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Colour gamut mapping using vividness scale

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Abstract

A gamut compression algorithm (GCA) and a gamut extension algorithm (GEA) were proposed based on the concept of vividness. Their performance was further investigated via two psychological experiments together with some other commonly used gamut mapping algorithms (GMAs). In addition, difference uniform colour spaces (UCSs) were also evaluated in the experiments including CIELAB, CAM02-UCS and a newly proposed UCS, $J_za_zb_z$. Present results showed that the new GCA and GEA outperformed all the other GMAs and the $J_za_zb_z$ was a promising UCS in the field of gamut mapping.

Introduction

Colour management is essential when communicating colours between devices. It usually involves three major components, i.e. device characterization, uniform colour space and gamut mapping. Among them, gamut mapping is the key to connect two gamuts having different capabilities of rendering colors.

Gamut mapping algorithms (GMAs) can be divided into 2 categories, i.e. gamut compression algorithms (GCAs) and gamut extension algorithms (GEAs). For GCAs, mapping is usually performed from a relatively large gamut into a small one. The International Commission on Illumination (CIE) recommended two GCAs, HPMINDE and SGCK, as anchors to reconcile the different interval in different experiments [1]. The former one is a clipping method, which keeps all colours in destination gamut unchanged and maps colours out of gamut onto the nearest point on the destination gamut boundary. The latter one is a colour-by-colour compression method, mapping colours towards a single focal point on the lightness axis having the same lightness value as the cusp, i.e. the colour having the maximum chroma in a hue plane. Instead of mapping towards a single focal point, many algorithms first divide the original gamut into regions and then apply different focal points for each of them. Kang [2] proposed a GCA having three focal points for different lightness regions. MacDonald [3] developed a multi-direction GCA (referred as TOPO), which constructed a set of mapping chords according to the positions of source colours.

On the contrary, GEAs map colours from a small gamut into a larger one. Most algorithms in this category are based on the hypothesis that memory colors are often in a low chroma region and should be preserved unchanged while more saturated, unnatural colors can be extended utmost to achieve a pleasing colour reproduction. Such kind of GEAs involve Ward et al.'s hybrid colour mapping (HCM) [4] and Justin et al.'s high chroma boost method (HCB) [5]. Another kind of GEA was proposed by Zamir [6] using an image energy function. Minimization of this function led to an increase of image contrast and also the extension of the gamut of an input image.

In this paper, two gamut mapping algorithms will be proposed, including a gamut compression algorithm and a gamut extension algorithm. Their performance was evaluated via two psychological experiments with all these algorithms mentioned above. In addition, three uniform colour spaces (UCSs) including the most uniform UCS, CAM02-UCS [7], a newly developed UCS, $J_za_zb_z$ [8] and the most widely used UCS, CIELAB were also investigated. Results were analyzed to find a best GMA and UCS combination in the field of gamut mapping.

Development of new GMAs

There are 2 GMAs developed in this study based on the concept of vividness [9]. Vividness is a new colour appearance scale proposed by Berns and is defined as the distance to the gamut black in a uniform colour space. Berns claimed that vividness was a good representative of visual experience and was then verified by Cho et al. [10,11] to have a strong correlation with human perception.

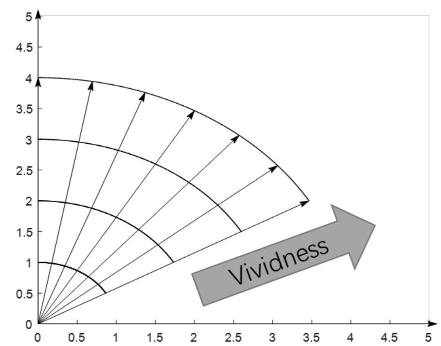

Figure 1. Illustration of vividness. The points in the vectors away from black were said to have different vividness.

New GCA development

A new GCA, vividness-preserving (VP) is developed in this paper with the aim of preserving as much vividness as possible in gamut compression. Its steps are as follows,

1) Non-linear lightness mapping

A linear lightness mapping was applied to the source gamut boundary using Eq.1. Hence, a new gamut boundary can be built as the dot dashed line in Fig. 2, having same lightness range as the destination gamut.

$$L' = \frac{L - min(L_O)}{max(L_O) - min(L_O)} * (max(L_r) - min(L_r)) + min(L_r) \qquad (1)$$

where L and L' represent the lightness value of the source colour and its lightness mapped result, respectively; o refers to the original and r refers to the reproduction respectively.

For any colour within the 90% region of the newly constructed gamut (core region), it would be kept unchanged; otherwise it was mapped towards the focal point E, which has the same lightness of the cusp of the source gamut. The function adopted to perform such mapping is as follows:

$$\overline{EP'} = \begin{cases} \overline{EP};\ \overline{EP} \le 0.9 * \overline{EP_d} \\ 0.9 * \overline{EP_d} + \frac{\overline{EP} - 0.9*\overline{EP_d}}{\overline{EP_s} - 0.9*\overline{EP_d}} * \frac{\overline{EP_d}}{10};\ \overline{EP} > 0.9 * \overline{EP_d} \end{cases} \qquad (2)$$

where E is the focal point, P is the source colour in the original gamut, P' is the mapping output of this step, P_s is the intersection of the line $\overrightarrow{EP}$ and the original gamut boundary, and P_d is the intersection of the line $\overrightarrow{EP}$ and the destination gamut boundary. This nonlinear lightness mapping is quite similar to the last step of the SGCK algorithm, which uses the similar knee function as described here.

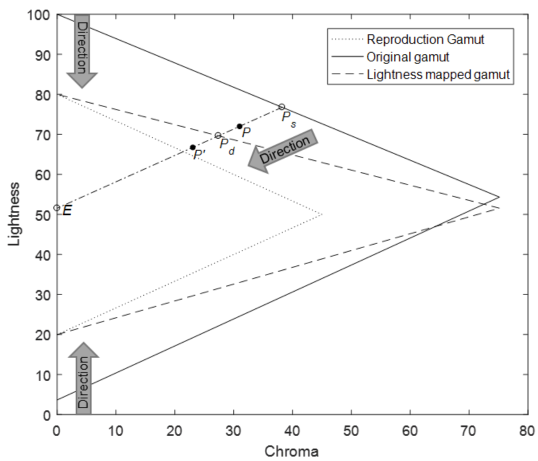

Figure 2. Illustration of non-linear lightness mapping

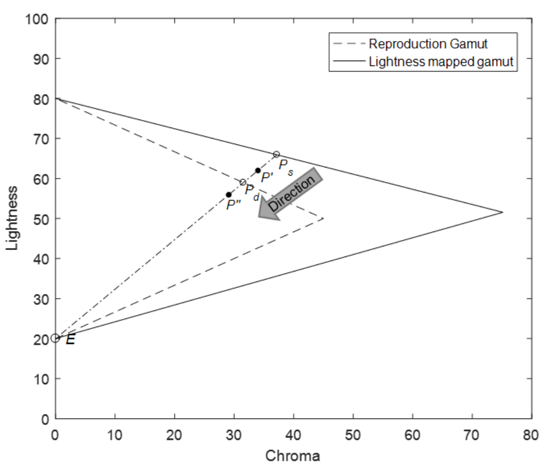

Figure 3. Mapping towards the gamut black

2) Vividness compression

Fig.3 shows that colours from Step 1) were further mapped along the vividness direction, i.e. towards the gamut black. Eq. 2 was applied to have as many points unchanged as possible. Specifically, if $\overline{EP'}$ was smaller than $0.9 \times \overline{EP_d}$, then it was in the core region. Otherwise, it would be mapped towards the focal point. Note that, if there was no intersection between the destination gamut boundary and the line $\overrightarrow{EP}$, then the upper side of the boundary should be extended.

3) Mapping towards lightness axis

After Step 2, most colours were in the destination gamut. However, a small number of colours, e.g. P'' in Fig. 4, in the lower region still needed a final 'make-up'. Eq. 2 was again adopted in this step to map them into the destination gamut. The focal point was set at the lightness axis having the same lightness as the colour to be mapped. Also, if $\overline{EP''}$ was smaller than 90% $\overline{EP_d}$, the colour was kept unchanged.

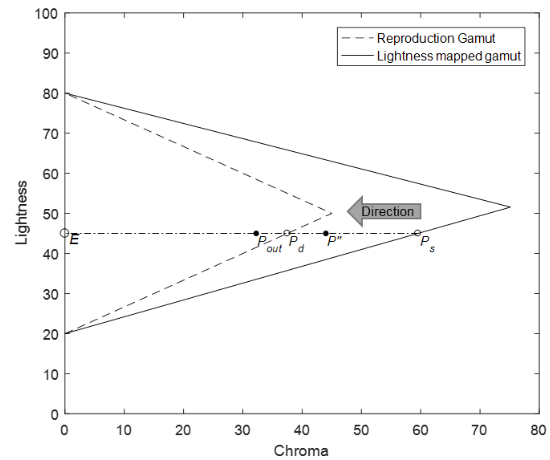

Figure 4. Mapping towards the lightness axis

New GEA development

A new GEA, vividness-extension (VE), is developed in this study with the aim of exploiting colour gamut along vividness direction. Its steps are as follows,

1) Mapping towards lightness axis

As is shown in Fig. 5, the first step of VE was to map colors having a smaller lightness value than the cusp towards the lightness axis using Eq. 3. After that, a new boundary could then be built as illustrated using dot dashed line in Fig. 5. This was to provide a smooth and straight lower boundary of the source gamut to avoid any mathematical problems in later steps.

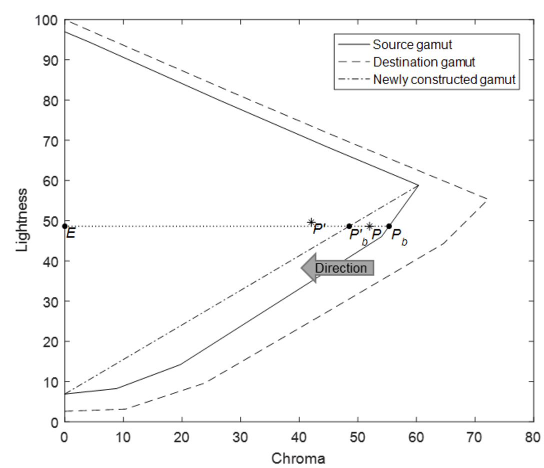

Figure 5. Mapping towards lightness axis

$$\overline{EP'} = \begin{cases} \overline{EP};\ \overline{EP} \le 0.6 * \overline{EP_b} \\ 0.6 * \overline{EP_b'} + \frac{\overline{EP} - 0.6*\overline{EP_b}}{\overline{EP_b} - 0.6*\overline{EP_b}} * 0.4 * \overline{EP_b'};\ \overline{EP} > 0.6 * \overline{EP_b} \end{cases} \qquad (3)$$

where P is the source color and P' is the mapped color after Step 1). P_b and P_b' are the intersection of line $\overrightarrow{EP}$ with the source and 'make-up' gamuts, respectively. E is the mapping center in the lightness axis having the same lightness value as point P.

2) Vividness extension

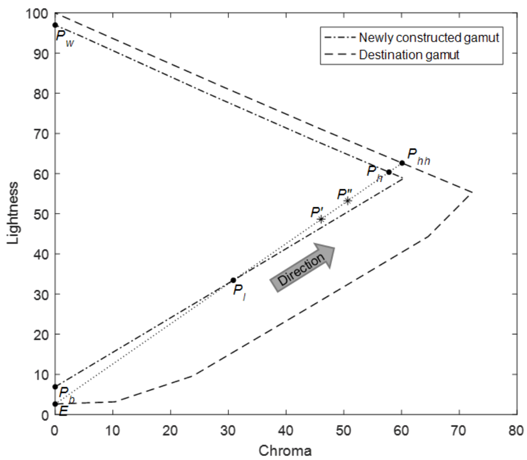

Figure 6. Mapping along vividness direction

Colours from Step 1) were further mapped along the lightness direction using Eq. (4) and (5),

$$\overline{EP''} = \overline{EP_{hh}} * \left(\frac{\overline{EP'}}{\overline{EP_h}} - k * v\right) \qquad (4)$$

$$v = \frac{\overline{EP_b}}{\overline{EP_w}} \text{ and } k = \frac{\overline{P'P_h}}{\overline{P_l P_h}} \qquad (5)$$

where P' is the source color, P'' is its mapping result in this step. E is the focal point (black) in the destination gamut. P_l is the intersection of $\overrightarrow{EP'}$ with the lower source boundary. P_h is the intersection of $\overrightarrow{EP'}$ with the upper source boundary. P_{hh} is the intersection of $\overrightarrow{EP'}$ with the higher destination boundary.

3) Chroma extension

It was found that the destination gamut was not fully used for colours having smaller lightness values than cusp. Hence, a chroma extension was performed using Eq. 6. for those colours. This is illustrated in Fig. 7.

$$\overline{EP_{out}} = \begin{cases} \overline{EP''};\ \overline{EP''} \le 0.6 * \overline{EP_i} \\ 0.6 * \overline{EP_i} + \frac{\overline{EP''} - 0.6*\overline{EP_i}}{0.4*\overline{EP_i}} * 0.4 * \overline{EP_d};\ \overline{EP''} > 0.6 * \overline{EP_i} \end{cases} \qquad (6)$$

where E is the mapping center in the lightness axis having the same lightness value as point P''. P_i is the intersection of $\overrightarrow{EP''}$ with the source boundary after Step 2) and P_d is the intersection of $\overrightarrow{EP''}$ with the destination boundary. P_{out} is the final output.

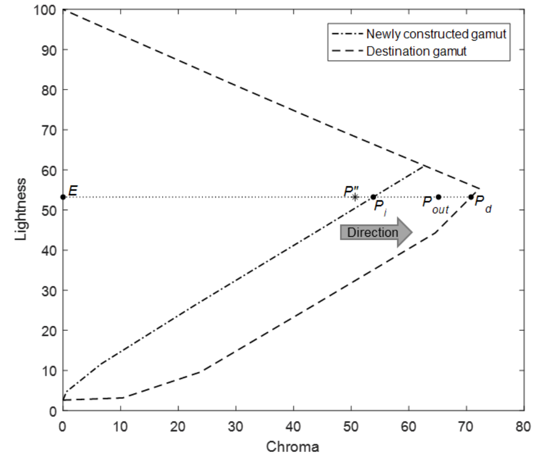

Figure 7. Mapping along chroma axis

Psychological experiment

GCA experiment on fidelity

GCA experiment was performed on a NEC PA272W LCD display. It was well calibrated to have a same peak white of D65 and a luminance of 130 cd/m^2. Characterization was implemented using Gain-Offset-Gamma (GOG) model [12] to have a predication accuracy of 0.86 ΔE^*_{ab}, averaged from 24 colors of Macbeth ColorChecker chart. Gamut mapping was performed from the relatively large display into a smaller simulated sRGB gamut. Their gamuts are shown in Fig. 8. Note that sRGB is fully enclosed by the display gamut.

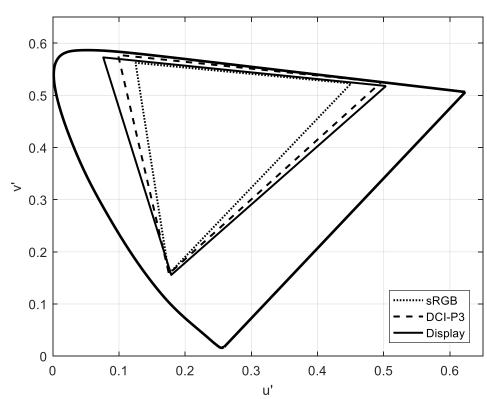

Figure 8. 2D gamuts of display, standard DCI-P3 and sRGB in 1976 u'v' diagram.

Six images containing different image contents were included in this study. They are shown in Fig. 9. Three of them were some SCID (Standard Colour Image Data) images recommended by ISO 12640 [13, 14] for the research and applications in graphic arts area. The other two images were frequently used in gamut mapping research, ski and picnic from CIE TC 8-3. Finally, a colour chart was produced from the NCS samples, they were chosen from the light series of pages from 4 unitary hues. It was particularly useful to check the hue linearity of a colour space. Overall, they included synthetic and natural images, having the features required to test GCAs.

Figure 9. Test images in the GCA experiment.

Four GCAs including CIE recommended HPMINDE and SGCK, TOPO and our VP method were investigated in this study. They were processed using three UCSs, i.e. the most widely used CIELAB, the most uniform CAM02-UCS and a newly proposed UCS, $J_za_zb_z$ designed for HDR (high dynamic range) and WCG (wide colour gamut) applications. Hence, 4 (GEAs) × 3 (UCSs) = 12 reproductions were generated per image.

The paired-comparison method was used. Fifteen observers with normal vision took part in this experiment. Three images were presented side by side within a scene, with the source image in the middle and two reproductions on each side. Observers were asked to decide which one appears to be more similar to the original one. Each image can then have 12 × 11/2 = 66 comparisons. In this study, an image is repeated to calculate observers' repeatability and thus 6930 comparisons, i.e. 66 comparisons × 7 images × 15 observers, were made.

GEA experiment on preference

The experimental setup for GEA experiment was quite similar to that of GCA, except for a lower luminance of 110 cd/m^2 was adopted. Again, GOG model was applied to perform characterization and its accuracy was now 0.64 ΔE^*_{ab}. The source gamut and destination were assigned as the simulated sRGB gamut and the larger display gamut respectively.

Eight images were selected in the GEA experiment following the same criteria to cover typical scenes for display applications. They are shown in Fig. 10.

There were 4 GEAs included in GEA experiment, i.e. Zamir's, HCM, HCB and our new VE method. In addition, two uniform colour spaces, i.e. CAM02-UCS and $J_za_zb_z$ were also included. Since HCM adopted the 1976 *u'v'* diagram only, each image finally generated 7 reproductions, i.e. 2 (UCSs) × 3 (GEAs) + 1 (GEA). Hence, there are 21 reproduction pairs, i.e. 7 × 6/2, per image.

Eighteen observers participated in this part. They were asked to judge each reproduction pair on the display in terms of preference. Note there is no source image (reference) at this time. In total, 3024 comparisons, i.e. 21 (comparisons) × 8 (images) × 18 (observers) were made.

Figure 10. Test images in the GEA experiment.

Results and discussion

Wrong decisions (WDs) [15] were calculated to reveal the reveal intra- and inter- observer variability for both GCA and GEA experiments. They were 17.33% and 25.32% for GCA experiment and 25% and 33% for GEA experiment respectively. This is reasonable since there is no reference in GEA experiment and 'preference' varies from person to person to some extent.

Raw data were then transformed into z-score values following the Case V of Thurstone's Law of Comparative Judgment [16]. In this study, a higher z-score value means a better algorithm performance, i.e. fidelity for GCAs and preference for GEAs, respectively. The standard deviation was assumed to be $\sigma = \frac{1}{\sqrt{2}}$ and the 95% confidence interval (CI) can therefore be calculated as Eq. (7):

$$\mathrm{CI} = 1.96\frac{\sigma}{\sqrt{N}} \tag{7}$$

Fig. 11 shows the results for GCA experiment. As is shown, HPMINDE and VP gave similar performance and they markedly outperformed the other GCAs. A detailed inspection was performed for HPMINDE since it was expected to lose details for chromatic regions. However, this is not always true especially for two gamuts having similar gamut shape. Most source colours were reproduceable in this experiment. And even if some details were lost such as the cello in Fig. 9(3), such local difference in small areas still could be easily ignored when focusing on the overall impression of image. Hence, HPMINDE was rated high. The major difference of VP, SGCK and TOPO lies in their different focal points, gamut black for VP to preserve vividness gradation, middle grey for SGCK to make full use of high chroma region, and multi-chords for TOPO to emphasize image contrast. A high z-score value for VP means that vividness was influential in colour perception of an image. A smaller change of vividness led to a more constant image perception.

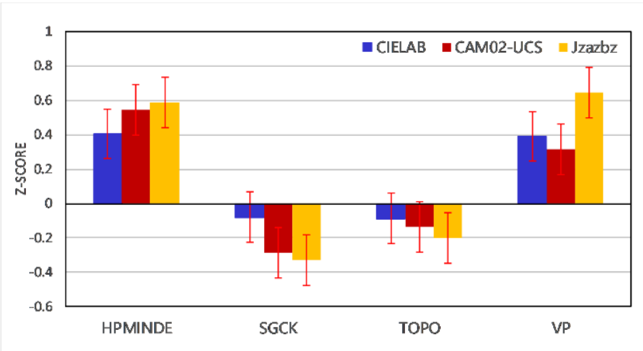

Figure 11. Results for the GCA experiment

Fig.12 shows the model performance for the GEA part. It's clearly shown that VE is excellently better than the other GEAs investigated. HCM was found to be the worst due to the change of hues for some colours especially for blue sky. Zamir's method was reported to have a slight halo effect when color changes rapidly and it could also lead to a hue shift since it was not performed in a constant hue plane. HCB enlarged chroma for chromatic colours. However, little enhancement was done for colours of low chroma. Although this works well for memory colours, it failed in some other colour like building paints.

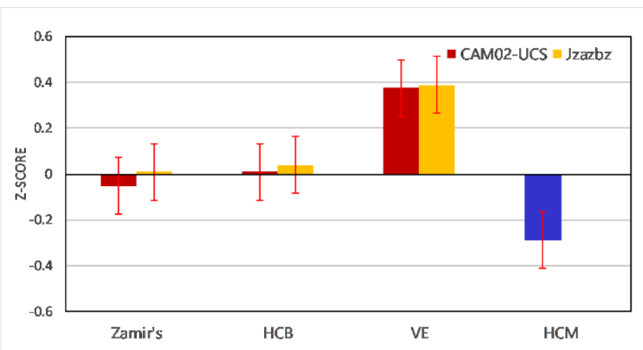

Figure 12. Results for the GEA experiment

For the UCSs investigated, it was found that no single UCS performed constantly better for the GCA experiment. CAM02-UCS had a good performance for images having large objects with a single colour such as Image 9(1) (Fruit basket) and Image 9(4) (Colour patches). $J_z a_z b_z$ was ranked the best for images 9(3) (Musician) due to its good hue linearity especially in blue region. Surprisingly, CIELAB did not perform badly for the images tested: only some colour shifts in the blue region were observable. However, for the GEA experiment, $J_z a_z b_z$ always gave a slightly better z-score value compared with CAM02-UCS, indicating it was promising UCS in the field of gamut mapping.

Conclusion

In this study, vividness has been proved to be an effective scale for human's colour perceptions. A GCA and a GEA were developed and both of them were verified to give reasonably well performance among all the GMAs tested via two psychological experiments. And the fact that $J_z a_z b_z$ was able to give a comparable performance as CAM02-UCS is of interest and indicates it is a promising uniform colour space in the field of gamut mapping.

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Author Biography

Baiyue Zhao received his BS in Printing Engineering from Wuhan University (2017) and has been a MS candidate supervised by professor Ming Ronnier Luo at Zhejiang University since 2017. His work has focused on gamut mapping and image quality evaluation.

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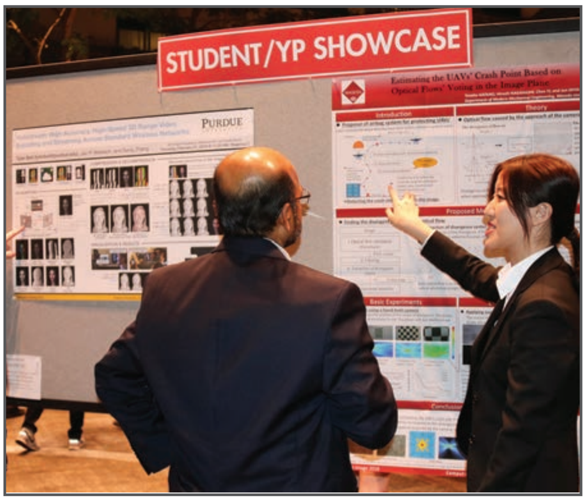

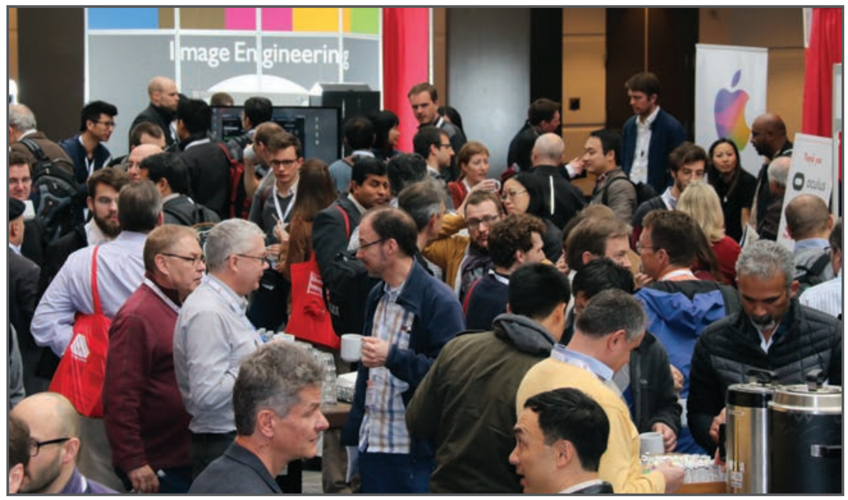

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