A Survey of Insect Eye Inspired Visual Sensors

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Abstract

Recent progress on computer technologies is focused on mobility and size reduction rather than functionality. That provided us researchers and commercial manufacturers with low-cost, compact and high-capability electronic hardware. Visual sensors are no exception. Hereby in the light of recent technological advance it is possible to organize sensors with a two dimension array hierarchy and build very-capable systems which are not enormous. These systems can be used and is being used in variety of needs like surveillance, virtual environment applications and robotic vision. Nature is a step ahead of us in this subject.

1. Introduction

Nature always has been a source of inspiration for humans. Living creatures developed to find the optimal solutions to problems and adapt the environment. These solutions are within the nature now, hidden inside creatures. This kind of vast knowledge, which is the result of hundreds millions of years of real-life testing is a charming source for researchers. Since the last decades of 19th century insect eyes are studied in the field of both biology and optics. By the half of 20th century, computers are emerged, and so the field "Computer Vision". First applications of this field are inspired by human eye, so inadequacies that present at human sight, has been inherited to computer vision. It's not possible "modify" human eye to "enhance" vision, but principle of engineering is another story. Man-made visioning systems do not have to inherit that inadequacies. A number of works are made to enhance existing sensors by using insect inspired methods. In this work we aim to give instructions about basics of insect vision and present some of the works that used insect vision principles to enhance computer vision.

This paper is structured as follows. In section 2, basics principles and types of insect eyes will be presented. In section 3 a comparison between insect vision and vertebrate vision will be presented. In section 4 some work that uses insect eye configuration and principles will be presented. Our paper will conclude with section 5.

2. Insect Eyes

Application of insect eye principles at the field of computer vision is focused on this paper. For that purpose, basics of insect eyes is explained briefly.

Arthropods have compound eyes which dates back to 500 Million years ago, Cambrian period [1]. Since the first emergence of multiaperture eyes, every specie evolved their visual systems to adapt their own environment and conditions, resulting various solutions that can be applied to modern problems of computer vision [2, 3].

As configuration, a compound eye is composed of hundreds, thousands of visual channels that are called ommaditia. These channels can be completely isolated or share same neural receptors depending on the compound eye type [1, 4]. There are two main types of insect eyes will be presented.

2.1. Apposition Eye

At apposition eyes, every lens which resides upon hemisphere of eye has a singular rhabdum to refract light upon. This visual structure which is composed of rhabdum and lens is called ommiditia. In apposition eyes visual channels are isolated from each other by opaque walls. These opaque walls are formed from pigment to avoid receiving light from adjacent ommaditias which would cause ghosting effect [4].

Apposition eyes in nature have various ommaditia numbers that may range from several hundred (water fly) to tens of thousands (dragonflies) increasing with the speed of movement [4]. From an engineering perspective apposition eyes are parallel systems. Visual information received from each isolated channel are processed in parallel [5] which will result as higher temporal resolution. That will let the insect see and react faster.

2.2. Superposition Eye

Visual channels in superposition eyes are not isolated. Multiple lenses focuses their light to shared photoreceptor layer. On the photoreceptor layer a single image is formed unlike apposition eyes at which each visual create a different image [4, 5].

Comparing to the apposition eyes, super position eyes are more capable in dim light. That resulted as highly occurrence at nocturnal insects like moths and lobsters. In adding to that because of combination of images, superposition eyes have higher spatial resolution than apposition eyes [4].

3. Human Vision vs Insect Vision

Both insect vision and human vision has their own advantages. Human eye is a single-aperture sensor with advantage of higher sensitivity [4] and higher spatial resolution [5]. But in return human eyes have a smaller field-of-view that will require head or eye movement to see full environment. In addition to that because of acquired high resolution and detailed single vision, process of visual information requires a high brainpower [4].

4. Objectives

Insect eye inspired sensors can be used to reach multiple objectives.

- *Spatial Resolution:* Resolution enhancement requires sensors to record a small field of total FOV (Field-of-view) at high resolution, to ensure this lenses should be used. By combining obtained visuals from multiple sensors to form a single image increases resolution. For this objective, every field of compound sensors, FOV should be in, at least one sensors FOV. Also for an efficient compound sensor, sensors should be arranged accurately to minimize overlapped FOV. After visuals are obtained, image-fusion techniques should be used to obtain a seamless image [6, 7]. Spatial resolution can also be enhanced by PTZ cameras, but a PTZ camera needs a long time to obtain very high resolution image. Because of that PTZ cameras requires a static environment to capture an image. Also it's not possible to record a very high resolution video with PTZ cameras [8].
- *FOV:* Field-of-view enhancement works very similar to resolution increasing techniques. Placing sensors as their FOV's combination will cover a wide-FOV, and fusing visuals obtained from sensors with image-fusion techniques will result as a wide-FOV visual [9]. FOV can be widened by use of rotating cameras, mirrors and lenses[10].
- *Temporal Resolution:* Placing sensors to share same FOV and coordinating sensors capturing frame intervals a video with very high temporal resolution can be obtained [11].

5. Applications

Using multiple classical sensors to form a single insect eye inspired compound sensor with application-specific configurations can enhance multiple features. Resolution limit of single aperture sensors caused by optical aberrations and data transfer rates can be surpassed by insect eye inspired sensors. Multiple works [6-8, 12] has broken gigapixel barrier. In addition to spatial resolution, works aimed to enhance temporal resolution [11] and field-of-view [9, 13, 14] are present. These works are focused on multiple areas like autonomous navigation [15], surveillance [7], virtual reality [16].

Willburn et al. [11] used a camera array to capture a very high speed video. Their array was composed of 52 cameras which can capture 30 FPS video. Each camera in this array was placed to share same field-of-view. By coordinating cameras' shooting frames intervals precisely, they managed to capture a video with 1560 FPS.

Willburn et al. [17] also developed a high resolution visual sensor composed of multiple cameras. Cameras packed tightly to form a 12 * 8 array configuration. After stitching of acquired images and color correction to overcome visual defects caused by lighting, an image of high spatial resolution (respectively 7.6 MP) has been obtained. Although their implementation is not defined as "insect eye inspired", their sensor array shares the same operating logic with insect eyes. A configuration of high temporal resolution has also been implemented. Cameras placed to share same field of view with 10 x 10 array configuration.

Nomura, Zhang and Nayar [10] developed an imaging device takes advantage of using multiple imaging devices to capture scene from multiple viewpoints, and use image fusion techniques to obtain a single image. Using multiple sensors resulted as higher spatial resolution. As sensor array placed on a flexible layer, it's possible to bend the layer. By taking advantage of the bending it becomes possible to change viewpoints of cameras as desired, which results as ability to change FOV in real time. Their presented implementation showed improvements at both FOV and spatial resolution.

ARGUS-IS is a new generation very high resolution surveillance system developed by BAE Systems. ARGUS-IS is composed of three sub-systems but only the imaging-sub-system will be described. Imaging system of ARGUS-IS is composed of 4 sub-imaging systems. Each of these sub-imaging-systems are composed of 92 sensors which have 5MP resolution each. Each of sub-imaging-system creates 460 MP frames. Combination of frames received from 4 sub-imaging-systems forms the final frame which has 1.8 GP resolution [7].

Davis et al. [18] developed a visual sensor with apposition eye configuration. They mounted sensor on a robot and observed autonomous navigation capabilities provided with this compound sensor. They arranged seven sensors with a single fan pattern to form compound sensor. Their performed various test scenarios to evaluate robots ability to avoid obstacles and moving towards a target. Their complex scenario was avoiding dynamic obstacles when tracking a dynamic target. Robots managed to perform complex navigation tasks with a non-complex bio-inspired visioning system that inspired from diurnal insects and arthropods.

Brückner et al. [19] focused on enhancing sensor by shrinking them. They replaced single-aperture optics in sensor with multi-aperture optics. An array of microlenses used instead of one. By using a microlens array, total FOV is split and recorded independently on a single CMOS sensor. After recording of multiple visual channels as one visual, acquired visual is processed to perform a single image. Their implementation "eCley" used a 17 x 13 microlens array and a 3 MP CMOS sensor. After stitching, an image of 0.4 MP has been acquired. In conclusion it is indicated that eCley managed to achieve approximately VGA resolution when track length of sensor reduced to two times shorter than a normal VGA sensor.

Marefat et al. [20] developed an insect eye inspired sensor. Their sensor is composed of a central board, multiple sensor boards and phototransistors. Central board is a circular one and contains 32 connectors which are compatible with sensor boards. Sensor boards are quadrant shaped boards. Sensor boards also has connectors compatible with the center board and 8 photoreceptors for photo sensing. By connecting sensor boards with the central boards such as their circular centers match, hemispherical shape of sensor is formed. Marefat et al. used 16 sensor boards (resulting 128 photoreceptors) for their test. Wide angle but low resolution images has been produced at the rate of 90 FPS.

Afshari et al. [13] presented a visual system named Panoptic camera. Panoptic camera is an insect eye inspired sensor concept capable of acquiring omnidirectional video. Their design consists of four layers. First layer is a spherical layer that sensor has placed upon. Second layer is composed of FPGA boards. It is stated that a FPGA board can handle processing of 20 sensors. Third layer is the master FPGA for access and management. And the forth layer is display layer which is not specified and not relevant. Their sample shot taken by a thirteen camera configuration presented in the article. Further testing of purposed Panoptic Camera is presented in their next work [21]. Two systems has constructed to test their designs. Fifteen camera and thirty camera prototypes. Their test which includes 30 sensor in the first layer, showed that their design is capable of capturing 32 MP resolution and streaming at 6.25 MP per second for per FPGA board in second layer.

AWARE Program [6] is the DARPA project aimed to develop gigapixel sensors with wide field-of-view. AWARE-2 is one of the prototypes that have been developed. It is a monocentric multiscale camera composed of 98 microcameras that has 14 MP resolution each. These sensors are placed on a layer shaped like a dome as their sensing side, lies on the inner surface. That placement focuses microcameras towards to the ball lens that resides at the center of the dome. Outer side of this lens forms an image of wide field-of-view. Microcameras focused to inner side of lens, records a portion of all image. Composition of all recordings forms a complete image. AWARE-2 sensor has 120° x 50° field-of-view and nearly 1 gigapixel resolution. By using purposed design principles, it is possible to manufacture cameras that has resolution up to 50 gigapixels.

Aldalali et al. [22] developed a sensor that added flexibility to existing multi-aperture sensors. Sensor used is composed of 1mm x 1mm cameras with 250 x 250 pixels resolution. Each camera also has a specially fabricated NOA lenses placed upon. These sensors are bridged to each other by Ecoflex bridges. Bridges are made by 3D printers. Material of bridges is Ecoflex, a silicone rubber that can elongate to 90 times of its length. In the conclusion it is indicated that camera is able to adapt configuration changes in real-time. They able to acquire with up to 130° FOV and 643 x 366 pixels resolution.

Akin et al. [14] developed an omnidirectional video recording system that uses multiple visual sensor to enhance its field of view and resolution. System is composed of three layers. Only the first layer which is an insect eye inspired compound sensor will be described. This sensor is composed of 44 sensors that has 5 MP resolution each. Fusion of frames acquired from multiple sensors results as final video. System is capable of recording video with 80 MP at 8 FPS and with 22 MP at 30 FPS.

Cogal et al. [9] developed an ultra-high-resolution aerial surveillance camera called GigaEye-1. GigaEye-1 is an improved version of their previous work OMNI-R [14]. Architecture of systems are very similar. By this work they improved their FPS (from 8.5 to 9.5) and resolution (from 80 MP to 82.3 MP) at maximum boundaries of system. At the end of their work it's indicated that their next work GigaEye-2 is under development. GigaEye-2 will have a composite sensor composed of 48 cameras with 20 MP resolution each. Their aim is to develop a 1 GP sensor and break the gigapixel barrier.

Table 1. Present Systems

Work	Media Type	FOV	Resolution	FPS
[11]	video	-	0.3 MP	1560
[17]	image	-	7.6 MP	-
[7]	video	-	1.8 GP	12
[6]	image	120*50	0.98 GP	-
[13]	video	360*180	0.25 MP	25
[14]	video	360*100	21.6 MP	30
			80 MP	9
[9]	video	360*180	21,6 MP	30
			82,3 MP	8,5
[22]	image	Max 130	0.25 MP	-

Use of multiple sensors is also used in deep space telescopes. As indicated in [23], dark energy camera DECam, uses 62 CCD cameras to capture the space, to reveal secrets of dark energy and universe. Each CCD of the composite sensor has 2K x 4K resolution. Total resolution of sensor generates an image with 570 MP resolution.

Table 1 shows a quick comparison of present systems, by their media type, field of view, resolution and frame rate.

6. Alternative Camera Configurations

A PTZ (pan-tilt-zoom) sensor is composed of a visual sensor and a platform that allows sensor to perform pan, tilt and zoom motions. Motions can be controlled by scripts or by a human operator. Movement can be configured as needed to achieve desired tasks. Although researchers used PTZ sensors to acquire very-high resolution images [8, 24], PTZ sensors mostly used for surveillance purposes. But despite the fact that PTZ sensors have its own strong advantages, a PTZ sensor is no alternative for an insect eye inspired sensor. The requirement of time for performing the motion, PTZ sensors are "slow" comparing to insect inspired sensors. Kopf et al. [8], by using a PTZ sensor, capturing frames and constructing an image of 1.2 Gigapixels took 210 minutes. Leininger et al. [7], showed even a higher resolution (1.8 GP) video could be recorded with 12 FPS by a insect inspired sensor. Only advantage PTZ sensors have over insect eye inspired sensors is being low-cost.

A rotating sensor is composed of a visual sensor and a platform that rotates the visual sensor. As sensor rotates around a center, it keeps capturing. Combination of multiple frames forms the final image which has a wide 360 degree FOV. Rotating sensor configuration is mostly used in creating panoramic images. Generating videos with rotating sensors is not feasible. Like PTZ sensors, rotating sensors have only single advantage over insect eye inspired sensors, which is being low-cost.

Mirror assisted systems take advantage of using reflective surfaces to enhance sensors. Basically light-field manipulated by specialized mirror gets recorded by a sensor, so spatial and temporal resolution of system depends on the sensor and cannot be enhanced by mirror assistance. Mostly used for widening FOV of sensors, mirror assisted sensors utilizes different shaped mirrors like spherical, paraboloidial and hyperboloidial. In addition to varying shapes, a number of works that takes advantage of changing arrangement of mirrors is present, like mirrors with PTZ motions and mirror pyramids. Despite the fact that using mirrors is a low-cost and feasible solution to widen FOV, it also have several comebacks. Specialized mirrors cause more distortion and data loss at the media comparing to the insect inspired sensors, mirror assisted systems requires additional image processing to acquire perspective vision. Also mirrors used in systems are mostly custom produced surfaces. Because of that; modifying these systems requires new specially designed mirrors. Comparing to a highly parallel insect eye inspired sensor which can be produced by using state-of-art, low-cost electronics; mirror assisted systems are lacks flexibility and configurability.

Lens assisted systems are very similar to mirror assisted ones. Light collected from field of view, gets refracted as passing through the lens and reaches to sensor. Like mirror assisted systems lenses can be used to widen FOV. Temporal and spatial resolution of the system is depends on the visual sensors capabilities. Data loss, distortion of media and lack of configurability also applies to lens assisted systems.

7. Conclusion

Insect eye configurations can be used to enhance state-of-art sensors in multiple ways. Numerous works used that configuration to enhance spatial resolution, temporal resolution, FOV and shrinking sensor sizes.

Firstly, configuration of insect eyes, principles of insect vision and its advantage over human vision are described. Later, features that can be enhanced by insect eye configuration is described, alternatives of configurations are presented as an approach from an engineer point of view. Finally, some of significant works are presented. Also alternatives of insect eye configurations are presented. Comparing the alternatives, most capable configuration is insect eye inspired sensor configuration. It can be used to widen FOV, increase temporal and spatial resolution at both video and image media types. As seen in the nature, this configuration is suitable to perform parallel operations. Regarding the mentioned characteristics; insect eye inspired systems seems to be a hot research field. Numerous work had been done in last three decades, but much more can be done.

Next step will be publish an extensive survey about insect eye configuration, sensors that uses insect eye configuration and alternatives of insect eye configuration. Also an insect inspired sensor that has gigapixel resolution and a time based parallel video database which will eliminate one of the common problem -the I/O bottleneck- will be developed.

8. References

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