Frontiers in Photosensor Materials and Designs for New Image Sensor Applications

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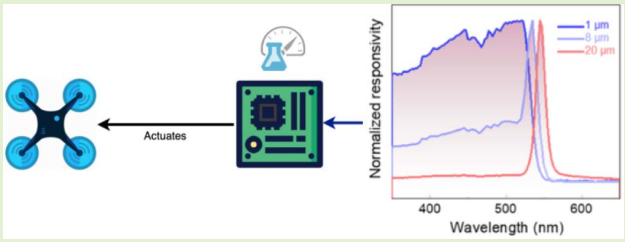
***Abstract*—Certain applications of image sensors require capabilities that are beyond the technology of current image sensors, such as automated color-based quality inspection systems operating under varying levels of illumination. This paper serves to provide a brief overview of image sensor technologies involving the use of alternative photosensor materials (organic semiconductors and perovskites) being developed to meet these needs. The discussion around such developments is typically confined to chemistry and physics "silos"; by publishing in this special edition, the authors hope to bridge the knowledge gap between scientists developing new photosensor materials and engineers developing image sensors for new machine vision systems.**



***Index Terms*—Machine vision, image sensors, image color analysis, flexibility, organic semiconductors, perovskites.**

I. Introduction

COMPANIES such as Cognex, Basler and Omnivision have made significant strides in developing Machine Vision (MV) systems enabling robots or machines to accurately capture and analyze images in a variety of contexts and make decisions based on what they 'see'. As humans, we don't even think about this process, whereas for computers and machines it is a very complex challenge, especially when other factors constrain the machine from capturing data about the image accurately, such as the color of an object under varying illuminant conditions (especially low light) or the position of an image sensor within the automated machine. Such challenges are especially pertinent to certain industrial applications involving automation, and within new technologies encompassing unmanned aerial vehicles (UAVs), smart and autonomous vehicles, and advanced robotic inspection systems. One example of these applications is in the identification of cracks in surfaces [1]. The current trend is to use robots for detection of damages in infrastructure, removing humans from potentially dangerous environments [2], [3]; i.e. humans do not directly interact with the environment, and they rely on robots to perform this role. However, transferring human visual and decision-making capabilities to a robot has major limitations. For instance, due to changes in color, dangerous structural damages (e.g., exposed metal) may not be automatically identified by a robot. If sensors that would reliably return the same measurement for a given color were developed, automatic detection of issues with aging infrastructure could be possible. The true perception of colors independent of the color from the light source will be referred as "color constancy" throughout this paper.

MV is supported and enhanced by optoelectronic devices as the output from a MV system can provide information about the content of the optoelectronic signal [4]. The main barrier to progress in these realms lies in the fact that traditional image sensor technologies used in MV such as Complementary Metal Oxide Semiconductor (CMOS) sensors are dependent on the incorporation of inorganic semiconductor-based materials such as silicon (Si) as the photosensor layer. A key attraction of using Si is that the photosensor and underlying circuitry are made of the same material, meaning that the photoactive layer can be monolithically integrated with the electronic readout. Si provides many other advantages in image sensing technologies – as is evident from its current usage in image sensors globally and the manner in which it has been repurposed to fit new applications [5]. However, it also has certain limitations which are particularly problematic for MV applications. For example, Si has a low absorption coefficient;

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therefore, a relatively thick and rigid active layer is required to enhance the light sensitivity, while the fabrication of Si image sensors entails a high-temperature fabrication process which is expensive and precludes the use of flexible substrates, likely to be destroyed in the process [6]. Furthermore, because Si absorbs light broadly across the visible spectrum (including in the NIR), color filters must be integrated within the image sensor system to achieve color recognition [7]. These restrict the amount of light reaching the pixels, limiting the ability to miniaturize the image sensors and increase the pixel density [8]. Color filters also hinder image sensor modification to fit within certain architectures [5], [9] and reduce the dynamic range and color accuracy of the image sensor [10].

One way around these deficiencies is to use alternative photosensor materials [11]. The three main classes of materials that have been explored include organic semiconductors (OSCs) [12]–[16], perovskites [17]–[20] and, to a lesser extent, colloidal quantum dots (QDs) [21]–[23]. Since OSCs and perovskites are more established as color-sensitive photodetectors, the focus of this paper will only be on OSC and perovskite image sensors.

The main objectives of this paper are to introduce OSCs and perovskites in light of the progress that has been made in the development of OSC and perovskite image sensors, and to discuss potential prospects for these materials in new and future technologies. It is hoped that in so doing, we will cultivate opportunities for integration between the more engineering-focused fields of robotics or MV and the more science-focused fields of chemistry, physics and materials science involved in designing these new materials.

This paper is divided as follows. In Section II, alternative image sensing materials are discussed. These are materials that are used in chemistry research but rarely find their way into engineering applications or discourse. Section III briefly discusses autonomous engineering systems and why new materials would enhance the applicability and autonomy of autonomous vehicles. Finally, Section IV concludes the paper and discusses some possible ways forward.

II. Alternative Image Sensing Materials

OSC and perovskite photodetectors have demonstrated performance parameters (e.g. External Quantum Efficiency, Responsivity, Noise Equivalent Power, Linear Dynamic Range, and Specific Detectivity) equal or superior to traditional inorganic semiconductors such as Si [6], [24], [25]). These materials have the added benefit of being soluble in common solvents, opening the way for solution processability as a means of fabrication. This typically requires less drastic conditions for device fabrication and enables the formation of mechanically flexible image sensors [6], [26]–[28]. There are several ways in which photodetectors consisting of OSCs and perovskites can be fabricated [6], [16], [29], [30]; the approach taken depends on the surface area of the photodiode, the desired pixelation process, and the equipment availability. The flexibility of resultant OSC and perovskite electronic devices is well documented in the contexts of wearable electronics [31] and photodetectors [32], [33].

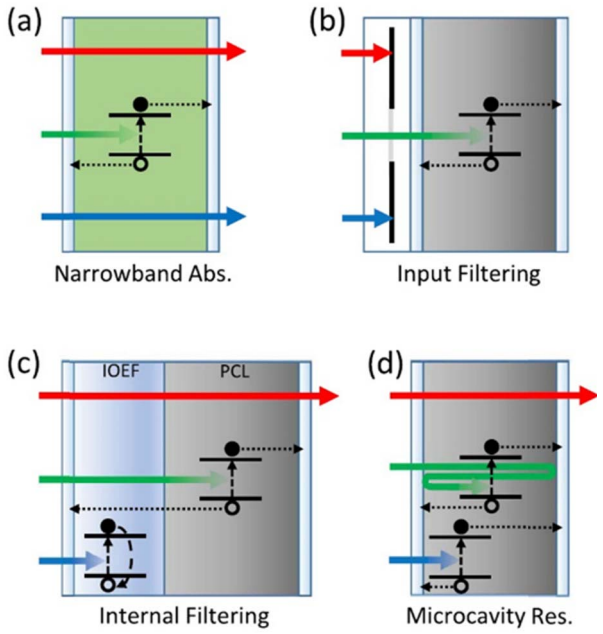

Fig. 1. The four approaches to achieving narrowband light absorption using OSCs or perovskite materials: (a) chemical engineering of the photoactive layer (in this case, using a green light-sensitive combination of molecules), (b) input filtering: the use of external color filters with a broadband photoactive layer, (c), internal filtering: exploiting the optoelectronic properties of the photoactive layer to suppress undesired photoresponse, and (d) microcavity resonance (reproduced with permission from [12]).

Another key feature of both OSCs and perovskites – as mentioned previously, is their capacity to be used as filter-free narrowband light absorbers in color imaging applications [34]. There are four general strategies to achieving narrowband absorption [12]– either with OSCs or with perovskites: (a) through chemical engineering of the specific OSC molecules, enabling them to absorb light of desired wavelengths (perovskites absorb broadly across the visible spectrum in general so this strategy is not applicable to them); (b) input optical filtering, (c) internal filtering, and (d) microcavity resonance (Fig 1).

The chemical engineering aspect forms the body of the discussion in Section II(A), so is not expounded on here. Suffice to say, this approach involves the selection or design of OSCs able to absorb targeted wavelength ranges, such that all other light passes through the photoactive layer without causing any photoresponse or photoactivation (Fig 1a).

Input optical filtering is to the same as color sensing in traditional image sensors in that it combines a broadband absorbing OSC or perovskite material with an optical color filter (Fig 1b). The application of optical filters in OSC and perovskites was in fact derived from traditional color proficient inorganic-based image sensors. However, in some cases, OSCs and perovskites can themselves be used as color filters [35], [36].

Internal filtering refers to the use of a double-layered broadband organic photodetector capable of suppressing the photoresponse outside of the desired spectral range. Thus, while one layer of the photosensor is responsible for the photoconversion process (i.e. the Photoconversion layer, PCL), the other dissipates incident photons that are not

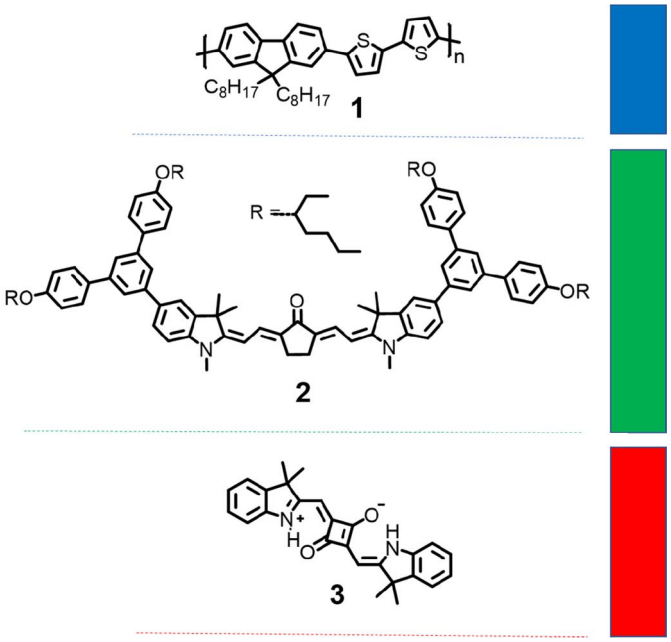

Fig. 2. Chemical structure of a blue light-absorbing polymer (**1**), a green light-absorbing dendrimer (**2**), and a red-light sensitive small molecule (**3**), in this case, a squarylium molecule.

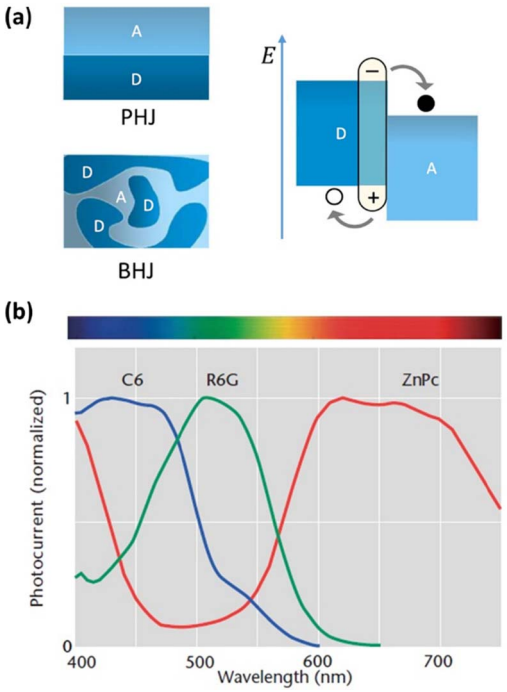

Fig. 3. (a) The structure and working principle of a typical organic photodiode (Taken from [12], used with permission). (b) An example of the spectral photoresponses of three organic materials (C6: B-, R6G: G- and ZnPc: R-light sensitive). Reproduced with permission from [61].

within the target spectral range (this is referred to as the internal optoelectronic filter, IOEF) (Fig 1c). This strategy has been demonstrated with both OSCs and perovskites using a variety of approaches [19], [37]–[41]. For a full explanation of these, please refer to an excellent review of this topic by Pecunia [12]. While 'internal filtering' is similar to what is achieved with Foveon X3 sensors, Foveon X3 sensors differ in that they exploit the ability of silicon to absorb different wavelengths of light at different depths within silicon [42].

The final strategy involves the use of reflective electrodes within the device structure, turning the photodetector into a resonant microcavity (Fig 4d). This causes constructive interference, meaning that control of the absorption onset is possible through tuning of the inter-electrode distance and judicious selection of the photoactive material used [43], [44]. At the time of publication, there was only one report of a perovskite photodiode employing this approach [45]. It should be noted that this approach has its roots in traditional inorganic photodiodes [46].

The aim of the following sections is not to expand on these studies but rather to introduce OSCs and perovskites and to pinpoint certain examples that demonstrate their capabilities in new image sensing technologies.

A. Organic Semiconductors

OSCs are carbon-containing ('organic') molecules containing conjugated π-bonding systems [47]. They can occur as polymers, macromolecules (including dendrimers), or small molecules (e.g. **1**, **2** and **3**, respectively, in Fig 2), and, as such, can be chemically engineered to absorb specific wavelengths of light either broadly across the spectrum [48], [49] or narrowly, for example absorbing only blue (B) [50], [51], green (G) [10], [52]–[54] or red (R) [55], [56] light (Fig 2). Through slight chemical modifications of the absorber molecules, it is possible to fine-tune the light absorbing characteristics of the photodetector to desired wavelengths and quantum efficiencies [57].

The operation of organic photodiodes is similar to that of traditional inorganic semiconductor-based photodiodes: incident photons are absorbed by the organic molecules, 'exciting' the molecule and resulting in the concomitant formation of neutral states called 'excitons' (these are essentially bound hole-electron pairs) within the molecules rather than free charges, which is the case in inorganics [14].

The most common approach to separate the charges involves mixing the 'electron accepting' (A) and 'electron donating' (D) materials (analogous to *n*- and *p*-type materials) in a blended heterojunction (BHJ) [58]. Conveniently, BHJs can be achieved through simple solution-processing fabrication, and typically result in higher extraction efficiencies compared with planar heterojunctions (PHJs) (Fig 3a). Separation of the excitons into holes and electrons then occurs at A/D junctions, based on differences in the ionization potential and electron affinity of the A and D molecules. An externally applied electric field (bias) is typically needed to extract the charges and produce an electric current, although this is not always the case [59]. As such, OSCs tend to have relatively low charge carrier mobilities compared with Si. This may not necessarily be disadvantageous as it could reduce the potential for pixel crosstalk, which is somewhat problematic in traditional image sensors [60].

The A and D molecules selected are crucial to the performance of the photodetector. Initially, fullerene molecules were viewed favorably as an A, mainly due to their capabilities

in organic solar cells. However, these molecules absorb blue light (reducing the color purity of green, red and yellow photodiodes) and are expensive (∼USD$220/0.1 g). Thus, there has been a shift to use 'non-fullerene' A molecules, and recent reports show that these are enabling higher cell efficiencies than with fullerenes in organic photodetectors [62].

To achieve optimal color discrimination under conditions of varying illuminance, three separate photosensors are required, able to adopt the tristimulus standard color matching functions of human eye cone cells, and each with an absorption profile having a Full Width at Half Maximum (FWHM) ∼ 100 nm [63]. This is challenging in practice because of the need for both an A and D molecule per color sensor, although it is possible to engineer A and D to have matching absorption spectra [64], [65]. A further challenge is that the absorption spectra of molecules in the solid state tends to broaden compared to spectra in solution due to increased intermolecular interactions. There are several strategies that can be used to narrow the FWHM of the photoactive molecules in the solid state, largely based on segregation of the individual chromophores [10], [63], internal filtering strategies [37], or modifications made to the D-A character of the molecules [65].

B. Perovskites

Perovskites are typically inorganic materials with the calcium titanium oxide ($CaTiO_3$) structure. They were named after the Russian mineralogist Lev Perovski. Typical perovskite materials have the general formula ABX_3, where A and B are cations, usually with significantly different sizes. The larger cation A is typically the organic methylammonium (CH_3NH_3) or formamidinium ($HC(NH_2)_2$) ion in hybrid perovskites. The smaller cation B is often the Pb^{2+}. Cl^-, Br^- or I^- are used as the anion X [66]. For example, Fig 4 shows the chemical structure of $CH_3NH_3PbI_3$. (i.e. A = CH_3NH_3, B = Pb, and X = I^-): each cation A is coordinated with 12 anions X, forming cubes. B coordinates with six X anions, forming octahedrons.

The interesting electronic properties of metal halide perovskites originate from their band structure. The degenerate unoccupied *p*-orbitals of Pb, the antibonding *s*-orbitals of Pb and the antibonding X *np*-orbitals of the halides combine to form the lower part of the conduction band. The valance band is formed by the Pb 6*s*-orbitals and X *np*-orbitals. Although, the methylammonium (MA) or formamidinium cations B do not contribute to the band edges, the interaction of these cations with the inorganic framework reduces the binding energy of the exciton and eases charge transfer. Hybrid lead halide perovskites show interesting optical properties due to the $CH_3NH_3^+$ ions orientation in the inorganic framework, like the photo-ferroic effect produced by the $CH_3NH_3^+$ dipole which is supposed to enhance carrier collection [67].

Metal halide perovskites have 'strongly allowed' optical transitions due to their direct band gap. Excitons in metal halide perovskites are Wannier-Mott type owing to the high dielectric constant. This makes the excitons dissociate at room temperature. The exciton binding energy (E_b) in 3D-lead iodide-based perovskites is in the range of 2 - 50 meV.

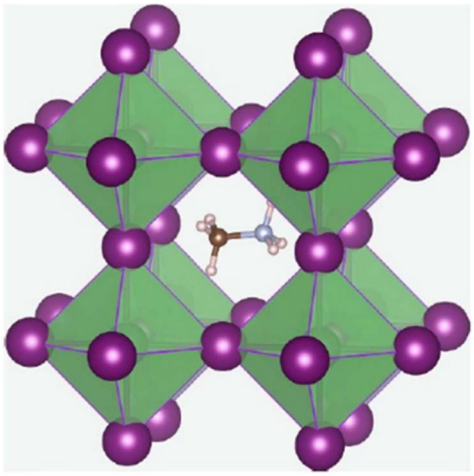

Fig. 4. Chemical structure of perovskite $CH_3NH_3PbI_3$. The methylammonium cation (CH_3NH_3) occupies the central A site surrounded by 12 neighboring iodide ions in corner-sharing PbI_6 octahedra (reproduced with permission from [66]).

Following light absorption, excitons spontaneously dissociate into electrons and holes travelling in the conduction and valence bands, respectively. The detailed free charge and exciton dynamics depend on the polymorph. Perovskites can crystallize in two phases at room temperature: tetragonal or orthorhombic. The tetragonal phase which has a very small E_b supports primarily free charges. The orthorhombic phase which has a larger E_b supports both free charges and excitons [20]. Although single crystals with low defect concentration are desirable, perovskite devices are mainly made from polycrystalline films.

The first attempt at developing a perovskite-based photodetector was in a dye sensitized solar cell structure, in which the perovskite replaced the dye [68]. The trial, with a power conversion efficiency (PCE) of 3.8% represented a new paradigm in solar cell technology. Methylammonium lead halides demonstrated efficient photovoltaic activity for the first time. Shortly after, solution-processable solar cells and photodetectors based on a highly crystalline perovskite absorber with intense absorptivity extending from the visible to near-infrared were built. Mixed halides $CH_3NH_3PbI_{3-x}Cl_x$ were developed and applied to a mesoporous Al_2O_3 scaffold layer. The so-called meso-superstructure perovskite solar cell had a PCE of 10.9% [69]. A planar heterojunction perovskite structure could also be formed by co-evaporation of the lead halide and the MA [70]. This yielded 15.4% PCE, a world record for hybrid organic-inorganic devices which are amenable to wet-processing over large areas. A new research area was born, and perovskite solar cells became classified as a new type of solar cell device (Best Research-Cell Efficiency Chart www.nrel.gov/pv/cell-efficiency.html, accessed July 28, 2020). Today's PCE world record for perovskite solar cells is 25.2%, which is reaching close to the world record for single-crystal silicon solar cells (27.6%). Interestingly, unlike silicon, metal halide perovskites can be wet processed.

Typical metal halide perovskite photodetectors have a sandwich structure consisting of the perovskite photoactive layer

absorbing in the desired wavelength range. It has a thickness of few hundred nanometers and it is sandwiched between metallic-like layers; namely, an electron transport layer and a hole-transport layer. Several charge transport designs have been developed and reviewed [71]. When the perovskite device is illuminated, charge carriers are generated within the perovskite photosensitive layer, they are separated by the electron and hole-transport layers, and collected at their respective electrodes, thereby generating an electric current and voltage. The charge transport layers sandwiching the perovskite layer greatly contribute to the efficiency and stability of the device.

One fundamental advantage of perovskite over silicon is the possibility to build flexible photodetectors owing to its low-temperature processing and mechanical durability. Additionally, perovskites can be solution-based manufactured on a plastic substrate [72], with 19.11% champion photovoltaic efficiency [73].

The response spectrum of metal-halide perovskites can be adjusted utilizing different halides [17]. Band-gap energy of $MAPbI_3$ is 1.61 eV (deep red), it is 2.3 eV (green) in $MAPbBr_3$ [74] and 2.9 eV (blue) in $MAPbCl_3$ [75]. The use of different halides and/or combinations of them may have interesting applications in developing color vision sensors. The efficiency and spectral performance of narrowband organic and perovskite photodetectors has been comprehensively reviewed [12]. In pioneering work, Burn, Meredith and co-authors [19] used a solution-processed photoactive layer made of mixtures of either an organohalide perovskite or lead halide semiconductor ($CH_3NH_3PbI_{3-x}Br_x$) with varying halide ratios to demonstrate the tunability principle (Fig 5a). However, this is not sufficient for realizing separate red, green and blue photodiodes, which requires the shorter wavelength onset also to be manipulated. To make this happen, they used OSCs. The OSCs modify the optical and electrical properties of the photodiode and facilitate charge collection narrowing of the device's external quantum efficiency (Fig 5b). The as-designed red, green, and blue photodiodes each possess a FWHM $<$ 100 nm.

In another design, Xu, Song, Zeng and coworkers [76] developed an ultra-narrow response photodetector with FWHM $\sim$ 12 nm. To make this narrow bandwidth possible, they used the concept of surface charge recombination into which only the exciton generated close to the bottom of the thick photoactive layer will be able to dissociate into charges that will reach the inter-digitized Au electrode with 20 μm interval finger distance (Fig 6). Tuning over 4 colors spanning the full visible range was achieved by varying the halide composition: $CsPbCl_3$, $CsPbClBr_2$, $CsPbBr_3$, and $CsPbBr_{1.5}I_{1.5}$.

In another different design, Li and coworkers [77] developed highly tunable narrowband photodetectors based on two-dimensional (so called Ruddlesden–Popper) perovskite single crystals with varying layer number n. The band gap energy in two-dimensional materials depends on the layer number n. The color tuning capability of the 2D-crystals is illustrated in Fig 7.

The development of lead halide hybrid perovskite photosensors is still challenging owing to environmental issues with lead. It is also challenging owing to stability issues with methyl ammonium which is sensitive to water. $Cs_2SnCl_{6-x}Br_x$ was proposed as an alternative composition: an inorganic lead-free perovskite grown as single crystal by the hydrothermal method. Variation of the composition x allows color tuning between 400 and 650 nm [78].

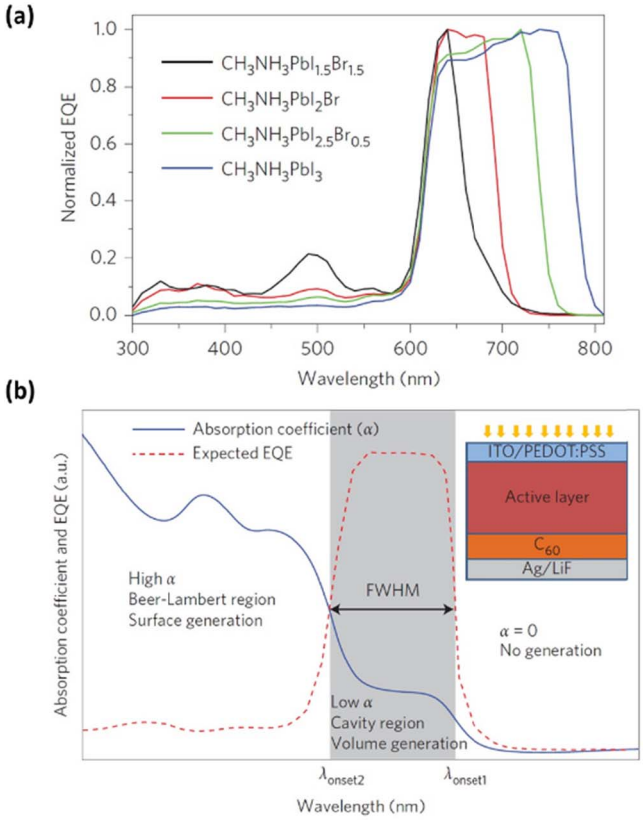

Fig. 5. (a) External quantum efficiencies (EQEs) of the red narrowband photodiodes fabricated with different ratios of PbI_2 and $PbBr_2$. The long- wavelength edge of the photoresponse window can be controlled by the semiconductor optical gap (λ_{onset1}, part b); (b) The absorption coefficient profile of an active layer of defined thickness with separate high and low absorption (α) regions (solid blue line). Reproduced with permission from [19].

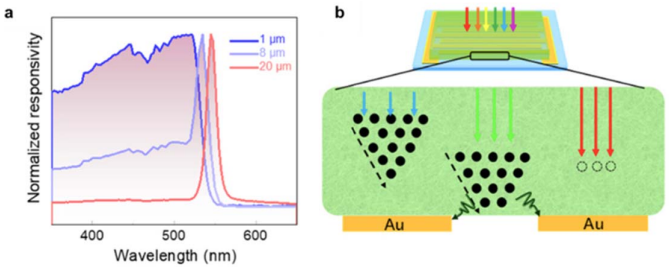

Fig. 6. (a) EQE spectra of CsPbBr3 films of different thicknesses; (b) the proposed mechanism for surface-charge recombination assisted filter-free narrowband photodetectors. Reproduced with permission from [76].

III. Autonomous Engineering Systems

The alternative photosensor materials described above can be used in MV applications in robotic systems. Robots have recently been proposed for sensing applications in a variety of fields. For example, robots can be used to assess the structural

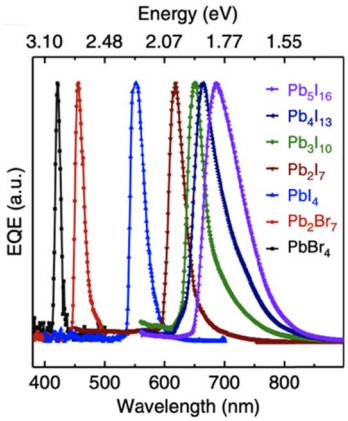

Fig. 7. Normalized EQE spectra of the studied devices based on 2D perovskite of different halide compositions and layer number *n*. Figure reproduced with permission from [77].

Fig. 8. General autonomous system including a ground vehicle and drone for identification of issues in infrastructure.

health of infrastructure [1], [79]. In this situation, the vehicles are usually equipped with a general-purpose camera for identification and classification of potential issues. Fig. 8 shows a drone and a ground robot that inspect a structure, in this case a building. Since general-purpose cameras do not guarantee color discrimination invariance, the inspection becomes more complex. Therefore, this process of identification and classification can either be done by a human or be the result of a MV algorithm running either on a ground station or on-board of the vehicles.

In the first case (manual processing of images), these vehicles would be in general teleoperated. The second approach (on-board processing), the vehicles would be fully autonomous, wherein they receive a mission definition from a specialist and perform it without much interaction with human operators.

When the mission is teleoperated, the processing can be done on the ground as sensors are not used for control and navigation of the vehicles. Fig. 9 shows such a system in

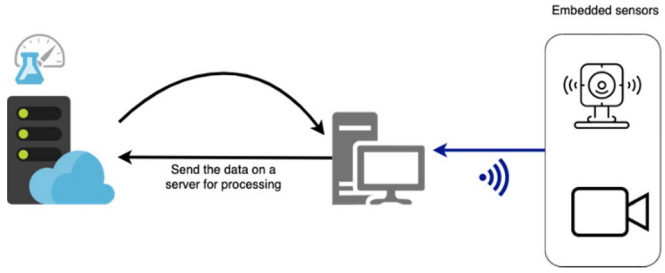

Fig. 9. Sensor input being processed by a ground station and information being stored in the cloud.

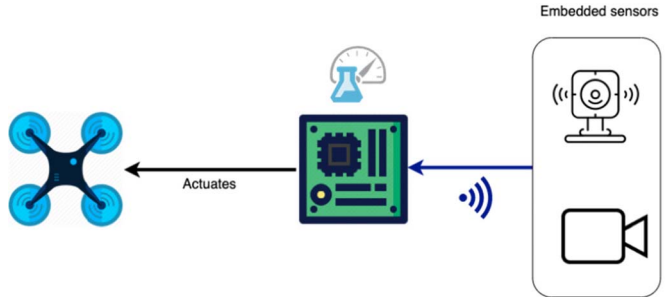

Fig. 10. Autonomous architecture for vehicle inspection.

which the sensors transmit the data to a ground station that stores the information in a cloud server.

When the missions are performed by autonomous vehicles instead of teleoperated, different requirements arise. One of them is the increased necessity of on-board processing, for delays in receiving commands may result in instability for systems with fast dynamics such as drones. The necessity of more processing is, to a great extent, due to the sophisticated MV algorithms required. The pipeline in this case is shown in Fig. 10. In the figure, one can see that the sensor needs to be processed by the computational resources on board of the vehicle before the images are either stored or used for further investigation. This raises the issue of how much processing can be performed on the usually limited on-board computers, for this type of vehicles usually presents limited payload capabilities (limiting the weight that can be carried) as well as limited power capacity. Notice that both issues are in fact linked as to increase the power capacity, the vehicle would need to carry more batteries.

The computation required that is linked to the MV algorithms usually involve the definition of several filters (including color filters), as well as statistical analyses. One somewhat new approach is to use Field Programmable Gate Arrays (FPGAs) to speed up the computation at a relatively low power cost [80]. However, if sensors are developed that reduce the need for filters, vehicles will tend to be lighter and more capable, as the extra processing can be used for vehicle navigation and control instead of processing of sensor inputs. Without special photosensor materials, color invariance can only be achieved with considerable computations [81] as alternative MV algorithms need to be developed. These algorithms, can be based on particle filters [82] and learning approaches [83], for example. Furthermore, the efficiency

of methods based on deep learning depend on good color representation [84]. However, by using alternative photosensor materials, processing for color constancy does not need to be considered and processing could be significantly reduced. For example, in [80], it was found that filters dealing with issues of color constancy was responsible for 67% of processing. Moreover, if modern machine learning techniques such as convolutional neural networks with deep learning [80] were to be used, with these materials, they could be readily applied without architectural changes.

Therefore, using the alternative sensing materials described in section II would have a large impact in the development of autonomous engineering systems. We note that this has not been a very active area of investigation. Nevertheless, this may be due to the engineering and chemistry communities being involved in different investigations and not understanding the needs of the others as well as what each other has to offer. This paper serves as a first step in breaching this gap.

Furthermore, another advantage of the alternative image sensing materials is their malleability. In theory, these sensors could be mounted in the format of the object to be sensed. For example, the sensor could be mounted at the tip of a robotic manipulator and the sensor could be moved very close to the object to be inspected. Combined with the color constancy abilities of the new materials, autonomous inspection could be greatly improved.

IV. Industrial Development of Image-Sensing Technologies

The use of alternative sensor materials has already resulted in the development of several commercial optoelectronic devices.

ISORG (https://www.isorg.fr/) has developed devices with contactless printed user interfaces from OSCs. Samsung Institute of Technology (https://www.sait.samsung.co.kr/) has been developing "next generation semiconductor materials" to "overcome the limits of Si semiconductors"; in this quest, they have published several reports showcasing the fabrication and capabilities of organic image sensors [61], [62], [85]. Likewise, both Panasonic Corporation [86]–[88] and Fuji [89]–[91] have made significant contributions towards successfully realizing an organic image sensor.

In terms of perovskite devices, there are no companies focusing on the development of image sensors. However, significant advances have been made with perovskite solar cells by the following companies: Panasonic [92], [93], Microquanta (http://www.microquanta.com/en/) and Toshiba (https://www.toshiba.co.jp/rdc/rd/detail_e/e1806_03.html) [94].

V. Conclusion

This paper describes photosensor materials that have the potential to impact the performance of systems by allowing different configurations due to their physical malleability and by improving MV algorithms.

The new technologies have the potential of improving the identification and classification resulting from MV algorithms while also reducing the computational requirements for on-board processing. Combining both of these advantages may result in increased autonomy of engineering systems applied to surveillance, inspection, and maintenance,

Moreover, the malleability of the sensors allows for the deployment of sensors to places that would be inaccessible otherwise. Actually, the combination of both characteristics can increase the applicability of autonomous systems by simplifying the MV algorithms and improving the control of autonomous vehicles. Overall, this could potentially increase the applicability of the new materials to engineering applications using autonomous vehicles.

Despite the advantages offered by OSCs and perovskites, there are some challenges to be overcome. Firstly, although they can be solution processed, the synthesis of new molecules can be expensive and time consuming and, in the case of polymers, variation may occur from batch to batch. It would be reassuring to know that the synthesis of these photoactive materials can be carried out cheaply on an industrial scale (kg). Secondly, the integration of OSCs and perovskites on CMOS sensors is not as established as that of Si monolithic systems although certain companies (e.g. Samsung Electronics) have made considerable progress in developing organic image sensors. A tutorial review covering this would be most welcome.

The applications are vast for such systems. For example, inspection of bridges, roads, airplane fuselage and other structures; monitoring of natural disasters (e.g., floods and fires); and robotic maintenance of heavy machinery.

In the near future, we intend to start experimenting with these alternative materials to determine their performance in actual engineering applications.

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