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Automatic image quality tuning framework for optimization of ISP parameters based on multi-stage optimization approach

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Abstract

Image signal processors (ISP) plays a significant role in camera systems by converting the RAW image from image sensor to a processed image. In order to achieve best image quality, the ISP parameters have to be configured in an iterative manner for various lighting conditions and scenarios, which is carried out by a camera tuning engineer. Usually, the manual tuning process takes up to several weeks to months due to huge number of ISP parameters to be optimized and the iterations involved to achieve good image quality. In this paper, we present a novel approach to automatically tune ISP parameters based on a multi-stage multi-criteria optimization approach using Non sorted Genetic algorithm (NSGA-II) for achieving objective and subjective image quality. In this approach, we focus on important blocks in ISP such as noise reduction, sharpness and tone mapping for human vision use-cases for camera systems widely used for smart phones or smart home IoT devices. The experiments for validating our approach are carried out under different scenarios using Qualcomm's Spectra 380 ISP simulator and OV13880 sensor and the performance of automatic tuned IQ is compared with manual tuned IQ and some of the previous works done for automatically tuning ISP parameters. With the automatic ISP tuning approach, we verify the significant performance improvement in terms of IQ metrics and time consumed for the tuning process when compared to manual tuning approach.

Introduction

Camera systems used in smartphones and smart home IoT devices consists of an important component called Image signal processors (ISP). ISP is responsible for converting the RAW input image captured by image sensors to a processed final image which are used for human-vision interpretations and analysis. ISP pipeline (Figure 1) commonly consists of processing blocks such as noise reduction, white balance, demosaicing, color correction, contrast and edge enhancement. This pipeline plays a key role in the overall quality of the images produced by the camera systems.

In order to achieve good quality images from these camera systems, in addition to sensor calibration process, the ISP pipeline parameters are configured by Image quality (IQ) tuning engineers in an iterative manner. The tuning process (Figure 2) is performed for various scenes with controlled lighting conditions in lab and fine-tuned later for real world scenarios. The quality of the images is usually evaluated objectively using key performance indicators (KPIs) and subjective score or opinions of IQ experts. Standard test charts are used to evaluate the objective IQ metrics for different blocks in the pipeline. Some of the commonly evaluated objective metrics include Signal-to-Noise Ratio (SNR), Modular Transfer Function (MTF), Texture acutance, Dynamic Range etc. Subjective IQ evaluation involves multiple reviews from experts in the field of camera image quality. The process of manually tuning the ISP blocks is a challenging task since it takes several weeks to months to achieve good image quality. This is due to the complexity of the algorithms involved in the pipeline and the huge number of parameters to be tuned.

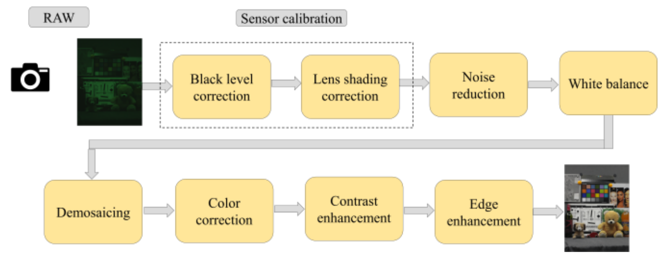

***Figure 1.** Camera Image Signal Processor (ISP) pipeline*

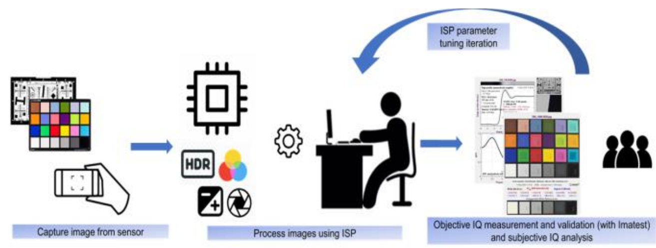

***Figure 2.** Camera ISP tuning process*

In this paper, we present a novel approach to automatically tune ISP parameters based on a multi-stage multi-criteria approach using the evolutionary optimization Non-sorted Genetic algorithm (NSGA-II) [1]. NSGA-II optimization algorithm is used for solving multi objective optimization problems where the objective functions can be conflicting in nature. In this work, we focus on automatically tuning ISP parameters using NSGA-II optimization algorithm to obtain better objective and subjective image quality. We achieve this by solving the ISP tuning task as a multi-objective optimization problem which uses objective and perception based IQ metrics to define the loss function for optimization. In this work, we have considered automatically tuning some important ISP blocks such as noise reduction, sharpness and tone mapping for human vision use-cases for camera systems widely used for smart phones or smart home IoT devices.

In this automatic approach of ISP tuning, we use optimization algorithm to minimize loss functions defined with objective and subjective IQ metrics to compute the optimal parameters in order to achieve good image quality. The multi-stage approach consists of optimally obtaining the noise reduction and sharpness parameters in the first stage and the tone mapping parameters in the second stage. In order to automatically tune the ISP blocks in the multi-stage approach, the optimization algorithm uses loss functions defined with IQ KPIs specific to the ISP block. The first stage of optimization is a multi-criteria loss evaluation using objective IQ metrics visual noise and modular transfer function and a subjective preference metric called BRISQUE. In this work, NSGA-II optimization algorithm uses the above-mentioned multi-criteria loss function to optimally obtain noise reduction and sharpness tuning parameters. The second stage of optimization uses a perception-based metric called Tone Mapping Quality Index (TMQI) to optimally obtain tone mapping parameters.

The experiments for IQ validation are carried out under different scenarios using Qualcomm's Spectra 380 ISP simulator and OV13880 sensor and the performance of automatic tuned IQ is compared with manual tuned IQ and some of the previous works done for automatically tuning ISP parameters. With the proposed approach we show that Image quality performance of automatically tuned ISP parameters outperforms the traditional approach of manual tuning. We verify significant performance improvement in terms of objective IQ metrics, subjective image comparisons and the time consumed for the tuning process when compared to manual tuning approach and some of the previous works done in the field of automatically tuning ISP blocks.

Related work

In [2], the authors propose an automatic method for tuning denoising and sharpness parameters using Particle Swarm Optimization (PSO) algorithm. In this approach, Camera Phone Image Quality metrics is used to define the objective function for optimization. In [3], the authors propose an automatic method for tuning of noise reduction and sharpness parameters using Differential Evolution optimization. In the above approaches, the automatic tuning of ISP parameters is solved as a single objective optimization problem. The objective function for optimization is defined as a weighted sum of objective image quality metrics which quantify the performance of noise reduction and sharpness blocks. In [2] and [3], authors show the performance improvement of automatically tuning noise reduction and sharpness parameters when compared to manual tuning, in terms of objective image quality.
In this work, we propose an approach to automatically tune ISP blocks that helps to achieve better objective and subjective image quality. The proposed work comprises of multi-stage multi-criteria approach of tuning noise reduction, sharpness and tone mapping blocks. We use the NSGA-II optimization algorithm to automatically tune noise reduction and sharpness parameters as a multi objective optimization problem. The multi-criteria loss function is evaluated using a set of objective and subjective image quality metrics corresponding to the performance of noise reduction and sharpness blocks. This helps us to tune the ISP blocks to achieve better image quality in terms of objective metrics and subjective performance when compared to manual tuning. Using the multi-stage approach, we also tune the tone mapping parameters which has not been explored in the previous works mentioned above.

Proposed Approach

Multi-stage Optimization

In this work, we tune the parameters of noise reduction, sharpness and tone mapping blocks of the ISP apart from traditional sensor calibration. The architecture of proposed approach (Figure 3) comprises of a multi-stage, multi-criteria loss function evaluation for optimization of ISP parameters using NSGA evolutionary optimization algorithm. In this approach, the first stage is the optimization of noise reduction and sharpness parameters using a multi-criteria loss function evaluation with objective metrics Visual Noise (VN), MTF50 and subjective image quality metric, BRISQUE score [4] (Figure 3). The second stage is the optimization of local tone mapping parameters using a loss function evaluation with a perception-based metric called Tone Mapping Quality Index (TMQI) [5].

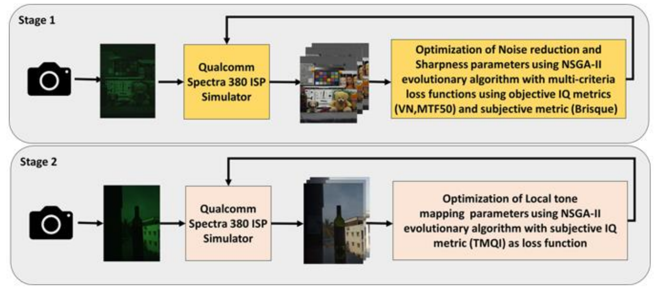

Figure 3. *Block diagram showing the multi-stage multi-criteria approach for automatically tuning ISP parameters using NSGA evolutionary optimization*

NSGA-II is an evolutionary optimization algorithm, a type of heuristics-based optimization approach. It works on the basis of survival of the fittest to solve complex real-world problems of optimization. The algorithm (Figure 4) is initialized by evaluating the fitness/loss function of an initial population. It uses the genetic operators selection, mutation and crossover and the fitness/loss function to create an offspring population. In each iteration of optimization, the parent and offspring population are used to find the best survived individuals using the crowding distance. The optimization algorithm is terminated using some criteria based on number of iterations or certain threshold of the fitness evaluation to obtain the optimal solution.

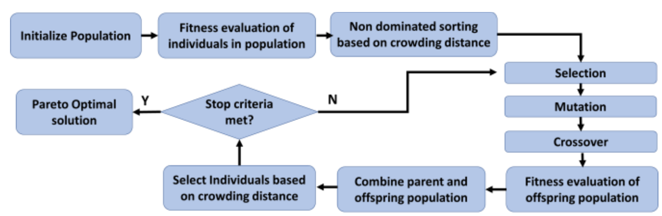

Figure 4. *Block diagram showing NSGA evolutionary optimization algorithm flow*

In this work, we use the NSGA-II algorithm to automatically obtain the tuning parameters of ISP blocks by initializing the algorithm with default values of the tuning parameters. The algorithm uses the mutation and crossover operations to search the parameter space and find the optimal tuning parameters which minimize the objective function defined. In the first stage of optimization, NSGA-II is used to optimally obtain a 17-dimensional noise reduction and sharpness parameters as a multi-objective optimization problem using multi-criteria loss function. And in the second stage of optimization, NSGA-II is used to optimally obtain 3-dimensional tone mapping parameters as a single objective optimization problem**.** In each iteration of optimization, the intermediate parameters calculated are applied to the RAW image using the ISP simulator to obtain a processed JPEG image. The loss functions are evaluated on the processed images to obtain a single loss value which is minimized by the optimization to give the optimal tuning parameters. The performance of the optimally obtained tuning parameters is then validated using objective IQ metrics, subjective image comparisons and total time taken to tune the ISP blocks.

The loss functions used in the proposed approach is defined in the next section.

Loss function Definition

The loss functions used for multi-stage optimization of noise reduction, sharpness and tone mapping parameters are described in this section. The first stage of optimization uses Visual noise (VN) [6], MTF50 [6] and BRISQUE [4] metric for loss function evaluation, which are calculated as below:

$$(1 - (| VN_{target} - VN_{derived} | \ / VN_{target})) * 100 \quad (1)$$

$$VN = \sigma_{L^*} + 0.852 * \sigma_{u^*} + 0.323 * \sigma_{v^*} \quad (2)$$

$$(1 - (| MTF_{target} - MTF_{derived}) | / MTF_{target})) * 100 \quad (3)$$

where VN is visual noise calculated in L*U*V* color space using a weighted sum of standard deviations of each of the color space channel denoted by σ_{L^*}, σ_{u^*} and σ_{v^*} respectively. The VN_{target} and MTF_{target} are the target values of visual noise and MTF metrics which are set to specific values based on the intended use-case. The $VN_{derived}$ and $MTF_{derived}$ are the values derived during each iteration of the optimization stage.

Blind/Reference less Image Spatial Quality Evaluator (BRISQUE) [4] is a No-Reference IQ metric. It gives an indication of naturalness of the image by measuring the scene statistics of the intensity normalized image. The BRISQUE metric is evaluated by extracting the natural scene statistics and statistical feature vectors and predicting the image quality score using a SVM model computed with the TID 2008 dataset [7] (Figure 5).

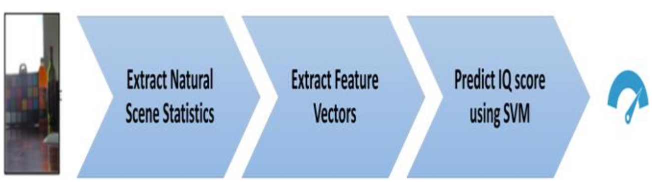

Figure 5. *Block diagram showing evaluation of subjective image quality metric BRISQUE*

The second stage of optimization uses perception based TMQI metric as mentioned in (4). The TMQI metric is used to evaluate the objective image quality of tone mapped images by measuring structural similarity index and naturalness statistics using a high dynamic range reference image.

TMQI: $Q = a * S ^\wedge \alpha + (1 - a) * N ^\wedge \beta$ (4)

where S denotes structural fidelity measure and N denotes statistical naturalness measure and $0 \leq a \leq 1$ adjusts the relative importance of S and N; α and β determine their sensitivities.

Experimental Setup

In this work, we use a simulation environment based on Qualcomm's Spectra 380 hardware accurate ISP simulator for performing the ISP processing to convert the RAW images captured from sensor to a processed JPEG image. The parameters of Spectra 380 ISP's noise reduction, sharpness and tone mapping blocks used for optimization are shown in the Table 1.

In the first stage of optimization, we optimize the noise reduction and sharpness parameters using RAW images captured for a lab scene with standard test charts such as Macbeth Colo checker, ISO12233 chart and some real-world objects with various textures and details. The 17-dimensional parameters space is optimally obtained using NSGA optimization algorithm with loss function evaluated using visual noise, MTF metric and BRISQUE score. To evaluate the loss function in this stage, we calculate the visual noise and MTF metrics from specific ROIs in the image as shown in Figure 6. In our experiments, we have set the target values of visual noise and MTF KPIs to 20 and 5 respectively. The loss functions for these metrics are calculated as a percentage deviation from the target KPIs set and the optimization algorithm iteratively tries to find the best parameters to minimize the loss value. We then validate the image quality performance of the above-mentioned approaches in the next section. We compare the performance of noise reduction and sharpness tuning performed using the proposed approach to some previous work done in the field of automatically tuning ISP parameters. We have used a python-based library PYMOO [8] to implement the evolutionary optimization algorithms used for our experiments. The details of the previous works adopted for comparison with our approach is described in Table 2.

In the second stage of optimization of tone mapping parameters, we have captured images of real world HDR scene consisting of dark shadows and bright regions. The 3-dimensional tone mapping parameters are optimally obtained using NSGA optimization algorithm with loss function evaluated using the perception based TMQI metric. The TMQI metric for the tone mapped LDR image is derived by taking a HDR image of the same scene as reference. In our work, we have captured the HDR reference image using smartphone Google Pixel 3a. We then compare the performance of local tone mapping tuning performed using the proposed approach to manual tuning results.

Table 1: Spectra 380 ISP parameters

ISP block	Parameter (dimension)	Value range
Noise reduction	Noise preservation (5) Denoise strength (4) Edge softness (4) Level-based NR (1)	[0,5] [0,5] [0,5] [0,63]
Sharpness	Layer 1 gain positive (1) Layer 1 negative scale (1) Layer 1 gain weight (1)	[0,7.9] [0,7.9] [0,0.9]
Local tone mapping (LTM)	LTM strength (1) Dark boost (1) Bright suppress (1)	[0,4] [0,4] [0,4]

Figure 6. Gray patch ROI (left) and Slanted edge ROI (right) used for visual noise and MTF metric evaluation respectively.

Table 2: Different approaches used for comparison analysis

Manual approach	PSO apporach
• Manual tuning of denoising and sharpening tuning parameters.	• Automatic tuning of denoising and sharpening parameters based on perception model using Particle Swarm Optimization (PSO) [6]
DE approach	**Proposed apporach**
• Automatic tuning of denoising and sharpening tuning parameters using Differential evolution (DE) [7]	• Automatic tuning of denoising and sharpening tuning parameters using NSGA evolutionary optimization approach.

Experimental Results

The experimental results section shows the performance comparison of the proposed automatic tuning approach with the other approaches as described in the proposed approach section. The performance results are validated using objective IQ metrics, subjective perception metrics and image comparisons. In the results table shown below, SNR and Total visual noise is measured using gray patches in Macbeth Colorchecker chart, MTF50 is measured using slanted edge of the ISO12233 chart. The objective IQ metrics above are evaluated with Imatest software [9].

The results below (Table 3 and Figure 7,8,9,10,11) shows the objective metrics and subjective image comparisons for noise reduction, sharpness performance of the four approaches mentioned in proposed approach section. The objective metrics SNR, MTF50 and Visual noise are evaluated with Imatest software. SNR and total visual noise are measured for gray patches in the Macbeth colorchecker chart and MTF50 measured on slanted edge of ISO12233 chart. With NSGA approach, the sharpness tuning performance is good when compared to PSO and DE approach and significantly better compared to manual tuning. With NSGA approach, noise reduction tuning performance is similar to the PSO and DE approach.

Table 3: Comparison of performance results of Noise reduction and sharpness tuning of different approaches

Approach	Manual	PSO	DE	NSGA (proposed)
SNR (in dB)	36.8	44.7	44	43
MTF50	0.27	0.41	0.43	0.51
Visual noise	1.4	0.54	0.62	0.75
Brisque*	57.8	40.5	37.2	34.1
~ Time taken for tuning	~ 2-3 weeks	2 hrs	1.5 hrs	1.7 hrs

** - Lower Brisque score indicates a better Image quality*

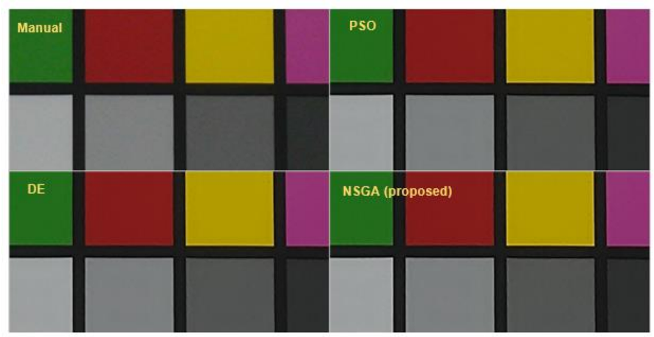

Figure 7 *Subjective comparison of noise reduction and sharpness tuning done with different approaches)*

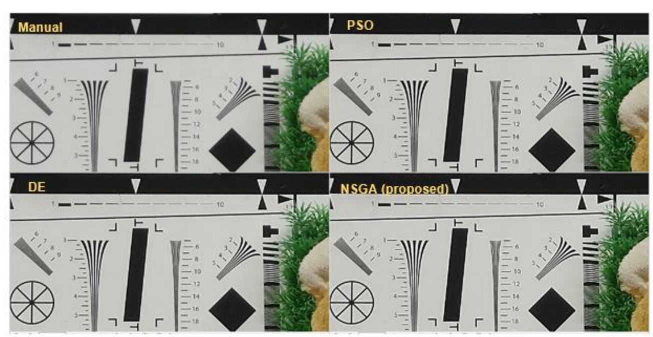

Figure 8. *Subjective comparison of noise reduction and sharpness tuning done with different approaches*

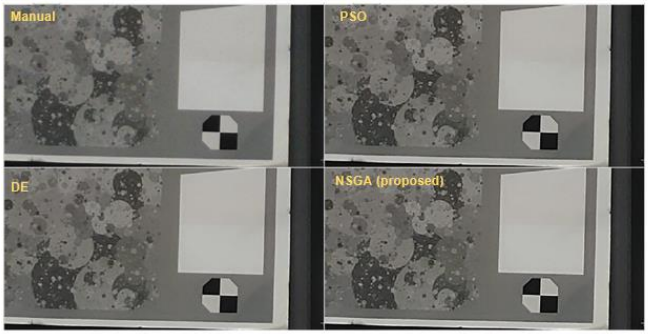

Figure 9. *Subjective comparison of noise reduction and sharpness tuning done with different approaches*

Figure 10. *Subjective comparison of noise reduction and sharpness tuning done with different approaches*

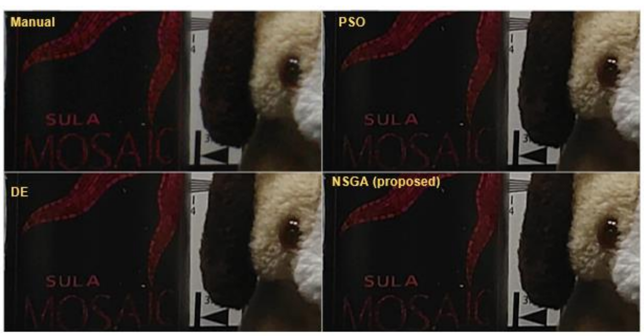

Figure 11. *Subjective comparison of noise reduction and sharpness tuning done with different approaches*

The results below (Table 4 and Figure 12,13,14) show the performance of local tone mapping for manual tuning and the proposed approach using TMQI scores. The TMQI scores evaluated for different HDR scenes show that the performance of local tone mapping with the proposed approach is better when compared to manual tuning. Subjective image comparisons of the local tone mapped images show that the visibility of details in the dark regions is better with the proposed approach when compared to manual tuning. We also show that the time taken to obtain the tone mapping tuning parameters is significantly less when compared to manual tuning.

Table 4: Comparison of performance results of local tone mapping tuning of different approaches

Approach	Manual	NSGA (proposed)
TMQI score* (Scene 1)	0.202	0.214
TMQI score* (Scene 2)	0.172	0.213
Time taken for tuning	~ 1 week	25 minutes

** - Higher TMQI score indicates a better Image quality*

Figure 12. *Subjective comparison local tone mapping performance using manual tuning and proposed approach*

Figure 13. *Subjective comparison local tone mapping performance using manual tuning and proposed approach*

Figure 14. *Subjective comparison local tone mapping performance using manual tuning and proposed approach*

Conclusion

In this paper, we show that by automatically tuning ISP parameters of noise reduction, sharpness and tone mapping blocks, we are able to achieve better image quality in shorter time when compared to manual tuning approach. The objective and subjective experimental results show that the sharpness performance is better when compared to previously done works using PSO and DE approaches. Also, the noise reduction performance is similar to PSO and DE approaches. The objective IQ metrics and subjective image comparisons results show that with the proposed approach of automatic tuning, the performance of noise reduction and sharpness of the camera is better when compared to manual tuning approach. With the proposed approach, we are also able to automatically tune local tone mapping parameters and achieve better image quality when compared with manual tuning.

Experimental results show that with our approach we are able to achieve significant improvements in terms of achieving desired image quality par with manually tuning approach, reducing the time taken for tuning from few weeks to few hours.

Future Scope

As a continuation to the proposed work, we plan to scale the automatic Image quality tuning framework for machine vision use-cases where the traditional manual tuning approach based on subjective preference might not be suitable to achieve good Image quality to improve the downstream application's performance. We also plan to extend the proposed framework to automatically tune other ISP blocks using relevant IQ metrics for loss function evaluation.

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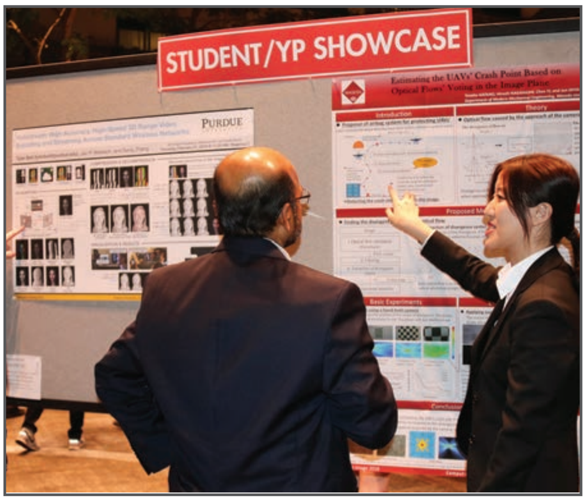

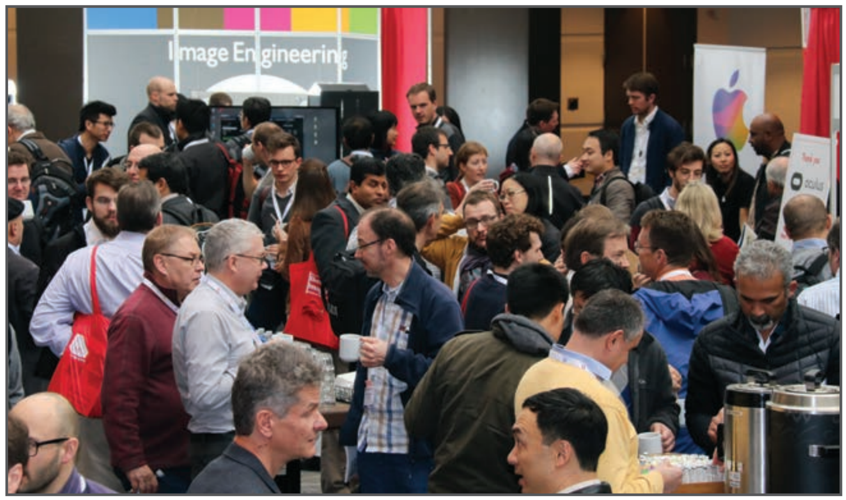

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