Preparing a Fly Eye Sensor for Real-World Application

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Abstract

Previous research efforts have resulted in a proof-of-concept, neural superposition, compound vision sensor based on the visual system of the common house fly, *Musca domestica*. The developed sensor is capable of resolving very fine movement and performing high speed, analog, edge detection, but due to its power consumption requirements and size, it is not yet ready for highly mobile real-world applications such as obstacle detection and avoidance for Unmanned Aerial Vehicles (UAVs). We seek to lower the power requirements and reduce the size and development time of the system using Field Programmable Gate Arrays (FPGAs) in place of the device level analog hardware.

In this paper we will introduce the compound vision sensor and the methods we will use to reduce the size and power consumption of the system. Heavy focus will be given to the problems associated with digitization of the image data and possible solutions will be presented. Results of simulations of the digitization process will be included and suggestions will be made to others who may wish to approach compound vision using similar methods. The culmination of this research represents the final step in preparing compound vision sensors for widespread real-world use.

Introduction

Digital cameras based on CCD or CMOS array technology are widely used for image capturing. These cameras give satisfactory results in most applications, but when it comes to imaging objects smaller than the pixel size of the camera or resolving object movement at the inter-pixel level (movement distances smaller than the pixel spacing) then the performance of CCD or CMOS cameras exhibit less than satisfactory performance[1, 2].

Fly eye sensors are motivated from the common house fly, *Musca Domestica* which has a smaller brain but can detect the direction from which an object is coming and the speed at which it is coming even if the object is tiny and quickly moving. This ability of detecting motion of tiny objects surpasses those of higher order animals [3, 4].

Previous research into common house fly inspired compound vision sensors produced multiple prototypes, two of which are comprised of an optical front end containing seven photodetectors using either photodiodes or optical fiber[5-7]. The layout of the photodetectors is shown in Figure 1. Each photodetector of the module is placed just outside the focal length of a lens which produces the overlapping Gaussian shaped waveform seen in Figure 2. Each individual Gaussian waveform corresponds to a single photodector, so there will be seven overlapping shapes for seven photodetectors.
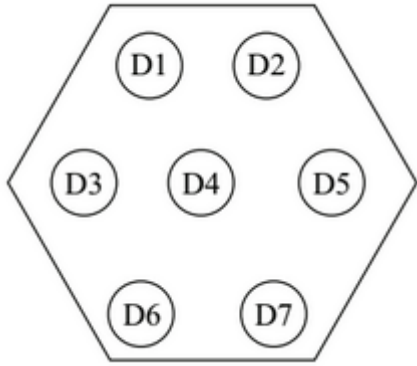
Figure: 1 The arrangement of the module of photodetector is shown above. D1-D7 are the seven photodetectors which form a module.[8]
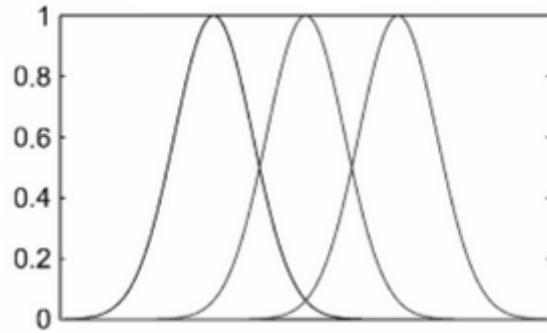
Figure 2: Normalized Overlapping Gaussian response from the photoreceptors.[8]

The Gaussian waveform shown above result from the individual response of three photodetectors which are adjacent to each while an object moves across the sensor's field of view (FOV). The overlapping Gaussian shapes allow the system to exhibit motion hyperacuity meaning the system can resolve motion at the inter-pixel level[4] With the optical front end's designed, analog hardware was developed to mimic the vision system of the common house fly. While useful as a proof-of-concept, the existing analog hardware is bigger in size and consumes more power than is acceptable in most applications[10].

To begin utilizing the benefits of fly vision, the circuitry and optical front ends must be designed to be smaller and more power efficient. One way to achieve this is to digitize the system and implement it on a Field Programmable Gate Array (FPGA). The resulting digital hardware will be much smaller and consume less power than the analog version of the sensor. This conversion will also allow for: quicker development of application specific hardware, storage of sensor data for post processing, and increase robustness to noise.

Figure 3 shows the block diagram of the analog signal conditioning system designed for the fly eye sensor. The system described by Figure 3 is called the primary system, because the blocks in this system are required for all fly vision applications. The photodetectors in the optical front end generates a current relative to the incident light for each channel. These currents are amplified and converted to a voltage in the optical electrical interface using either a transimpedance amplifier (indoor applications) or a log compression circuit (outdoor applications). The filter was designed to reduce 60 and 120 Hz flicker generated by indoor lighting. The output of the light adaptation block is made immune to changes in the background light radiation by removing the average signal response received by all channels. Thus, any change detected at the primary system output is due to changes in an imaged object. More details about these systems is available[8,10].

The current goal of the fly eye project is to reproduce the primary system, shown in Figure 3, using an FPGA. The focus of this paper is digitization of the analog system. Specifically, this paper answers the following questions. At what point in the primary signal path should the analog signals be converted to digital? How should these signals be digitized?
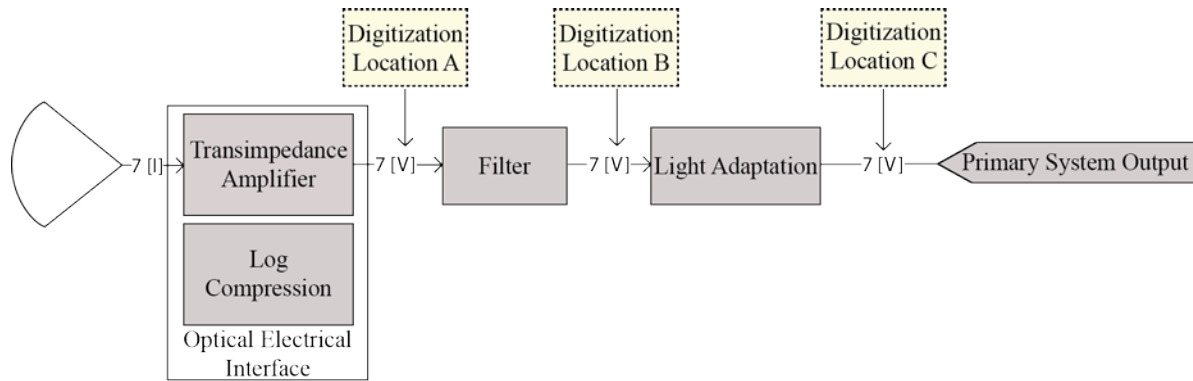
Figure 3: Previously developed analog model of Fly Eye Sensor[8,10]. Starting from left is optical front end consists of 7 photoreceptors which gives output in the form of current from 7 channels. The seven current outputs fed to a transimpedence amplifier or log compression circuit depending on the application to get voltage output for 7 channels. Filter is to deal with flickering indoor light. The last is light adaptation which removes the baseline present in the signal.

Digitization (Trade-offs)

Due to the large range of light intensities the sensor must handle, there are a number of trade-offs that must be considered when determining where in the signal path digitizing will occur. The three locations where digitization or analog to digital (A/D) conversion can occur are illustrated in Figure 3 as Locations A, B, and C. At which ever location the A/D converter is placed all downstream system blocks will be handled within the FPGA. With the stated goal of reducing the size, power consumption, and development time of the system, the more blocks handled by the FPGA the better. Placing an A/D converter at either Location A or B will require the digitization of the average background light radiation while placing the converter at Location C will require more analog hardware, but provides the benefit of only digitizing the signal of interest.

Location A or B

To place the A/D converter at Location A or B requires that all analog system blocks upstream of the digitization block be designed with power rails that match the dynamic range of the A/D converter. This redesign of the optical electrical interface (and filter) is the primary drawback to placing the A/D converter at Location A (B).

The original system was designed on a 15 V rail which allowed for a higher resolution to minor changes in input light intensities. For example, when the system was designed for indoor lighting, the maximum output voltage of the optical electrical interface was 12 V at 4000 Lux, but typical office lighting was around 350 Lux which provided a baseline voltage of 1 V[10]. With this baseline, a black object on a white background produces a Gaussian trough of approximately 1 V. Changes in contrast or distance will adjust the depth of the trough within this 1 V range. If the average background light intensity decreases, so does the ability to resolve changes in the scene.

Placing an A/D converter at Location A or B complicates matters due to the trade-offs of dynamic range and resolution. To achieve maximum measurement resolution at different light intensities a larger dynamic range is required, but to keep the A/D resolution constant the number of bit used to digitize the system will have to increase with the dynamic range. Maximizing A/D resolution by using a 1.2 V dynamic range produces a baseline voltage of 105 mV at typical office light intensities.

Location C
Digitizing at Location C does not require the digitization of the average background light intensity. Therefore, the signal of interest can theoretically be matched to the dynamic range of the A/D converter thereby increasing overall resolution. At first glance, this appears to be the better option, but a number of drawbacks exist. Placing an A/D converter at Location C requires that the entire primary signal path be constructed using analog hardware. All the drawbacks of the original analog hardware will still exist in the system. Additionally, there is no way to predict a-priory what the signal strength output by the light adaptation hardware will be. Again this depends on distance from the target and contrast in the scene. A new analog hardware module would have to be designed that matched the light adapted output signals to the A/D dynamic range in real-time. It should be noted that the fly's biological system utilizes this method. It performs light adaption then boost the signal to match the dynamic range of its large monopolar cells[11]. At present it is unknown if an analog solution could be designed to meet the needs of the fly eye sensor system.

General Requirements of Digitization
The two primary requirement of the A/D converter, when used in the fly eye system, are the same for any system, sample rate and resolution. The sample rate of the A/D converter effects temporal aliasing and the maximum throughput of the system. Aliasing or proper temporal signal reconstruction is only a concern when imaging moving scenes that contain repetitive objects, e.g., imaging a picketed fence from a moving vehicle. The slates of the fence will produce a temporal frequency on the primary signal path that requires the sample rate of the A/D converter to be higher than the Nyquist rate in-order to avoid aliasing. It should be noted that a stationary image of a single slate will have high spatial frequency content near the edges of the slate. The sample rate of the A/D converter plays no role when reconstructing this high spatial frequency image content.

 In addition to aliasing, the sample rate of the A/D converter is tied to the conversion time. To image quickly moving objects the total conversion time must be less than the time it takes for the object to move through the field of view (FOV) of a single channel. However, the maximum speed of the object will be much lower than the theoretical limit imposed by the conversion time. To maintain motion hyperacuity, the object must appear stationary to the sensor during the conversion time. Stated another way, any delay in the signal path degrades motion hyperacuity. Once a digitization method is chosen, the theoretical object velocity limit will be calculated and compared to experimental data.

The second requirement of the A/D converter is resolution. Both the overlap and continuous nature of the Gaussian wave forms make motion hyperacuity possible. Digitizing with too few

bits will produce a stair step reconstruction. The sensor will be blind to object movement while multiple samples remain at the same quantization level resulting in a sever degradation to motion hyperacuity. In addition, every channel of the system must be digitized and the data must be sent in parallel to the FPGA. For a single sensor the FPGA must be able to accept the number of bits output by a single A/D converter multiplied by seven channels. A 10-bit converter would require 70 I/O pins for a single sensor. It is a long term goal of the project to construct a system utilizing numerous sensors to better mimic the fly's visual system. Thus, the number of bits required for the A/D converter is important.

Simulation Results

Simulations were used to aide in determining the optimal digitization technique considering all factors. Data was acquired from the original analog system at digitization Location B. The data was gathered using a data acquisition card that digitized the data at a sample rate of 1000 Hz with a 10-bit resolution. The data was loaded into MATLAB, and a polynomial fit of order 30 was applied to each channel in an attempt to remove the effects of the data acquisition digitization. The test data signals from the middle channels (*D3* through *D5*) are shown in Figure 4.
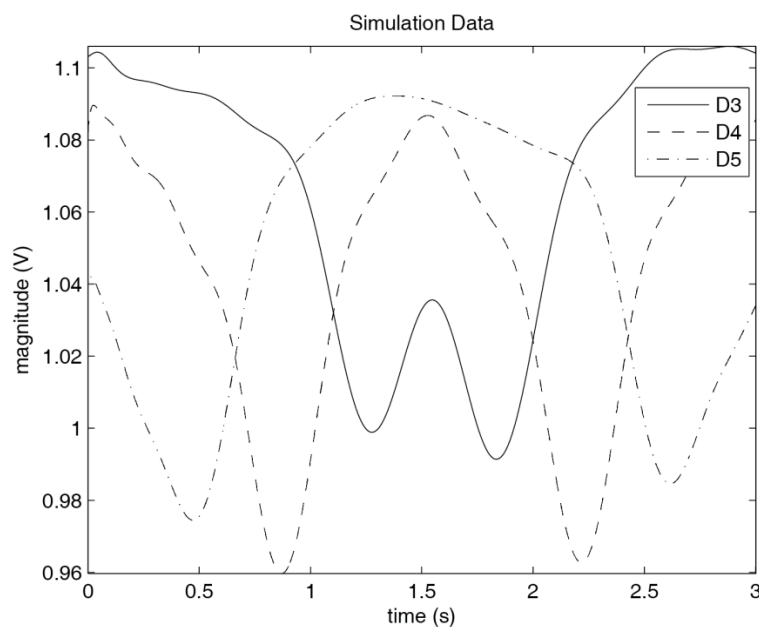
Figure 4: Simulation data measured from the analog version of the Fly Eye sensor viewing a 5 mm black dowel rod moving through its FOV from left to right then right to left. Each trough corresponds to a photodetector imaging the object. The transition from left to right motion to right to left motion occurs at approximately 1.7 seconds.

The signals obtained were adjusted to simulate an A/D converter with a 1.2 V dynamic ranged placed at Figure 3 Locations A and C. For Location A, the signal strength was adjusted to match a simulated gain change in the optical electrical interface such that the output range matched the dynamic range of the A/D converter for indoor light intensities. For Location C, the DC

component of each channel was removed to simulate the light adaptation block. However, with the DC component removed, the signal response to the dark object became negative, so an absolute value was applied before matching the signal to the dynamic range of the A/D converter. The adjusted data for each digitization location are presented in Figure 5.
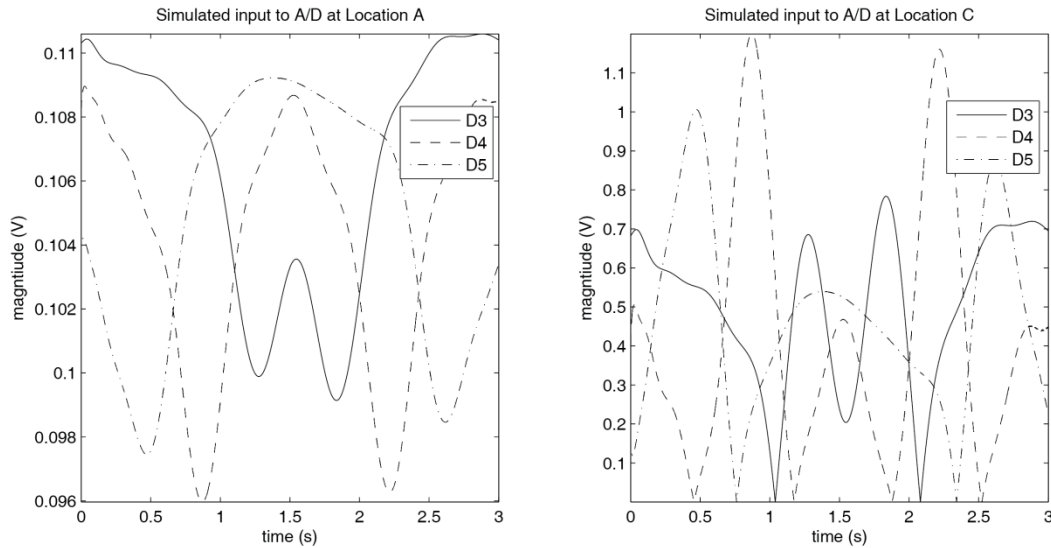
Figure 5: Simulated input data to an A/D converter located at Location A (left plot) and Location C (right plot). The adjustments to the data were made to simulated the output of analog signal conditioning hardware upstream of the A/D converter.

Effects of A/D Sample Rate

The data in Figure 5 was passed through a simulated successive approximation A/D converter at different sample rates and different resolutions. The effect of different sample rates was evaluated first. A sample rate that is too low will greatly reduce or remove the systems motion hyperacuity, because the sensor is in-effect blind to motion that occurs between samples. To measure this effect, the polynomial fit was used to generate signals at various sample rates. A simulated "continuous" time signal was generated by up-sampling the input data to 1 MHz. This signal was used as the control to which all other signals were compared. Simulated data was generated at sample rates that were multiples of the Nyquist frequency. At each of the sample rates the signals were up-sampled using linear interpolation and compared sample-by-sample to the control. The total absolute error measured on channel *D4* was calculated. This error gives an indirect measure of how "blind" the system was to motion between samples. A larger error implies that the signal changed more rapidly between samples, and since signal dynamics directly relate to object motion, more data was lost due to inadequate sample rate. This analysis does not take into account any signal interpolation which may be possible in real-time on the FPGA. The results are summarized in Table 1. The larger signal magnitude input to an A/D converter at Location C produces a higher error at all frequencies. For all locations, a factor of 10 increase in the sample rate stops having a significant effect around 1000x the Nyquist rate. At low object speeds used in the laboratory, 1000x the Nyquist frequency is easily achieved with commercially available A/D converters. If higher speeds are desired, other techniques will need

to be investigated. These results give a good starting point for initial prototyping and laboratory testing.

Table 1: Effect of various A/D sample rates at all digitization locations. Total error was measured by comparing to a control signal at a much higher sample rate.

	Location A or B	Location C
Freq. Above Nyquist	Total Error (V)	Total Error (V)
5x	1.124E3	190.1E3
10x	334.1	54.51E3
100x	5.63	1.945E3
1E3x	2.07	319.29
1E4x	2.03	272.63
1E5X	1.87	245.78

Effects of A/D Resolution

Using the data found for different sample rates, a sample rate of 1000x the Nyquist frequency was set and the data was passed through a simulated A/D converter at different resolutions from an 8-bit to a 24-bit resolution. Again, the largest drawback to digitizing the analog signals is loss of motion detection ability. Using an A/D converter with too low of a resolution will result in multiple samples occurring at the same quantization level. The system is unable to resolve motion while the A/D converter remains at a constant quantization level. To measure the effect of the A/D resolution, the average percent error between the original signal and the digitized signal was computed along with a measure of how long the digitized signal remained at the same quantization level. The results are shown in Table 2.

Table 2: Effect of various A/D resolutions at all digitization location. Percent average time at same quant. level is a measure of how long the signal remained at the same quantization level. While at the same quantization level the system is "blind" to object movement.

	Location A or B		Location C	
Resolution	Percent Average Time at Same Quant. Level	Average Percent Error	Percent Average Time at Same Quant. Level	Average Percent Error
8-bit	99.65	2.092	64.88	1.83
10-bit	98.88	0.562	24.98	0.541
12-bit	95.65	0.139	7.37	0.159
14-bit	82.53	35.1E-3	1.69	46.8E-3
16-bit	43.49	8.74E-3	0.419	10.7E-3
18-bit	13.98	2.19E-3	0.128	3.32E-3
20-bit	3.64	0.544E-3	33.31E-3	0.793E-3
22-bit	0.923	0.137E-3	9.52E-3	0.194E-3
24-bit	0.243	34.1E-6	4.76E-3	43.4E-6

As expected, the ability to match the desired signal to the dynamic range of an A/D converter at Location C produced the best results, but recall that the analog circuitry that allows for dynamic

range matching has yet to be designed for the fly eye system. Except for application requiring extreme motion resolution abilities, it appears that digitizing at Location A or B is possible with commercially available 20-bit to 24-bit resolution A/D converters.

Conclusion

Considering the trade-offs of digitizing after the optical electrical interface verses digitizing after the light adaptation module and the results of the simulations presented in this paper, we predict the optimal solution is to digitize flowing the optical electrical interface using an A/D converter with a resolution above 20-bits and sample rate at or above 1000x the Nyquist frequency. We will proceed by confirming these results in hardware before a final digitization method is utilized.

Bibliography

[1] G. C. Holst, *CCD array cameras and displays*, 1st ed. SPIE Press and JCD publishing..

[2] J. Nakamura, Ed., *Image sensors and signal processing for digital still cameras*, 1st ed. Taylor & Francis Group, 2006

[3] M. Srinivasan, R. Pinter, and D. Osorio, "Matched filtering in the visual system of the fly: Large monopolar cells of the lamina are optimized to detect moving edges and blobs," in *Proceedings of the Royal Society of London. Series B, Biological Sciences*, vol. 240, June 1990, pp. 279-293.

[4] E. Tomberlin, "Musca domestica's large monopolar cell responses to visual stimuli," Master's thesis, University of Wyoming, June 2004.

[5] J. B. Benson, C. H. G. Wright, and S. F. Barrett, "Redesign and construction of an artificial compound eye visual sensor," *Journal of Biomedical Sciences & Instrumentation,* vol. 44, pp. 367-372, April 2008.

[6] G. P. Luke, C. H. G. Wright, and S. F. Barrett, "A multi-aperture bioinspired sensor with hyperacuity," *IEEE Sensors Journal*, vol. 12, no. 2, pp. 308-314, 2012.

[7] D. T. Riley, S. F. Barrett, M. J. Wilcox, and C. H. G. Wright, "*Musca domestica* inspired machine vision system with hyperacuity," in *Proceedings of the SPIE 12th International Symposium on Smart Structures and Materials: Smart Sensor Technology and Measurement Systems Conference,* vol. 5758, pp. 304-320, March 2005.

[8] B. K. Dean, C. H. G. Wright, and S. F. Barrett, "Biomimetic Signal Conditioning and Light Adaptation for Compound Vision Sensors," *IEEE Sensors Journal*, under review.

[9] R. S. Prabhakara, C. H. G. Wright, and S. F. Barrett, "Motion detection: A biomimetic vision sensor versus a CCD camera sensor," *IEEE Sensors Journal*, vol. 12, no. 2, pp. 298-307, 2012.

[10] B. K. Dean, "Light Adaptation and Applications for a Fly Eye Vision Sensor," PhD Dissertation, University of Wyoming 2012.

[11] S. B. Laughlin and R. C. Hardie, "Common strategies for light adaptation in the peripheral visual systems of fly and dragonfly," *Journal of Comparative Physiology A*, vol. 128, pp. 319-340, 1978.