12] as

$$\beta = \alpha \frac{D-z}{|z|}, \tag{3}$$

where α is the spatial frequency of the displayed image.

The spatial frequency α of the displayed image is limited because of the angular interval of the multi-view images and the diffraction of light rays at the diffusing screen. Because the maximum projectable frequency α_{max} through the pixel of the projected image on the screen is $\alpha_{max} = f/2g$, where g is the viewpoint interval of the multi-view image, the corresponding maximum spatial viewing frequency β_{max} is expressed as

$$\beta_{max} = \alpha_{max} \frac{D-z}{|z|} = \frac{f(D-z)}{2g|z|}, \tag{4}$$

where f is the focal length of Condenser lens 1 in Fig. 5.

The displayed 3D image is sampled by the pixel on the screen. The sampling period is p/D [rad] where p is the pixel pitch on the screen. Thus, the Nyquist frequency β_{nyq} of the sampling is,

$$\beta_{nyq} = \frac{D}{2p}. \tag{5}$$

When the Nyquist frequency β_{nyq} is smaller than the maximum spatial viewing frequency β_{max} of the 3D image, the viewer observes the 3D image with aliasing. That means the 3D image is not always visible at the maximum spatial viewing frequency β_{max}. Therefore, the spatial frequency γ of the 3D image observed is expressed as follows:

$$\gamma = \min\{\beta_{max}, \beta_{nyq}\} = \min\{\frac{f(D-z)}{2g|z|}, \frac{D}{2p}\}. \tag{6}$$

Figure 6 shows these analysis results. The resolution of the 3D image displayed near the screen is equal to the Nyquist frequency β_{nyq}. However, the resolution of the 3D image displayed further from the screen is dominated by the maximum spatial viewing frequency β_{max} and it decreases as the image is displayed

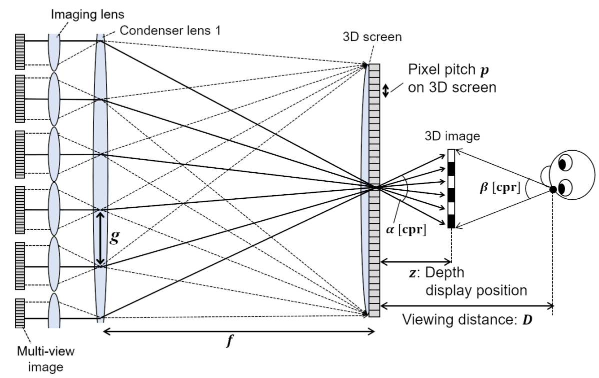

Figure 5. *Resolution characteristics of 3D image.*

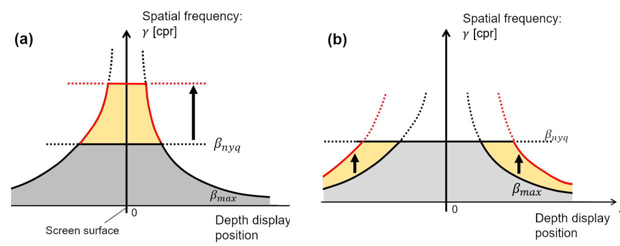

Figure 6. *Resolution characteristics of 3D image in (a) half of pixel pitch with wobbling and (b) half of viewpoint interval with TDLS.*

further away from the screen. Figure 6(a) shows the case of the wobbling method used to halve the pixel pitch p on the screen and Fig. 6(b) shows the case of the TDLS method used to halve the viewpoint interval g of the multi-view images. Therefore, it is expected that the resolution of the image displayed near the screen is improved by the wobbling method. However, the TDLS method could improve the resolution of the image displayed further from the screen.

Display system

Figure 7 shows the overall view of the prototype display system. The optical shift system as shown in Fig. 7(d) is used only when the TDLS experiment is conducted. Table 1 shows the default specifications of the display system. We developed six compact 4K projectors with wobbling devices, and these projectors are arranged in a zigzag formation as shown in Fig. 7(b). Because a high-quality lens is used for each projector, it can project at a pixel density of 800 ppi. The frame rate of each projector is 60 fps. Because a multi-view image consisting of 25 viewpoint images in 5 horizontal and 5 vertical directions is displayed from each projector, the resolution of each viewpoint image is 768 and 432 pixels in the horizontal and vertical directions, respectively. Each viewpoint image is projected on each lens of the imaging lenses arranged in a two-dimensional array, as shown in Fig. 7(c). Then, each viewpoint image is condensed at Condenser lens 1 and superimposed on the 3D screen. This prototype system reproduces light rays of 99,532,800 using time-division. The display size is 16.5 inch, the default number of viewpoint images is 150, and the default angular interval θ is 0.9° (H) $\times$ 0.5° (V).

The optical shift system as shown in Fig. 7(d) is set at the po-

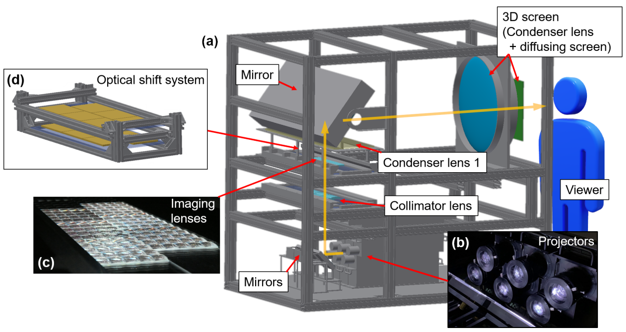

Figure 7. *Developed display system: (a) overall view in the system, (b) six projectors, (c) imaging lenses arranged in two-dimensional array, and (d) optical shift system used for TDLS experiment.*

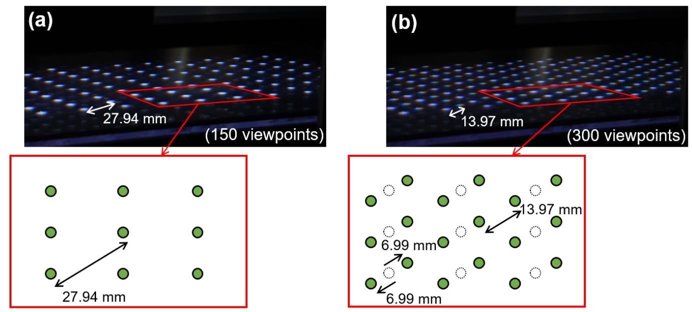

Figure 8. *Doubling the number of viewpoints from (a) without TDLS to (b) with TDLS.*

Table 1. Specifications of developed display system.

Projector	Resolution	3840 × 2160 pixels
	Number	6
	Frame rate	60 fps
3D Image	Display size	16.5 in.
	Resolution	768 (H) × 432 (V) pixels
	Viewpoints	150 (Default)
	Angular interval	0.9 ° (H) × 0.5 ° (V) (Default)
	Viewing angle	14.4 ° (H) × 5.0 ° (V)

sition between the imaging lenses and Condenser lens 1 because we do not need to increase the number of the imaging lenses. The PGs can also be tiled in a two-dimensional array without bezel influence because this position is where each viewpoint image is condensed. Hence, the TDLS method can shift large area light rays at the same time. The diffraction pitch Λ of the PGs for the TDLS method is 3.5 μm and the shift amount Δs to shift by half a pitch of the multi-view images in a diagonal direction is $\Delta s = 6.99$ mm. Therefore, the distance l between the PGs of the optical shift system is adjusted at 49.5 mm calculated from Eq. 2.

Figure 8 shows the results of doubling the number of viewpoint images by the TDLS method. These figures are captured at the position between the optical shift system and Condenser lens 1 in Fig. 7(a). These convergence light points indicate the number of viewpoints. As a result, we confirmed that the number of viewpoints becomes double in time division and the pitch interval of the multi-view image becomes half. The shift amount predicted by the theory of Eq. 2 can also be achieved. Therefore, it is suggested that the TDLS method is more effective when the light rays are shifted significantly.

Experiments

Figure 9 shows the results in the wobbling experiments. These 3D images are displayed at 20 mm from the screen to the front side. In this system, the resolution γ of the 3D image is dominated by the Nyquist frequency β_{nyq} of Eq. 6 when the depth display position z is $-34.2\,\text{mm} \leq z \leq 33.0\,\text{mm}$. Therefore, the resolution of the 3D image displayed near the screen can be improved by wobbling. Without wobbling as shown in Fig. 9(a) and (b), aliasing occurs at the spatial frequency of 1089 cpr. However, by using the wobbling method, the spatial frequency is improved to 1720 cpr, which is double the improvement expected based on the principle of Eq. 6. However, an improvement of about 1.6 times is confirmed in this experiment, largely because of the calibration accuracy. In this research, a marker pattern is displayed for each viewpoint and captured by a digital camera. The projected image is geometrically corrected so that each marker point matches the reference position [13]. When the wobbling method is used to improve the quality of 3D images, calibration accuracy is required in sub-pixel units. Therefore, we need to consider the calibration using a camera with a higher resolution and the optimization of the calibration method in the future.

Figure 10 shows the results of the TDLS experiments. These teapots are displayed at 100 mm from the screen to the front side, where the resolution of the 3D image is determined by β_{max}. It is noted that the diffusion angle of the diffusing screen with TDLS is set to 1.0 ° while without TDLS is set to 2.0 ° because the angular interval of the multi-view image becomes half with TDLS, such that the required diffusion angle to eliminate the blind spots in the 3D images also become half. From these figures and profiles, the edge of the 3D image can be seen clearly with the TDLS method. Thus, it is suggested that the resolution of the 3D image displayed further from the screen could be improved by using that method.

Conclusion

In this research, we proposed two time-division light ray multiplexing methods to improve the quality of 3D images in a full-parallax 3D display system. Wobbling can shift light rays by half a pixel from a projector. On the other hand, the TDLS method uses an optical shift system consisting of two PGs and can shift light rays by approximately 7 mm. We then analyzed and conducted experiments to verify the effect of the two proposed methods. As a result, the wobbling method doubles the resolution of each viewpoint image and the resolution of the 3D image displayed near the screen is improved. When the TDLS method is used, the angular interval of the multi-view image becomes half. Moreover, the depth resolution of the 3D image could be improved by TDLS. These methods make it possible to easily enhance the 3D image characteristics without using several extremely high-definition projectors. In future work, we will further improve the 3D image quality by increasing the multiplicity of time division using a high frame rate display.

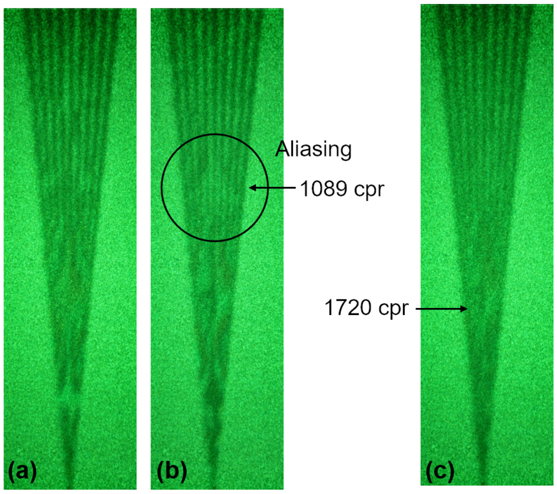

Figure 9. *Results of 3D images displayed at 20 mm of depth from the screen to front side of (a) odd frames and (b) even frames without Wobbling, and (c) with Wobbling.*

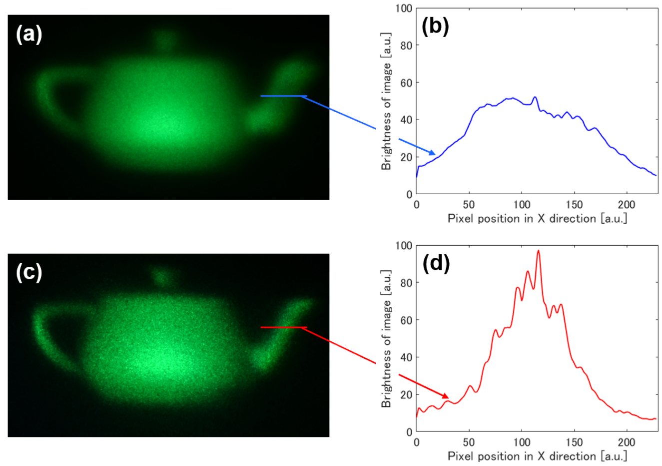

Figure 10. *Results of 3D images displayed at 100 mm of depth from the screen to front side and brightness profiles of 3D images: (a) and (b) are results without TDLS, and (c) and (d) are results with TDLS.*

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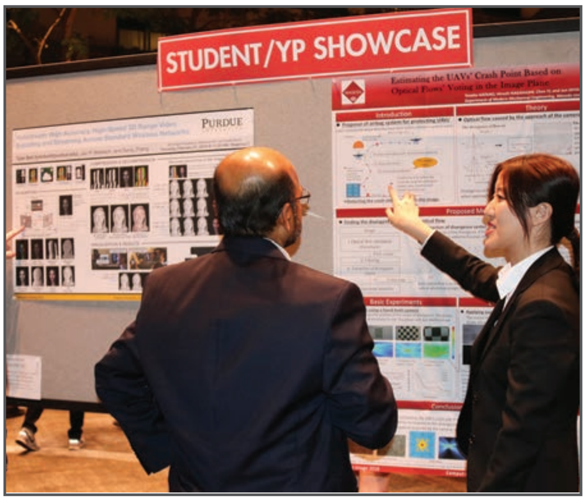

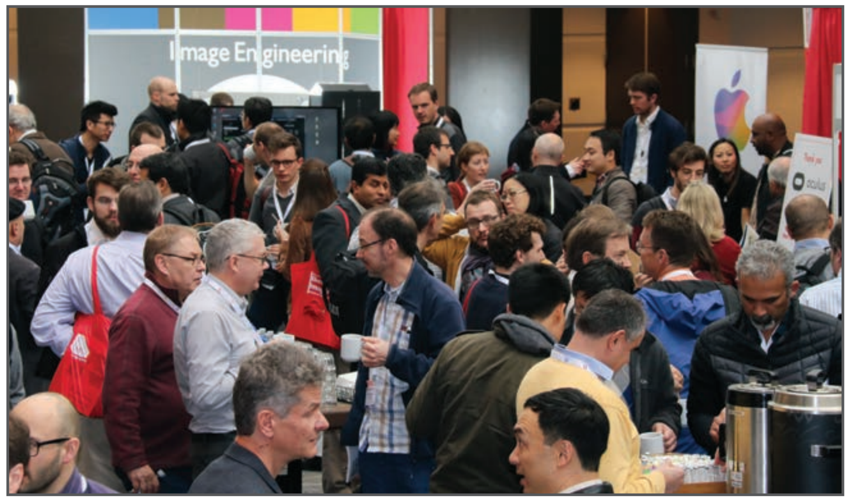

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