Summary

Biological systems are a source of inspiration in the development of small autonomous sensor nodes. The two major types of optical vision systems found in nature are the single aperture human eye and the compound eye of insects. The latter are among the most compact and smallest vision sensors. The visual system of insects allows them to fly with a limited intelligence and brain processing power. A CMOS image sensor replicating the perception of vision by insects is discussed and designed in this book for industrial (machine vision) and medical applications.

Visual perception is the ability to detect light and interpret it. In chapter 1 of the book different vision perceptions found in the animal kingdom are briefly described. Among the known optical vision systems in nature, the single aperture eye is more popular with camera researchers for its ability to form high resolution images. Compound eyes are typically not suitable for high resolution images. However they are known to process information more efficiently and are good examples of low power vision systems. Light emanating from reflections is partially polarized. Single aperture eyes are polarization blind, but compound eyes are able to detect polarization. The compound eyes are also more suited for motion detection, have high sensitivity in low light conditions and offer wide field of view at a cost of low optical resolution. Though the compound eyes are not the best in terms of image quality, the advantages that they offer makes them better suited for machine vision applications than the single aperture eyes.

Compound eyes are composed of many ommatidia or facets. The natural compound eyes are classified broadly into apposition and superposition eyes. In apposition eyes each facet receives light only from one direction while in superposition eyes the light rays from different facets are superimposed. To design an artificial compound eye inspired by the natural compound eye, a micro-optical lens array and a detector array are required. In chapter 2 and 3, a realization of a single camera system wherein the scene is optically distributed across multiples lenses using a single detector array is presented. To optically distribute the scene, a compound lens structure has been designed by Vrije Universiteit Brussel *(VUB)*

within the project of which this work is also part of. The designed lens has a field of view of 124°, a maximum contrast of 0.3 line pairs per degree (LP/°) and an angular resolution of less than 1°.

In chapter 3, the design of the detector array for said optical system is presented. The designed image sensor consists of an array of 128 by 128 pixels, it occupies an area of 5mm x 4mm and it has been designed and fabricated in the $0.18\mu m$ CMOS CIS process from UMC. The pixel used in the design is a smart pixel, which is a form of an active pixel sensor. Each pixel contains a pinned photodiode $(p^+/n/p)$ and 33 transistors to perform low level image processing. The size of the pixel is $25\mu m$ x $25\mu m$ and the size of the photodiode is $10\mu m$ x $10\mu m$ which corresponds to 16% fill factor. The pixel also has an in-pixel analog and digital memory, which enables in-pixel digitization and real-time dynamic range adaptation. The designed image sensor can be operated in two modes: double differential mode and differential imaging mode. In case of double differential mode each pixel samples the voltages at the photodiode node twice: once after reset and again after the exposure period. In the differential mode two samples are obtained after different exposure periods.

In the designed image sensor only half of the available pixel array of 128 by 128 is used for normal imaging. The other half of the pixel array is used to analyze polarization information using metallic wire grid structures discussed in chapter 4. The three basic characteristics of light are intensity, color and polarization. Polarization vision and the mechanisms of the polarization of light from unpolarized light beam along with the representation of the polarization information are also discussed in detail in chapter 4. Polarization vision is a generalization of intensity and is analogous to color vision. In section 4.5 a metallic wire grid micropolarizer operating in spatial mode is presented which is designed using the metal layers available with the standard CMOS technology. Normally such a wire grid structure would function as a simple diffraction grating but when the pitch of the wires is less than half the wavelength of the incoming light, it becomes a polarizer. The designed polarization sensing sensor has an embedded linear polarizer in each pixel with varying orientations. The linear wire grid polarizer is implemented using thin metal strips with a line/space of 240nm/240nm (pitch of 480nm). The absorption of the EM waves to completely *s*-polarize or *p*-polarize the transmitted wave through the wire grid is dependent on the pitch of the wire grid and so the performance of the wire grid as a polarizer also varies with the pitch. With the scaling of the CMOS technologies, the pitch of the wire grid will also scale thus improving their performance as a polarizer.

The pixel array used for polarization sensing is further split into two 64 by 64 pixel regions designated sense regions 1 and 2. In sense region 1, the wire grid is oriented horizontally and vertically to measure the 0° and 90° polarization intensity. While in sense region 2 beside the horizontal and vertical orientations the wire grid oriented in 45° is also present. Linear polarizers are characterized by two main specifications: transmittance and extinction ratio. In the sense region 1, for 0° polarization the maximum and the minimum transmittances observed are 38.9% and 7% respectively. For 90° polarization the maximum and the minimum

transmittances observed are 44.4% and 0.1% respectively. Similarly, in sense region 2 for 0° polarization the maximum and the minimum transmittances observed are 38.4% and 5.4% respectively while for 90° polarization the maximum and the minimum transmittances observed are 42.4% and 0.6% respectively. The extinction ratios obtained in the sense region 1 and 2 are 6.3 and 7.7 respectively. These extinction ratios are higher than reported in literature for configuration similar to the designed sensor.

In chapter 5, material classification using polarization information is presented. Materials are broadly classified into metals and dielectrics. The classification of the material type can provide vital information about the scene in computer or machine vision. Unpolarized light becomes partially polarized after specular reflection. The state of polarization for the diffuse and specular components of the reflection depends on the reflecting surface and the measurement of the state of polarization of the reflected light serves as an indicator for the type of material surface. The magnitude of oscillations of the maximum and minimum transmitted irradiance due to the variations in the reflection pattern of the metal and dielectric surface was shown to be useful in classifying them. Various other measurement metrics, such as the degree of polarization and the polarization Fresnel ratio were also shown to measure the variations in the reflection pattern of the metal and dielectric surface. The Stokes degree of polarization was also evaluated to classify materials. The polarization of the reflected light also varies with the conductivity of the metallic surface and this was further explored and was shown to be able to serve as a tool to classify among highly conductive and lowly conductive metallic surfaces.

In chapter 6, navigation using polarized light is discussed. The navigational strategies of insects using skylight polarization are interesting for applications in autonomous agent navigation because they rely on very little information. The polarization pattern in the skylight varies in a systematic fashion both in *e*-vector and degree of polarization, according to the position of the sun. The Stokes parameters are used to calculate the ellipticity and azimuthal angles of a Poincaré sphere and these angles are shown to be correlated to the incoming light ray direction. A correlation coefficient higher than 0.94 was obtained in all the measurements. This method thus provides a way to determine the incoming polarized light direction which could be used to determine the angular positional information useful for autonomous agent navigation. The ability to compute on-chip or in real-time the positional information would result in highly miniaturized navigational sensors and saving computational power. Further the degree of polarization was shown to vary with the polarization of the incoming light ray direction which could also serve as a compass for autonomous agent navigation algorithms. The variation in the degree of polarization with the position of the sun can further be explored in sun position detection based on skylight polarization.

In chapter 7 the ability of the insect to detect fast motion is explored and also the concept of representing polarization information in binary format is presented. The ability of flying insects to detect fast motion in the visual scene and avoid collision using low level image processing and little computational power makes their visual processing interesting for real time motion/collision detection in machine

vision applications. The designed image sensor can also be operated in temporal differential mode and spatial integration of one-dimensional binary optical flow to detect motion/collision of moving objects replicating the "flickering effects" of the insects. The binary optical flow is generated in-pixel from multiple images stored in the in-pixel memories and spatially integrated using a counter. Both horizontal and vertical motions are easily detected using the binary optical flow which is computed relatively easily in the pixel. A collision alert algorithm to an approaching object as close as 2 cm is demonstrated. Such a collision detection algorithm would allow for the design of simple, miniaturized, low power and narrow path autonomous navigating agents. The designed sensor when operated in differential imaging mode provides for a background illumination invariant motion detection system. The generated binary optical flow is shown to have an angular dependence to the linear polarizer and with increasing the wire grid orientations the digital representation of the polarization resembles the analog form.

In chapter 8, along with the summary of achievements a multichannel imaging system was discussed. The integration of the compound lens from *VUB* with the designed detector array would result in a multichannel imaging system. With high field of view and a low angular resolution, these optical vision systems would find applications not only in machine vision but also in medical applications.

Acknowledgments

"You can complain because roses have thorns, or you can rejoice because thorns have roses", exactly summarizes how you want to look into the long years spent on this book. This book is an extension of my PhD thesis. It is so very obvious to be influenced by many during the course of these seemingly never ending years.

There are many whom I want to thank for helping me finish with my thesis. I will start with my promoter Albert Theuwissen, who has been very supportive and encouraging over these years. I am really thankful to him for accepting me as a PhD student even with me not having any background knowledge on image sensors and for being a constant source of motivation.

I would also like to thank Imec, Eindhoven for financing the project and particularly Bert Gyselinckx who offered me the PhD position at Imec and Margot Nijkamp who took care of the official requirements. For the New Year celebrations, I was gifted twice by Holst, the normal Christmas gift and a new supervisor to work with which made life more interesting. I started the project with Guy Meynants and I am immensely grateful to him for imparting to me his knowledge on image sensors. I designed my first working chip under his supervision and it will remain an unforgettable achievement for years to come. Patrick Merken taught me to be patient and it was fun to have him around. If my technical writing ability has improved the credit has to go to San Segundo Bello David, for his constant guidance on this aspect. He has been very supportive of my work and has always motivated me. David has also immensely helped me in writing my thesis.

I would also like to thank Chris Van Hoof for all the travel budgets for the conferences that I attended. I imagined Chris declining the idea every time I approached him for a conference attendance but he never did. The exposure that I got from the conferences was really very helpful for my scientific and personal growth, and I am really indebted to him for that. Thank you, Chris.

The office colleagues in Imec, Eindhoven have always supported me in my work. I would particularly like to mention a few names, Jiawei with whom I had lots of discussions on amplifiers and general analog circuit design. Besides circuit design we often ended up talking about the share markets, one passion that we both shared and it helped that we were in the same office. Richard van der Hoven, my coffee

partner and Friday evening party mate. I always had a company to go out with and that helped to charge up after a long week at work. Thanks to Richard and Pieter Harpe for helping me to translate my summary and propositions to Dutch. All the other office colleagues were also supportive always. Amongst all, I would like to particularly acknowledge Phillips Mattelaer, the Business Development Manager of Holst. Occasionally he would drop by my office and would ask his famous question "Can your facet eye do this?" to which I always replied "Sure, why not". Thank you Phillip for all the discussions we have had on crazy technologies possible using the insect's vision and for always motivating me to think for ideas and possibilities.

I would also like to sincerely thank Adri Mierop of Dalsa for allowing me to use his experimental setup for measurements and helping me with the debugging process that eventually brought the sensor to life. The thesis writing has been a long journey and thanks Mini for helping me with it.

I would also like to thank Hans Boeve and Martin Ouwerkerk from Philips research, Eindhoven who helped me to move to Netherlands from Germany for my master thesis and later was when applying for a PhD position at Holst. Particularly I want to thank Hans who showed a lot of confidence in me and encouraged me to go for a PhD in the first instance.

And last but not the least, I would like to thank my family who has been a pillar of support all these years. I particularly thank my Mom who supported me in all my engagements and had confidence in me all the way even when others doubted. Love you, Mom.

New Delhi, October 2012   Mukul Sarkar