A computer vision sensor for efficient real time object detection under varying lighting conditions

Technical Field

The present invention relates, in general terms, to computer vision sensors. In particular, some embodiments of the present invention relate to computer vision sensors for object detection or object tracking or motion detection.

Background

Artificial intelligence paradigms such as neural networks (NNs) and in particular deep neural networks (DNNs) or convolutional neural networks (CNNs) have attracted much attention in recent years due to their outstanding performance in image processing operations. Image processing operations may include object detection, motion detection, object classification, image segmentation, texture analysis, for example.

Variability in lighting conditions, glare and light reflection during capture of images can corrupt the image processing operations conducted by NNs, leading to false object detection and inaccurate outcomes. The variability in lighting conditions may occur due to variability in natural light over the course of a day or over seasons. The variability in lighting conditions may also occur due to variability in artificial lighting. Even though this problem may be mitigated using a more extensive training dataset for the NNs, the immense computational and energy resources required to continuously run the NNs during always-on applications, such as surveillance or self-navigation, pose a serious challenge for battery-reliant mobile systems.

The ability to track objects is vital for autonomous systems such as self-navigating vehicles, security surveillance, or traffic monitoring. One

problem in object tracking is occlusion, which occurs when two or more objects cross each other in a field of view of an image sensor, causing the computer to stop tracking the objects or to track the wrong object. While the human brain is capable of compensating for the invisible parts of the blocked object, computers lack such scene interpretation skills.

Computers may be trained to recognize an object by learning all possible existing images of this object. When the computer actually sees that object, it compares and matches this object with all the corresponding images from the large dataset it learned from in order to recognize the object. The robustness of object detection heavily relies on the completeness of the "big data" dataset used for network training. However, this approach is energy and computation intensive and requires large memories, adding to higher cost, not to mention the fact that it is very unlikely to cover all possible images of a specific object under all possible lighting conditions. This dependence on a predefined training dataset may cause object detection failures when exposed to non-trained images or lighting conditions. Such a scenario may lead to fatal accidents caused by self-navigating vehicles if for instance the trained CNN or DNN cannot recognize a pedestrian crossing the street when the weather changes. While CNNs and DNNs are powerful, a more computationally efficient and power efficient method is preferable. Particularly in mobile applications, energy consumption and computational costs need to be minimized in order to conserve battery life.

It would be desirable to overcome or alleviate at least one of the above-described problems, or at least to provide a useful alternative to existing solutions for improved image processing operations.

Summary

The present disclosure focusses on hardware-based solutions for object

tracking and the like. The solutions reduce power consumption and reduce or remove reliance on a training dataset.

Disclosed herein are sensors comprising a plurality of pixels, wherein each pixel is a photovoltaic cell arranged to output an analog signal that is dependent on a time of illumination of said pixel by a light source.

In some embodiments, the plurality of pixels comprise at least a subset of fault-tolerant pixels for which the output analog signal varies by less than a threshold over a predetermined range of illumination intensities. In some embodiments, the threshold may be 0.

In some embodiments, the fault-tolerant pixels have a charge recombination rate such that the output analog signal varies by less than the threshold over the predetermined range of illumination intensities. In some embodiments, the threshold may be 0.

In some embodiments, each pixel of the sensor is connected to a transistor for multiplexed readout of respective analog signals of respective pixels.

In some embodiments, one or more pixels are connected to a respective counter electrode for simultaneous readout of respective analog signals.

In some embodiments, each pixel may be a dye-sensitized photovoltaic cell (DSSC). The DSSC may comprise an electrolyte containing a redox couple. The DSSC may also comprise a solid-state charge transport layer containing a redox couple. In some embodiments, oxidizing species of the redox couple may be present in an amount that is less than that of a reducing species of the redox couple, to thereby lower the charge recombination rate of the photovoltaic cells.

In some embodiments, the electrolyte may contain only a reducing agent,

such that the oxidizing species is only generated on dye regeneration during illumination.

In some embodiments, each pixel may be associated with a photodetector for measuring light intensity at said pixel. In some embodiments, the respective photodetectors are located alongside respective pixels. In some embodiments, the respective photodetectors may be located within respective pixels.

In some embodiments, the pixels may be arranged in a first array and the photodetectors may be arranged in a second array; and the second array may overlie the first array such that the photodetectors are in register with the pixels. In some embodiments, the photodetectors may be photodiodes.

In some embodiments, the analog output signal may be an open circuit voltage VOC or short circuit current Isc of the photovoltaic cell.

The sensor of some embodiments may comprise a processor for determining a speed of the light source based on the analog signal from one or more of the pixels.

The sensor of some embodiments may comprise a processor for identifying an object based on the analog output signal of the fault-tolerant pixels.

In some embodiments, each fault-tolerant pixel may be a photocapacitor.

The sensor of some embodiments may be configured for tracking movement of the light source based on the analog output signal of a plurality of the pixels.

Present sensors can quickly and correctly react to unforeseen situations in real time like lighting condition changes due to weather variations for

instance. A DNN may give erroneous object detection in such scenarios if the data set used for training did not involve the particular lighting scenario faced at real time.

The present sensor does not need extensive training datasets to detect objects at various lighting levels. That is, the present sensor requires a much less extensive training data set to cover changing lighting conditions, thus using significantly less memory and less computation, leading to cheaper computer vision in terms of both hardware and operational costs.

Brief description of the drawings

Embodiments of the present invention will now be described, by way of non-limiting example, with reference to the drawings in which:

Figure 1 illustrates an operational framework of a fault-tolerant sensor;

Figure 2 illustrates graphs of tuning of the light intensity ranges covered by fault-tolerant pixels (FTPs) of the fault-tolerant sensor;

Figure 3 illustrates images and graphs of detection of a 24-pixel object subject to varying lighting conditions;

Figure 4 illustrates graphs of detection of a 24-pixel object exposed to moving glares and shadows;

Figure 5 illustrates charts of response characteristics of a silicon photodiode and a sensor;

Figure 6 illustrates images frames with no occlusion and a response characteristic graph associated with the image frames for a sensor;

Figure 7 illustrates image frames with partial occlusion and a response characteristic graph associated with the image frames for a sensor;

Figure 8 illustrates image frames with partial and complete occlusion and a response characteristic graph associated with the image frames for a sensor;

Figure 9 illustrates a response characteristic graph of a fault tolerant sensor with respect to various white LED light intensities;

Figure 10 illustrates a 24 pixel sensor that is fault tolerant to a moving shadow and an associated response characteristic graph;

Figure 11 illustrates response characteristic graphs for various sensor pixel configurations and illumination periods;

Figure 12 illustrates a schematic diagram of 2-D matrix sensor circuitry;

Figure 13 illustrates response characteristic graphs of a pixel with white light LED illumination time at various intensities;

Figure 14 illustrates response characteristic graphs of a fault tolerant sensor exposed to various white LED light intensities;

Figure 15 illustrates a schematic of an object tracking sensor comprising smart DSSC pixels; and

Figure 16 illustrates graphs of open circuit voltage output of a photovoltaic motion detecting pixel in response to various light pulse durations and various light intensities.

Detailed description

The present disclosure provides hardware-based solutions to reduce computational resources, total energy and memory requirements when compared with neural networks and other computationally intensive image processing models. The sensors of some embodiments comprise pixels that can handle both glare and shadow filtering with minimal or no energy consumption. These pixels reduce or avoid reliance on complex software computation for image processing operations such as object detection, object tracking, motion detection, and speed estimation of moving objects. The sensors also comprise minimal pixel circuitry. By avoiding complex circuitry, the size of pixels can be reduced and the pixel density can be increased to capture high resolution images.

A sensor may be referred to as a vision sensor, or an object tracking sensor (OTS). The term "pixel", as used herein, refers to a physical photosensitive or a photovoltaic cell or a unit provided in a light detecting sensor. In general, in a sensor a pixel is the smallest unit or component that can perform independent light sensing/detection operations. The term "sensor" may refer to a device comprising a single pixel or an array of pixels arranged in a desirable configuration to sense image data. Each pixel of the sensor is a photovoltaic cell (or a photovoltaic pixel) arranged to output an analog signal that is dependent on a time of illumination of the pixel by a light source. The pixels may also be referred to as fault tolerant pixels (FTPs), or object detecting pixels (ODPs), or optoelectronic OTS pixels.

Some embodiments relate to a vision sensor capable of autonomously correcting for sudden variations in light exposure of a scene under observation, without invoking any complex object detection software. The autonomous correction may be performed as a video pre-processing operation by the sensors. Such video pre-processing may be efficiently performed on images obtained using sensors with photovoltaic pixels

tailored to be insensitive to specific ranges of light intensity alterations. In this way, the pixels may behave similarly to neurons of eyes, wherein the execution of object detection software is only triggered when light intensities shift above or below a certain threshold value. The sensors according to the embodiments allow for efficient fault-tolerant object detection to be implemented with reduced training data as well as minimal energy and computational costs. The sensors according to the invention demonstrate how hardware engineering can complement software algorithms to improve the overall energy efficiency of computer vision operations.

Sensors herein incorporate a fault-tolerant device architecture. Figure 1 shows a fault-tolerant operational framework, where Figure 1(d) illustrates fault-tolerant pixels for which the output analog signal varies by less than some amount (i.e. a threshold) over a predetermined range of illumination intensities. Control of the output analog signal is achieved by controlling the charge recombination rate of fault tolerant pixels.

The architecture of the sensors enables reduction of the computational load associated with image processing operations and in particular image processing operations for object detection under varying lighting conditions. The pixel sensor may comprise two independent units. One unit being an object-detecting pixel (ODP) like silicon photodiodes. The other unit being a fault-tolerant pixel (FTP) that corrects for lighting alterations.

Both ODP and FTP can be constructed next to each other or in a stacked tandem structure (provided the FTP is transparent enough to transmit sufficient light to the ODP). Such division of visual tasks to handle the complexity of vision resembles the layered construction of the retina where different photoreceptive nerves process certain features of vision as well. As glares and shadows are simply changes in greyscales, the FTP just needs to manage white light. The idea behind achieving insensitivity to glares and

shadows is for the output of the FTP to only change if alterations in light intensity exceed a certain threshold. This is similar to the behaviour of a neuron, where a signal is only fired when the stimulus overcomes a fixed threshold.

In this way, the neuromorphic sensor of the embodiments can serve as a video pre-processing filter layer for image sampling, signalling the computer to run a CNN only for those pixels where light intensity changes have exceeded a pre-set threshold. This reduces the overall computational complexity associated with the image processing or object detection operations. In contrast to similar silicon-based technologies, pixel sensors described with reference to Figure 1 do not require additional circuitry for image processing that may consume energy. The pixel sensors also do not unreasonably limit pixel size for high video resolution.

To illustrate, Figure 1(a) contains images 112, 114 and 116 of a common object (a cat) captured under varying lighting conditions. In image 112 (frame 1), the object (cat) is detected by processing the image 112 using a trained CNN. Images 114, 116 are other images of the cat of image 112 but captured under less favourable lighting conditions.

For images 114 and 116 (frame 2), the pre-filter pixels of the embodiments will output different voltages depending on the specific lighting conditions of the respective frames. If the variation is mild, as shown in image 114 (frame 2, case 1), the voltage output of the FTP remains within the pre-set threshold. With the voltage output remaining within the pre-set threshold, there may be no need to trigger the object detection software for image 114. When the light intensity varies significantly, as shown in image 116 (frame 2, case 2), the FTP will output a dramatically different voltage value. This change in the output voltage values can then be used to trigger the execution of object detection software (CNN).

Figure 1(b) is a schematic illustration of different types of shadows cast on a 24-pixel representation of a rectangle (white squares represent one pixel each of the sensor). In illustration 122, no shadow is cast on the sensor. In illustration 124, a moderate shadow is cast on some pixels of the sensor. In illustration 126, an extreme shadow is cast on some pixels of the sensor. The shadow of 126 may trigger object detection, similar to the image frame 116. Whereas, the shadow of 124 may fall within the pre-set threshold and may not trigger object detection, similar to image 114. The FTPs can therefore generate analog output signals that discriminate between modest changes and significant changes in lighting conditions. The quantum of the change required to trigger detection may be modified by the charge combination rate.

Figure 1(c) is an image of a 24-pixel sensor (132) and schematic architecture diagram (134) of a dye-sensitized solar cell (DSSC)-based single FTP. Each pixel may comprise an electrically independent 500μm by 500 μm square DSSC, the pixels only sharing the same electrolyte and counter electrode. The DSSC sensor may comprise Y123 organic dye sensitized mesoporous TiO_2 photoanodes infiltrated by a liquid methoxypropionitrile electrolyte containing 0.1 M $Co(II)(bpy)_3[TFSI]_2$ as the reducing agent. All pixels are configured to be measured concurrently without any delay by multiplexing in order to probe their true time responses to light exposure. Fault tolerance behaviour could be expressed as an invariance in V_{OC} delivered by the DSSC pixels in response to the specific range of intensities variation. Layer 136 represents the dye-sensitized TiO_2 mesoporous photoanode film. Spheres 137 represent TiO_2 molecules in the layer 136.

Figure 1(d) is a graph 140 of the open-circuit voltage (VOC) response of an FTP at various white LED light intensities of a representative pixel of a 24-pixel sensor.

Figure 1(e) is a graph 150 of the percent deviation in VOC of an FTP with respect to the highest V_{OC} value (at highest light intensity) as derived from graph 140 of figure 1(d). Error bars 152 of graph 150 were derived from errors of each of the 24 different FTPs.

Figure 1(d) in graph 150 shows the V_{OC} output of a single representative pixel as a function of illumination time at different light intensities. The different intensities relate to different intensities of white LED light. The percent V_{OC} deviations from the value obtained at the highest probed intensity of 57.2 k Lx are shown in Figure 1(e). It is evident that for the intensity range from 57.2 to 7.1k Lx, the pixel's maximum-saturated VOC values stay within a 10% margin, thus exhibiting fault-tolerant object detection within a 50.1 k Lx intensity variation. As the difference in light intensity increases, i.e., toward lower values (1.5 k Lx in Figures 1(d), (e)), the V_{OC} response grows further apart as well. This demonstrates that this particular FTP is most useful within the 57.2k to 7.1 k Lx range, which corresponds well to outdoors daylight applications.

The images of Figure 1(a) illustrates a plausible example of images suitable for fault tolerant object detection by pixel sensors according to the embodiments. Notably, not all of the pixels of a sensor need to be fault-tolerant. There may be a combination of fault-tolerant and other pixels types.

The images of Figure 1(a) may be subjected to synchronous image frame-based object detection by a trained CNN. The following steps illustrate how the images of Figure 1(a) may be processed by the sensor.

Step 1: First, the image data captured by the ODPs allows the detection of a new object entering the scene in the image frame 112 (frame 1) by processing the image data using a trained CNN. Images 114 and 116 are examples of images captured after the image 112 under a lighting

conditions different from image 112.

Step 2: For the subsequent image frames 114 and 116, the sensor may compare pixel values (or image data) from FTPs with those from the previous frame (112) to check if there are any changes. The changes may relate to changes in the image data due to a change in the lighting conditions. This step can be conducted at a much lower computational cost than the computational cost of object detection by a CNN for every single frame.

Step 3, image 114 (frame 2, case 1): If the FTP values (image data values captured by the FTP) remain within a pre-set threshold, then the FTP values may be considered to indicate that the sensor "sees" the same object, despite exposure to variations in lighting conditions. In this case, these FTPs will not signal the computer to process the image 114 using CNN on the ODPs in this frame and for all successive image frames until such a time that the FTP threshold has been exceeded. The FTP threshold may be exceeded by the introduction of a new object or more extreme lighting changes, for instance. In this way, the neuromorphic FTPs of the embodiments minimize runtime of CNN, thereby reducing the overall energy and computational burden.

Step 3, image 116 (frame 2, case 2): If, in contrast, some pixels vary due to more extreme lighting condition changes, triggered, for instance, by the appearance of a completely different object or by the onset of motion of the perceived stationary object, then the transformed FTP values will trigger CNN to conduct object detection (step 1). After this, step 2 of this algorithm may resume. Image frame 116 illustrates an image of the object of image 112 captured under different lighting conditions with part of the object is obscured. The FTP values associated with image 116 may exceed the FTP threshold in comparison to image 112. Accordingly, capture of image 116 may trigger processing of the image 116 by a CNN.

The sensor of some embodiments may comprise a processor for identifying an object based on the analog output signal of the fault-tolerant pixels of the sensor 132. The processor may receive a digital form of the analog output signal that may be processed by a CNN accessible to the processor to identify an object based on the received analog signal. In alternative embodiments, the analog output signals generated by the sensor 132 may be processed directly by an analog neural network.

Sensors of the embodiments may be more efficient and impactful when dealing with moderate lighting alterations that do not severely mask key features of an object (images 112, 114). In these cases, CNNs do not have to be executed for each image frame, thus significantly reducing energy and computational costs.

In contrast, for more "extreme" shadows leading to complete obscuring of a major piece of a rectangle for instance (images 112, 116), the FTPs perceiving the shadow will output voltages exceeding the predefined tolerated threshold, triggering the computer to run CNN or other shadow detection and removal software to correctly identify the object. Accordingly, the sensors of the embodiments through the FTPs and the predefined tolerated threshold enable the striking of a balance between exertion of computational resources for object detection while maintaining adequate accuracy of object detection outcomes despite variations in lighting conditions.

In some embodiments, each pixel of the fault tolerant sensor may be a dye-sensitized photovoltaic cell (DSSC). The DSSC may comprise an electrolyte containing a redox couple. The DSSC may comprise a solid state charge transport layer containing a redox couple. An oxidizing species of the redox couple may be present in an amount that is less than that of a reducing species of the redox couple, to thereby lower the charge recombination rate

of the photovoltaic cells. The electrolyte may contain only a reducing agent, such that the oxidizing species is only generated on dye regeneration during illumination.

To attain the desired invariant FTP output with varying light intensities, the embodiments utilize dye-sensitized solar cells (DSSCs) in an open-circuit potential V_{OC} mode. Since the V_{OC} depends logarithmically on light intensity, it is hence less sensitive to lighting variations than the short-circuit current. Any photovoltaic device such as silicon, perovskite, or organic photovoltaics can be utilized for this purpose. The reason for choosing DSSCs over other sensors such as silicon-based devices is the ease of modifying the V_{OC} response sensitivity of the pixels via simple electrochemical means, as will be described. The ability to tune the V_{OC} response to the degree of light exposure is crucial to some embodiments as the FTP cannot be too insensitive to a wide range of intensities. If the FTP is too insensitive to changes in light intensities, scene variations, such as the appearance of a new object, expressed as a major change in lighting contrast, cannot be perceived anymore.

Figure 2 shows graphs of tuning of the light intensity ranges covered by fault-tolerant pixels (FTPs) of the fault-tolerant sensor. Upon light exposure, the photoactive dye molecule absorbs a photon and promotes an electron to the dye's lowest unoccupied molecular orbital (LUMO), shown by process 1 of diagram 210 in Figure 2(a). The promoted electrons are then injected into the TiO_2 conduction band (CB), as shown in process 2 of diagram 210 of Figure 2(a). Under open-circuit conditions, the injected charges accumulate in the TiO_2 film, leading to a shift in the TiO_2 quasi-Fermi level toward the CB. The difference between the quasi-Fermi level and the redox potential of the redox couple in the electrolyte determines the V_{OC}. When the now-oxidized dye molecules gain an electron from a nearby reducing agent in the electrolyte through a process called dye regeneration (process 3 in diagram 210 of Figure 2(a)), the dye molecules

are restored to their initial state. This enables the whole cycle of photon absorption and electron injection to restart. The injected electrons in the TiO_2 CB may also be transferred to nearby oxidizing agents present in the electrolyte via a loss mechanism known as charge recombination (process 4 in diagram 210 of Figure 2(a)). This process would result in a decrease in TiO_2 electron density, which leads to the lowering of the quasi-Fermi level, thus reducing the open circuit potential of the pixel.

For the FTPs to exhibit minimal deviation in V_{OC} with changing light intensities, the number of electrons residing within the TiO_2 photoanode must be similar for all light intensities within the range of interest. Generally, the TiO_2 electron density, and hence the V_{OC}, is dependent on both the light intensity and the recombination rate. For instance, the higher the intensity, the more photons available to be harvested by the dyes, resulting in more electrons being injected into the TiO_2 film. In contrast, when for example the recombination rate is high, the TiO_2 electron density decreases, leading to lower VOC. Hence, understanding the interplay between light intensity and recombination rate is crucial for achieving V_{OC} invariance under varying light exposure.

Fault-tolerant behaviour of the sensor includes an invariance in open-circuit potential V_{OC} delivered by the DSSC pixels in response to the specific range of light intensity alterations. Here, invariance means that the V_{OC} does not exceed a user-defined threshold value. In some embodiments the user-defined threshold may be defined to be of maximum 10% V_{OC} deviation limit upon changes in light intensity. Different V_{OC} thresholds can be used, depending on the range of light intensity variation intended to be covered for the desired object-detection application.

Further scaling down of TiO_2 pixel sizes can potentially be achieved using inkjet printing to yield higher-resolution image detection. The individual DSSC FTP comprises an organic dye-sensitized mesoporous TiO_2

photoanode infiltrated by a liquid electrolyte containing 0.1 M $Co(II)(bpy)_3[TFSI]_2$ as the reducing agent.

Figure 2(b) in graph 220 shows the TiO_2 electron life times as a function of light intensity, with the inverse of these electron lifetimes representing the charge recombination rates. For the intensity range where fault-tolerant behavior is exhibited (from 57.2 k Lx to 7.1 k Lx, curve 221), the TiO_2 electron lifetimes, and hence the recombination rates, are similar despite a 50 k Lx intensity variation. This result suggests that, despite the differences in TiO2 electron densities generated within the 50 k Lx range, the TiO2 quasi-Fermi level, and hence the observed V_{OC} does not significantly shift when charge carrier losses are minimal, as mirrored by the similar recombination rates. At lower light intensities outside the fault-tolerant range where the V_{OC} values decrease and are no longer invariant, the TiO_2 electron lifetimes are prolonged as illustrated in graph 220 of Figure 2(b). Typically, extended electron lifetimes and hence slower recombination rates yield higher V_{OC} due to more suppressed electron losses. The observed lower V_{OC} implies that the fewer electrons injected at lower light intensities play a more crucial role in determining the VOC as compared with the slower recombination rate, contrary to the fault-tolerant region where the light intensities have little impact on V_{OC}.

In some embodiments, DSSC pixels are fabricated, containing, in addition to the 0.1 M $Co(II)(bpy)_3[TFSI]_2$, the oxidizing agent $Co(III)(bpy)_3[TFSI]_3$ at the same 0.1 M concentration for the purpose of enhancing charge recombination. Curve 242 in graph 230 in Figure 2(c) shows the percent V_{OC} deviation from the value obtained at the highest probed illumination (at 57.2 k Lx, Figure 1(d)) as a function of light intensity for the enhanced recombination pixels. In contrast to the $Co(II)(bpy)_3[TFSI]_2$-only FTP, the 10% V_{OC} deviation threshold only holds for a narrower intensity range. That is, the lower fault-tolerant threshold occurs at higher light intensities in the presence of $Co(III)(bpy)_3[TFSI]_3$. For these pixels, the TiO_2 electron

lifetime, as expected, is shorter than that in the $Co(II)(bpy)_3[TFSI]_2$-only FTP for all probed intensities, as shown by curve 222 of graph 220 in Figure 2(b).

Pixels exhibiting the higher recombination rates cannot maintain a comparable number of TiO_2 electrons at lower light intensities in relation to the higher intensities, leading to the observed narrower fault-tolerant intensity range. That is, at low intensities, fewer electrons are injected into the TiO_2 photoanode than at higher intensities. If, in addition, the loss mechanism is more severe, as is the case for the pixels exhibiting faster recombination, then the V_{OC} values will differ more significantly. In contrast, if recombination is efficiently suppressed, as in the $Co(II)(bpy)_3[TFSI]_2$-only FTPs, the differences in TiO_2 electrons generated within a larger intensity range do not impact the V_{OC} as dramatically.

In some embodiments the $Co(II)(bpy)_3[TFSI]_2$-only FTPs were fabricated without any dense TiO_2 blocking layer (136 in Figure 1(c)). The absence of such a blocking layer creates additional recombination sites, leading to shorter TiO_2 electron lifetimes, as shown by curve 224 in graph 220 in Figure 2(b). Such FTPs exhibit a similarly narrower V_{OC} invariant light intensity range as the $Co(III)(bpy)_3[TFSI]_3$ containing FTPs, thus underscoring the importance of charge recombination rates on the FTPs' fault-tolerant behavior. The simple manipulation of the recombination rates allows tailoring of the V_{OC}-invariant light intensity region.

The present sensors can conduct fault-tolerance analysis without computational operations from the computer, dramatically minimizing computational load.

Figure 3 shows V_{oc} response graphs and corresponding images of object detection by a 24-pixel sensor, with the object subject to varying lighting conditions. In image 312 of Figure 3(a), the object is not artificially

illuminated and is subject to ambient light in an experimental environment. The stationary object as illustrated in images 312, 314, 316 and 322 was subject to the sudden appearance of varying lighting conditions. A 24-pixel sensor arranged as a rectangle comprising two rows of 12 pixels (as illustrated in Figure 1(c)) was illuminated at low light intensity of 7.1 k Lx (image 314). Subsequently, the sensor was exposed to higher light intensities to simulate the emergence of glare. In images 314, 316 and 322 of Figures 3(a) to 3(d), the object of image 312 is illuminated with light of an intensity of 7.1 k Lx, 33 k Lx and 57.2 k Lx respectively. Illumination by light of an intensity of 33 k Lx or 57.2 k Lx may correspond to a glare in images captured in the real world for object detection purposes.

A $Co(II)(bpy)_3[TFSI]_2$-only FTPs was used to process the images. All pixels were measured concurrently (without multiplexing) to probe their true time responses to light exposure without any delay caused by consecutive pixel sampling.

Figure 3(a) shows that the V_{OC} values of all sensor pixels are invariant within a 10% range in the presence of a glare at 33 k Lx. The brightest glare that can be tolerated occurs for an alteration of light intensity from 7.1 to 57.2 k Lx (Figure 3(b)), where the individual V_{OC} pixel values remain within the 10% preset threshold as well. This demonstrates highly efficient fault-tolerant behavior. Similarly, positive results are obtained for the introduction of shadows as illustrated in Figure 3(c) and 3(d). In Figure 3(c), the graph 330 begin with a V_{OC} value of a bright object (illuminated by light at an intensity of 57.2 k Lx as illustrated in image 322). The object of image 322 is subsequently exposed to the sudden occurrence of a shadow to obtain image 316 where the same object is illuminated by light at an intensity of 33 k Lx. The V_{OC} response graph 330 accordingly indicates a fall in the $\Delta V_{oc}(\%)$ value associated with the change in the illumination level. Figures 3(c) and (d) show the percent V_{OC} deviation of all sensor pixels for shadows at 33 and 7.1 k Lx, respectively, indicating that the FTPs'

V_{OC} values still reside within the 10% variation limit required for fault-tolerant object detection.

Figure 4 shows V_{OC} response graphs obtained from experiments where an object was exposed to moving glares and shadows. The sensor 405 comprises 24 pixels and the V_{OC} response graphs have been segmented across the Figures 4(a)-(d) for clarity of representation. Figures 4(a), 4(c) include graphs for the first twelve pixels (from the left to right) of the sensor 405. Figures 4(b), (d) include graphs for the remaining twelve pixels of the sensor 405. Dashed vertical lines indicate in the respective graphs a peak V_{OC} of each of the two pixels in register detecting the moving vertical glare or shadow strip.

Exposure of an object to moving glares or shadows is an important scenario that occurs frequently in everyday situations in the real world. Exposure to moving glares and shadows is particularly detrimental for motion-detecting algorithms using background subtraction techniques. Motion-detecting algorithms commonly involve the computer comparing successive image frames and subtraction of individual pixel values in the image data to determine which objects or which pixels have undergone a change. The results of the subtraction may signal possible motion of objects. In the presence of glare or shadows in the scene under observation, motion detection algorithms may yield erroneous results, which can trigger high instances of false alarms, especially for autonomous surveillance systems.

Figures 4(a) and 4(b) represent V_{oc} response graphs obtained from a sensor 405 that was subjected to a vertical two-pixel glare strip. Figures 4(c) and 4(d) represent V_{oc} response graphs obtained from the sensor 405 that was subjected to a shadow moving at a frame rate of 50 ms.

The sensor 405 was illuminated with white light from a projector (representing a stationary 24-pixel rectangle), together with a brighter

two-pixel strip traveling from left to right at a 50 ms frame rate, representing a moving glare. Figures 4(a) and 4(b) show the percent V_{OC} deviations of the sensor 405 during this simulation. The pixels exhibit an increase in V_{OC} at the instance of glare appearance, as indicated by the spikes in V_{OC}. However, this V_{OC} deviation remains within the 10% threshold for all pixels.

Similarly, the sensor's ability to detect a stationary object exposed to a moving shadow was demonstrated by conducting a similar experiment, but with a dimmer two-pixel strip, representing the traveling shadow instead. Figure 4(c) and (d) shows the percent V_{OC} deviation of the sensor 405 in response to a two-pixel strip shadow traveling at a frame rate of 50 ms. The negative percent change in V_{OC} mirrors the registration of the moving shadow. For all probed pixels, the V_{OC} deviation is well within the 10% threshold, demonstrating that the sensor is capable of detecting objects despite alterations in lighting conditions. Further increasing the number and density of sensor pixels could allow for the detection of more complex objects.

The neuromorphic sensors according to the embodiments are capable of detecting objects subjected to light intensity variations, without incurring computationally expensive object recognition operations such as processing of image data by CNNs. The sensors according to the embodiments are suitable for fault-tolerant object detection under low to moderate lighting alterations, where key features of the object are still visible and not completely obscured.

Various in lighting conditions such as glares and shadows occurs quite frequently in everyday life and the "noise filtering" capability of the sensors can dramatically minimize energy and computational burden for the computer processing image data originating from the sensors. The neuromorphic hardware of the sensors may advantageously be

incorporated within existing computer vision design frameworks as a strategy to boost energy and computational efficiency while maintaining or improving accuracy.

With regard to the device structure, each sensor pixel may comprise a DSSC. Each cell corresponding to each sensor pixel contains a screen-printed mesoporous transparent semiconductor photoanode sensitized with a photoactive dye (Dyenamo Red dye DN-F05, chemical structure that may be purchased from Dyenamo). The photoactive layer was deposited on FTO (Fluorine-doped Tin Oxide) coated on glass (TEC 7, purchased from Greatcell). Further, the cell contained an electrolyte sandwiched by a counter electrode. This sensor architecture may contain photoactive films that could be printed as individual pixels, where the photoactive films were electrically isolated via FTO etching. The counter electrode as well as the electrolyte could be shared by all pixels of a sensor.

To fabricate the device, patterned FTO-coated glasses (purchased from Latech 14 ohm sq 1) for the 24-pixel sensors was cleaned by heating at 500^{o}C for 10 min. Subsequently, a compact TiO_2 layer was coated onto these glasses by spin coating a solution of titanium isopropoxide (TTIP) (254 mL TTIP/5.6 mL HCl 35%/2 mL ethanol). Spin coating was conducted at 2000 rpm for 60 s. These spin-coated substrates were sintered at 500 C for 30 min. Then, TiO_2 paste (30NR-D Titania paste from Greatcell Solar) was deposited via screen printing to form a transparent mesoporous layer. Subsequently, the substrates were sintered at 500^{o}C for 30 min. Once the glasses were cooled down, they were immersed for 1 day in an organic dye (Dyenamo Red DN-F05) solution (0.1 Mm in tert-butanol/acetonitrile 1:1 v:v). These photoanodes were sealed with bare FTO-coated glass (Greatcell Solar TEC7) acting as the counter electrode, using a thermoplastic sealant film Surlyn (50 mm thin). The electrolyte was injected from previously drilled holes onto the counter electrode. Two different electrolytes were used, 0.1 M Co(II)$(bpy)_3[LiTFSI]_2$ and 0.1 M Co(II)$(bpy)_3[LiTFSI]_2$/0.1 M

$Co(III)(bpy)_3[LiTFSI]_3$ (purchased from Dyenamo DN-C14) in 50 mL methoxypropionitrile (MPN). As the final step, the counter electrode holes were sealed using Surlyn.

In characterising the devices, the open-circuit voltage (V_{OC}) of fabricated solar cells was measured using a National Instruments NI PXIe-1071 24-channel source measurement unit (SMU). For the light source, a high-power LED day white light Solis-3C from Thor Labs was used. Moving glares and shadows were projected using an EPSON EH-TW3200 projector. Motion movies were created with Microsoft PowerPoint using different shades of gray to mimic varying light conditions.

The sensors of some embodiments may be referred to as an object tracking sensor (OTS). The OTS may comprise a plurality of pixels, for example 20 pixels. Each pixel may be of a size of 1mm by 1mm. FTO stands for fluorine doped tin oxide, which is a transparent conductive oxide film provided in each pixel as shown in Figure 1(c). TiO_2 nanoparticles sensitized with photoactive dyes are disposed in a liquid electrolyte containing a cobalt based redox couple as shown in Figure 1(c). The OTS may be configured to perform one dimensional motion detection first. Two-dimensional motion can be achieved using more pixels in the OTS.

To achieve a more energy and computationally efficient approach towards tracking occluded objects, some embodiments include an optoelectronic sensor that pre-processes visual data without having to run complex software. The object tracking sensor (OTS) is configured to detect motion without relying on any motion detecting software. Pixels provided in the OTS output distinct electrical signals dependent on the illumination time. Since light from faster moving objects will dwell on a pixel for a shorter time than slower moving objects, such illumination time dependent response provides temporal information about the perceived motion of objects is a field of view of the OTS. To handle occlusion of objects in the

field of view, the OTS automatically stores data relating to a detected moving object such that, despite blockage of key features of the object, the complete object can be "inferred" based on a partially occluded image of the object.

The optoelectronic OTS pixels comprise a mesoporous transparent TiO_2 layer containing photoactive dyes chemically anchored on the TiO_2 particles' surfaces. An electrolyte infiltrates this photo sensitive layer. The counter electrode allows connection of the OTS pixel to an external load for signal extraction.

Figure 5 shows charts of response characteristics of a commercial silicon photodiode and a sensor. Commercial silicon photodiodes found in cameras do not exhibit any illumination time dependence (the open circuit voltage immediately saturates upon light exposure) nor any memory effect (the open circuit voltage is not maintained but immediately drops back to zero when switching back to the dark), as illustrated in graph 510 of Figure 5(a). OTS pixels on the other hand can operate completely differently. As Figure 5(b) illustrates, the OTS pixel open circuit potential VOC slowly rises with illumination time. This analog V_{OC} response provides temporal information about the detected motion, i.e. at a given light intensity, the V_{OC} pixel values reveal the speed of the moving object.

There are two major conventional approaches for the realization of machine vision: a Digital camera + computer + software and an event based camera approach.

When compared with standard computer-software based system and Dynamic Vision Sensor (DVS) approaches, sensors described herein can significantly reduce energy consumption and computational requirements for object detection or motion sensing image processing operations. Each pixel of the sensor comprises one integrated electronic component, namely

a photovoltaic cell, which is itself is capable of detecting motion independently of other related electronic components. Essentially, the sensor pre-processes visual information in terms of moving objects (estimating speed and acceleration) at zero or nearly zero energy cost (using only photovoltaics in some embodiments) and no computational requirement from a computer for the pre-processing operations. Sensors according to the embodiments enable the realization of cheap, fast, and energy efficient machine vision, especially for mobile devices where battery life is crucial.

The motion sensors according to the embodiments provide temporal resolution of moving objects. In contrast to conventional DVS, present sensors need minimal additional circuitry, allowing the use of smaller pixels (for higher visual resolution, more pixels possible per unit area) at zero or nearly energy consumption for the operation of the pixel.

Present sensors avoid the need for computationally expensive frame by frame analysis of moving objects, in this way relieving the computer from heavy image processing operations. This allows the computer to perform other processes in parallel in a faster manner.

The sensors according to the embodiments do not require any sampling of redundant pixels (pixels that do not correspond to motion of objects) by the computer, in stark contrast to the software-computer system or DVS. The absence of pixel sampling minimizes oversampling and thus avoids detection and analysis of redundant, useless visual information.

Figure 6 shows photos of a device 610 with no occlusion by an object and a response characteristic graph associated with the image frames for the device. Figure 6(a), (b), (c) are images of a rectangle 615 of light projected on an OTS 605 of the device 610 moving from left in Figure 6(a), centre in Figure 6(b) to right in Figure 6(c).

Figure 6(d) shows pixel numbering for 20 pixels in the OTS 605 and a dot point plot of the V_{OC} values of those 20 pixels up to the point where illumination of the corresponding pixel ends. This represents the instance in which the object is moving on to the neighbouring pixels. The OTS 605 comprises a 2x25 array of pixels. The pixel of the two rows of the array are arranged in pairs. As a result, the pixels in each pair are illuminated at the same time. For example, as shown in Figure 6(d), pixels 1 and 2 (bounded by box 620) are illuminated concurrently. Data of Figure 6(d) could be processed by a computer to estimate speed or determine an indication of speed of the tracked object. Motion as illustrated in Figures 6(a)-(c) was uniform, accordingly the V_{OC} response values illustrates in Figure 6(d) are invariant with time. Here, the V_{OC} pixel values vary with different speeds, indicating that the present OTS can successfully detect motion.

To understand the origins of the illumination time dependence, the various charge transfer mechanisms take place in a OTS pixel during light exposure as illustrated in Figure 2(a). As part of process 1, as discussed above with reference to Figure 2, the photoactive dye molecule of the OTS absorbs a photon and excites an electron from the highest occupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO).

Subsequently, in process 2 the excited electron within the LUMO is injected into the TiO_2 photoanode conduction band (charge injection). The dye is now missing an electron, it is in its oxidized state. In order to continue absorbing photons and injecting electrons into the TiO_2 photoanode, this oxidized dye molecule regains an electron back from a nearby reducing agent in the electrolyte as part of process 3 referred to as dye regeneration.

The reducing agent now becomes an oxidizing agent after having transferred an electron to the oxidized dye. If this oxidized agent is near the TiO_2 photoanode, electrons injected into the photoanode may transfer

to this oxidized agent to reduce it back as part of process 4. This electron loss process 4 is referred to as charge recombination and will reduce the charge carrier density within the photoanode. This reduction in electron density within the TiO_2 layer lowers the TiO_2 conduction band (CB) and thus decreases the delivered open circuit potential V_{OC} defined as the potential difference between the TiO_2 conduction band and the redox potential of the redox agents.

The analog V_{OC} rise with illumination time can be explained by slow migration of the reducing agent ion within the liquid electrolyte. That is, during light exposure, solvated cations slowly diffuse from the bulk electrolyte towards the mesoporous TiO_2 surfaces, forming an electric double layer. With illumination time, this electric double layer will become stronger, in this way reducing charge recombination, thereby yielding the observed gradual rise in V_{OC}. The mass of the reducing agent as well as the viscosity of the electrolyte are factors that influence the rate of ion diffusion and are hence crucial tools for tuning the V_{OC} rise time.

The V_{OC} pixel value may not always uniquely correspond to one specific speed of the observed object. The V_{OC} values at different light intensities may be similar or identical but may represent different illumination times, as illustrated in graph 520 of Figure 5(b). To resolve this ambiguity, a double layer sensor could be employed in which an OTS layer is stacked on top of a reference object detecting layer (illustrated in Figure 15) . The object detecting reference layer can be a commercial camera measuring only light intensities. Once the pixel's light intensity is known, the corresponding V_{OC} pixel value from the OTS can be uniquely assigned to represent a specific speed of the observed object. Thus, such data set pair may comprise of light intensity (from reference layer) and V_{OC} pixel value (from OTS layer) may allow robust temporal motion tracking.

Sensors according to the embodiments need not rely on synchronous, well

timed image frame recording to detect motion like for conventional cameras. The sensors allows asynchronous motion detection that can minimize redundant data analysis. Synchronous frame by frame motion detection may generate redundant data especially for stationary objects. The sensor can eliminate or reduce the need for frame by frame motion detection, leading to more computationally efficient motion detection system.

Due to the analog signal encoding of speed in the output by the sensor, the sensor is compatible with artificial neural networks (ANNs), much more so than any other vision sensor technology relying on timer electronics. The sensors operate analogously to biological synapses that require electrical input like voltages and currents. To translate speed information of the moving object to ANN for further processing, a conventional camera would provide image frame data involving the moving object. Such successive image frames may include redundant data like stationary backgrounds, forcing the ANN to deal with useless information. Most importantly, ANNs are not intended to work synchronously like conventional cameras, ANNs are more dynamic and generate asynchronous data similar to the sensors. Hence, the sensor can capture data for estimating or generating an indication of the speed of a moving object without the need for any timer electronics associated with the sensor.

To describe how the OTS handles occlusion (e.g. mobile occlusion), the disclosure first considers the case where the occluding entity is moving towards the object intended to be tracked. The way the OTS deals with such a scenario is to retain data relating to the appearance of the object (learn the object) obtained prior to occlusion and to recall the data relating to the appearance of the same object when parts of it are masked by an occluding entity entering the scene. To implement such unsupervised learning, the OTS pixels implement the capability to retain data relating to appearance of an object in a memory provided in the OTS.

As Figure 5(b) reveals, when light is turned off after light exposure, the V_{OC} drops slowly in the dark and is almost invariant at low intensities, revealing learning and memory capabilities not achievable by conventional silicon photodiodes (Figure 5(a)).

Figure 7 shows images of an experimental setup and results illustrating how an OTS handles mobile occlusion. A 20-pixel OTS was exposed to a moving rectangle 705 (tracked object) facing a thin occlusion strip 715 moving in an opposite direction and acting as the occluding entity. Figures 7(a) to 7(d) are images of the occlusion event, with both objects 705, 715 moving at the same speed of 50ms per frame. Figure 7(f) depicts the corresponding OTS response graph 760 expressed as the V_{OC} value measured at the instance a pixel ceases to observe light, similar to the previously described motion tracking case (Figure 6(d)).

Most pixels show only minor deviations from the not occluded reference scenario (data points in Figure 7(f)), implying that the OTS successfully tracked the object despite occlusion. If this was not the case, the pixels seeing the rectangle 705 and blocked by the occlusion strip 715 should deliver a significant drop in V_{OC} similar to the silicon photodiode as illustrated in Figure 5(a). The absence of such V_{OC} decay upon occlusion is due to the memory effect of the OTS pixels. To ensure that a significant and immediate V_{OC} drop is not actually prevented by the light of the occluding strip, the OTS pixel response with red light illumination time was measured as illustrated in plot 753 of Figure 7(e) which shows change in V_{OC} over time under light of various colours. This is to be contrasted with the V_{OC} change evident under blue light (plot 751) under which a sharp change in V_{OC} was observed, and green light (plot 752) under which a more gradual change in V_{OC} was observed. The observed low V_{OC} (below 100 mV) clearly shows that the present OTS pixels respond poorly to red light and hence is not the source of the observed similar V_{OC} behavior during

occlusion.

In the dark all electrons accumulated and stored in the TiO_2 conduction band of the OTS would typically discharge during illumination through recombination, lowering the V_{OC}. The discharge rate is governed by the recombination rate. With the cobalt reducing agent employed in the sensor, recombination is suppressed resulting in the observed memory effect expressed as a slow V_{OC} decay in the dark as illustrated in the graph 520 of Figure 5(b).

Figure 8 illustrates a second occlusion case, namely partial to complete blockage of a moving object by a stationary obstacle (stationary occlusion). In contrast to mobile occlusion of Figure 7, the pixels seeing the stationary hindrance (foreground) cannot see the moving object (background) at any time and may hence not register an object to be tracked. This is illustrated in graph 870 of Figure 8(g) showing the response of a 20-pixel OTS without and with stationary occlusion. The images in Figure 8(a) to 8(f) illustrate an experimental setup for obtaining the stationary occlusion V_{oc} response data of Figures 8(g) and 8(h).

The pixels of the OTS exposed to a stationary occluding rectangle 814 may deliver low V_{OC} throughout the whole occlusion event, hence potentially failing to address the problem of stationary occlusion. To address this problem, the OTS of some embodiments incorporate a path tracking method or routine utilizing the learning function of the pixels of the OTS. That is, the OTS compares the occluded object with the one prior to the occlusion event in order to determine with high probability that both are the same. This is akin to comparing a current image frame (for example image frames 830, 840, 850 or 860 of Figures 8(c)-(f)) with previously capture image frame image frames (for example image frames 810, 820 of Figures 8(a)-(b)) to determine whether the image frames comprise a partially or majorly occluded representation of the at least some features

of object 812.

In Figure 8(c) for instance, the computer may already stop tracking the object 812 because major parts of the object are masked by the occlusion 814. To deal with this type of occlusion, a path prediction routine or method may be implemented, which can be performed by utilizing the learning function of the OTS. Figure 8(h) depicts a V_{OC} response graph 880 of all 20 pixels of the OTS over the time during which the whole path of the moving rectangle (object 812) has been tracked as illustrated in Figure 8(a) to 8(f). Pixels 9 to 14 deliver significantly lower V_{OC} responses due to the presence of the stationary occluding rectangle 814 as foreground for the pixels 9 to 14. The lack of uniformity of all 20 V_{OC} pixel values may have arisen from light scattering from neighbouring illuminated pixels. The time period between the two vertical dashed red lines is the time period where the complete or nearly complete occlusion of the object 812 by the occlusion 814 (Figure 8(d)) takes place. Within this time period, pixels 9-14 fail to correctly handle occlusion. However, it is evident that pixels 1-8, which have tracked the object prior to the complete occlusion, all nearly maintain similar V_{OC} values even in the instance of complete occlusion (corresponding section 882 within the two vertical dashed lines). Hence, probing those learned pixels provides path prediction data or information that can be used to estimate or determine a more "complete" representation of the invisible occluded parts of the object 812 or even the whole missing object 812.

While in principle, probing of previous pre-occlusion image frames could also be accomplished by commercial cameras, such an approach is quite inefficient and redundant for images of slow moving objects taken at high frame rates, requiring external memory of many previous frames, each having to run image recognition software for proper image segmentation and classification. The sensor pixels of the OTS according to the embodiments on the other hand memorize the values corresponding to the

moving object for a longer period of time as illustrated in graph 880 of Figure 8(h). By memorizing the values corresponding to the moving object for a longer periods the OTS reduces computational cost associated with comparison of image data with image data or previously acquired images.

The OTS is very insensitive to extreme contrast changes in grey scale, as depicted by graph 520 of Figure 5(b) with illustrates minimal drop in V_{OC} values despite all lights being off (complete darkness). This insensitivity improves the robustness of the sensor for occlusion handling. Due to the high tolerance to contrast variations, the sensors of the OTS do not significantly react or memorize any newly appearing object. This high tolerance to contrast variations is not provided by commercial silicon pixels. To reset the pixels of the OTS to track a new object, the pixels of the OTS undergo short circuiting, like discharging a capacitor or a photocapacitor.

In some embodiments, each fault-tolerant pixel may be a photocapacitor. A photocapacitor is an element or a cell that absorbs light that falls on the photocapacitor and accumulates an electric potential as a function of the intensity or frequency/wavelength of light the photocapacitor was subjected to. The accumulated electric potential may be measured to determine an indication of the properties of light that the photocapacitor was subjected to. The photocapacitor may be short circuited to reset the photocapacitor and initiate a subsequent observation.

The OTS according to the embodiments provides a very efficient self-learning computer vision sensor for handling tracking of occluded objects. Each pixel sensor of the OTS accomplishes this task without the need for any extended pixel circuitry, allowing high resolution and energy efficiency. Furthermore, the video pre-processing sensor form a basis for a potential multi-layer device in which each layer performs a specific visual task such as motion sensing, memory, shape detection, etc. in order to compress and to simplify complex visual data.

As mentioned above, some embodiments provide a vision sensor that is insensitive to light intensity alterations within a certain range. Thus, the sensor acts like a neuron that only changes output when light intensities shift above a certain threshold (threshold over a predetermined range of illumination intensities). This neuromorphic feature or design allows energy and computationally efficient fault tolerant object detection under varying lighting conditions using state of the art synchronous stationary image frame sampling method or prospective artificial neural networks operating with analog video input. Since the proposed sensor pixels are composed of photovoltaic cells, the device according to the embodiments is also highly space and energy efficient, allowing high resolution fault tolerant object detection at minimal energy and material costs.

Figure 9 illustrates the V_{OC} output of all 24 pixels of a sensor 905 in as a function of illumination time at different light intensities. It is evident that for the intensity range of 37k Lux (graph 910, Figure 9(a)) to 61k Lux (graph 920, Figure 9(b)), there is little change in the pixels' V_{OC} behaviour. Therefore, the sensor 905 exhibits fault tolerance within this intensity range spanning a 24k Lux deviation. As the light intensity gap increases, i.e. towards lower values, up to 7.1k Lux, the V_{OC} just declined by about 10% from its maximum value as illustrated in graph 930 of Figure 9c), indicating that even at this large intensity difference of about 54k Lux, fault tolerance is still possible within a 10% deviation.

Figure 10(a) illustrates a 24 pixel sensor 1005 that is fault tolerant to a moving shadow. Figure 10(b) illustrates a V_{OC} response graph 1020 of all 24 pixels of the sensor 1005 subject to the moving shadow. Figure 10(c) illustrates a V_{OC} response graph 1030 of all 24 pixels of the sensor 1005 subject to the moving glare.

To further illustrate the sensor's ability to perform fault tolerant object

detection, the whole 24 pixel sensor 1005 was exposed to light. The light represented the perception of a stationary rectangle since the pixels of the sensor 1005 are arranged as a rectangle comprising two rows, each containing 12 pixels as illustrated in Figure 10(a).

A darker square 1015 covering 2 by 2 pixels was moved from left to right at a 50 ms frame rate, as illustrated in the image 1010 of Figure 10(a). The experiment simulated the detection of a stationary object subject to a moving shadow, like a shadow moving along a wall. Figure 10(b) shows a V_{OC} response graph 1020 of the sensor 1005 during this simulation. The pixels exhibit a decrease in V_{OC} at the appearance of a shadow, as indicated by the dips 1025 in V_{OC} graph. However, this V_{OC} decline is not significant, about a 15% maximum deviation from the shadow free V_{OC} values (horizontal lines in Figure 10(b)) for the worst performing pixels. For most pixels, the deviations are around 10%. Thus, the sensor 1005 is capable of detecting a simple stationary object despite alterations in lighting conditions.

The analogue V_{OC} response with illumination time of the fault tolerant pixels allows detection or estimation of speed of objects under observation by the sensor 1005. Fast speed means short illumination of the individual pixels, leading to lower V_{OC} values than slower objects with longer light exposure. Such analog response is beneficial for interfacing with analog devices used to mimic neuron behaviour. Therefore, the sensor 1005 can be configured to perform speed labelling of objects under observation or motion pre-processing operations that assigns weights to the speed of objects due to pixel dwelling time. These weights are compatible with analog artificial neural networks (ANN) comprising instance of memristors, spintronic, or phase changing devices. The advantage of using ANN for motion and speed detection is that, in contrast to highly synchronized DNN, ANN run asynchronously, with no frame by frame pixel sampling required, in this way saving energy and computations. Since the sensor 1005 operates

asynchronously as well, it is very suitable for tracking moving objects subject to changing lighting conditions, a task currently requiring significant computational power by relying on synchronous frame by frame sampling methods.

Figure 11(a) illustrates a V_{OC} response graph 1110 of 24 pixels of a sensor subject to a moving strip that illuminates two pixels at a time for a period of 50 ms. Figure 11(b) illustrates a V_{OC} response graph 1120 of 24 pixels of a sensor subject to a moving strip that illuminates two pixels at a time for a period 300 ms. Figure 11(c) illustrates a V_{OC} response graph 1130 of a single sensor pixel at 50 ms and 300 ms light exposure times, highlighting more clearly the differences in V_{OC} values for each detected speed.

Ideally, all 24 pixels of the sensor should provide similar V_{OC} values. The discrepancies in the peak value and timing of the V_{OC} values in graphs 1110 and 1120 may be explained by light scattering to neighbouring pixels as the strip is moving. Nevertheless, it is still observable that the V_{OC} responses are different for the two varying speeds probed. To further clarify this effect, Figure 11(c) depicts the V_{OC} response graph 1130 of one particular pixel subject to different illumination times, showing distinct V_{OC} values for altered speeds, underlining the sensor's ability to estimate or determine a weight corresponding to the speed of an object being observed by the sensor.

As mentioned above, pixels can be made insensitive to changes in light intensities within certain ranges by manipulating the electrochemical processes occurring in the electrochemical cells of the sensor. Using the open circuit voltage V_{OC} as the output signal, the number of electrons residing within the TiO_2 photoanode is similar at the light intensity range of interest. Generally, the V_{OC} scales with light intensity since the higher the intensity, the more photons are present to generate more electrons (process 1 and 2 in Figure 2(a)). Therefore, to achieve similar V_{OC} at various

intensities, the electron density residing in the TiO_2 photoanode may be tuned by controlling the both the charge recombination and the dye regeneration rates (process 4 and 3 in Figure 2(a) respectively). A fast charge recombination allows reduction of charge carrier density within the TiO_2 photoanode at high light intensities, thus allowing comparable V_{OC} at lower light intensity. Similarly, dye regeneration rate also determines how many electrons can be injected into the TiO_2 photoanode. Therefore, tuning those two processes using different redox couples at various concentrations yields similar electronic responses at altered light intensities.

The sensors according to the embodiments are capable of fault tolerant object detection under varying lighting conditions. This is achieved by tailoring the photovoltaic pixels of the sensor in such a way that their V_{OC} responses are similar within a certain range of light intensities. Furthermore, the V_{OC} analogue behaviour with illumination time allows speed labelling, with those weighted speeds serving as inputs for artificial neural networks. Therefore, the sensors may perform video pre-processing for object detection or speed estimation while operating at low energy and computational costs for real time and always on object detection even under unexpected changing lighting conditions.

Sensors according to the embodiments are configured to not react to sudden lighting changes in a scene under observation. That is, the output electrical signals of pixels of a sensor remain unaltered despite variations in light intensity in the scene being observed by the sensor. The data generated by the sensors thus enables standard object detection software to perceive the same object in the captured image data despite variations in illumination in an observed scene in the real world.

Figure 12 is a schematic diagram of a 2-D matrix sensor circuitry 1220 of a matrix of object detecting pixels 1210.

Each sensor pixel comprises an electrochemical photoactive cell or of a dye sensitized solar cell. The cell contains a mesoporous transparent semiconductor photoanode sensitized with a photoactive dye. The photoactive layer is deposited on a surface of a transparent conductive oxide film on glass as illustrated in Figure 1(c). Further, the cell contains an electrolyte (136 in Figure 1(c)) containing redox shuttles that can be organic, inorganic, or transition metal complex redox pairs, or a hole conducting film sandwiched by a counter electrode as illustrated in Figure 1(c).

Each pixel of the sensor may be connected to a transistor for multiplexed readout of respective analog signals of the respective pixels. In some embodiments, one or more pixels may be connected to a respective counter electrode for simultaneous readout of respective analog signals.

A detection sensor comprises a 2-dimensional matrix of those photovoltaic pixels, with each pixel being connected to a transistor such that pixel sampling via multiplexing for object detection is possible as illustrated in the schematic diagram of sensor 1220 of Figure 12. This sensor architecture contains photoactive films that are printed as individual pixels and connected to a pixel addressing transistor 1222. A counter electrode is one electrode shared by the entire matrix of pixels.

The electrolyte or hole conductor film may be shared by the whole pixel matrix as well. The electrolyte contains an organic solvent and redox couples dissolved in them. These redox couples can be transition metal complexes or organic hole conductor molecules. The sensor uses a mesoporous transparent TiO_2 film with organic dyes chemically anchored to the TiO_2 particles as the photoanode. The electrolyte may contain $Co(II)(bipyridine)_3[LiTFSI]_2$ as a reducing agent dissolved in methoxypropionitrile, but can contain other types of redox couples and solvents or solid state hole conductor films as well.

Illustrated in Figure 12 is a column selection register 1224 and a row selection register 1226. Values of the row and column selection registers 1224, 1226 may be set by a processor 1240 to select a particular pixel within the array of pixels 1220. Output of the selected pixel may be accessible to the processor 1240 via the output of the analog multiplexer 1225 based on the values of the row and column selection registers 1224, 1226. While at least a part of the output of the pixel may be in an analog form, the analog output may be converted to a suitable digital form by an intermediate analog to digital signal converter before processing by the processor 1240.

Figure 13 illustrates response charts of a pixel exposed to various light intensities. It is evident that within the range of 26,000 – 20,000 Lux of white LED light intensity, the V_{OC} is comparable. Hence, it is shown that the present sensor is insensitive to a light intensity change of 6,000 Lux. More light intensity ranges can be reached as well with proper tailoring of the electrochemical charge transfer processes summarized in Figure 2.

Figure 13(a) illustrates an open circuit voltage V_{OC} response graph 1310 of a pixel (2mm by 2mm square) in response to white light LED illumination time at various intensities. Figure 13(b) illustrates a V_{OC} response graph 1320 of the same pixel as in Figure 13(a) enlarged for the fast response when subjected to a 1 second illumination period.

Sensors according to the embodiments may be configured to operate with conventional object detection software based on image processing techniques such as image processing using DNNs. The sensor may replace a conventional digital camera which inherently does not have the insensitivity to changes in light intensities. More specifically, when light conditions vary, the corresponding pixels of the sensor exposed to different light intensities do not output a significantly altered electronic signal, in this

way allowing the object recognition software to detect the same object despite variations in light conditions. This image or video pre-processing using the sensors is fast as well as energy and computationally efficient. The sensors enable more accurate object detection when subjected to untrained situations involving unexpected alterations in lighting scenarios such as changes in weather. Furthermore, a much smaller training dataset may be required to train the object detection software processing image data generated by the sensors. Use of smaller training datasets allows lower occupation of valuable memory space in object detection systems.

There are two operational modes for object detection and tracking that particular embodiments of the sensor can adopt:

1. Fault tolerant object detection: The sensor can operate in conjunction with common synchronously clocked computers that analyze video as successive image frames pixel by pixel (pixel sampling). Object detection may be performed by image recognition software such as deep neural networks (DNNs). The sensor provides a hardware approach to alleviate the problem of object detection under changes in lighting conditions. To achieve this goal, the sensor's voltage or current outputs change only if it detects light intensities alterations above a certain threshold. This is analogous to the behaviour of biological neurons that also only fire a signal when the stimulus overcomes a particular threshold. The neuromorphic sensor according to the embodiments can then be used as a video pre-processing layer implementing a threshold for image sampling, in this way reducing computational steps. More specifically, if an object is subject to lighting variations (within a threshold), the neuromorphic fault tolerant sensor will generate similar pixel values. The following algorithm could be used to minimize computational loads with the help of the sensor when performing synchronous image frame based object detection based on DNN:

Step 1: First, a trained DNN (implemented on a computer) detects a new object entering the scene under observation by the fault tolerant sensor.

Step 2: For the subsequent image frame, the computer compares pixel values from the fault tolerant sensor with those from the previous frame to check if there are any changes. This computational step can be carried out at a much lower computational cost than running DNN analysis for each frame.

Step 3: If the fault tolerant pixel values are the same, then it means that the present sensor sees the same object, even though the object may be subjected to variations in lighting conditions, as long as those lighting changes are within the tolerated range of the present sensor. In this case, the computer will not run DNN for this particular subsequent frame because the present sensor did not output different pixel values.

Step 4: If, on the other hand, some pixels vary due to more extreme lighting condition changes, triggered for instance by the appearance of a completely different object, then the transformed fault tolerant pixel values will trigger an execution of the DNN to perform object detection. After this, step 2 of this algorithm may resume.

2. Speed labelling motion pre-processing camera: The analogue V_{OC} response with illumination time of the fault tolerant pixels allows very speed detection or estimation of speed of objects in a field of view of the sensor. Fast speed of an object results in short illumination of the individual pixels, leading to lower V_{OC} response values in comparison to slower objects with a longer light exposure. Such analog response may advantageously allow interfacing the sensor with other analog devices used to mimic neuron behaviour.

Hence, sensors according to the embodiments may perform speed labelling

or motion data pre-processing. The data or image data or V_{OC} response data captured by the sensors may enable assigning of weights to the speed of objects based on pixel dwelling time of light being reflected from the objects.

One important objective of machine vision techniques is the ability to track moving objects. Current technology relies on frame by frame image analysis to detect motion. Such conventional methods however require heavy computational load and hence consume significant energy which is especially disadvantageous for mobile applications.

The optoelectronic sensors according to the embodiments that can track moving objects at minimal energy and computational cost. In particular, the sensor comprises an array of smart photovoltaic pixels that exhibit an analog voltage response to light illumination time. This sensitivity to light exposure time allows motion sensing without the need for frame by frame image analysis. The sensors of the embodiments enable motion of objects in a field of view of the sensor to be represented in the form of a string of pixel voltage data sets that can be easily and efficiently evaluated by an image processing computer, enabling computationally efficient and fast object tracking for computer vision.

Sensors described herein are also configured to output different voltage signals as a function of the speed of the perceived motion without the need for a more frequent pixel and image frame sampling by a computer. More specifically, this sensor comprises an array of photosensitive pixels, each yielding an analog response to the light dwelling time.

A moving object is then detected using data from the sensors as follows: the pixels sensing the object are illuminated by light of a certain intensity from that object. As the object moves in the field of view of the sensor, a different pixel of the sensor is illuminated or the intensity of light

illuminating the earlier pixel changes with the movement of the object. That is, the pixels of the sensor are subjected to light intensity changes due to the motion of the object. The time it takes for such an intensity transition to occur is equivalent to the light dwelling time on the pixel. Therefore, this light dwelling period represents an indication of the speed at which motion is being perceived. If for instance the object is moving rapidly, then light dwelling time on each pixel will be shorter that for a slower object. Using the light dwelling period information, pixels of the sensor allow motion detection without the need for constant successive image frame analysis and pixel sampling.

The smart pixel, in a non-limiting exemplary embodiment, comprises a dye sensitized solar cell (DSSC) with a Y123 sensitizer chemically attached to a mesoporous TiO_2 layer, together with a liquid electrolyte containing 0.1 M $Co(II)(bpy)_3(TFSI)_2$ in methoxypropionitrile.

Figure 14(a) illustrates an illumination time dependent voltage output graph 1410 of a DSSC pixel exposed to repeated 5s of illumination followed by 5s of darkness (or lower light intensity). Figure 14(b) illustrates an illumination time dependent voltage output graph 1420 exposed to repeated 500 ms of illumination followed by 500 ms of darkness (or lower light intensity). The upper dashed line (1412, 1416) denotes the maximum voltage attained while under light exposure, whereas the lower dashed line (1414, 1418) depicts the minimum voltage achievable after the transition to a lower light intensity level.

As a non-limiting example, the size of the pixel is a square with the dimension of 2 mm by 2 mm. To mimic motion detection by a single pixel, it was illuminated by white light from an LED source with an intensity of 130,000 Lux as measured by a lux meter to obtain the graphs of Figure 14. Figure 14(a) illustrates the open circuit voltage V_{OC} output of the DSSC pixel under slow (5 s) light intensity changes (long light dwelling times,

representing slow motion), whereas Figure 14(b) reflects the open circuit voltage response upon faster (500 ms) light pulses (shorter light dwelling time, mirroring faster motion).

For the 5 s transition time, the V_{OC} decay upon the onset of light intensity decrease is gradual and follows a slow exponential decay. Even after the long 5 s dark period, the V_{OC} did not approach zero. This behaviour is in stark contrast to state of the art CMOS photodiodes that reaches zero voltage almost instantaneously once the CMOS sensor is not exposed to light. It is exactly this slow V_{OC} decay in the sensor that allows their use as analog motion detectors. Based on this retarded V_{OC} drop after illumination, it is apparent that different dark periods will yield different specific V_{OC} values, as illustrated in Figure 14(b), representing faster light pulses of 500 ms duration. In Figure 14(a), the V_{OC} drops to a lower value (approximately 0.1V, line 1414) than for the shorter (500 ms) dark period (approximately 0.2V, line 1418). Therefore, successive V_{OC} values that differ from each other are capable of indicating a speed of a moving object. This data representation allows object tracking to be performed without the need for (or less frequent need for) frame by frame analysis of stationary images, where each image's pixels will also have to be sampled. Instead, the DSSC pixel is capable of compressing visual data of movement into a string of V_{OC} values that can be easily evaluated either by a computer or by artificial neurons.

The slow V_{OC} decay upon the transition from high to lower light intensities originates from retarded recombination between the injected electrons within the TiO_2 film and the $Co(III)(bpy)_3$ redox couple under open circuit condition. Typically, for $Co(III)(bpy)_3$, this recombination is fast and takes place within milliseconds. However, in the sensors of the embodiments, the V_{OC} decay in the dark is very slow, taking tens of seconds. This slow decay stems from the absence of the oxidizing species $Co(III)(bpy)_3$ in the cell in the dark, since the electrolyte within the present device contains the

reducing agent $Co(II)(bpy)_3$ only. The oxidizing species will only be generated within the cell upon dye regeneration during illumination. Therefore, the number of oxidizing species is so overwhelmingly low as compared to the reducing agents, resulting in highly retarded recombination, thus leading to the observed slow V_{OC} decay in the dark.

In some embodiments, each pixel of the sensor may be associated with a photodetector for measuring light intensity at said pixel. The respective photodetectors may be located alongside respective pixels. The respective photodetectors may be located within respective pixels.

To prevent ambiguous values of V_{OC} that could occur at various light intensities, it is necessary to specify the exact intensity at which the V_{OC} response is being measured. This can be accomplished by embedding a photodetector within the DSSC motion sensor pixels. The whole pixel would thus transmit the light intensity value as well as part of the motion detection event.

The pixels may be arranged in a first array (1550 of Figure 15) and the photodetectors may be arranged in a second array (1540 of Figure 15). The second array may overlie the first array such that the photodetectors are in register with the pixels. The photodetectors may be photodiodes. The analog output signal of the sensor may be an open circuit voltage V_{OC} or short circuit current I_{sc} of the photovoltaic cell.

One device architecture for an object tracking sensor 1500 is illustrated in Figure 15. Sensor 1500 has a hierarchical structure comprising two levels of functional devices. The first layer (direction layer 1540) encompasses an array of photodiodes (1510) that could be for instance CMOS based. Commercial digital cameras can be used for this intensity determining layer. In addition to providing the light intensity values of each pixel, this layer also conveys information about which pixels exactly receive light, in

this way being able to reveal the direction of the moving object (but not the speed). On top of this directional layer 1540, an array (object and speed recognition layer 1550) of the DSSC smart pixels (1520) is deposited. This second layer 1550 generates data indicative of the speed of the tracked object, as described above. Therefore, this two level object tracking sensor 1500 is capable of detecting motion, including both direction and speed, without the need for computation heavy frame by frame image analysis and pixel sampling. A counter electrode layer 1530 is provided in the sensor 1600. The counter electrode 1530 is one electrode shared by the entire matrix of pixels in the sensor 1500. The sensor 1500 constantly outputs voltages from both layers as compressed visual data at minimal energy and computational costs.

The sensor of some embodiments may comprise a processor for determining a speed of a light source based on the analog signal from one or more of the pixels. The signal provided to the processor may comprise the outputs voltages each pixel from both the layers 1540 and 1550. The output voltages may be processed by the processor to determine speed of a light source before the sensor 1500. In some embodiments, inputs to the processor may be in the form of voltage data represented in Figure 14.

The smart pixel 1520 may be implemented using a dye sensitized solar cell (DSSC) serving as a motion detecting pixel. Each smart pixel 1520 may comprise an organic sensitizer and transition metal based redox couples in a liquid electrolyte or a hole conductor.

The conceptual basis for motion detection, especially speed estimation, lies on determining how long light of the same intensity is dwelling on each pixel until an intensity change occurs, signalling movement. For stationary or very slow moving objects, light dwelling time will be longer, whereas fast moving bodies trigger a rapid change of light intensity observed by the pixel for a shorter period of time. The temporal resolution of the light dwelling

time gives temporal information of movement such as speed and acceleration. Adding the direction of the movement provides a complete description of an object's motion. Such directional information is gained by sending the address of the active pixel's location within the motion sensor's matrix.

The smart pixel 1520 does not require timer electronics or any additional electronic circuitry to measure this light dwelling time. Instead, it utilizes the rates at which electrons injected into the mesoporous semiconductor recombines with the redox couples or hole conductor of a dye sensitized solar cell (electron e- in a TiO_2 layer transferring to E^+). The recombination rate data or values are reflected in an analog response of voltage and current in dependence of light illumination time and light intensity. To achieve long illumination time responses in the milliseconds to several seconds, appropriate redox couples or hole conductors have to be employed that yield electron recombination times in this time range.

The pixel 1520 may comprise a glass or polymer layer disposed on a side of the pixel intended for receiving light from objects or a scene being observed. A similar glass or polymer layer may be provided on an opposite side of the pixel 1520 to physically enclose the components of the pixel. A transparent anode layer is provided on an inner side of the glass or polymer layer and a cathode layer is provided on an inner side of the glass or polymer layer. Provided between the anode and cathode layers is a layer of mesoporous TiO_2 layer and a dye. The output signal of the smart pixel 1520 may include one or both of a voltage signal and a current signal. The motion of an object can be determined based on the output signals of the plurality of smart pixels 1520 of the object and speed recognition layer 1550.

Figure 16 illustrates open circuit voltage output values of a photovoltaic motion detecting pixel in response to various light pulse durations,

switching between a LED white light of intensity of 60,000 Lux to darkness. The peaks arise during illumination, whereas the valleys result from the light switching off to darkness. The light pulses last for 5s, 2s, 500ms, 10ms for graphs 1610, 1620, 1630 and 1640 respectively.

Motion sensing requires the acquisition of both the directional and temporal components. Figure 16 illustrates graphs of the open circuit voltage V_{OC} output of the pixel of some embodiments in response to various light pulse durations, simulating different light dwelling times and hence various speeds of a moving object. The peak V_{OC} values gradually increase with increasing illumination time, until the V_{OC} values reaches a maximum saturated value (approximately 0.5 V). This analog V_{OC} response to light dwelling duration thus encodes an observed speed or an indication of a speed of a moving object. As illustrated in Figure 16, the peak V_{OC} values corresponding to a short illumination (10 ms) is much lower (0.1 V) than the peak V_{OC} values longer illuminations (500 ms and longer), representing fast and slow movement respectively.

When illumination of the pixel stops or changes to a lower light intensity, the V_{OC} gradually decreases with time. This gradual decrease in the V_{OC} values thus provides information about the speed of the detected motion as well. For instance, fast uniform motion is seen as alternating light intensities at constant low intensity/high intensity intervals. In such a case, the motion sensor can translate such fast motion as a higher V_{OC} minimum during its decay as compared to slower motion. This effect is illustrated in Figure 16 where for instance the 500 ms light on and off pulses yield higher V_{OC} minima (approximately 0.2 V in graph 1630) after each pulse (intensity changing event) than the slower 2 s light pulses (0.1 V in graph 1620). Therefore, the V_{OC} values and in particular the peak and minima values measured upon light intensity alteration provides information about the duration of this light intensity change event.

To handle ambiguous values of V_{OC} that could occur at various light intensities, it is thus necessary to specify the exact intensity at which the V_{OC} response is being measured. To address this, the photovoltaic motion sensor pixels may comprise an embedded photodetector (illustrated as 1510 in Figure 15). The whole pixel can thus transmit the light intensity value as well as part of the motion detection event.

The lighting condition insensitive computer vision sensors described herein have the following commercial applications, among others:

Any autonomous machines requiring computer vision to visually interact with their environment in a more robust way, especially for minimizing object detection errors under changing lighting conditions frequently occurring in everyday life. Such systems include robotics, surveillance cameras, self-navigating vehicles, military or commercial surveillance drones, computer vision for quality control, just to name a few.

Some present sensors are particularly well suited for mobile applications where low energy consumption and minimal computational cost for object detection are advantageous for prolonging battery lifetime of mobile systems. Such mobile systems include for instance surveillance, military, or package delivery drones, self-navigating vehicles, or mobile robotics for elderly care or facility cleaning.

Another important field of application is motion detection or object tracking. Current state of the art motion detection software relies on a so called background subtraction algorithm. That is, the computer compares two successive image frames and determines whether light intensities measured by the camera pixels have changed. Only the objects represented by changing pixel values highlight a moving object. The stationary objects denoted by pixels with unaltered light intensities are then subtracted from the two image frames, in this way revealing only the moving objects.

However, this conventional approach is error prone to changing light intensities. For instance, if the computer wants to detect a person walking in a room, the software can subtract out the stationary background like the walls or the furniture. This may work well in a very well defined scenario. But such conventional processes may be subject to faults or errors when suddenly between image frames the light conditions change, like a shadow is forming on the walls. In such cases, the pixel values will change, tricking a computer to determine that the walls are moving even though they are not. Such a problem could lead to fatal accidents for self-navigating vehicles. The sensors that are fault tolerant despite variations in lighting conditions can help improve object tracking software and make object tracking more robust in such detrimental lighting conditions.

Present sensors may be incorporated in any surveillance technology such as surveillance cameras or visual quality control of products that are moving along conveyor belts and need to be quickly screened for any possible defects. Since the motion sensors according to the embodiments encode motion with temporal information as analog voltage or current signals, those signals can be conveniently used as input for other analog electric components (i.e. transistors) or even digital circuits (i.e. Boolean logic) for more complicated analysis of moving visual objects. For instance, the analog motion sensor of the embodiments could send signals into a neural network that subsequently performs facial recognition of multiple moving humans.

Abbreviations

FTP: Fault tolerant pixel

V_{OC} : Open Circuit Voltage

CNN: Convolutional Neural Network

ODP: Object Detecting Pixel

DSSCs: Dye-sensitized solar cells

LUMO: Lowest unoccupied molecular orbital

CB: Conduction Band
OCVD: Open-circuit voltage decay
DNN: Deep Neural Network
TPMS: Time resolved photovoltaic motion sensor

It will be appreciated that many further modifications and permutations of various aspects of the described embodiments are possible. Accordingly, the described aspects are intended to embrace all such alterations, modifications, and variations that fall within the spirit and scope of the appended claims.

Throughout this specification and the claims which follow, unless the context requires otherwise, the word "comprise", and variations such as "comprises" and "comprising", will be understood to imply the inclusion of a stated integer or step or group of integers or steps but not the exclusion of any other integer or step or group of integers or steps.

The reference in this specification to any prior publication (or information derived from it), or to any matter which is known, is not, and should not be taken as an acknowledgment or admission or any form of suggestion that that prior publication (or information derived from it) or known matter forms part of the common general knowledge in the field of endeavour to which this specification relates.

CLAIMS

1. A sensor comprising a plurality of pixels, wherein each pixel is a photovoltaic cell arranged to output an analog signal that is dependent on a time of illumination of said pixel by a light source, and on a change of light intensity, the sensor tracking movement of the light source based on the change of light intensity and determining a direction of movement based on which said pixels are illuminated by the light source.

2. A sensor according to claim 1, wherein the plurality of pixels comprises at least a subset of fault-tolerant pixels for which the output analog signal varies by less than a threshold over a predetermined range of illumination intensities.

3. A sensor according to claim 2, wherein said fault-tolerant pixels have a charge recombination rate such that the output analog signal varies by less than the threshold over the predetermined range of illumination intensities.

4. A sensor according to any one of the preceding claims, wherein each pixel is connected to a transistor for multiplexed readout of respective analog signals of respective pixels.

5. A sensor according to any one of claims 1 to 3, wherein one or more pixels are connected to a respective counter electrode for simultaneous readout of respective analog signals.

6. A sensor according to any one of the preceding claims, wherein each pixel is a dye-sensitized photovoltaic cell (DSSC).

7. A sensor according to claim 6, wherein the DSSC comprises an electrolyte containing a redox couple.

8. A sensor according to claim 6, wherein the DSSC comprises a solid state charge transport layer containing a redox couple.

9. A sensor according to claim 7 or 8, wherein an oxidizing species of the redox couple is present in an amount that is less than that of a reducing species of the redox couple, to thereby lower the charge recombination rate of the photovoltaic cells.

10. A sensor according to claim 9 when dependent on claim 7, wherein the electrolyte contains only a reducing agent, such that the oxidizing species is only generated on dye regeneration during illumination.

11. A sensor according to any one of the preceding claims, wherein each pixel is associated with a photodetector for measuring light intensity at said pixel.

12. A sensor according to claim 11, wherein respective photodetectors are located alongside respective pixels.

13. A sensor according to claim 11, wherein respective photodetectors are located within respective pixels.

14. A sensor according to claim 11, wherein the pixels are arranged in a first array and the photodetectors are arranged in a second array; and wherein the second array overlies the first array such that the photodetectors are in register with the pixels.

15. A sensor according to any one of claims 11 to 14, wherein the photodetectors are photodiodes.

16. A sensor according to any one of the preceding claims, wherein the analog output signal is an open circuit voltage V_{OC} or short circuit current I_{sc} of the photovoltaic cell.

17. A sensor according to any one of claims ~~1 to 16~~11 to 15, wherein the time of illumination corresponds to a light dwelling time of light from the light source on the respective said pixel, the sensor comprising a processor for determining a speed of the light source based on the light dwelling time of one or more said pixels~~analog signal from one or more of the pixels~~.

18. A sensor according to claim 2 or 3, comprising a processor for identifying an object based on the analog output signal of the fault-tolerant pixels.

19. A sensor according to claim 2, 3 or 18, wherein the threshold is zero.

20. A sensor according to claim 2, 3, 18 or 19, wherein each fault-tolerant pixel is a photocapacitor.

~~21. A sensor according to any preceding claim, for tracking movement of the light source based on the analog output signal of a plurality of the pixels.~~