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Sun tracker sensor for attitude control of space navigation systems

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Abstract

We report a sun tracker sensor for attitude control of space navigation systems. The sensor exploits the concept of asynchronous operation previously devised by the authors for those devices. Asynchronous luminance sensors optimize sun trackers operation because only illuminated pixels are readout and can transmit data. This approach outperforms classic frame-based sun trackers in terms of bandwidth consumption, latency, and power consumption. The new sensor under study has been optimized for operation and interaction with other attitude control systems when it is embarked. The sensor power consumption is quite reduced. To save power, its pixels enter automatically in standby mode after gauging illumination levels. The device operates with only 0.45V. The pixel matrix has been devised to optionally be directly powered by energy harvesting systems based on photovoltaic diodes connected to a storage capacitor without a DC-DC converter.

Introduction

Sun trackers or sun sensors are devices that gauge the sun position (latitude and azimuth) referred to its centroid [1]-[4]. They are used in multiple application scenarios, either terrestrial or related to the implementation space navigation systems. In this second application scenario, they are usually employed to control spacecrafts or satellites' attitude. Low temporal resolution and low power consumption are the major requirements demanded in this case, [2],[4].

Conventional digital sun sensors [1]-[4] are built with frame-based image sensors. An entire pixel matrix is scanned, readout, and processed before determining the sun position. This approach is highly inefficient because the majority of pixels are not illuminated. Thus, they do not provide meaningful information to track the sun position. Sensors' temporal resolution is limited by the size of the pixel matrix, and the amount of data to be transmitted/processed is quite high.

Recently, in a prior work, it was proposed an alternative sun sensor architecture based on pixels with asynchronous and continuous operation [5],[6]. A spiking luminance sensor was employed to sense pixels' illumination levels [7]-[9]. The advantages of this approach are several: Firstly, only illuminated pixels send data off-chip. In consequence, the sensor operation and the data post-processing is remarkably simplified. Secondly, such sensors have a much lower temporal resolution than conventional imagers, satisfying the temporal requirements associated to attitude control. Thirdly, the operation of such pixels is autonomous; they do not have to be scanned periodically because they pulse with a frequency proportional to illumination. Finally, spiking sensors have higher dynamic range than frame-based sensors, that are typically limited to 70dB [10]-[11]. Their operation is not conditioned by the selection of an integration time. Therefore, the circuitry dedicated to control the exposure time, depending on the illumination conditions can be avoided, simplifying even more the sun tracker design.

In this article, based on the accumulated experience on the framework of the 4DSpace initiative [12], we present an optimized pixel architecture for the implementation of an attitude control system for small satellites. The pixel has by default Time-to-First-Spike (TFS) operation [13]-[15] to reduce its power and bandwidth consumption even more. In small satellites, sun sensors do not need to operate continuously. To save power and bandwidth consumption, the sensors can be activated by other instruments when the sun position has to be determined. The pixel design is intended to sense illumination levels on demand. It has been validated on a standard CMOS fabrication technology. Pixels, at the most, are only allow to spike once. Then, pixels power-off to save energy consumption until the sun position has to be measured again. In parallel to the pixel matrix design, we have implemented photodiodes operating as solar cells to harvest energy.

Pixel operation voltage is compatible with integrated diodes operating as photovoltaic cells because the pixel matrix can be directly powered at *0.45V*. Thus, the system power consumption can be reduced even more if diodes operating as solar cells are available on chip.

Context and motivation

Sun trackers are nowadays highly demanded to determine the sun position to control the attitude of space microsatellites. The use of small satellites is increasing with many new applications at industrial level. The concept of New Space is changing the classical space paradigm with quick and low-cost developments. According to recent Euroconsult report [16], over 7,000 small satellites will be launched in the next ten years, six times the total launched during the last decade. Most of these satellites will require pointing capabilities through sun trackers with very low temporal resolution. Depending on the sun position, a certain cluster of pixels is exposed to light, as it is depicted on Figure 1. To compute the sun position, the centroid of an illuminated region (Region of Interest, ROI) is determined based on basic trigonometric calculations.

In such application scenarios, the preferred specifications for image sensors are low bandwidth, low power consumption and low latency. Conventional sun trackers are frame-based imagers with a dedicated optics [1]. All pixels are scanned and readout to gauge the sun position. As we previously demonstrated [5][6], sun trackers bandwidth consumption and latency can be reduced by implementing autonomous event-based pixels that pulse with a frequency proportional to illumination. Their operation principle is described in Figure 2. Only illuminated pixels' outputs are readout. Low latency is an inherent characteristic of the aforementioned spiking pixels. Typically, a pixel temporal resolution in the order of milliseconds is achieved. Pixels spiking frequency is given by:

$$f_{osc} \approx \frac{I_{ph}}{V_{DD}-V_{ph}} = \frac{I_{ph}}{\Delta V} \quad (1)$$

Where V_{ph} is the comparator's threshold. The requirements of low power consumption for space navigation systems is what indeed motivates this research work. Space navigation systems demand sensors with very low power consumption and that can eventually use solar energy to operate. The power consumption can be reduced following several strategies addressed in this work: The first one is to make sensor operation not continuous in time. Once, the sensor provides the desire output, it enters automatically into a standby mode until it is activated again. Second, the pixel can be designed by reducing its power consumption during the image acquisition and in standby mode. Finally, compatibility with pixel energy harvesting circuitry that can be added to the chip design is an asset.

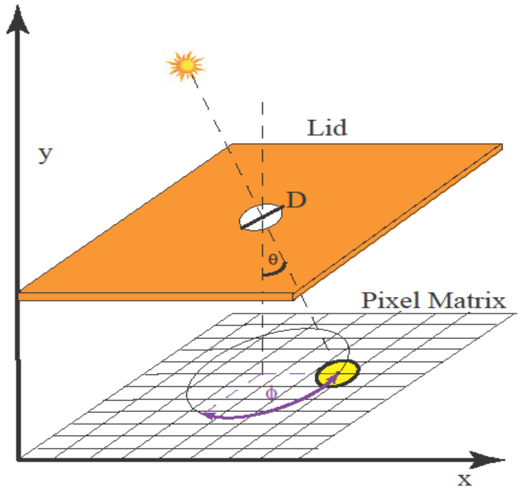

Figure 1 *Sketch of a sun sensor implementation. A pinhole lens is covering the pixel matrix. The sun position can be inferred by gauging the centroid of the illuminated region.*

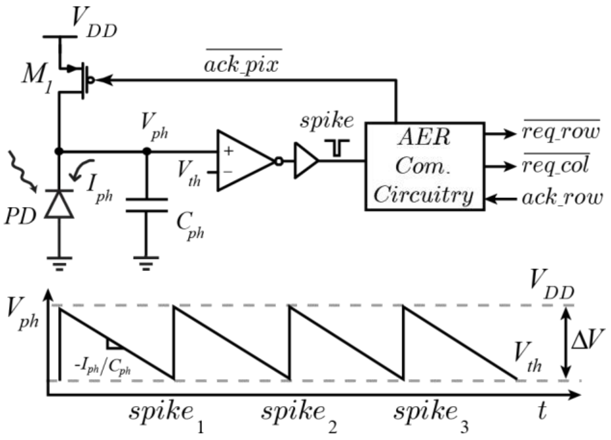

Figure 2 *Implementation of a generic spiking luminance pixel. Initially the voltage at the integration capacitance is reset. Then, the photodiode discharges the integration capacitance with a slope proportional to illumination. When a voltage threshold, Vth, is reached, the pixel self-resets and sends an event off-chip.*

Pixel implementation

The sensor was designed in the standard UMC180nm process. We display the pixel architecture in Figure 3. There are three main differentiated modules. The first one, surrounded by a green dash line, performs a light-to-frequency conversion, generating spikes with a frequency proportional to illumination, as it is depicted in Figure 2. The second one, surrounded by a red dash line, is made with some logic to stop the operation of the first block once one spike is conveyed off-chip, implementing the TFS operation. The final one, surrounded by a blue dash line, is compounded of specific logic to implement the pixel AER communication protocol [17],[18]. All pixels share the digital signal *pix_on* that enables their operation. The control signal *mode* allows to toggle between two operation modes that will be described in the next section. The control signal *lock* is activated by each pixel when its conveys its illumination value off-chip. Thereafter, the pixel enters into a standby mode until the *pix_on* signal is toggled to take a new measurement. In standby mode, the comparator power consumption is reduced by switching off its biasing transistors. In Figure 4, the comparator implementation is detailed. Its architecture is compatible with a 0.45V power supply voltage.

In Table I, it is summarized how the C-element that locks the pixel operates, depending on the value of its two inputs. Initially, both inputs are always set to zero. Then the pixel is enabled to sense light when pix on goes high. If the pixel generates one spike and its address is sent off-chip, the signal *ack_pix* will be set high [19], locking the pixel and disabling any possible further pixel communication. The user can decide how many pixel outputs are used to compute the sun position. Not do all the illuminated pixels have to be necessarily readout. Once the required number of events are received off-chip, the signal *pix_on* is set low, disabling all the pixels until the whole pixel array is activated again. In Figure 5, a time line illustrating how the digital signals are activated sequentially during the pixel operation is shown.

There is an additional global control signal, mode, that allows two possible operation modes combined with TFS operation. We describe them in the next subsections.

Table I Sensor expected features.

pix_on	*ack_pix*	*y_n=lock*
0	*0*	*0*
0	*1*	*y_{n-1}*
1	*0*	*y_{n-1}*
1	*1*	*1*

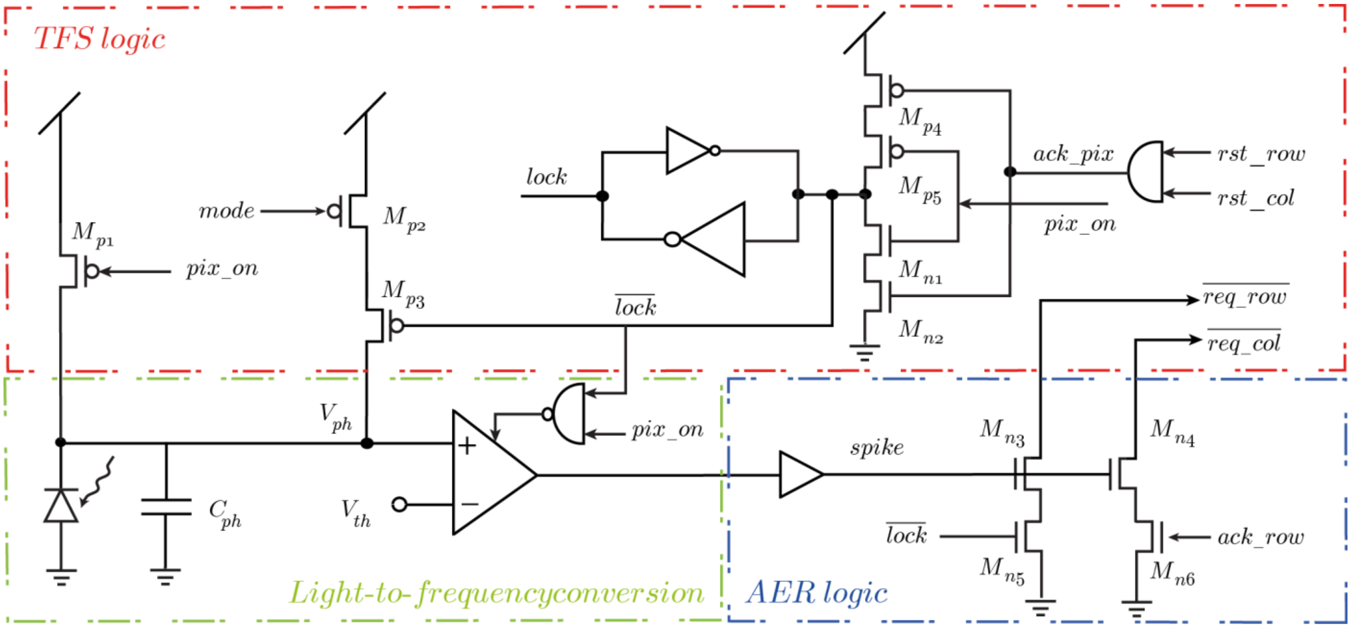

Figure 3 *Pixel schematics. Main pixel constitutive blocks are highlighted in different colors. In green, there is light-to-frequency conversion stage. In blue, the asynchronous logic that handles the pixel communication with the peripheral communication logic. In red, a C-element and the pixel logic that disables each pixel once it has transmitted its illumination level off-chip.*

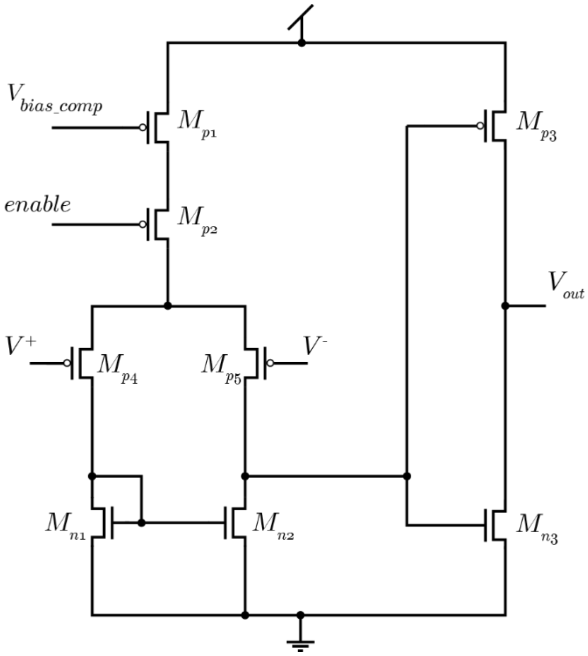

Figure 4 *Schematics of the pixel comparator. To save power, it enters into a standby mode when the pixel has measured its illumination value or when the entire sensor operation is disabled.*

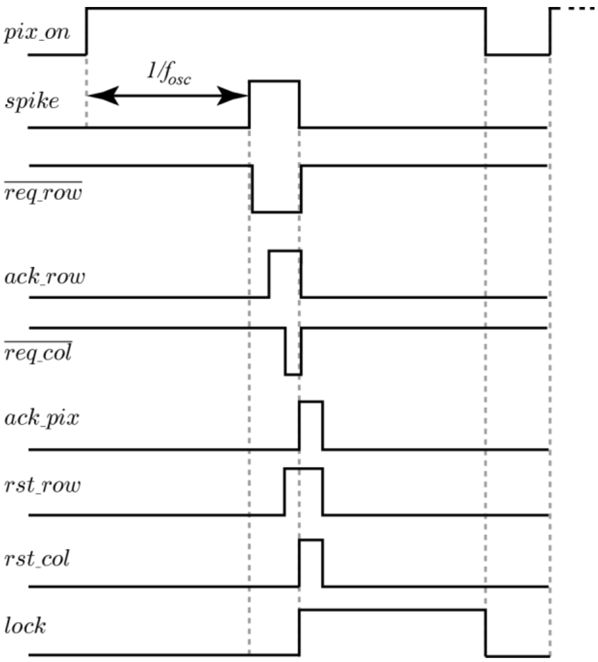

Figure 5 *Time line of the signals involved in the pixel operation during an event transmission.*

Pixel operation modes

Two different pixel operation modes are possible. By selecting each one, the user can trade between latency and power consumption.

Fast reset operation mode

This operation mode is depicted in Figure 6. The control signal mode is set low during the pixel operation. When the pixel spikes and sends an event off-chip, it self-resets, preparing the pixel for the next readout. This operation mode is suitable to track the sun position at high speed. The amount of time and current to reset the integration capacitance between different light measurements is more reduced. ΔV in Equation 1, for all the pixels, meets that $\Delta V \leq V_{DD} - V_{th}$. Thus, power consumption associated to the reset of the integration capacitance is saved. Sensor operation speed is faster because pixels do not continue integrating charge when the voltage at the integration capacitance reaches the threshold voltage, V_{th}.

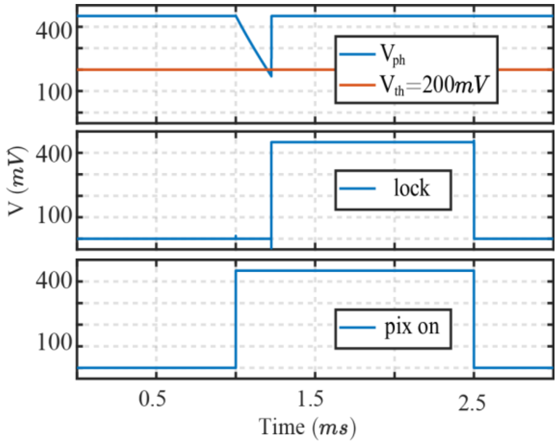

Figure 6 Transient signals involved in the pixel fast reset operation mode.

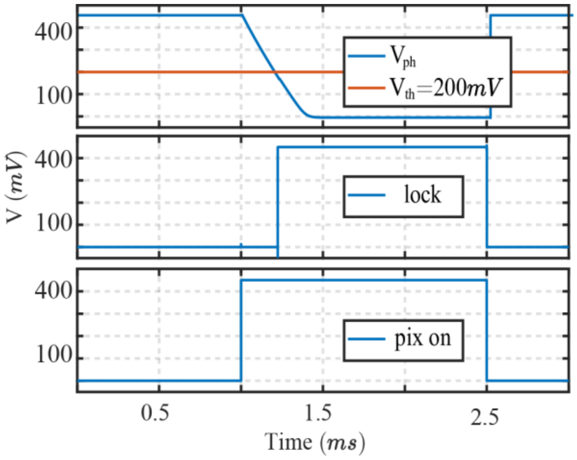

Figure 7 Transient signals involved in the power-saving operation mode.

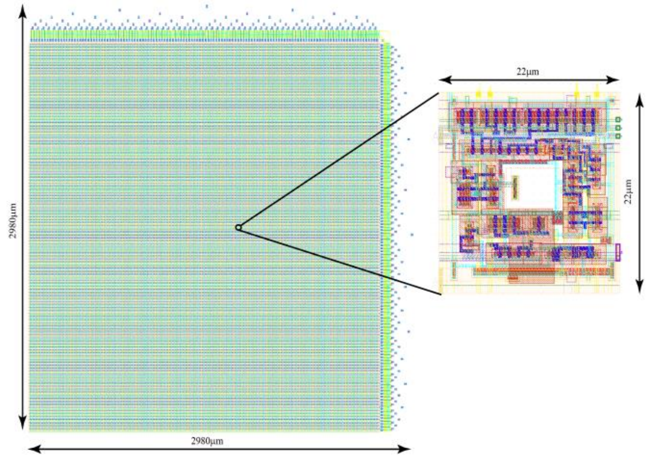

Figure 8 Sensor and pixel layout. Pixel pitch is $22\mu m$. The pixel array has 128 × 128 pixels.

Power-saving mode

This operation mode is depicted in Figure 7. It is enabled by setting high the control signal mode. It is intended for situations in which the sun position does not need to be tracked at high speed or just to activate a standby mode after taking a measurement. Hence, the expected time interval between different luminance measurements is high. In this case, pixels send an event off-chip when the voltage threshold at the integration capacitance is reached. Then, they do not self-reset and they continue integrating charge until the integration capacitance is fully discharged. The advantage of this operation mode is that power consumption due to the diode dark current and photocurrent is reduced, keeping the potential between the photodiode cathode and anode, V_r, close to zero [15], i. e. $\Delta V \approx V_{DD}$ in Equation 1.

The dark current value, I_{dark}, can be expressed as, [20]:

$$I_{dark} = \frac{A_j \cdot q \cdot n_i \cdot W(V_r)}{2 \cdot \tau_0} \tag{2}$$

It depends on the effective lifetime of minority carriers, τ_0, that has also a strong dependence with temperature; the width of the depletion region, W; the doping, n_i; and the effective area of influence of the incident light, A_i. Technological photodiode parameters are not disclosed by the foundry and precise simulation results taking into account its impact cannot be provided. However, it is important to remark that he dark current value strongly depends on the width of the depletion region, W, that increases with the applied reverse bias voltage, V_r. Hence, keeping this voltage close to zero, the impact of dark current in the power consumption is minimized. Furthermore, pixels that are exposed to higher illumination are the ones that dissipate more power through the reset transistors, M_{p1} and M_{p3} in Figure 3. Since those ones spike first, they are also disabled first. Their photocurrent is also reduced keeping the V_r voltage close to zero because the width of the photodiodes depletion region is reduced. Thus, the diodes are less efficient capturing electron-hole pairs and the photocurrent flowing across the them is consequently lower.

The drawbacks of this operation mode are: 1) The higher amount of time required to reset the pixels' integration capacitances after re-starting the pixel operation. 2) The higher power consumption associated to a full charge the integration capacitance. Thus, this mode is suitable for situations in which the sensor stays inactive for long periods in the satellite.

Sensor implementation

We designed the sensor in the standard UMC180nm fabrication technology. In Figure 8, we depict the pixel layout and the entire sensor layout. Pixel dimensions are $22\mu m \times 22\mu m$. The sensor has a 128 × 128 pixel matrix and its dimensions are $2980\mu m \times 2980\mu m$. On the periphery, we have added the asynchronous arbitration logic necessary to handle the event communication. For the sake of simplicity, we employed the same arbitration scheme than it was used in prior designs [19][9]. It can handle event rates up to 10Meps that is enough to assure the sensor operation with high illumination. We must remark that only a small group of pixels (ROI) will be illuminated. In Figure 9, the layout of the arbitration logic is depicted. This module is used to arbitrate the row and column pixel petitions.

On Table II, the expected sensor features are summarized. The pixel can operate with a nominal power supply voltage of 0.45V compatible with the use of photovoltaic cells to power the chip. In standby mode, the pixel power consumption is only $20pA$. When pixels are active integrating charge, their power consumption is $450pA$.

Table II Sensor expected features.

Technology	UMC180nm
Power supply	0.45V
Pixel latency	<1ms@400lux pixel irradiance
Pixel current consumption (standby)	~20pA
Pixel current consumption (normal operation)	~450pA
Sensor resolution	128 × 128
Pixel pitch	22µm × 22µm
Fill factor	13.3%
Pixel complexity	33 transistors + 1 capacitor
Sensor dimensions	2980µm × 2980µm
Dynamic range	>100dB

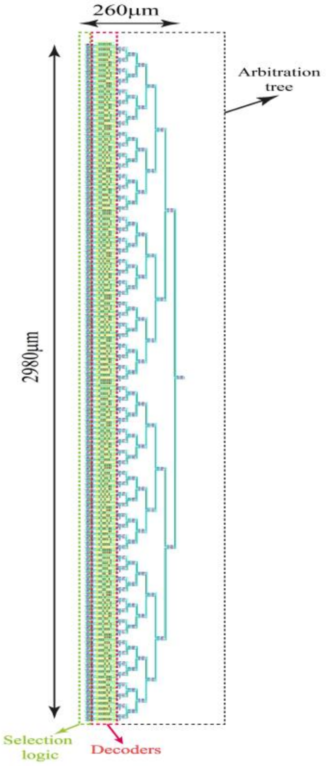

Figure 9 Detail of the arbitration logic. This module arbitrates the row and the column pixel petitions.

Conclusions

A new sun tracker sensor for attitude control in space systems has been presented. It embraces the concept of asynchronous spiking sun trackers devised by the authors simplifying remarkably the sensor operation. Only pixels that are illuminated are readout. Pixels are autonomous and do not need to be scanned periodically. The proposed sensor improves the operation of the initial spiking sun sensors prototypes reported so far. The sensor operation has been optimized to operate on board on space navigation systems by reducing significantly the pixel power consumption. Pixels have been devised to automatically power-off when they gauge their illumination levels whether they are illuminated. Two operation modes can be selected: fast response between consecutive measurements and low energy consumption are available. Thus, the user can tradeoff between speed and power consumption. Furthermore, the sensor operation at 0.45V is directly compatible with the energy harvested with photovoltaic diodes. The next step of our research is to incorporate diodes on chip that can harvest energy to feed the entire sensor without using DC-DC converters that degrade the efficiency of energy harvesting systems.

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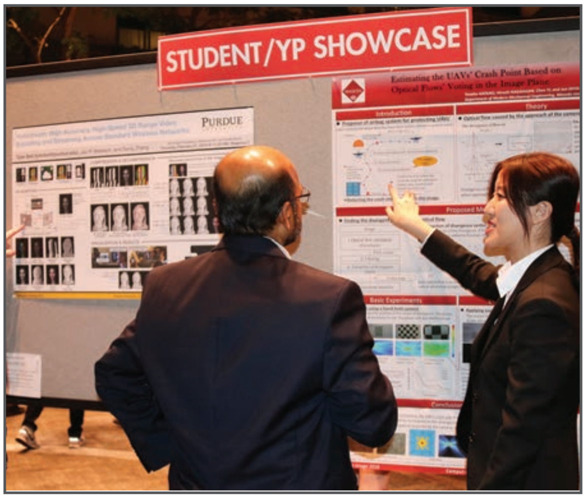

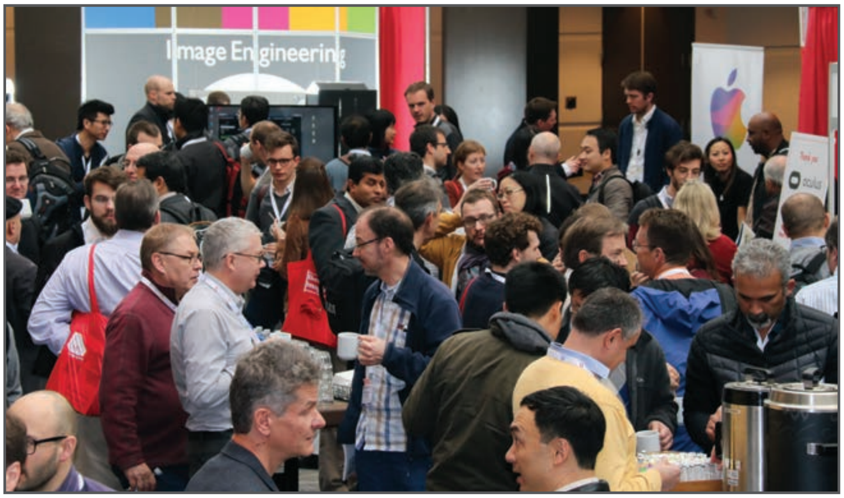

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