Chapter 1
Introduction

Visual perception is the ability to detect light and interpret it. The early explanation of vision was provided by two major ancient Greek schools of thought. One believed in the “emission theory” championed by scholars like Euclid and Ptolemy, according to which vision occurs when light rays emanate from the eyes and intercepted by visual objects. The other school championed by scholars like Aristotle and Galen, believed in “intromission” where vision occurs by something entering the eyes representative of the object [1]. The Persian scholar Ibn al-Haytham (‘Alhazen’) is credited for refining the intromission theory into the modernly accepted theory of perception of vision [2]. In his most influential “Book of Optics”, he defines vision to be due to the light from objects entering the eye [3], [4].

Perception is unavoidably selective; one cannot see all there is to see. Visual perception is not merely a translation of retinal stimuli. As John Berger and Jean Mohr [5] quote “A photograph quotes from appearances, but in quoting, simplifies them”. The primary objective of this book is to simplify the perceived visual world (i.e. the photograph) for machine vision applications.

This chapter presents a short overview of various perceptions of vision prevalent in different optical vision systems. The motivation and challenges to design an optical vision system based on the compound eye of the insects as opposed to the more conventional approach of mimicking single aperture eyes is presented.

1.1 Perception of Vision

Objects become visible through many different phenomena of light example reflection, refraction. The way in which creatures see differs in regard to their shape, perception, color visualization, resolution and depth perception. Most animals see the world in fuzzy shades of gray while some animals can see in total darkness, or even see colors beyond the human visual spectrum. Hunting birds use binocular vision to spot prey from thousands of feet above. Dogs and cats are color blind but have better peripheral and night vision than humans and are more sensitive to movements. The sensitivity of owls is 50-1000 times greater to low light intensities

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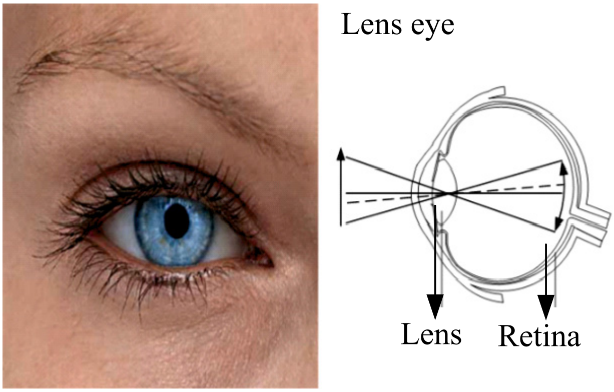
than unaided human night vision. Snakes have thermal pits in addition to normal eyes extending their spectral sensitivity into the infrared. Horses and zebras have their eyes pointing sideways giving them outstanding peripheral vision thus warning them of the presence of predators.

Eyes can be simply defined as organs or visual systems for spatial vision. There are fundamentally two different ways in which high resolution spatial vision can be achieved: either by increasing the number of photoreceptors in the visual system or by multiplying the visual system in its entirety [6]. These two alternatives lead to simple or single chambered eyes and compound eyes, respectively. The human eye is a single chambered eye with a lens and works much like a camera as shown in figure 1.1(a). Animals with such eyes comprise less than 6% of the species in the animal kingdom. More than 77% of the known animal species are insects and crustaceans with compound eyes as shown in figure 1.1(b). Such compound or complex eyes are composed of numerous simple single aperture eyes.

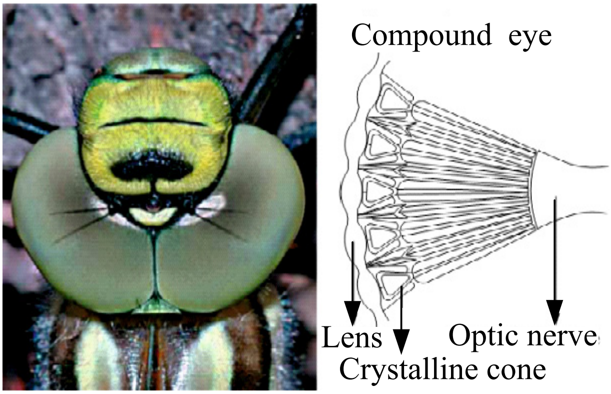
The performance of any eye is principally affected by three structural and two environmental features [7]. Among the former are (a) the angular spacing of the receptors, which determines the spatial resolution; (b) the quality of the optical structures; (c) the diameter of the photoreceptors. Among the latter are (a) the amount of light available to the receptors, and (b) motion (self or image) [8].

The term "resolution" is used in a loose way to mean "ability to resolve fine details" [8]. Resolving power or visual acuity is used to describe the smallest single object that an eye can detect. The two fundamental limitations to the resolving power or resolution of eyes are the wave (diffraction) and the particle (photon noise) nature of light. The wide lens aperture in humans provides a very fine resolution due to the narrow airy disc of a point object caused by diffraction. An airy disc is a diffraction pattern resulting from a uniformly illuminated circular aperture which has a bright region in the center with concentric rings around. The resolution of the small individual lenses of the compound eye is diffraction limited to about 1°.

The other limitation of the resolution is the photon noise. Each photoreceptor can only detect a finite number of quanta, and any such count is associated with an uncertainty. Effectively, this limits the ability to detect differences in luminance (contrasts) across the image. For a given size, an eye can split up the captured light between many receptor cells (high spatial resolution), or it can use the light to activate fewer receptor cells more strongly (high sensitivity). The luminance generated by natural light sources varies over eight orders of magnitude between sunlight and starlight [7]. In 1941, Hecht et al. [10] discovered that human vision is limited in dim light by the small numbers of available photons. At the absolute human threshold, each receptor receives one photon on an average for every 40 minutes and this is the same for insects [10]. The uncertainty in the detection of the number of quanta (photons), increases in low light conditions, thus degrading the visual signal-to-noise ratio [11], [12]. As there needs to be a certain amount of light captured in order to be reliably detected, the eyes of nocturnal animals tend to be optimized for sensitivity rather than spatial resolution [8]. The visual sensitivity of the compound eye is enhanced by the summation of the spatial information in the neighboring visual channels [13], [14], [15].



(a)



(b)

Fig. 1.1 (a) Single aperture eye, (b) Compound eye [9]

The visual acuity depends on both the spatial and the temporal resolution of the eye, as visual systems often detect and respond to objects that move relative to the animal itself [16]. As an object moves across the visual field, the individual receptor channels are progressively turned on and off due to a series of changes in the light intensity. This creates a *"flicker-effect"* known as the flicker frequency rate. The temporal resolving power for moving processes of a compound eye is considerably higher than for a single aperture eye, because of the high flicker frequency fusion rate. With their high speed of reaction, flying insects can resolve 250 images per second. In contrast the human eye sees only about 24 images per second. Eyes with high flicker fusion frequencies are able to recover responsiveness in shorter times than those with lower fusion frequency. Thus compound eyes are ideal for motion detection.

Motion blur is the smearing of a moving visual image due to the finite width of the impulse response of the photoreceptor. The combination of low spatial and high temporal resolutions makes the insects' visual system less sensitive to motion

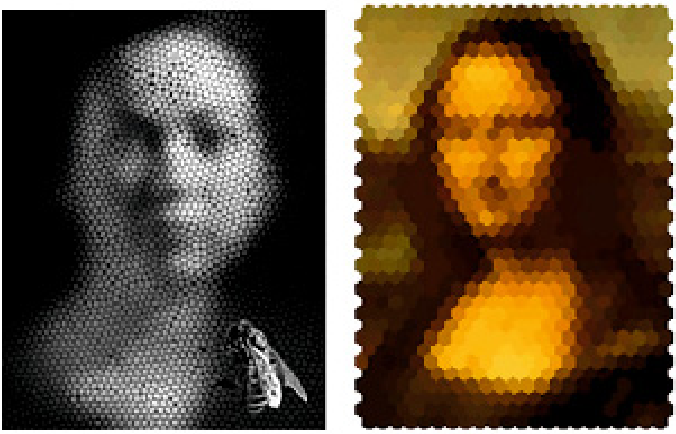


Fig. 1.2 An artistic impression of Insects (housefly's) vision [17]

blur than the human visual system. Theoretically, a fly's vision becomes blurred at an angular velocity of about 1.5°/7ms=200°/s, while in humans this occurs at 2'/25ms=1.4°/s. The wide field of view of the compound eye also aids in motion detection. The field of view of a compound eye is as close to 360° with respect to a two-dimensional plane, whereas the field of view of human eyes is around 160-208°.

Although an image of sorts forms in the eye, it is now accepted that for the majority of insects an image per se has no physiological significance. Figure 1.2 shows artistic impression of two images, as perceived by a housefly. The real function of the compound eye appears to be that of movement perception.

Besides being excellent in motion detection, compound eyes are also able to detect polarization. Light emanating from the sky and reflected light from a watery surface or shiny leaves is polarized i.e. it has greater vibration in some planes than in others. The microvillar organization of the insect's photoreceptors makes its visual systems inherently sensitive to the plane of polarization of light.

1.2 Motivation

The natural evolution of eyes to increase the spatial resolution by either increasing the number of photoreceptors in the visual system or by multiplying the visual system in its entirety has been of interest in the image sensor research field over the last 25 years. The increase of photoreceptors can be compared to the present day phenomenon of the "mega-pixel-race" and the design of autonomous multiple visual systems can be related loosely to the present day "neuromorphic image sensors". The neuromorphic approach implements specialized sensory processing function inspired by biological systems in analog electronic circuits. Neuromorphic vision sensors process images directly at the focal plane with circuits that try to emulate the first stages of visual processing in biological systems.

The perceptual world of animals is very different from that of humans as explained in section 1.1. Insects in general are exquisitely sensitive to image motion, which provides them with useful cues for avoiding obstacles and distance based landing. Thus insects' eyes are better suited for compact, robust and cheap vision systems.

The photoreceptor in a visual system is used to capture and convert the light photons to electric charge. The two most common semiconductor based photoreceptors used for artificial vision systems are CCD (charge coupled device) and CMOS (Complementary Metal Oxide Semiconductor) image sensors. CCDs produce a uniform output increasing the image quality, as all the pixels are only devoted to capture light. However CCDs usually have very limited output nodes, often only one for the pixel's charge to be converted into voltage to be sent off-chip. Also, CCDs have to be read out completely, and thus are inconvenient for region based readouts, affecting the output bandwidth of the sensor. They also require supporting circuits which increase the complexity and size of the camera design, thereby increasing the cost and power consumption. CMOS image sensors on the other hand use generic fabrication process, and in principle work very similarly to CCD sensors. In addition to being less expensive when compared to CCDs, they also allow for the integration of processing circuitry with the photoreceptor. CMOS image sensors also allow for random accessibility, enhancing the output bandwidth. The image quality of a CMOS image sensor is however not at par with that of a CCD as the in-pixel and in-column circuitry often produces a "fixed pattern noise" in the image.

Over the last decade, the resolution of the image sensor has been constantly increasing. Digital cameras with 12 Megapixels or more are now available in the market. To maintain the image quality with increasing resolution or decreasing pixel size, the hardware and firmware performance has to be increased, significantly affecting the complexity, size, cost and power consumption of the system.

Another area of research in vision systems has focused on neuromorphic or intelligent ways of processing the visual data. Until recently the artificial eye has been modeled based on the single aperture eye of the humans, wherein the output of the video-camera is scanned by a variety of spatial and temporal filters. This needs processing of huge volumes of data, defeating the purpose of having simple low power high sensitive vision sensors. Insects use minimal computations even for complicated functions like vision guided flying and thus are more suited for machine vision applications than single aperture eyes.

As we have discussed in the previous section, the compound eyes of insects offer low spatial resolution compared to single aperture eye but also offer other advantages for machine vision applications. These include:

- Wide field of view
- Better suited to detect moving object
- Higher sensitivity to light intensity
- Ability to detect polarization information

The focus of the book is to study each of the above mentioned advantages and to investigate new concepts and design techniques to implement the advantages of the compound eye on conventional CMOS image sensors. Each of these advantages will be addressed in detail in this book.

1.2.1 Wide Field of View

A wide field of view is required in many applications like endoscopy, surveillance and automobile cameras. The most popular method to obtain this is image mosaicing, wherein multiple images are 'stitched' to obtain a larger image. This has a great redundancy in data, with each point being captured multiple times.

In comparison to the human eye which uses a spherical volume, compound eyes use only a spherical shell, permitting a large field of view but requiring less signal processing. Compound eyes have a field of view of near 360° obtained by the superposition of multiple simple lenses. Two such artificial insect facet eyes with this ability are the cluster eye and the artificial apposition compound eye *(APCO)* [18]. The cluster eye is inspired by the apposition eye and consists of three micro-lens array of different pitch. The optical axis of these micro-lenses are titled with respect to each other, and each micro-lens samples a small part of the object. The number of micro-lenses used determines the sensitivity and resolution. The *APCO* system is also based on the apposition eye where each channel samples one direction in space. The *APCO* system consists of a micro-lens array and a pinhole array with a slightly different pitch than the micro-lens array. The pinhole array defines the sensitivity and resolution. Both cluster eye and the *APCO* system has lower field of view *(FOV)* because the lenses are not tilted outwards, as is the case in insects.

The major technical drawback with wide angular field of view in artificial compound eyes is that the spherical optical world is mapped onto flat surfaces of the photo detector. The curved base of natural insect eyes offers several advantages including panoramic vision. Panoramic vision would mean far more information with which to monitor and control one's movement in the world. From a technological point of view, special fabrication techniques are being developed to have curved photodetectors, which would aid in the wide field of view vision [19].

1.2.2 Motion Detection

In conventional machine vision, motion is detected using a CMOS or CCD image sensor which samples the visual field at tens to thousands of times per second. This generates a huge volume of data to be processed for recognition and localization of the target. The precision of the system has a positive correlation with the computation payload. The higher the precision required, the higher is the payload.

The high flicker fusion frequency of the compound eye allows for much faster processing of the images than the single chambered eyes. The reaction time reported for honeybees to an object suddenly appearing in its visual field is 0.01s while that for humans is 0.05s. Additionally the division of the scene into multiple sub-images allows parallel image processing and non sequential readout of the selected sub-images. This facilitates high speed object tracking while reducing image processing bottlenecks.

There are numerous architectures for motion detection based on the compound eye. Optical flow measurements have been explored by [20], [21], while frame differencing is used in [22]. Multi-resolution architecture has been proposed leading to variable spatial acuity imaging or region based motion detection [23], [24]. A CMOS image sensor with integrated circuits for basic decision making and image compression on the focal plane has also been presented [25]. The correlation motion detectors have been used to explain the direction selective motion using elementary motion detectors *(EMD)* [26]. One of the objectives of this book is to investigate on the algorithms to design a fast and simple motion detection algorithm with minimal complexity and processing.

1.2.3 High Sensitivity to Low Light Intensity

A real-world scene is composed of varying levels of brightness within it. The human eye has a very high dynamic range that enables it to detect subtle variation in the brightness and interpret scenes under different illumination conditions. However, while human vision is very poor in low light conditions some insects are known to have very good night vision. In dim light, to increase the visual signal-to-noise ratio, the visual system has to collect as much light as possible. The receptive field is optically enhanced in insects by summing the outputs of neighboring visual channels (spatial summation) or by increasing the sampling time also known as exposure period (temporal summation). The spatiotemporal summation can extend vision to light intensities more than 100,000 times dimmer than when relied on optics alone [27]. In apposition eyes, wider facets and wider photoreceptors can increase the sensitivity by one to two log units [28]. Receptor integration time may increase up to five fold in the dark. The enhancement of visual sensitivity by summation has negative effects on the spatial and temporal resolution.

As vision based safety measures for automotives eventually become mandatory in Europe starting 2013 [29], imaging innovations in low light vision systems will have to be in place. The current area of CMOS image sensors in the automotive industry focuses on high dynamic range and near infra-red type of image sensors. The dynamic range of an artificial optical system can be enhanced either by changes in the exposure period or with an adaptive photodetector [30]. These sensors coupled with night vision ability and more signal processing for intelligent decisions within the image sensor would be a value addition in assisted driving.

1.2.4 Polarization

The three basic characteristics of light are intensity, color and polarization. Polarization provides a more general description of light than either the intensity or the color alone, and can therefore provide richer sets of descriptive physical constraints for the interpretation of the imaged scene. Further a polarization sensitive image sensor along with the ability to measure intensity and color will make it possible to sense the complete set of electromagnetic parameters of light incident on the camera.

The presence of linearly polarized light (the most common type of polarization in nature) in the optical environment can be qualitatively demonstrated by the use of a linear polarizer. The latest polarization image sensors utilize optical imaging systems that are external to the detectors [31]. These polarization filters are either single or multi-axis arrays which measure the polarization information in real time. The compactness of design and the speed at which polarized images are generated can be enhanced greatly by incorporating an array of microscopic polarization filtering optics directly onto a photosensitive chip. Micro-polarizers can be made either from organic materials [32] or using metallic wire grid available with the standard CMOS technology [33].

Light rays get reflected when they strike a reflecting surface, and the reflected light is polarized depending on the incident light and the nature of the reflecting surface. This polarized component can be used to detect the nature of the surface, for example to discriminate between a metal and a dielectric surface [34].

The polarized light in the optical environment is also known to be used by insects such as desert ants for navigation. The ability of the desert ant to navigate effortlessly in complex environments has been a subject of research in robotics [35]. The current vision sensors for navigation use a generalized algorithm of capturing two-dimensional images using a standard CMOS or a CCD camera and then processing those captured images for vector calculations to determine the motion and direction vector. This involves intensive processing along with high power consumption, as most of the post processing of the images is done in the digital domain on a FPGA or a microcontroller. Some of the cheap computational strategies that insects use to navigate have been already modeled in the past [36], [37].

In conclusion, the focus of this book can be summarized as

- Design of an image sensor with an intelligent or a smart pixel, to extend the functionality of the active pixel. The presence of a large number of active elements will limit the resolution. However as a large number of images can be processed at the pixel level, the overall output bandwidth of the image sensor will be improved. Furthermore pixel level processing will also reduce the amount of digital computations helping to design low power fast motion detectors.
- Design of a polarization detection sensor using a metallic wire grid using the metal layers available with a standard CMOS technology. By spatially orienting the micro-polarizer in varying directions polarization information from the optical world can be obtained. Further it is desired to show the real time detection and analysis of polarization information in machine vision applications like material classification and navigation.

1.3 Book Organization

This book consists of seven chapters. Chapter two begins with an overview of the compound eye found in the insects. The different types of the natural compound eye like the apposition eyes and superposition eye are described. The properties of the compound eye like the visual acuity, interommatidial angle, angular sensitivity function, acceptance angle, filed of view, colour and spectral sensitivity are detailed. The polarization vision in the compound eyes of the insects is elaborated. The design of artificial compound eye is discussed along with available designs in literature. The design consideration for an artificial compound eye are presented, following which a description of the artificial compound eye designed in collaboration with the Vrije Universiteit Brussel *(VUB)* is presented.

Chapter three being with an introduction to the Charge-Coupled-Devices (CCD) and Complementary-Metal-Oxide-Semiconductor (CMOS) image sensors. The basic operation of the CMOS image sensor is further elaborated. The process of photodetection, and the available standard pixels operation are described in detail. The performance metrics of the CMOS image sensors are also elaborated. Further, the design and operation of the designed image sensor based on the compound eye of the insects is described. The performance characterization of the designed image sensor are also described.

Chapter four begins with an overview of the basic theory behind the polarization of light and its states. The absorption of the incident electromagnetic waves using specifically aligned metallic grid layers and its effect on the transmission intensity and wavelength are discussed using theoretical simulations. The micro-polarizer realized in the standard CMOS process and placed on top of the photodiode with varying transmission axis is described and characterized. The polarization information detected using the wire grid micro-polarizer can be used for many applications. Two such applications, material classification and navigation, are presented in chapter four and five respectively.

Chapter five begins with the overview of the Fresnel reflections of a polarized light ray after specular reflection. The metallic wire grid micro-polarizer in the designed image sensor allows computing parallel and perpendicular Fresnel reflection coefficients along with the maximum and the minimum transmitted irradiance after reflection from the material surface. Using these measured parameters, various methods described in the literature are used to test the ability of the polarized reflected light to distinguish between a metallic and a dielectric surface. The measured coefficients are further shown to allow for differentiating between various metallic surfaces based on conductivity.

Chapter six begins with the introduction to the natural navigation patterns as exhibited by insects like *Cataglyphis fortis*. Navigation using the polarized state of the incoming light ray is proposed. The azimuthal and the elliptical position of the incoming light rays can be detected using the polarized state of the incoming light ray. This can further be used to detect the position of the sun, as naturally available skylight is always polarized and the degree of polarization depends on the position of the sun.

Chapter seven presents the ability of the image sensor to detect motion based on optical flow and differential imaging. The one-dimensional binary optical flow is used to detect collision (vertical motion) and also horizontal motion. The dynamic range of a sensor plays an important role in detecting motion. Partial charge transfer mechanism is shown to increase the dynamic range and also shows invariance to the changes in the background illumination. The one-dimensional optical flow varies with the polarization angle and can be used to present polarization in digital form.

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