IMAGE PERFORMANCE CHARACTERISTICS OF BIO-INSPIRED IMAGE SENSOR

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IMAGE PERFORMANCE CHARACTERISTICS OF BIO-INSPIRED IMAGE SENSOR

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Thesis

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ABSTRACT

Bio-Inspired imaging has the prospective to enhance machine vision and image performance characteristics. The rationale of this study is to explore the image formation by different insect eyes that will benefit the digital imaging with high resolution while maintaining wide field-of-view, for defense and military applications. In this study, three architectures of different compound eyes, namely, the apposition, the superposition and the neural superposition, were studied. Human eye is polarization insensitive and without usage of an artificial polarization filter, it cannot employ the polarization of light. In contrast, insect vision holds numerous advantages, as their compound eyes provides wide viewing angle, good tracking abilities due to large amount of photoreceptor units and foremost important can detect the polarized light. It is well known, that polarization of light provides enhanced structural and geometrical information, such as high contrast visualization of the surface contours, curvature of objects, surface structures, and locations of different materials. The five insect species that were considered for this study are Hemicordulia tau, Anoplognathus pallidicollis, Heteronympha merope, Melanitis leda and Phalaenoides tristifica.

In this study, several insect eyes architecture, were studied. Then, the imaging design parameters by varying the physical, geometrical, optical parameters of the eye architectures were simulated. Specifically, several physical, optical, geometrical, and imaging design parameters considered for this study, namely, the angular spacing of
receptors, the diameter of the photoreceptors, the optical field-of-view, flying speed; the modulation transfer function (MTF), optical-blur filters, image contrast, angular sensitivity, spatial and angular resolution, degree of blurring, signal-to-noise ratio, and motion artifacts, were simulated at varying of those parameters. The outcome of this study is to explore the phenomenology of the image formation by diverse insect eye architectures which may benefit the areas of defense and security, surveillance and navigation, healthcare, and others.
DEDICATION

I would like to dedicate my dissertation in the memory of my late Grandfather Mr. Kamlesh Kumar Agarwal who had seen a vision in me, motivated me and have been extremely loving and supportive throughout my life. I feel I have fulfilled his dream today, being the first person in the family to achieve Master’s degree.

I would also like to express deep gratitude towards my parents and family members who have been extremely loving and supportive throughout my life and without them this would not have been possible.
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CHAPTER I

INTRODUCTION

Present Unmanned Aerial Vehicles (UAVs) rely on external beacons for localization and navigation as they are limited by guidance systems and their incompetent design. Similarly, the guidance systems, Automatic target recognition (ATR) undergo several design issues and depend on external support. [7, 8] All these above paradigms require intensive operational dexterity and robustness in parallel with a highly efficient bio-inspired vision sensor that enhances guidance, navigation and control capabilities (GNC). [1]

Bio-inspired imaging technology thrusts better surveillance control, as the insect vision relies on polarization of light in contrast to human eye, which depends on external force as it is incapable of detecting polarization of light. Insects have compound eyes which are very different from the human eyes and it consists of ommatidium. Insect vision detects polarization of light along with the intensity of light and color, serving as supplementary source of visual information. [19]

Polarimetric sensing and imaging offer several advantages for problems related to wide range of detection and classification and yield high specificity images under high
dynamic ranges and scattering environments. \cite{1, 3, 5, 10} Compound eye of insects has large number of optical systems positioned around the convex surface. Compound eyes are classified into three different types as apposition, superposition and neural superposition. \cite{14, 16} Superposition eyes hold an advantage over apposition eyes due to their light collection efficiency it can operate and convey a picture in low light conditions. Apposition eyes which are generally the common type of compound eye, has photoreceptor elements called ommatidium which operate independently from each other and intercepts the light arising from an image. \cite{14} Each ommatidium hexagonal in shape and lined with pigment cells, which encloses a thin, tapered tube capped with cornea beneath, is referred as rhabdom, which is transparent crystalline cone through which the rays unite to an output image at the receptive unit. Superposition eye on other hand operate at tandem to collect light from single image which is in contrast to apposition eye in which ommatidia from small segregated image to final output image at brain. \cite{14, 15}

Figure 1.1: Insect vision Architectures. A) Apposition compound eye. B) Optical Superposition compound eye. C) Neural Superposition compound eye. \cite{1}
Insect vision holds numerous merits due to their excellent wide viewing angles, fast movement tracking and ability to detect polarized light. The outcome of this study is to explore the phenomenon of the image formation by diverse insect eye architectures which would benefit the areas of defense and security, surveillance and navigation, healthcare, etc. [14-17, 20-22]

The study was divided into two categories, namely: a) study of different insect eyes architectures, and; b) imaging design parameters simulations by varying the physical, geometrical and optical parameters for given insect eye structure.

The steps are as shown below:

**STEP-1:** Study of different insect eye architecture and specifications of USAF Bar pattern image.

**STEP-2:** Write an algorithm in Matlab to plot footprint of different insects at different distances using intensity equation.

**STEP-3:** Plot the footprints of different insects at distances 1m, 5m and 10m

**STEP-4:** Write algorithm in Matlab to plot footprints for USAF Bar pattern image of different insects at different distances using intensity equation.

**STEP-5:** Plot the footprint of USAF bar pattern image for different insects at distances 1m, 5m and 10m.
**STEP-6:** Study the effects of each parameter on the footprint simulation and the bar pattern image and obtain the output images to validate the effect of parameters on different insects.

**STEP-7:** Plot footprint simulation of USAF bar pattern image at distances 1mm, 100mm, 1cm, 10cm and 100cm (1m) to validate the above effect of parameters and delta row’s effect on blurring.

**STEP-8:** Study the concept of MTF and spatial frequency to evaluate the performance of insect vision and plot MTF vs spatial frequency (degree) using Matlab.

**STEP-9:** Write Matlab algorithm to calculate MTF and Spatial frequency in lp/mm for USAF bar pattern image at different distances for different insects using Bar pattern chart.

**STEP-10:** Plot between MTF vs Normalized spatial frequency (lp/mm) for different insects was plotted using Matlab.

**STEP-11:** Study the concept of Contrast and SNR and plot log contrast and normalized SNR for different insects by considering different lights of the day and different integration times to evaluate the performance characteristics of different insects.

**STEP-12:** Study the motion artifacts and characteristics of different insects and their effects on the images perceived by the insects.

**STEP-13:** Compute angular velocities and new acceptance angle function for different insects at different velocities and at different insects for bar pattern image and obtain output images for different insects.
**STEP-14:** Plot acceptance angle function and the distances at different velocities for different insects to evaluate the motion characteristics for different insects.

**STEP-15:** Extend motion artifacts study on other animals like Mantis Shrimps and obtain the performance characteristics for them by following the same procedure as for other insects.
CHAPTER II

BACKGROUND

2.1 Insect Vision

After several years of research on insect vision capabilities, wide variety of optical type of compound eyes has been discovered and several methods to improve imaging by combining optics with insect vision has been developed. Some compound eyes form various inverted images and some form a single erect image. The primary consideration in designing an eye is relatively simple laws of optics. However, it is important to address important questions about the compound eyes: How is the eye structure organized? How do these eye structures function? Why the particular functions have been developed?\textsuperscript{[23]}

Since 1920’s extensive research has been done to learn about the insect visual capability, their use of various colors, detecting the polarized light & their sensitivity to pattern and motion.\textsuperscript{[14]} The platform for studying the acuity of insects was laid earlier in 1890s and Exner’s great monograph of 1892 presented an inclusive account of physiological optics of insect eyes. Even though it presented detailed account of insect vision optics, it lacked the spatial resolution limits for the insect vision.\textsuperscript{[24]} This issue was addressed in a paper by Mallock in 1894 whose notable insights did not receive proper appreciation for next 60 years. Mallock’s paper expressed concerns about insect vision to be poor as in the
compound eyes of insects each ommatidium, the receptor unit has its own lens usually tiny and samples the image of surroundings. Mallock also realized that diffraction limits the resolution of these tiny lenses, also limiting the resolution power of microscopes and telescopes about $1^\circ$, which is acuity approximately one hundredth, that of a human eye with significantly larger aperture. [25] To have a compound eye with similar resolution of a human eye would require millions of lenses, each as larger than human lens. Such compound eye will have a radius of around 6m. [28]

Physical optics of compound eyes of insects caught the interest again in researchers in 1950s with the researchers de Vries [26] and Barlow [27], and particularly the discussion of limiting role of diffraction in insects by Kirschfeld [28] and Snyder [29]. In 1941, Hecht et al [30] discovered that human vision is limited in dim light due to less number of available photons which proved an important aspect for insect vision. Various other discoveries added importance to insect vision, such as the discovery of elongated receptor structures called rhabdom’s which act like waveguides. By 1980s, the principal optics mechanism of compound eyes was clearly understood. [14]

During this period even other important discoveries and questions were addressed in accordance with physiological optics. Exner’s classification of compound eyes into apposition and superposition compound eye was challenged and proved misguiding during 1960s. [13] The issue with the optical and retinal arrangement of Dipteran flies where the rhabdomeres of receptors in each ommatidium are not fused together when compared to other apposition eyes was resolved by Kirschfeld in 1967 [32-33] and termed it as neural superposition eyes. In 1984, Nilsson et al [34-35] observed that apposition eyes of
butterflies and the superposition eyes of moth shared common optical system. Also, he completely reviewed the current acquaintance with optics of compound eyes.\textsuperscript{[36]}

2.2 Polarimetry

Polarization vision can be considered as prominent medium for offering high-level acuity and vision applications. Polarization vision holds its significance in various tasks such as object recognition, contrast enhancement, signal detection and camouflage breaking. Human eyes cannot detect light’s vector orientation, but they can utilize polarizing optics to visualize the invisible polarization patterns.\textsuperscript{[1], [11]}

Sky polarization patterns are utilized by many insects for navigation. For example, Honeybees use celestial polarization to move back and forth between the hive and scavenging locations, Salmon fish utilize sky polarization pattern to orient themselves in underwater light fields and Water Beetles utilize light reflection from the water surfaces for their orientation. Reflected polarized light are utilized by aquatic insects such as dragon flies, mayflies, etc to discriminate the water surfaces from the virtual surfaces. Polarization vision also helps insects to detect their prey and insects can use camouflage as vital tool to overcome visual detection by their predators. Polarization vision patterns are also useful for signaling by various insects by controlling the reflection of linearly polarized light. For example, forest butterfly presents their wings as identifiers, Mantis Shrimps uses polarized light signals and color signals.\textsuperscript{[18]}
2.3 Rayleigh Scattering

Light from the sun is non-polarized and it generally interacts with the atmosphere through Rayleigh scattering and becomes partially polarized. In the same way even the sea surfaces interacts with sun light and becomes partially polarized. Generally, skylight is plane polarized where a particular orientation of electric field dominates in any direction of the sky. E- vector pattern is also known as the polarization pattern. \[1\]

![Figure 2.1: Rayleigh Scattering \[1\]](image)

Polarization can be defined in terms of orientation of the plane in which the electric field vibrates and also it can be defined in terms of degree of polarization (DOP) which is expressed terms of the stoke parameters. \[1\]
CHAPTER III

THEORETICAL BACKGROUND

This chapter provides the theoretical background of performance characteristics of different insects used in this study.

3.1 Spatial Frequency

Acuity is defined as the inverse of minimum resolvable angle, which generally refers to the angle subtended at eye by two stripes which are equal grating of light and dark stripes. [79] Acuity or generally termed as “Spatial Frequency” denoted by “v” cycles/degree or cycles/radian, where, $1 \text{ radian} = \frac{180^\circ}{\pi} = 57.3^\circ$. For any insect, its maximum acuity or maximum spatial frequency is represented as $v_{\text{max}}$. [14]

Even though physics of the grating differs as the single objects or stripes generally tend to yield too much smaller angular thresholds, acuity is also used to illustrate the smallest single object that any eye can detect. If we go by the past literature and the work done, the single object thresholds or grating were referred as “minimum visible” and “minimum separable.” Generally, objects with complex details such as foliage can be considered as multitude of gratings with diverse periods and the finest details visible by an insect is given by acuity. [14]
For navigation and ranging applications as the distance is greater, the acuity is better. Queen bees, dragon flies, etc are the examples of the insects with small targets for which the most apposite performance measure would be single object threshold, where the good resolution can be termed as the point where the small targets can be easily detected at greater distances. \[14\]

3.2 Characteristic Features contributing to an Eye’s Acuity

The performance of any eye is predominantly affected by three fundamental and two environmental features. The three fundamental features are: (i) The angular spacing of the receptors which concludes how finely the image can be resolved. (ii) The quality of the optics used. (iii) The diameters of the photoreceptors or rhabdom, as in case of wide photoreceptor or rhabdom, the image details is lost if the width is smaller and narrow diameter receptors introduce waveguide effects. The environmental features are: (i) Amount of light available to the receptors as there are not enough photons available at low light levels to provide reliable signal and detect contrast. (ii) Motion, as the image motion causes blurring in the eye in case of highly maneuverable insects. \[14\]

3.3 Interommatidial Angle (\(\Delta \phi\))

Interommatidial angle is considered as the principal factor of acuity and it is the angle between the two detectors in an array. In case of camera-type eye, interommatidial angle is the subtending line between two receptors at nodal point, where the light rays are not deviated and the angles in object and image space remain same. In case of apposition compound eye, the definition of interommatidial angle differs as the receptors are replaced by the ommatidia as the essential sampling units. The rhabdom composed of
photo pigment bearing upto eight other photoreceptors act as single light guide and produces final image at the tip. [14]

For simple eye (human eye or camera), the angle between two detectors $\Delta \phi$ is, [1]

$$\Delta \phi \cong \frac{s}{f}$$  \hspace{1cm} (3.1)

where, “s” is the receptor separator and “f” is the focal length.

For apposition compound eye, the interommatidial angle is the angle between the optical axes and the adjoining ommatidia,

$$\Delta \varphi \cong \frac{D}{R}$$  \hspace{1cm} (3.2)

where, “D” is the diameter of the facet lens and “R” is the radius of curvature of the eye.
Eye’s composition if it has two detectors to view each cycle of grating, one for the dark and the other for the light stripe. Thus, the acuity or sampling frequency is given by,

\[ v_s = \frac{1}{2\Delta\phi} \] (3.3)

In case of bee’s eye, the horizontal rows of Ommatidial angle are divided vertically by less than the interommatidial angle, as the lattice is hexagonal and hence the angle is termed as \( \Delta\phi/2 \), even though it is referred as \( \Delta\phi \) for measuring acuity on proper basis. [37,38]
3.4 Optical Quality

Contrast of image decreases as the object details get finer and at some point it becomes zero. All the optical systems have cut-off frequency due to the diffraction limit. Focus defects can also cause blurring in the image limiting the high spatial frequencies.

Figure 3.2: Modulation Transfer function corresponding to the normalized spatial frequency. \[14\]

If the cut-off frequency is $v_{co}$, then the resolution is maximum if the image optics is capable of being resolved. \[14\]

$$v_{co} = v_s = \frac{1}{2\Delta\varphi} \quad (3.4)$$

where, $v_s$ is defined in equation 3.3, and $v_{co}$ is same as $v_s$ for insect eyes.
For human eye, during daylight $v_s$ and $v_{co}$ both are close to 60 cycles/degree. In insects, the receptors with rational amount of contrast let the human retina perceive the resolution limit, i.e., $v_s$ is approximately $v_{co}/2$. \[39, 40\]

### 3.5 Diffraction Limit

If the image optics is without any defects then the resolution is set by diffraction. The diffraction pattern for an image of point object is commonly known as airy disc. Diffraction limit has maximum central intensity among the series of minima & maxima of decreasing intensities. More wider the lens aperture ($D$), narrower the airy disc and more finer is the resolution of the image. The most desirable performance measure for the pattern is the width of central disc at half maximum intensity which is approximately $\lambda/D$ radians, where “$\lambda$” is the wavelength of light. \[42\] Point spread function (PSF) is the distribution of light of a point source in an image which is wider than the airy disc due to optical imperfections. \[14\]

\[
hw_{PSF} = \frac{\lambda}{D} \tag{3.5}
\]

As the grating period in the image approaches to PSF, contrast of image decreases and approaches zero at cut-off frequency ($v_{co}$). \[14\]

\[
v_{co} = \frac{D}{\lambda} \tag{3.6}
\]

### 3.6 Modulation Transfer Function (MTF)

The most important performance characteristic of eye optics is given by modulation transfer function (MTF) which describes lens performance and is the ratio of image
contrast and object contrasts for gratings of all spatial frequencies. Contrast is given by \((I_{\text{max}} - I_{\text{min}}) / (I_{\text{max}} + I_{\text{min}})\), where “Imax” is maximum intensity of the image and “Imin” is minimum intensity of the image. [42, 70]

3.7 Effect of Rhabdom Diameter

Rhabdom with narrower diameter will fit the intensity of single striped image, whereas the wider rhabdom can fit as many striped images into its diameter. For camera type and superposition eyes, rhabdom diameter is not a problem as the receptors are contiguous to each other. But for apposition eyes, there is no restriction on rhabdom width but it compromises on image resolution. [14]

The rhabdom’s with the narrowest width of less than 2um failed to act as point-detectors as the rhabdom behaved as if the diameter is greater than the actual width. The light forms interference patterns called waveguide modes with narrow light guiding structures. [41,42] The fundamental mode which comprises of narrowest receptors has significant amount of energy outside the structures which guides it. This has two consequences: Firstly, for apposition eyes narrower receptors always tend to appear having larger diameter, compromising on image resolution. Lastly, for eyes with adjoining receptors, the light energy from one receptor can find its way into other adjoining receptors which damages the image resolution. Thus, limiting the rhabdom diameter to range 1-2 um. [14]

3.8 Angular Sensitivity and Acceptance Angle

The combination of optical blurring of lens, width of receptor and waveguide modes is not simple to calculate. But, in the past [43-46] the results has been predicted accurately and
it is measured as the angular sensitivities of retinal receptors. Snyder’s approximation simplifies the problem of combining the two blurring functions on many occasions. If Point-spread function and rhabdom acceptance function are considered as Gaussian then their half-widths (hw) is given as follows:

\[
\text{hw}_{\text{comb}}^2 = \text{hw}_{\text{lens}}^2 + \text{hw}_{\text{rhab}}^2
\]  

(3.7)

where, “comb” is combination, “lens” is PSF of lens and “rhab” is the acceptance function of rhabdom (refer to figure 3.1). For the receptors with wider width greater than few micrometers, the acceptance function is half-width of the rhabdom diameter, which is given in angular term by d/f. The airy disc half-width is given by \(\lambda/D\), where, “D” is lens diameter. The half-width of receptor’s angular sensitivity is termed as ommatidial acceptance angle \(\Delta\rho\) and it is given by,

\[
\Delta\rho \approx \frac{\lambda^2}{D} + \frac{d^2}{f}
\]  

(3.8)

The effective cut-off frequency of system including the rhabdom is given by,

\[
v_{opt} = \frac{1}{\Delta\rho}
\]  

(3.9)

The \(\Delta\rho\) equation tends to overestimate \(\Delta\rho\) upto 30% in the eyes with narrow rhabdom’s, but works well for wider rhabdom’s. For example, in the fly Calliphora Erythrocephala \(\Delta\rho\) is 1.83° for the receptors 1-6 and for the method which considers the optical coupling of the lens diffraction pattern to the waveguide mode of rhabdom gives the value of 1.24°. [45-46]
If the acceptance function is approximated as the function of Gaussian with half-width $\Delta \rho$
then the Modulation transfer function, MTF of the receptors is given by, \(^{[14]}\)

$$M(\nu) = e^{-3.56(\nu \Delta \rho^2)}$$  \hspace{1cm} (3.10)

where, $M(\nu)$ is the contrast ratio at respective spatial frequencies. (This is another
definition of MTF)

3.9 Photons, Sensitivity and Resolution

Photons enter the rhabdom’s at a very low rate at lower light levels and at absolute
human threshold, each receptor receives 1 photon per 40 minutes. \(^{[30, 31]}\) Generally, small
values signify poor statistics. Small number of events sampled from large pool follows
poisson statistics where, the mean is equal to its variance. \(^{[30,49-50]}\) Low contrast requires
large number of photons for their detection and the average number of photons per
receptor required for grating the contrast is given by, \(^{[50,53]}\)

$$\bar{N} > \frac{1}{C^2}$$  \hspace{1cm} (3.11)

where, “$C$” is contrast. If the contrast grating is 0.5 then the number of photons is 4. The
integration time for most of the insects is less than 0.1s. Thus, at low contrast each
receptor would require million photons available only during daylight. \(^{[51]}\)

Low number of photon limits the acuity and contrast. With 10 photons per integration
time, the contrast will be limited to 0.32 and the spatial frequency will be limited to 60%
of its cut-off frequency. \(^{[52, 53]}\) The number of photons available to receptors at different
lighting conditions is given by,
\[ N = \frac{0.621D^2d^2}{f^2} \] (3.12)

where, “I” is the luminance of the source. \( d/f \) is also called geometrical acceptance angle and \( \Delta \rho^2 \) can replace \( d^2/f^2 \) in the above equation.

During sunlight \( 10^{20} \) photons \( \text{m}^{-2} \text{sr}^{-1} \text{s}^{-1} \) are emitted, in room light \( 10^{17} \) photons are emitted, in moonlight \( 10^{14} \) photons are emitted and in starlight \( 10^{10} \) photons which is also the threshold for human vision. For an diurnal insect with dimensions \( D = 25 \text{um} \), \( d = 2 \text{um} \), \( f = 60 \text{um} \), the number of photons per receptor are \( 4 \times 10^7 \) for sunlight, \( 4 \times 10^4 \) for room light, 40 for moonlight and 0.0004 in starlight. \([14]\)

Most of the insects are crepuscular like moths, beetle, etc. But the some dragonflies like Zyxomma Obtusum \([54]\), Butterflies like Melanitis Leda \([55]\) and the Diptera fly at only light levels between room and moon light. In case of apposition eyes, wider facets “D” and wider rhabdom’s “d” increase the sensitivity upto 1-2 log units. \([56]\)

3.10 Effects of Motion on Resolution

The retinal image is subjected to motion blurring when the eye and surroundings move relative to each other due to the photoreceptors finite integration time, the image will start to lose contrast at high spatial frequencies when the motion exceeds the acceptance angle \( \Delta \rho \) per receptor integration time \( \Delta t \). Integration time can also be defined as half-width of response of a small light and its value for most of the insects is in the range of 5-50ms. \([51, 57]\) If the insect has \( \Delta \rho = 1' \) and \( \Delta t = 20 \text{ms} \), then the blurring will occur at angular velocities greater than \( 50' \text{s}^{-1} \). For highly maneuverable insects the speed can vary upto
several thousand degrees per second and therefore causing blurring as one of the vital issue. \cite{58,59}

Snyder estimated that the effects of motion blurring increases with increase in width of acceptance function $\Delta \rho$ by using gaussian approximations to obtain extended acceptance angle $\Delta \rho_v$. \cite{42}

\[
\Delta \rho_v^2 = \Delta \rho^2 + (v_a \Delta t)^2
\]  

(3.13)

Where, $v_a$ is the angular velocity across the retina.

3.11 Resolution and Eye Size

The multi-lens design of compound eyes of insects has adverse effects when high resolution comes into account as the small lens are diffraction limited thereby increasing the resolution factor by factor of two which requires doubling diameter for each ommatidium as well as number of ommatidia in a row. \cite{28,60} The consequence is that the eye should be square of the required acuity and to achieve vertebrate acuity the eye should be huge in size.

For a diffraction limited system, $v_{co} = v_s$ and thus, the radius of the eye, “R” is given by,

\[
R = \frac{\lambda}{2\Delta \phi^2} = 2\lambda v_s^2
\]  

(3.14)

Where, “$\Delta \phi$” is interommatidial angle. If the interommatidial angle is $1^\circ = 0.0175$ radians, wavelength “$\lambda$” is 0.5um then the radius of eye is 0.82mm. But when $\Delta \phi = 0.5$ minutes = 0.00015 rad then radius of eye becomes 11.7 meters. Dragonflies having largest insect
eyes have interommatidial angle of 0.25°. In reality, the only way in which the compound eye of an insect would achieve better resolution compared to the degree would be to build an acute zone, where the small regions will have larger facets and have larger acuity. [54,61]

Diffraction limited system pose another serious problem as it predicts square root relationship between the ommatidial diameter and the eye size. [25,27] Thus, D is given by,

\[ D = \left( \frac{R\lambda}{2} \right)^{1/2} \]  

(3.15)

But Barlow’s [27] study proves that the ommatidial diameter is proportional to square root of eye size.

3.12 Acuity in other types of Compound Eyes

For Apposition eyes, each rhabdom has its own lens and it is fused with the output of each receptor forming single light guiding structure. The three different variations of apposition compound eye are afocal apposition compound eye, optical superposition compound eye and neural superposition compound eye. [14]

Dipteran flies have apposition compound eye structure but their photoreceptors of each ommatidium maintain their individual rhabdomeres separated by 1-2 um. Kirschfeld [32,33] proved that the central rhabdomeres in ommatidium shares the field of view with one of the rhabdomeres in each of six ommatidia. Also, all the receptors image in same direction and send their axons through complex crossover arrangement to same cartridge in the lamina thus giving the name neural superposition compound eye. This arrangement will work only if the receptor separator s/f is same as the interommatidial angle \( \Delta \phi = D / R \).
For this complex arrangement the photon signals seven receptors and therefore it has $\sqrt{7}$ improvement in image contrast but still it compromises on resolution. The same arrangement in case of apposition eye would increase the rhabdom diameter by $\sqrt{7}$ which will increase the acceptance angle $\Delta \rho$ and decrease the resolution of image, but the result is very sensitive.\,[14]

Exner\,[24] discovered that the optical superposition compound eyes of moths and the nocturnal beetles are constructed differently as many facets contributed to single, real erect image. Each optical element has the property of two lens telescopes rather than the simple lens and each of these telescopic elements achieve their optical power from internal gradient of refractive index.\,[62, 63]

Considering eye optics, this type of eye should be treated as simple camera type eye because of its single image characteristics. From the geometrical point of view, the focal length is the distance from the center of the curvature to the image which is nearly half the radius of the curvature of the eye. The inter receptor angle and the acceptance angles are same as that of apposition eyes, but the main difference relies on sensitivity as the effective aperture “D” is equal to width of ten facets or more which increases the sensitivity by 1-3 log units and permitting insects such as moths, beetles, fireflies to mate during late evenings.\,[14]

Optical superposition compound eyes of butterflies have telescopic optical elements but their rhabdom’s are close to the proximal end as in case of the apposition eyes. This eye are usually referred as afocal as the light from distant point materializes as a parallel
beam rather than a focused spot and their acceptance angle $\Delta \rho$ value is set by the critical angle rather than its diameter. \cite{34,35}

3.13 Interommatidial Angle ($\Delta \phi$)

Measurement of interommatidial angle is generally simple, if the row of ommatidia subtends an angle of 90° in space and facet length of 45, then the average interommatidial angle is 2°. The problem with measurement is that the optical axis of ommatidia is not perpendicularly aligned to eye surface and therefore the external measurements tend to lose vital characteristics like acute zones. \cite{14}

In 1960’s, $\Delta \phi$ was usually measured using histological sections. \cite{64,65} Most recent measurements of interommatidial angle includes use of pseudo pupil which is a black dot that appears to move around a insect eye as the observer’s view changes and marks the ommatidia and absorbs the light from the observer. The line joining the pseudo pupil to the observer’s eye is the direction of view. Interommatidial angle can be measured by the ratio between a known small angle and the number of ommatidia crossed by pseudo pupil. Problems arise when the pseudo pupil is asymmetric and the interommatidial angles change drastically. \cite{14}

The final method for determining interommatidial angle is by using optokinetic response where the insect at center of a striped drum and it will turn the drum to minimize the displacement across the image, also $v_s$ is considered as $1/2\Delta \phi$. Srinivasan and Lehrer in their study used a different behavioral method to distinguish gratings with horizontal and vertical stripes at different distances in honeybees. Highest spatial frequency that can be
resolved by honeybee was $0.26$ cycle deg$^{-1}$ with grating period $1.9^\circ$ which is very less compared to the horizontal interommatidial angle which has minimum value of $2.8^\circ$. [66]

3.14 Acceptance Angle

During 1960’s the traditional method to calculate the angular acceptance function of a cell is by giving flashes from small light source and move through the center of the cell’s receptive field, then the $\Delta \rho$ is given by the width of the function at half maximum sensitivity. However, this method tends to produce a serious problem as it overestimates the value of acceptance angle due to the damage. [14] There was improvement made to this method [47] in 1970’s and the most recent development utilizes a light-clamp where the receptor’s response is hold constant by using a density wedge in feedback loop. [14]

The optical method to calculate acceptance function is by illuminating the eye so that the light emerges from the distant tip of the receptor by using antidromic illumination from behind the retina or by using reflected light back from the tapetum. [35, 70] This light can be collected by suitable optical system and the light distribution can be measured. The main theory behind reversing the light is that, the light accepted by the rhabdom should have exact distribution as that of the light emitted by the rhabdom. For blowfly Calliphora Erythrocephala, this method gives value of $\Delta \rho$ as $1.24^\circ$. [45]

3.15 Departure from Uniform Symmetry

Majority of the insects having apposition compound eye do not sample the surroundings in a uniform way. The non-uniformities are of two kinds: One is due to the variations in
local angular sampling density, creating foveas by giving higher resolution in some regions than the others. Secondly, there may be differences between the spacing of ommatidial axes in the horizontal and vertical directions. So, to predict the sampling of eye, one has to calculate $\Delta \phi_h$ and $\Delta \phi_v$ for all the regions of an eye.\cite{14}

The necessity for these asymmetries in insects arises from the fact that the insect eyes are restricted for space due to the limit to the resolution enforced by the diffraction. All the acute zones have to slink in at the expense of resolution and place where there is less need of horizontal acuity than the vertical acuity than the appropriate space can be saved but distorting the ommatidial axis pattern. Superposition compound eye show less distortion when compared to the apposition compound eye of an insect as the optical system does not allow much departure from the spherical form.\cite{14}

There are three patterns in the distribution of axes in apposition compound eye: a) pattern associated with the forward light, b) pattern associated with the acute zones concerned with capture of prey or mates and c) the horizontal acute strips associated with water surfaces.\cite{61}
Figure 3.3: Three ecological patterns in the distribution of axes in Apposition compound eye of an insect. a) Pattern associated with forward light. b) Acute zones in the frontal or dorsal regions of the insect eye. c) Horizontal acute strips associated with flat environments like water surfaces. (Without Permission)\textsuperscript{[14]}

The forward flight pattern is followed by insects like bees, butterflies, acridid grasshoppers and all flying herbivores. These insects follow a traditional pattern of changing the interommatidial axis density and the vertical/horizontal ratio across the eye. There are two gradients $\Delta \phi_h$ and $\Delta \phi_v$, among which, $\Delta \phi_h$ is smallest in the front of the eye and it increases towards the back of the eye, whereas, $\Delta \phi_v$ is smallest around the equator of the eye and it increases towards the dorsal and ventral pole.\textsuperscript{[61]} This pattern results in frontal acute zone with a band around equator with enhanced vertical but not horizontal
acuity. This pattern was originally observed in bees and butterflies and then consequently in locusts and other type of insects.\textsuperscript{[14]}

Figure 3.4: Patterns of ommatidial acceptance angles in different regions of eye of the Heteronympha Merope, the Australian woodland butterfly. (Without Permission)\textsuperscript{[14]}

The circles in the above figure of Australian butterfly pattern represent the dark adapted, optically measured acceptance angle which is $\Delta \rho = 1.9^\circ$\textsuperscript{[35]} which vary little compared to the facet diameter which varied from 21-26um. There are major variations in both $\Delta \phi_h$ and $\Delta \phi_v$ as, from the front horizontal to 120$^\circ$, $\Delta \phi_h$ doubles pulling the vertical rows apart and $\Delta \phi_v$ increases by three separating the individual fields in the vertical rows. Similar pattern has also been observed in honeybees.\textsuperscript{[61,67]} Locusts and grasshoppers are amidst
of bees and butterflies but some crickets like Tettigoniid grasshoppers that rarely fly have spherical eyes and do not have these distortion patterns.\textsuperscript{[72]}

The relation between the angular velocity \(v_a\) and the distance of an object from insect is given by,

\[
v_a = \frac{U \sin \alpha}{b}
\]  \hspace{1cm} (3.16)

Where, “U” is the insect’s linear velocity, “\(\alpha\)” is angle between the object and the forward direction, “\(b\)” is the distance of an object.\textsuperscript{[14]}

In the case of insects with region of high acuity like mantids, dragonflies, robber-flies, etc where both male and female insects have their specific interests,\textsuperscript{[72]} predation and more often male insects like simuliid midges, hoverflies, mayflies, drone bees has the acute zones implying for sexual pursuit. Male houseflies and blowflies have more acuity in forward flight in both the sexes. For male C. erythrocephala, the acute zone lies in range 20-30° above the equator with lower Δρ and larger facets compared to the female.\textsuperscript{[14]}

For hoverfly Syritta Pippiens,\textsuperscript{[58]} sex difference is more prominent and the male acute zone has Δρ about three times smaller compared to the female eye and it uses this as an advantage to track the female beyond her detection range. Dragonflies usually hunt the insects on the wing and have wide variety of configurations, usually having two acute zones, one pointing forward and other directed dorsally towards the prey.\textsuperscript{[54,73]}

Flying insects have more vertical acuity around the eye horizon reflecting its visual significance. Crabs have narrow band of high vertical acuity around the equator of the eye \textsuperscript{[74]} and ants like Cataglyphis that forage in the desert have high acuity around the
horizon. Water surface endow restricted visual environment, Water strider like Gerris Lacustris hunt prey trapped in a surface film and have narrow acute band of 10°. Empid flies inhibit water surface and look for a drowning prey. Hilaria and Rhamphomyia have band of enlarged facets around equator of the eye with 20° high acute region. For these insects the diffraction limit is improved due to wider facets and the vertical resolution is increases by factor of 3-4. [74]

3.16 USAF Bar Pattern

USAF Bar pattern is the traditional test chart by US air force 1951 to determine the resolving power and the performance of the imaging systems like microscopes, cameras and the image scanners. Series of sizes and contrasts are used in determining the minimum resolvable number of lines at given contrast of an image. This pattern consists of group of three bars, each dimensions ranging from big to small. [80]

The most common format of bar pattern is MIL-STD-150A consisting of series of elements having two sets of lines at right angles. Each set of line consists of three lines separated by equal space to the line width and each bar has length to width ratio of 5:1. [80]
Each element is arranged in six groups and each group is arranged in pairs. The even numbered groups inhabit the left side and the bottom right corner of the chart with a square feature and edge length equal to the line length of element 2 of the same group. The odd numbered groups inhabit the top right corner and the side of the chart. Both groups and the elements are labeled and can be distinguished by numbering adjacent to their features. The frequency or resolution values are in cycles/mm or line parts/mm and this value increases between each element by sixth root of two which is approximately 12.25% per step. \[80\]
The resolution for any target element can be calculated by using the formula,

\[
\text{Resolution} = 2^{\text{Group} + (\text{Element} - 1)/6}
\]  

(3.17)

1951 USAF Resolution Target

![Diagram of USAF Bar Pattern chart with Group and Element Labels]

Figure 3.6: USAF Bar Pattern chart with Group and Element Labels. [80]

Each group has six elements and each element is 3 horizontal bars and 3 vertical bars of same size. The groups area labeled with numbers -6, -2, 0, 1, 2, 3 and the elements are labeled from 1 through 6. The resolution limit of the system is determined by examining an image of resolution test target and to locate the element with highest frequency value where the horizontal and vertical lines are distinct and horizontal limit of resolution may be different than the limit of vertical resolution. [80]
4.1 Insects used for the study

The insects used for the study are as tabulated below with their respective acceptance angles and interommatidial angles.

4.2 Simulation and plot of Laser Footprint of Insects

The aim of this simulation is to model the spatial distribution of the laser beam and observe footprints of different insects at different distances from the image plane. Beam divergence is considered for calculating the intensity of the image. The beam divergence of the laser beam is 0.1mrad in x-z plane and its 0.2mrad in y-z plane. A well collimating lens with diameter 4.5mm leads to laser aperture of 4.5mm on x-plane and 1.8mm on y-plane. \[^{[1]}\]

The intensity of the laser beam is given by, \[^{[1]}\]

\[
I(\theta_x, \theta_y, R) = I_0 \exp\left\{-2\left[\left(\frac{\theta_x}{\alpha_x}\right)^2 + \left(\frac{\theta_y}{\alpha_y}\right)^2\right]\right\}
\] (4.1)

Table 4.1: Insects with their respective acceptance angles and interommatidial angle values

<table>
<thead>
<tr>
<th>Species</th>
<th>$\Delta \phi$ (Degree)</th>
<th>$\Delta \rho$ (Degree)</th>
<th>$\Delta \rho/\Delta \phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemicordulia Tau</td>
<td>0.9</td>
<td>1.4</td>
<td>1.56</td>
</tr>
<tr>
<td>Anoplognathus Pallidicollis</td>
<td>1.5</td>
<td>3.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Heteronympha Merope</td>
<td>1.25</td>
<td>2.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Melanitis Leda</td>
<td>1.44</td>
<td>1.5</td>
<td>1.04</td>
</tr>
<tr>
<td>Phalaenoides Tristifica</td>
<td>1.9</td>
<td>1.58</td>
<td>0.83</td>
</tr>
</tbody>
</table>

where, $\theta_x$ is given by,

$$\theta_x = \arctan \left( \frac{x}{R} \right)$$  \hspace{1cm} (4.2)

For $R \gg x$, $\theta_x$ changes to,

$$\theta_x = \frac{x}{R} - \left( \frac{1}{3} \cdot \frac{x}{R} \right)^3$$  \hspace{1cm} (4.3)

Where, “R” is radius of curvature of the lens

Similarly, $\theta_y$ is given by,

$$\theta_y = \arctan \left( \frac{y}{R} \right)$$  \hspace{1cm} (4.4)
And for $R>>y$, $\theta_y$ changes to,

$$\theta_y = \frac{y}{R} \left( 1 - \frac{1}{3} \frac{y}{R} \right)^3$$ \hspace{1cm} (4.5)

Now, assume $G_x = 5$ and $G_y = 2$. Where, $G_x$ and $G_y$ are Gaussian factors for $x$ and $y$ directions respectively. Substituting values of $G_x$ and $G_y$ in intensity equation we get, \cite{1}

$$I(x, y, R) = I_0 \exp \left\{ -2 \left[ \left( \frac{x}{R, \alpha_x} \right)^{G_x} + \left( \frac{y}{R, \alpha_y} \right)^{G_y} \right] \right\}$$ \hspace{1cm} (4.6)

Now, beam divergence along $x$ and $y$ axis is defined as,

$$a_x = 2 \arctan \left( \frac{x_1 - x_0}{2R} \right)$$ \hspace{1cm} (4.7)

$$a_y = 2 \arctan \left( \frac{y_1 - y_0}{2R} \right)$$ \hspace{1cm} (4.8)

Where, $x_0 = 4.5$ mm and $y_0 = 1.8$ mm.

At $R = 0$, the footprint of the laser can be estimated as,

$$\begin{align*}
x_1 &= 2R \tan \left( \frac{a_x}{2} \right) + x_0 \\
y_1 &= 2R \tan \left( \frac{a_y}{2} \right) + y_0
\end{align*}$$ \hspace{1cm} (4.9)

(4.10)

The applied geometry and the laser footprint observed at distance 1m away from the source is as shown in figure below.
After obtaining estimated laser footprint, footprint at different distances from image planes was obtained for different insects with their respective focal lengths. It was observed that, as the focal length value of the insect increases, the image is larger, i.e., if focal length value is more, the footprint is bigger, if focal length value is less, then footprint is smaller.

The footprints of different insects at their respective focal lengths can be observed in the table below.
Table 4.2: Footprints of different insects at their respective focal lengths.

<table>
<thead>
<tr>
<th>G (gain) = 2500</th>
<th>1m</th>
<th>5m</th>
<th>10m</th>
</tr>
</thead>
</table>
| **Anoplognathus Pallidicollis** (Beetle)  
  (F = 352um, Delta Rho = 3) | ![Footprint](image1.png) | ![Footprint](image2.png) | ![Footprint](image3.png) |
| **Phalaenoides Tristifica**  
  (F = 63.29um, Delta Rho = 1.58) | ![Footprint](image4.png) | ![Footprint](image5.png) | ![Footprint](image6.png) |
| **Hemicordulia Tau** (Dragonfly)  
  (F = 60um, Delta Rho = 1.4) | ![Footprint](image7.png) | ![Footprint](image8.png) | ![Footprint](image9.png) |
| **Heteronympha Merope**  
  (F = 5um, Delta Rho = 2) | ![Footprint](image10.png) | ![Footprint](image11.png) | ![Footprint](image12.png) |
4.3 Simulation of USAF Bar Pattern Image at different distances for different insects

For simulating Bar Pattern Image, same procedure is followed as for obtaining the footprints for different insects. Here, we input USAF bar pattern image before calculating the intensity and the beam divergences. We consider 200 * 259 pixel dimension USAF bar pattern image for the simulation as shown below:

![USAF Bar pattern Image](image)

**Figure 4.2: USAF Bar pattern Image.** [81]
This USAF Bar pattern image was used to obtain the images perceived by different insects at different distances away from the image plane. The results are tabulated as below:

Table 4.3: USAF Bar Pattern Images of different insects at different distances

<table>
<thead>
<tr>
<th>G (gain) = 2500</th>
<th>1m</th>
<th>5m</th>
<th>10m</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Anoplognathus Pallidicollis (Beetle)</strong> (F = 352um, Delta Rho = 3)</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
</tr>
<tr>
<td><strong>Phalaenoides Tristifica</strong> (F = 63.29um, Delta Rho = 1.58)</td>
<td><img src="image4" alt="Image" /></td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
</tr>
<tr>
<td><strong>Hemicordulia Tau (Dragonfly)</strong> (F = 60um, Delta Rho = 1.4)</td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
<td><img src="image9" alt="Image" /></td>
</tr>
</tbody>
</table>
4.4 Effects of Parameters on the Footprint and Bar Pattern Simulations of different insects

Parameters play vital role and have significant effect on the simulations and characteristics of different insects. It was observed that following equation holds most importance for observing the effects of parameters on different insects.

\[
\Delta \rho \approx \sqrt{\frac{\lambda^2}{D} + \frac{d^2}{f}}
\]  

(4.11)

Where, \( \Delta \rho \) is acceptance angle,

\( \lambda \) is wavelength,

\( d \) is diameter of rhabdom,
D is diameter of compound eye facet.

The parameters, “D”, “d” and “f” directly effects delta rho and it affects the blurring of the image. By changing the values of “f”, keeping values of “D”, “d” and “λ” fixed, running the simulation for footprint and Bar pattern image was it was observed that there is significant change in delta rho values which effects the blurriness of the image.

With vales of D = 25 μm, d =2 μm and λ = 785 nm, following effects in the simulations were observed for Bar Pattern Image.

At f = 10nm,

![Figure 4.3: Bar Pattern Image at focal length 10 nm, d = 2μm, D = 25nm.](image)

Figure 4.3: Bar Pattern Image at focal length 10 nm, d = 2μm, D = 25nm.
At \( f = 100\text{nm} \),

Figure 4.4: Bar Pattern Image at focal length 100 nm, \( d = 2\text{um} \), \( D = 25\text{nm} \).

At \( f = 1\text{um} \),

Figure 4.5: Bar Pattern Image at focal length 1 um, \( d = 2\text{um} \), \( D = 25\text{nm} \).
At $f = 10\,\mu m$,

![Figure 4.6: Bar Pattern Image at focal length 10 $\mu m$, $d = 2\,\mu m$, $D = 25\,\text{nm}$.](image1)

At $f = 100\,\mu m$,

![Figure 4.7: Bar Pattern Image at focal length 100 $\mu m$, $d = 2\,\mu m$, $D = 25\,\text{nm}$.](image2)
We can observe clearly from the above results that, the relationship between $f$, $D$, $d$ and delta rho has significant impact on the blurriness of the image. If “$f$” or “$D$” increases then delta rho decreases and the blurring of image decreases and vice versa. If “$d$” increases then delta rho increases and the blurring of image increases and vice versa.

Similarly, the simulation was run for footprint and bar pattern image for different insects at keeping distance constant and for different focal length values for the insects and the effects of parameters were observed.

Table 4.4: Footprints at different focal length “$f$” values and at fixed distances.

| Delta Rho = 0.1, Distance = 1m, G (gain) = 2500 |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| $F = 352\mu$m    | 63.29um         | 60um            | 5um             | 3.3um           |
| ![Footprint Image](image1.png) | ![Footprint Image](image2.png) | ![Footprint Image](image3.png) | ![Footprint Image](image4.png) | ![Footprint Image](image5.png) |

| Delta Rho = 1, Distance = 1m, G (gain) = 2500 |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| $F = 352\mu$m    | 63.29um         | 60um            | 5um             | 3.3um           |
| ![Footprint Image](image1.png) | ![Footprint Image](image2.png) | ![Footprint Image](image3.png) | ![Footprint Image](image4.png) | ![Footprint Image](image5.png) |
We can clearly observe from the above table that as Δρ value for insects increases it causes blurring in the image. So, less deltarow value has clearer image when compared to higher delta row value.

Similarly, running the simulation for Bar pattern image for different insects by varying focal length values and at fixed distance values, effects of parameters on results can be observed as shown in below table.

Table 4.5: Bar pattern at different focal length “f” values and at fixed distances.

<table>
<thead>
<tr>
<th>Delta Rho = 0.1, Distance = 1m, G (gain) = 2500</th>
<th>F = 352um</th>
<th>63.29um</th>
<th>60um</th>
<th>5um</th>
<th>3.3um</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delta Rho = 1, Distance = 1m, G (gain) = 2500</td>
<td>F = 352um</td>
<td>63.29um</td>
<td>60um</td>
<td>5um</td>
<td>3.3um</td>
</tr>
<tr>
<td><img src="image4" alt="Image" /></td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We can clearly observe from the table that as “f” value decreases the image size decreases and as the Δρ increases, it increases the blurring in the image.
4.5 Simulation and plot of Gaussian filter blur masks for different insects

The optical structure of insects introduce different degrees of unsharpness and in order to evaluate their impact on the detection of targets we use Gaussian smoothening filters of size \((2M + 1) \times (2M + 1)\) by using, \(^{[1]}\)

\[
g(M) = e^{-\frac{M^2}{2\sigma^2}} \tag{4.12}
\]

Now, consider a small value “\(\varepsilon\)” which represents the final value of the filter after it converges smoothly to zero.

\[
\varepsilon = e^{-\frac{M^2}{2\sigma^2}} \tag{4.13}
\]

Finally, the value of “\(\sigma\)” can be optimized as,

\[
\sigma = \frac{M}{\sqrt{-2\ln\varepsilon}} \tag{4.14}
\]

Where, “\(M\)” is the order of the Gaussian filter.

“\(\sigma\)” is related to the half-width values of \(\Delta\rho\) and their relationship is given by,

\[
\Delta\rho = 2\sqrt{2\ln2}\sigma \tag{4.15}
\]

and

\[
\sigma = \frac{\Delta\rho}{2\sqrt{2\ln2}} \tag{4.16}
\]

By solving this equation and assuming value of \(\varepsilon = 0.01\), different values of “\(M\)” were calculated and corresponding Gaussian blur filters for different insects were perceived. \(^{[1]}\)
Gaussian Blur filters for different filters obtained are shown below:

Hemicordulia Tau:

Figure 4.8: Gaussian Optical Blur Filter for Hemicordulia Tau (Dragonfly) with $\Delta \rho = 1.4^\circ$.

Melanitis Leda:

Figure 4.9: Gaussian Optical Blur Filter for Melanitis Leda with $\Delta \rho = 1.5^\circ$. 
Phalaenoides Tristifica:

Figure 4.10: Gaussian Optical Blur Filter for Phalaenoides Tristifica with $\Delta \rho = 1.58^\circ$.

Heteronympha Merope:

Figure 4.11: Gaussian Optical Blur Filter for Heteronympha Merope with $\Delta \rho = 2^\circ$. 
Anoplognathus Pallidicollis:

Figure 4.12: Gaussian Optical Blur Filter for Anoplognathus Pallidicollis (Beetle) with $\Delta \rho = 3^\circ$.

Footprint images for different insects were perceived after applying the Gaussian blur filters and matching the optical characteristics of different insects.

The footprint images obtained are as shown below:
Hemicordulia Tau:

Original Footprint

Grayscale image of footprint

Figure 4.13: Footprint and Grayscale Image for Hemicordulia Tau with $\Delta \rho = 1.4^\circ$.

Footprint with filter

Grayscale image for footprint with filter

Figure 4.14: Footprint and Grayscale Image with filter for Hemicordulia Tau with $\Delta \rho = 1.4^\circ$. 
Melanitis Leda:

Figure 4.15: Footprint and Grayscale Image for Melanitis Leda with $\Delta \rho = 1.5^\circ$.

Figure 4.16: Footprint and Grayscale Image with filter for Melanitis Leda with $\Delta \rho = 1.5^\circ$. 
Phalaenoides Tristifica:

Figure 4.17: Footprint and Grayscale Image for Phalaenoides Tristifica with $\Delta \rho = 1.58^\circ$.

Figure 4.18: Footprint and Grayscale Image with filter for Phalaenoides Tristifica with $\Delta \rho = 1.58^\circ$. 
Heteronympha Merope:

Figure 4.19: Footprint and Grayscale Image for Heteronympha Merope with $\Delta \rho = 2^\circ$.

Figure 4.20: Footprint and Grayscale Image with filter for Heteronympha Merope with $\Delta \rho = 2^\circ$. 
Anoplognathus Pallidicollis:

Original Footprint

Grayscale image of footprint

Figure 4.21: Footprint and Grayscale Image for Anoplognathus Pallidicollis with $\Delta \rho = 3^\circ$.

Footprint with filter

Grayscale image for footprint with filter

Figure 4.22: Footprint and Grayscale Image with filter for Anoplognathus Pallidicollis with $\Delta \rho = 3^\circ$. 
4.6 Simulation of Spatial frequency in correspondence to Interommatidial angles of different insects

Acuity which is generally defines as spatial frequency $v_s$ express the ability of the eye to resolve two objects which are close to each other. Spatial frequency is given by, $^{[1]}$

$$v_s = \frac{1}{2\Delta\phi} \quad (4.17)$$

Where, $\Delta\phi$ is interommatidial angle in degree

Spatial frequency for five different insects was calculated using above formula and a plot between the spatial frequency and interommatidial of different insects was attained using Matlab as shown below.

![Spatial Frequency](image.png)

Figure 4.23: Plot between the Spatial frequency $v_s$ and interommatidial angle $\Delta\phi$ in degree.
This plot indicates the depreciation of spatial resolution with increase in angle between the two adjacent receptor elements when measured center to center.

4.7 Simulation and Plot of Modulation Transfer Function (MTF)

MTF is the most widely used scientific method to represent the lens performance. It explains how the lens reproduces the detail from the object to the image produced by the lens. MTF for different insects can be calculated by approximating the total acceptance function as the quasi gaussian with half-width $\Delta\rho$, neglecting the spatial and blur functions and taking the Fourier transform. \[1\]

MTF for different insects is calculated by using formula,

$$M(\nu) = e^{-3.56(\nu\Delta\rho^2)}$$  \hspace{1cm} (4.18)

Where, “$\nu$” is spatial frequency.

Spatial frequency for different insects is calculated by using, $\nu = 1/2\Delta\phi$. Create an excel file with array of values for spatial frequency for each insect and normalize these values of spatial frequency after multiplying with $\Delta\rho$. Then plot a graph between the MTF values and the normalized spatial frequency values for different insects using Matlab.

The plot between MTF and normalized spatial frequency is shown below.
This plot indicates that as the acceptance angle of insects increases, the high frequency components decreases and ultimately causing blurring in the image.

4.8 Simulation of MTF using Bar Pattern Image for different insects

MTF can be traditionally calculated by using Bar pattern chart. The chart specifies spatial frequency for each line in terms of line parts per milli meter (lp/mm). MTF can then be calculated by using formula,
Here, the number of gray scale levels = $2^n - 1 = 255$.

A graph is plotted between MTF values for different insects at different distances with respect to the normalized spatial frequencies calculated using Bar pattern chart using Matlab as shown below. Here, study for locust was also included.

Figure 4.25: Plot between MTF and Normalized Spatial frequency (in lp/mm) using Bar pattern image for different insects at different distances.
We can observe that there is significant difference in both MTF plots for same insects when calculated using two methods as one uses interommatidial angle in degree and other uses frequency in terms of lp/mm.

4.9 Simulation and plot between Log Contrast and Normalized SNR

The number of photons available to the receptor under various geometrical and optical parameters as, \[1\]

\[ N = \frac{0.61I^2d^2}{f^2} = 0.61I^2\Delta\rho^2 \]  \hspace{1cm} (4.20)

Where, “D” is facet diameter and it is given by,

\[ D = \sqrt{\frac{AR}{2}} \]  \hspace{1cm} (4.21)

And “R” is radius of curvature and it is given by,

\[ R = \frac{\lambda}{2\Delta\phi^2} = 2\lambda\nu_s^2 \]  \hspace{1cm} (4.22)

To calculate Contrast “C”, the average number of photons per receptor must be,

\[ \bar{N} > \frac{1}{C^2} \]  \hspace{1cm} (4.23)

Here, contrast and SNR values for different insects were calculated by considering two different integration times for three different variations in a day, i.e. Sunlight, Moonlight and Starlight with integration time 1s and 20ms.

SNR is calculated for each insect depending on each pair of \(\Delta\phi\) and \(\Delta\rho\) by using formula for “D”, “R” and formula for SNR,
\[ SNR = \sqrt{0.61 \times I \times D^2 \times \Delta \rho^2} \]  

(4.24)

SNR and Contrast are calculated at different day times: sunlight with \( I = 10^{20} \), moonlight with \( I = 10^{14} \) and starlight with \( I = 10^{10} \) for integration time 1s and for 20ms. Then the values of contrast and SNR are normalized. SNR can be normalized by using formula,

\[ SNR_{\text{normalized}} = \frac{\langle \sqrt{N} \rangle_i}{\langle \sqrt{N} \rangle_{\text{max}}} \]  

(4.25)

With \( i = 1, 2, 3, 4, 5 \) for five different insects.

A graph between the Log Contrast and Normalized SNR was plotted using Matlab as shown below.
Figure 4.26: Plot between Log Contrast “C” and Normalized SNR at three different lights and at two different integration times.

This plot indicates with high integration times and increase in SNR increases the detection of low contrast objects.
4.10 Simulation and plot of Contrast and SNR by using Bar pattern image and different values of “D”, “d” and “f”

To calculate SNR and Contrast for bar pattern image, same procedure is followed as above for the above plot. Here, we vary the parameters “D” and “f” by keeping “d” fixed, to observe the effects in actual plot of Contrast and SNR.

Considering “D” as 5 um, 25 um, 50 um, 70 um, 100 um and 500 nm, “d” as 2 um (fixed) and “f” as 60 um, 70 um, 80 um, 90 um and 100 um, the plot between Log Contrast and normalized SNR is as shown below.

Figure 4.27: Plot between Log Contrast and Normalized SNR for different values of “D”, “d” and “f”.

![Log Contrast vs Normalized SNR](image-url)
We can observe that there is significant difference in plot compared to original plot which signifies the effect each parameter have on the simulation of characteristics for different insects.

4.11 Simulation of different Velocities at different distances for different insects

Although it has been examined in the literature review by numerous researchers, scientists and authors, the optical and visual parameters for different insects, however there is no systematic study on the imaging performance parameters of insect vision systems done yet. Our aim is to achieve the motion characteristics for different insects. Motion has its effects on the resolution and contrast of the image perceived by the insects. [14] In case of highly maneuverable insects, insects rotate upto speeds of several thousands of degree per second and the output image perceived by them is blurred.

Bar pattern image was used to estimate the motion characteristics of different insects at different speeds and at different distances. The angular velocities for different insects were calculated using,

\[
\text{Ang. Vel} = \frac{v \times \sin (\text{del phi})}{d} \quad (4.26)
\]

Where, “v” is velocity in m/s, “d” is distance in meters.

For observing motion characteristics for different insects, new value for ∆ρ is calculated by using,

\[
\Delta \rho_t = \sqrt{\Delta \rho^2 + (v \Delta t)^2} \quad (4.27)
\]

Where, “v” is angular velocity in degree/sec.
The values for new $\Delta \rho_i$ are then inputted in Matlab code for Bar pattern Image at different distances for different insects and the output images are recorded for distances, 20m, 40m, 60m, 80m, 100m and velocities 20m/s, 40m/s, 60m/s, 80m/s, 100m/s.

The output images perceived for Hemicordulia Tau at different velocities and different distances is as shown below.

Hemicordulia Tau, velocity 20m/s, 100m

Figure 4.28: Bar Pattern Image for Hemicordulia Tau at velocity 20m/s and at distance 100m.
Hemicordulia Tau, velocity 40m/s, distance 100m,

Figure 4.29: Bar Pattern Image for Hemicordulia Tau at velocity 40m/s and at distance 100m.
Hemicordulia Tau, velocity 60m/s, distance 20m,

Figure 4.30: Bar Pattern Image for Hemicordulia Tau at velocity 60m/s and at distance 100m.
Hemicordulia Tau, velocity 80m/s, distance 20m,

Figure 4.31: Bar Pattern Image for Hemicordulia Tau at velocity 80m/s and at distance 100m.
Hemicordulia Tau, velocity 100m/s, distance 20m,

Figure 4.32: Bar Pattern Image for Hemicordulia Tau at velocity 100m/s and at distance 100m.

From the above attained output images of Hemicordulia Tau we can clearly observe that as the velocities increases, the blurring in the image increases. Similarly, output images for other insects at different velocities and at different distances were obtained.

A graph between new $\Delta \rho_t$ and distances at different velocities for different insects was plotted in Microsoft Excel. The plots are as shown below.
Figure 4.33: Plot between $\Delta \rho_t$ and distance (m) at different velocities for Hemicordulia Tau.

Figure 4.34: Plot between $\Delta \rho_t$ and distance (m) at different velocities for Melanitis Leda.
Figure 4.35: Plot between $\Delta \rho_t$ and distance (m) at different velocities for Phalaenoides Tristifica.

Figure 4.36: Plot between $\Delta \rho_t$ and distance (m) at different velocities for Heteronympha Merope.
Figure 4.37: Plot between $\Delta \rho_t$ and distance (m) at different velocities for *Anoplognathus Pallidicollis*.

We can clearly observe that as velocities increases, delta row value increases which increases blurring. This proves our findings when doing simulation on insects without taking motion into account. When insect is moving or in motion, there will be more blurring, which is proved by the observed plots and results.

4.12 Simulation of different velocities at different distances for Mantis Shrimp

The motion characteristics for mantis shrimp were attained by following the same procedure as used for different insects as shown above. Mantis shrimp with $\Delta \phi = 3.7^\circ$ and $\Delta \rho = 2.4^\circ$ \cite{76-78} and using the formula for $\Delta \rho_t$, new values of $\Delta \rho_t$ were calculated and fed to the same Matlab code for obtaining the output images. Some of the output images are as shown below.
At velocity 20m/s, distance 100m,

Figure 4.38: Bar Pattern Image Mantis Shrimp at velocity 20m/s and at distance 100m.
At velocity 40m/s, distance 100m,

Figure 4.39: Bar Pattern Image Mantis Shrimp at velocity 40m/s and at distance 100m.
At velocity 60m/s, distance 100m,

Figure 4.40: Bar Pattern Image Mantis Shrimp at velocity 60m/s and at distance 100m.
At velocity 80m/s, distance 100m,

Figure 4.41: Bar Pattern Image Mantis Shrimp at velocity 80m/s and at distance 100m.
At velocity 100m/s, distance 100m,

Figure 4.42: Bar Pattern Image Mantis Shrimp at velocity 80m/s and at distance 100m.

A graph was plotted between the $\Delta \rho_t$ and distance (m) at different velocities for Mantis Shrimp using Microsoft Excel. The plot is as shown below.
Figure 4.43: Plot between $\Delta \rho_t$ and distance (m) at different velocities for Mantis Shrimp.

We can observe from the output images and the plot clearly that, as the velocities increases, delta row value increases which increases blurring.

4.13 Discussion

Following observations were made from the attained results:

1. It was observed that, as the focal length of insects increases, the bar pattern image increases. As the $\Delta \rho$ value of insects increases it causes more blurring in the image.

2. It was observed that by varying different values of “f” and with fixed values of “D”, “d” and wavelength, changes the value of $\Delta \rho$, which holds the role in effecting the blurriness of an image.

3. It was observed that, as the acceptance angle of insects increases, the high frequency components decreases and ultimately causing blurring in the image.
4. It was observed that, high integration times increases the SNR, leading to enhanced detection of low contrast objects, at the expenses of increased motion blur.

5. It was observed that, as the velocities increases, delta row value increases which increases blurring.
5.1 Conclusion

Although Bioinspired vision has been examined in the literature by numerous researchers, however, there is no systematic study on the imaging performance parameters of insect vision systems done yet.

The aim of this study on insect vision is to explore the phenomenon of the image formation and the image characteristics by different insect eye architectures. The study shows the characteristics and examples of how well the compound eyes of insect can adapt to several environmental conditions by subtle changes in its eye architecture. [1]

Different insect eye architectures and specifications of a USAF bar pattern image were studied. Footprints of different insects at different distances were obtained. Indeed, bar pattern images for different insect eye architecture, at different distances, were obtained by varying different physical, geometrical and optical parameters. It was observed that, as the focal length of insects increases, the bar pattern image is larger. As the \( \Delta \rho \) value of insects increases it causes more blurring in the image.
Effects of each parameter on image characteristics of insects were studied. that changes in value of $\Delta \rho$ holds the role in effecting the blurriness of an image. If “f” (focal length) or “D” (facet diameter) increases then delta rho decreases and the blurring of image decreases and vice versa. If “d” (diameter of rhabdom) increases then delta rho increases and the blurring of image increases and vice versa.

MTF and spatial frequency were calculated by using two methods i.e. by using formula and by using traditional method by using bar pattern chart, to evaluate the performance of insect architectures. It was observed that, as the acceptance angle of insects increases, the high frequency components decreases and ultimately causing blurring in the image.

Contrast and SNR were obtained to evaluate the performance of the image perceived by the insects. It was observed that, with high integration times and increase in SNR increases the detection of low contrast objects.

Motion characteristics were studied to observe the image performance characteristics in case of highly maneuverable insects. The motion characteristics were evaluated by calculating angular velocities and new acceptance angle at different velocities and at different distances for different insects. It was observed that, as the velocities increases, delta row value increases which increases blurring. This proves our findings when doing simulation on insects without taking motion into account. When insect is moving or in motion, there will be more blurring, which is proved by the observed plots and results. This study was also extended to evaluate the performance of Mantis Shrimp.
5.2 Future scope

The results of this study indicates how Bioinspired imaging has huge impacts on other areas like defense, security and healthcare and applicable in various medical, navigation, military and ranging applications. [1]

This study examines the apposition compound eye architecture. As part of a future study, it should be extended to superposition and neural superposition eye architectures and their image performance characteristics should be evaluated in the same manner. Furthermore, this study can be extended to study the characteristics of other insects apart from currently studied and we can observe if they hold any prime application which will be useful for the mankind. Overall, Bioinspired imaging may have significant impact on areas like defense, security and healthcare. [1].


APPENDIX A

MATLAB CODES

clc;
clear all;
close all;

sigm = [1.4, 1.5, 1.58, 2, 3]; % Defining acceptance angle for different insects
epsil = 0.01;% Defining epsilon value

M = 1*ceil(sigm * sqrt(-2*log(epsil)))); % Defining formula for M
h1 = fspecial('gaussian',M(1),sigm(1)); % Defining Gaussian blur filter for insect 1
h2 = fspecial('gaussian',M(2),sigm(2));% Defining Gaussian blur filter for insect 2
h3 = fspecial('gaussian',M(3),sigm(3));% Defining Gaussian blur filter for insect 3
h4 = fspecial('gaussian',M(4),sigm(4));% Defining Gaussian blur filter for insect 4
h5 = fspecial('gaussian',M(5),sigm(5));% Defining Gaussian blur filter for insect 5

x = -3.0:0.1:3.0; % Defining the aperture size along x-axis
y = -5.0:0.1:5.0; % Defining the aperture size along y-axis
R = 20; % Defining radius of curvature
ax = 0.00018144; % Defining the beam divergence along x-axis
ay = 0.00035014; % Defining the beam divergence along y-axis
Gx = 2; % Defining the grid size along x-axis
Gy = 2; % Defining the grid size along y-axis
R = R * 1000; % convert R to mm

[X,Y] = meshgrid(x,y);
intensity = exp(-2 * ( (X/(R * ax)).^(2 * Gx) + (Y / (R * ay)).^(2 * Gy) )); % Defining intensity using formula

intensity = intensity / max(max(intensity)); % Normalize the signal to unity
surf(X,Y,intensity)
axis off

outp1 = imfilter(intensity,h1,'replicate','same'); % Gives footprint for insect 1
outp2 = imfilter(intensity,h2,'replicate','same'); % Gives footprint for insect 2
outp3 = imfilter(intensity,h3,'replicate','same'); % Gives footprint for insect 3
outp4 = imfilter(intensity,h4,'replicate','same'); % Gives footprint for insect 4
outp5 = imfilter(intensity,h5,'replicate','same'); % Gives footprint for insect 5

figure, surf(X,Y,outp1);
figure, surf(X,Y,outp2);
figure, surf(X,Y,outp3);
figure, surf(X,Y,outp4);
figure, surf(X,Y,outp5);

Code 1: Matlab code for plotting Laser Footprint for different insects.

%Delta(\phi)=0.9, 1.25, 1.44, 1.5, 1.9
%Del row = 1.4 1.5 1.58 2 3
%F=0.44, 0.64, 1, 1.78*10^{(-12)}

clc;
clear all;
close all;
lamda = 785*10^{(-9)}; % Defining wavelength
D = 2.5*10^{(-5)}; % Defining facet diameter
D = 2*10^{(-6)}; % Defining distance
D = f = 10^{(-4)}; % Defining focal length
delrow = sqrt(((lambda^2)/D)+((d^2)/f)); % Defining formula for del row
sig=2*delrow; % Defining sigma
A=imread('A.jpg'); % Reads the image A
B=rgb2gray(A); % Converts the image A from RGB to Grayscale image
e=0.01; % Defining epsilon

M=sig*sqrt(-2*log(e)); % Defining M
M=ceil(M);
e=exp(-M^2/(2*sig^2)); % Defining epsilon
sig2=-(M^2)/(2*log(e)); % Defining sigma
x=([-M:M]').^2;
x=x*ones(1,2*M+1); % Defining filter size
y=x';
mask=exp(-(x+y)/(2*sig2)); % Defining filter mask
mask=mask/sum(sum(mask));
sigsqrt=sig2;
H=mask;

A_filtered=imfilter(A,H,'conv'); % Gives the Bar pattern image with filter at given distance value
B_filtered=imfilter(B,H,'conv'); % Gives gray scale bar pattern image with filter at given distance value
figure(1)
imshow(A)
figure(2)
imshow(B)
figure(3)
imshow(A_filtered)
figure(4)
imshow(B_filtered)

Code 2: Matlab code for obtaining Bar pattern images at different distances and to validate the effect of parameters on each insect.

clc;
clear all;
close all;

sig=1.58; % Defining acceptance angle
e=0.01; % Defining epsilon
M = sig * sqrt(-2 * log(e)); % Defining formula for M
M = ceil(M);
e = exp(-M^2 / (2 * sig^2)); % Defining formula for epsilon
sig2 = -(M^2) / (2 * log(e)); % Defining formula for sigma
x = ([[-M:M]].^2); % Defining the size of the filter
x = x * ones(1, 2 * M + 1);
y = x';
Mask = exp(-(x + y) / (2 * sig2)); % Defining the filter mask
Mask = Mask / sum(sum(Mask));

H = fspecial('gaussian', [13 13]); % Defining Gaussian blur filter
C = convn(H, Mask);
surf(C)

Code 3: Matlab code for plotting Gaussian Blur filters for different insects

% Delta(phi) = 0.9, 1.25, 1.44, 1.5, 1.9
% Del row = 1.4 1.5 1.58 2 3
clc;
clear all;
close all;
sig = 2 * 1.58; % Defining acceptance function, sig = 2*del row
A = imread('footprint.jpg'); % Reads the estimated footprint image.
B = rgb2gray(A); % Converts the estimated footprint image from RGB to gray
e = 0.01; % Defining epsilon
M = sig * sqrt(-2 * log(e)); % Defining M
M = ceil(M);
e = exp(-M^2 / (2 * sig^2)); % Formula for epsilon
sig2 = -(M^2) / (2 * log(e)); % Formula for sigma
x = ([[-M:M]].^2);
x = x * ones(1, 2 * M + 1);
y = x';
mask = exp(-(x + y) / (2 * sig2)); % Defining filter mask
mask = mask / sum(sum(mask));
sigsqrt = sig2;
H = mask;
A_filtered=imfilter(A,H,'conv'); % Gives the Footprint image of an insect with filter
B_filtered=imfilter(B,H,'conv'); % Gives gray scale image of footprint with filter

figure(1)
imshow(A)
figure(2)
imshow(B)
figure(3)
imshow(A_filtered)
figure(4)
imshow(B_filtered)

Code 4: Matlab code for plotting the Footprint images with filter and Gray scale images with filter for different insects.

clc;
clear all;
close all;

delsi = [0.9 1.25 1.44 1.50 1.9]   % Defining interommatidial angle
vs = 1./(2* delsi);                % Defining Spatial Frequency
plot (delsi, vs, 'c+:')            % Gives the plot between spatial frequency vs Delphi
vs= vs / max(max(vs)); % Normalize the spatial frequency to unity

xlabel('Delta phi(Degree)')
ylabel('SpatialFrequency')

Code 5: Matlab code for plotting Normalized Spatial frequency with respect to Interommatidial angle.
clc;
clear all;
close all;

% vs = [0.5556 0.4000 0.3472 0.3333 0.2632]

vs = 0:0.111:0.5556; % Defining spatial frequency of different insects obtained

delrow = [1.4 1.5 1.58 2.0 3.0] % Defining acceptance angle for different insects

M = exp(-3.56*vs*(delrow.^2)); % Defining formula for MTF

product = vs.*delrow

% norm = 1/max(product)
% norm = [ 0.7778/0.7896 0.6000/0.7896 0.5486/0.7896 0.6666/0.7896 0.7896/0.7896]

plot(vs.*delrow, M) % Plots graph between MTF and the product
xlabel('Normalized Frequency')
ylabel('Modulation Transfer Function')

Code 6: Matlab code for calculating MTF for different insects.

clc;
clear all;
close all;

% Defining MTF and product values for different insects
x = [0 0.19446 0.38892 0.58338 0.77784]
y = [1 0.379391 0.143937 0.054608 0.020718]
m = [0 0.3 0.6 0.9 1.2]
n = [1 0.040599 0.001648 0.0000669 0.00000272]
p = [0 0.1736 0.3472 0.5208 0.6944]
q = [1 0.290535 0.08441 0.024524 0.007125]
r = [0 0.124988 0.249975 0.374963 0.49995]
s = [1 0.513024 0.263193 0.135024 0.069271]
t = [0 0.103964 0.207928 0.311892 0.415856]
u = [1 0.557230 0.310506 0.173023 0.096414]

plot(x,y,m,n,p,q,r,s,t,u) % Plots MTF vs Normalized Spatial frequency

Code 7: Matlab code for plotting MTF vs Normalized spatial frequency.

% x, y are arrays, defining the grid to measure, in mm
% R is distance away from laser source, in meters
clc;
clear all;
close all;

I = imread('3_1cm3.png'); % Reads the image '3_1cm3.png'
II = double(I);
a1=max(II(:)) % Gives maximum intensity of the image
a2=min(II(:)) % Gives minimum intensity of the image
mtf=100*(a1-a2)/255 % Gives MTF value using bar pattern chart method

Code 8: Matlab code for calculating MTF using Bar pattern chart method.

clc;
clear all;
close all;

x = [0.25 0.353 0.5 0.707 1] % Defining spatial frequency for different insects obtained

y1 = [ 0.0549 0.0431 0.0352 0.0274 0.0039] % Defining MTF values for insect 1
y2 = [ 0.0941 0.0706 0.0549 0.0353 0.0039] % Defining MTF values for insect 2
y3 = [ 0.9568 0.9333 0.7686 0.5411 0.4352] % Defining MTF values for insect 3
y4 = [ 0.9490 0.9176 0.7490 0.5373 0.4157] % Defining MTF values for insect 4
y5 = [ 0.9608 0.9490 0.8000 0.5961 0.4941] % Defining MTF values for insect 5
y6 = [ 1 1 1 0.9725 0.8392] % Defining MTF values for insect 6
plot(x,y1,x,y2,x,y3,x,y4,x,y5,x,y6) % Plots MTF with respect to spatial frequency
xlabel('Normalized Spatial Frequency (Lp/mm)')
ylabel('Modulation Transfer Function')

Code 9: Matlab code to plot MTF with respect to spatial frequencies for different insects including Locust.

clc;
close all;
clear all;

sig= 2.457; % Defining the new delta row values at different velocities for different insects
A=imread('USAFbarpattern.jpg'); % Reads USAF bar pattern image
B=rgb2gray(A); % Converts image from RGB to Grayscale image

e=0.01;                        % Defining epsilon
M=sig*sqrt(-2*log(e));         % Defining formula for M
M=ceil(M);
e=exp(-M^2/(2*sig^2));        % Defining formula for epsilon
sig2=-(M^2)/(2*log(e));        % Defining formula for sigma
x=([-M:M]').^2;                % Defining filter size
x=x*ones(1,2*M+1);
y=x';

mask=exp(-(x+y)/(2*sig2));     % Defining filter mask
mask=mask/sum(sum(mask));
sigsqrt=sig2;
H=mask;

A_filtered=imfilter(A,H,'conv'); % Gives the Bar pattern image for different insects at different velocities.
imshow(A_filtered)
Code 10: Matlab code for obtaining Bar pattern images for different insects at different velocities.
APPENDIX B

CALCULATION OF MTF BY USING BAR PATTERN CHART FOR DIFFERENT INSECTS

Apex B, Table 1 Calculation of MTF values using Bat pattern chart for different insects

<table>
<thead>
<tr>
<th>Spatial Frequency</th>
<th>Insect 1</th>
<th>Insect 2</th>
<th>Insect 3</th>
<th>Insect 4</th>
<th>Insect 5</th>
<th>Insect 6</th>
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<tbody>
<tr>
<td>grp -2, ele 1</td>
<td>0.25</td>
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<td>94.9</td>
<td>96.08</td>
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APPENDIX C

CALCULATION OF CONTRAST AND SNR FOR BAR PATTERN IMAGE AT DIFFERENT VALUES OF “D”, “d” and “f”

Apex C, Table 1 Calculation of Log Contrast and Normalized SNR for different values of “D”, “d” and “f” for Bar pattern image.

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<th>D (m)</th>
<th>d (m)</th>
<th>f (m)</th>
<th>I</th>
<th>N</th>
<th>C</th>
<th>SNR</th>
<th>SNR_N</th>
<th>Log C</th>
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<td>2*10^{-6}</td>
<td>5*10^{-3}</td>
<td>1*10^{-11}</td>
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<td>0.000762</td>
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<td>0.000177</td>
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APPENDIX D

CALCULATION OF ACCEPTANCE ANGLE FUNCTION AT DIFFERENT VELOCITIES FOR DIFFERENT INSECTS

Apex D, Table 1 Calculation of new Acceptance angle function at different velocities for different insects.

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<th>v(m/s)</th>
<th>d(m)</th>
<th>v(degree/s)</th>
<th>delta t(s)</th>
<th>delta row t</th>
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<th>v(degree/s)</th>
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**Phalaenoides Tristifica**

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**Heteronympha Merope**

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APPENDIX E

CALCULATION OF ACCEPTANCE ANGLE FUNCTION AT DIFFERENT VELOCITIES FOR MANTIS SHRIMP

Apex E, Table 1 Calculation of new Acceptance angle function at different velocities for Mantis Shrimp.

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