A hyperacute Vibrating Optical Device for the Control of Autonomous robots (VODKA)

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Abstract. We built a minimalist optical sensor mimicking the optical properties of two adjacent omatidia in an arthropod compound eye. The VODKA sensor consists of an elementary vibrating retina mounted behind a small lens. Retinal micro-scanning is achieved by using a small piezo bender actuator driven at a frequency of $40Hz$. The VODKA sensor was shown to be able to locate a contrasting edge with a resolution 256-fold greater than its static resolution (i.e., without scanning), regardless of the scanning law imposed upon the retina. The hyperacuity thus achieved may shed a new light on tremor eye movements that have been described in both vertebrate camera eyes and arthropod compound eyes. In addition to its hyperacuity, the small size, low mass and low consumption of this optical sensor make it well suited to applications in robotics, aerospace and metrology.

Keywords: Optical sensor, hyperacuity, active vision, micro-scanning, position sensing device, photodiode, robotics

1 A visual sensor with bio-inspired optical features

The optics of the sensor is composed of two photodiodes (Ic-Haus LS2C) placed behind a lens (diameter $D = 5mm$, focal length $f = 8.5mm$), as shown in Fig.1 (inset). The lens-photoreceptor system was deliberately defocused so as to produce a Gaussian-like directivity function for each photoreceptor (see Fig.2), noted $s\left(\Psi \pm \frac{\Delta\varphi}{2}\right)$ where $\Delta\varphi$ is the interreceptor angle. This function mimicks that of each photoreceptor in the insect eye [3, 8].

$$s(\Psi) = \frac{2\sqrt{\pi \ln(2)}}{\pi \Delta\rho} e^{\frac{4\Psi \ln(2)}{\Delta\rho^2}} \tag{1}$$

where $\Delta\rho$ is the “acceptance angle”(i.e., the full width at half height) and Ψ the directivity angle.

Figure 1 shows that the VODKA sensor is able to determine the angular position Ψ_c of the contrasting edge present in its field of view (FOV) The characteristic curve obtained (Fig.1, bold curve) can be seen to be an even function

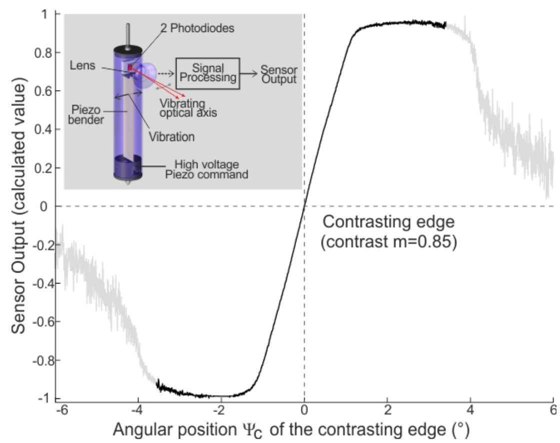

Fig. 1. Inset: CAD of the VODKA optical sensor. The two photodiodes mounted at the tip of a Piezo bender get translated to and from periodically at $40Hz$, making their optical axes jointly scan a small part of the environment (sinusoidal law, scanning amplitude 0.1°). Bold curve: measured "characteristic curve" of the OSCAR sensor, which expresses the sensor's response as a function of the angular position Ψ_c of a contrasting edge positioned in the frontal plane. The sensor's characteristic obtained is an even function of Ψ_c, and follows an hyperbolic tangent function at very high resolution ($\Delta\varphi = 2.87°$ and $\Delta\rho = 3°$)

of Ψ_c, which follows faithfully an hyperbolic tangent function and features a very high resolution.

The output signal of the two photoreceptors (noted respectively $Ph(\Psi(t) - \frac{\Delta\varphi}{2})$ and $Ph(\Psi(t) + \frac{\Delta\varphi}{2})$) placed in front of a contrasting edge can be calculated as follows:

$$Ph(\Psi) = \frac{1}{2}\left(1 + erf\left(\frac{2\Psi\sqrt{\ln(2)}}{\Delta\rho}\right)\right) \quad (2)$$

where the function erf is the classical sigmoid shape error function.

2 VODKA principle

The VODKA principle relies on two requirements:

- a Gaussian-like angular sensitivity function, as inspired by the angular sensitivity of photoreceptors in flies [4].
- a micro-scanning movement applied to the retina, as inspired by the retinal micro-movements observed in flies [2].

As depicted in figure 2, the VODKA output signal results from *the ratio of the difference to the sum of the differentiated photodiode output signals*. The

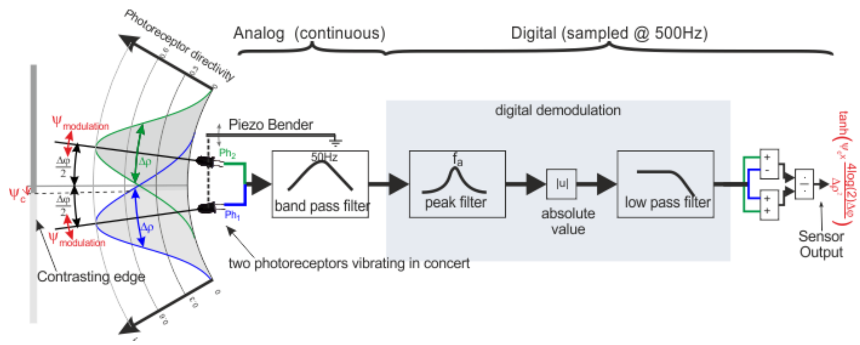

Fig. 2. Retinal actuation and visual processing in the VODKA sensor. A contrasting edge placed in the sensor's fiel of view is seen jointly by the two photodiodes that are made to vibrate in concert by the piezo actuator. The output signal from the two photodiodes are band-pass filtered and demodulated before computing the ratio of the difference to the sum. Early differentiation of the photoreceptor signals allows for a high gain amplification of the *dynamic part* of the signals, from which the angular position of the contrasted edge Ψ_c is resolved. A peak filter tuned to the scan frequency contributes to improve the signal-to-noise ratio.

filter is typically a band pass filter composed of a high pass section (acting as the differentiator proper), followed by a low pass section whose purpose is to reduce the high frequency noise.

$$S_{VODKA} = \frac{\frac{\partial}{\partial t}Ph\left(\Psi(t)-\frac{\Delta\varphi}{2}\right)-\frac{\partial}{\partial t}Ph\left(\Psi(t)+\frac{\Delta\varphi}{2}\right)}{\frac{\partial}{\partial t}Ph\left(\Psi(t)-\frac{\Delta\varphi}{2}\right)+\frac{\partial}{\partial t}Ph\left(\Psi(t)+\frac{\Delta\varphi}{2}\right)} \tag{3}$$

where $\Psi(t)$ depends on both the angular position of the contrasting edge Ψ_c and the small sinusoidal vibration of amplitude 0.1°.

Development of the expression S_{VODKA} results in a remarkably simplified expression as follows:

$$S_{VODKA} = \tanh\left(\Psi * \frac{4\ln(2)\Delta\varphi}{\delta\rho^2}\right) \tag{4}$$

3 Conclusion

The VODKA sensor was shown experimentally to be capable to locate the angular position of a contrasting edge with a resolution far better (256-fold better) than its static resolution (determined by the inter-photoreceptors angle $\Delta\varphi$) would allow. In other words, it has acquired *hyperacuity*. Besides, the even characteristic curve obtained (Fig. 1) makes the sensor a good candidate for integration into a visuomotor control loop, for example in the context of visual stabilization and tracking.

In addition, the VODKA sensor features the following remarkable properties:

1. It responds to naturally lit objects
2. It responds within a large range of luminance
3. It responds as well in the presence of interferences ($100Hz$ or $120Hz$) caused by artificial lighting
4. It is largely insensitive to contrast
5. It is not sensitive to the contrast polarity (ON edges or OFF edges)
6. It provides for a high refresh rate and low latency
7. It is lowweight, powerlean and simple to realize

In an extension of this work, we showed that the basic principle demonstrated here still holds for random vibrations, like those naturally produced by the propellers of a small aircraft [6, 5], making the sensor even simpler to realize. Since the VODKA sensor shares the same processing frontend as our optical flow sensors [1, 7], it is possible to create a dual optical position and optical flow sensor sharing the same FOV and the same (optical and electronical) hardware. As a final remark, the hyperacuity achieved in the VODKA sensor may shed new light on some miniature eye movements (tremor) that have been described in both vertebrate camera eyes and arthropod compound eyes.

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