Chapter 8
Future Works

In this book the design of a CMOS image sensor inspired by the compound eye of insects, as well as several applications of such image sensor are presented. The sensor is able to detect polarization information using a micro-polarizer oriented at various angles and created using the metal layers in a standard CMOS process. The detected polarization information is shown to be useful in classifying materials as well as detecting incoming light ray directions for use in autonomous agent navigations. Different algorithms used by the eyes of insects to detect motion were also studied and a model for collision detection has been proposed.

In this final book chapter an overview of possible future works are presented based on the previous chapters.

8.1 Future Works

The field of view of an imaging polarimeter is usually limited by the imaging optics. Commercially available photographic and video cameras have a field of view of about $30° - 50°$(horizontal) by 20°-40° (vertical) depending on the focal length and aperture. Ideally 180° field of view imaging polarimetry is desired to study the polarization patterns.

A 124° field of view camera with less than 1° angular resolution has been discussed in chapter 2 and 3. Such a camera would help to increase the sensitivity of the polarization measurements while allowing to gather wide field of view information.

8.1.1 Wide Field of View Imaging System with Polarization Sensitivity

Wide field of view imaging systems can potentially improve applications such as security surveillance, robot navigation or endoscopy. Such a system can collect image data points from a relatively larger area than the rectilinear lenses and thus can be employed in both contact and contactless endoscopy. The fish eye lenses which

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are generally used in endoscopy for images produce a significant distortion in the visual content. Contactless endoscopy is becoming the standard in the endoscopy world. The image sensor with wide field of view, high angular sensitivity and polarization sensitivity would enhance the application areas of the endoscopes.

The common requirements for a wireless capsule endoscope are high resolution, very low power, high dynamic range and high sensitivity. Resolution is needed to be able to see things clearly inside the digestive tract or the intestines. The state-of-the-art commercial wireless capsule endoscope product, the PillCam capsule, developed by Given Imaging Ltd transmits 256x256x8 bit data at a frame rate of 2 frames per second [1]. The sensor described in chapter 3 is able to transmit 128x128x12 bits of data at a frame rate of 15fps. Besides resolution, endoscopy applications demand a dynamic range of 60-80dB which is easily achievable. The dynamic range can be varied using the partial charge transfer as seen in chapter 7. The ability to do in-pixel processing of the data helps in data compression, which naturally helps to lower the output data rate and lower the power consumption of the system.

The ability of the designed sensor to detect polarization of the reflected light adds value to medical imaging. It is known that when light interacts with tissue, the reflectance, absorption and polarization of light is affected. The polarization parameters of light scattered from biological tissues contains rich morphological and functional information useful for medical purposes. Potential applications of such electro-optical system include imaging of superficial cancers and other skin lesions, early detection of diseased cells and microscopic analysis of tissues [2].

A potential application of linear polarization imaging techniques in dermatology has been proposed by [3]. This technique records a series of images corresponding to different combinations of illumination and polarization and calculates the intensity difference between orthogonal direction polarizations pixel by pixel. The degree of polarization information obtained from the surrounding muscles or blood can also be evaluated. In chapter 4, it was shown that it is possible to detect polarization information using metallic wire grids and it is also possible to compute the orthogonal polarization intensity difference and degree of polarization of polarization pixel by pixel. For the current version, these calculations are done off-chip but they can be easily incorporated onto the chip, which will further help in miniaturization of the endoscopes.

Besides endoscopy, wide field of view optical systems can also be used in imaging fluorescence microscopy. Fluorescence microcopy is used to investigate dynamic phenomenon in cells and living tissues and have seen dramatic increase in life science application in the last decade. Conventional CCD/CMOS cameras are not able to image the time-critical cellular events which change dynamically in less than a few seconds. To be able to capture these fast changes, multiple channel imaging optics are required to simultaneously track changes in the fluorescence signals. Besides fluorescence microscopy, fluorescence polarization imaging is also becoming popular in investigating the biochemical properties of samples, such as protein denaturation, protein-ligand interactions, protein-protein interactions, protein-DNA interactions, and the rotational rates of proteins [4], [5]. A wide field of view optical system with polarization sensitivity is ideal for biological investigations because it provides the ability to image simultaneously both the parallel and perpendicular polarization components of a fluorescence emission.

8.1.2 High Angular Resolution Imaging System with Polarization Sensitivity

In chapter 4, it was elaborated that the performance parameters of a wire grid micro-polarizer depend on the pitch used. To obtain a high transmission efficiency and extinction ratio *(ER)* in the visible region, the pitch has to be smaller than the incident wavelength. The 0.18μm CMOS technology used to fabricate the designed image sensor provides a minimum metal spacing of 0.24μm. Nevertheless, as CMOS technologies keep scaling and smaller feature sizes become available, it is possible to fabricate the suggested structures with smaller spacings.

The polarization sensitivity also depends on the wavelength of the incident electromagnetic wave and the angle of incidence. As wavelength and grating spacing becomes nearly equal, the angle of incidence of the light ray has more pronounced effects on the polarization detection sensitivity. In the case of a wide field of view lens with 1°angular resolution, it offers two advantages. Firstly, the polarization ratio for a specific angle of incidence is known and secondly, it is possible to spatially sum the polarization response over a wide field of view. For the current version of the sensor, the polarization profile was measured for only a single angle of incidence; however after the integration of the lens the polarization measurement for the entire field of view can be obtained which will increase the resolution and sensitivity of the polarization measurement.

8.1.2.1 Real Time Material Classification

In chapter 5, it was shown that it is possible to classify materials based on the polarization information from the reflected surface. To keep the system simple, the degree of polarization and *PFR* calculations were done off-chip. These calculations can be easily implemented on-chip, allowing for real time material classification. Further the transmitted intensities of the reflected light were measured for a single angle of incidence of the light ray. The measurement of the polarization Fresnel ratio *(PFR)* at each pixel is not very accurate when the diffuse component of the reflection dominates over the specular component. In such an scenario the measurement of the reflected transmitted intensities for varying angle of incidence of the light ray would serve to increase the resolution and the sensitivity of the *PFR* measurement.

The multichannel imaging system with an angular resolution of 1°would provide the polarization information of the reflected light over a wide field of view, thus serving as a more reliable measurement and classification system. The increased angular resolution with corresponding increase in the number of Fresnel reflection coefficients can provide a more intuitive way of investigating the specular and diffuse reflection changes as a function of physical parameters of the reflecting surface.

Furthermore, in this work only the differential changes in the intensities of the parallel and perpendicular component of the specular and diffuse reflections were explored and not the phase difference. Metals alter the phase of polarization of the incident light upon specular reflection while dielectrics do not [6]. This is important in the scenario of highly diffuse dielectric materials, which would often be misclassified as metals when using *PFR*. Ways to determine the change in phase of the incident and the reflected light by the reflecting surface need to be explored.

8.1.2.2 Real Time Navigation

In chapter 6, it was stated that insects use the egocentric form of navigation which computes the home vector from the direction of travel and the distance travelled. The possibility of using polarized light as a compass to determine the direction of travel was shown. The distance of travel computation were not discussed, however they are not very difficult to compute. One such method is proposed here which can be easily implemented on chip for distance of travel calculations.

Assuming the initial position of the object to be (x, y, t) then if the point has travelled to a new location after a time Δt the new location X and Y can be described as

$$X(t + \Delta t) = x(t) + \cos\theta(t) \times v(t) \times \Delta t \tag{8.1}$$

$$Y(t + \Delta t) = y(t) + \sin\theta(t) \times v(t) \times \Delta t \tag{8.2}$$

where θ is the angle of travel and $v(t)$ is the velocity of travel. Δt is the integration time to obtain the next frame information. The velocity can be computed from the optic flow as discussed in chapter 7. However the computation of the velocity from the optic flow would be computationally demanding. The velocity of travel is proportional to the change in the intensity of the image over time [7] and is expressed as

$$\Delta i \approx \Delta v \times \Delta t \tag{8.3}$$

where Δi is the change in intensity over the time interval Δt. Substituting equation (8.3) in equations (8.1) and (8.2) we get

$$X(t + \Delta t) = x(t) + \cos\theta(t) \times \Delta i \tag{8.4}$$

$$Y(t + \Delta t) = y(t) + \sin\theta(t) \times \Delta i \tag{8.5}$$

The new position is depended on the angular travel and the change in intensity during the time Δt. The change in intensity can be computed from the difference in two frames separated by Δt using partial charge transfer as discussed in chapter 7, while the angular information can be obtained from the compass discussed in chapter 6. Thus it would indeed be possible to have both the direction and distance information which would simplify the algorithms currently used for autonomous agent navigation.

8.1.2.3 Real Time Sun Position Detection

The proposed design will make it possible for an alternate method of angular position determination of the sun besides the slit sun digital sensors. The celestial compass based on skylight polarization is described in chapter 6. Depending on the angle the light from the sun hits the atmosphere; the light is polarized in a special way. These patterns maintain an interesting characteristic all over the day: they are always perpendicular to the solar meridian. Thus the degree of polarization has a maximum when the sun is at 90°angular position (with respect to solar meridian it is at 0°). It was shown that it is indeed possible to determine the elliptical and azimuthal position of an object based on the polarization patterns of the incoming light ray.

Due to the measurement setup constraints, it was not possible for the first version of the designed image sensor to test for the variability of the degree of polarization with respect to the angular position of the sun under open sky. The measurement setup can be simplified and an open sky measurement should be a valuable extension of the project. The study of the change of the degree of polarization with the position of the sun would immensely help in the navigation of autonomous agents which usually depend on heavy computations to determine the angle of travel. Further it is known that sun moves at a constant angular velocity. The change from the solar

Table 8.1 Comparison of sun position detection sensors

	GPS	Magnetometer	SSC [8]	proposed
Mass	∼20gm	∼50gm	∼20gm including processor	same as SSC
Power	∼0.5W	∼0.3-0.5W	∼0.2W	∼0.1W
Acquisition time	1 min	1 sec	10 min	10ms-1sec
Accuracy	0.15°-0.5°	0.5°if position is known	0.1°	Minimum of 1°
Operation on moving vehicles	Yes	Yes	No	Yes
Operational constraint	GPS coverage	Initial position must be known. Will not operate in polar regions	Needs to see the sun	High extinction ratio for increased polarization sensitivity

meridian (the point of highest degree of polarization) and the calculated orientation would also be able to predict the time elapsed.

A comparison between different sensors to determine the sun position is shown in the table 8.1 [8].

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