Local Motion Sensor, Artificial Compound Eye and Autoadaptive Retina:

From Sensors Design to Robotics Application

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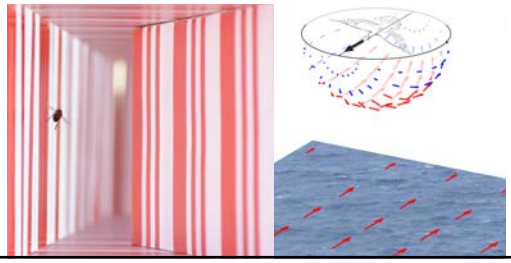
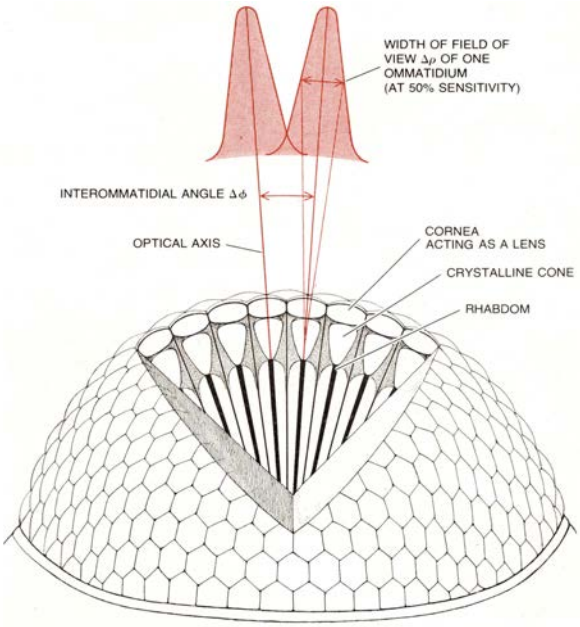
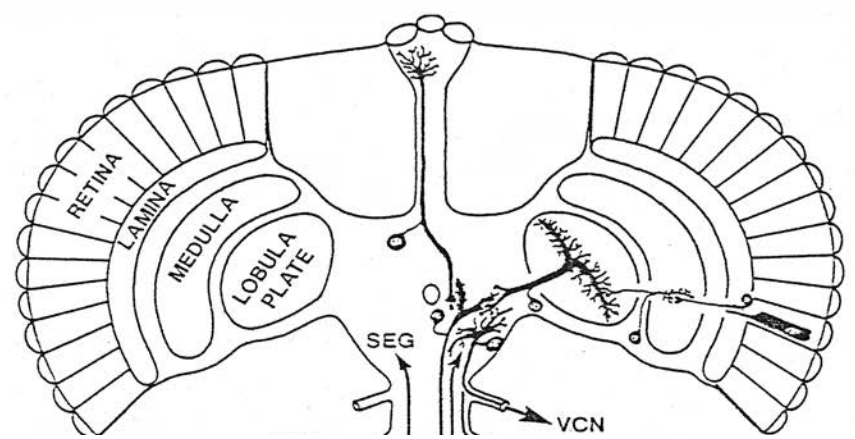


A simplified compound eye

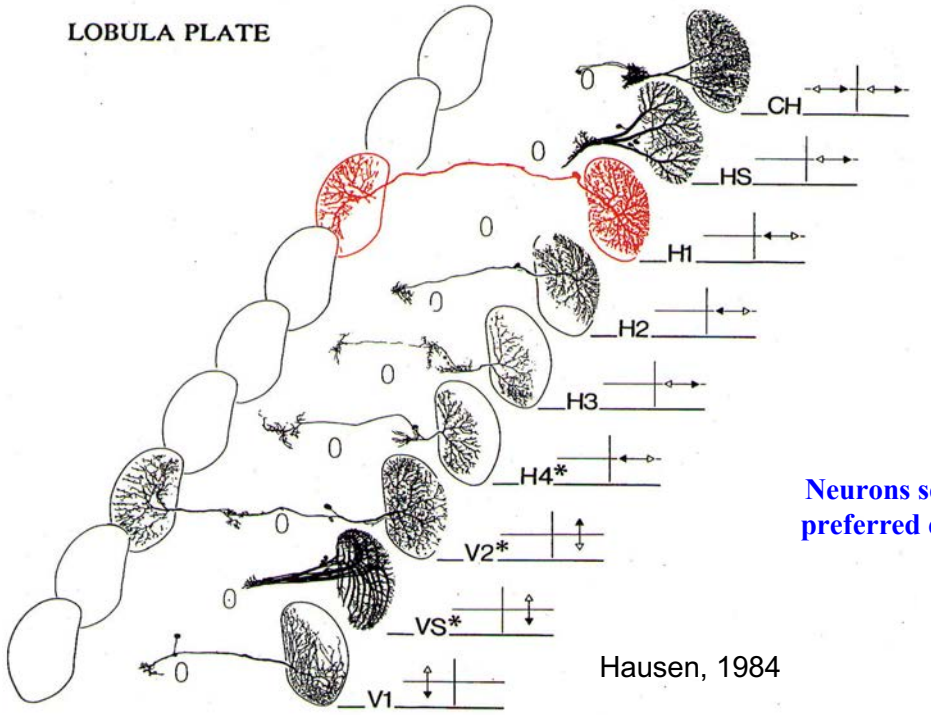


Horridge 1977

A simplified cross-section of a fly's compound eye



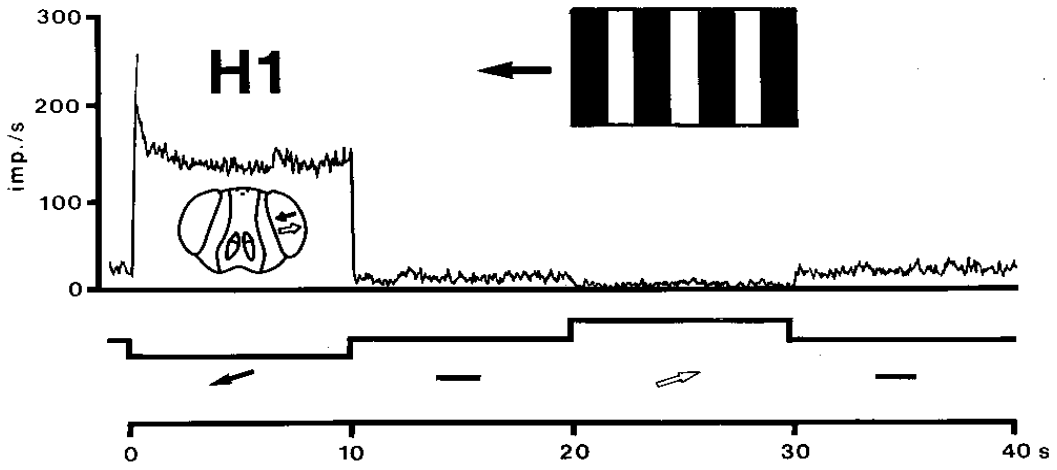
Hengstenberg, 1993



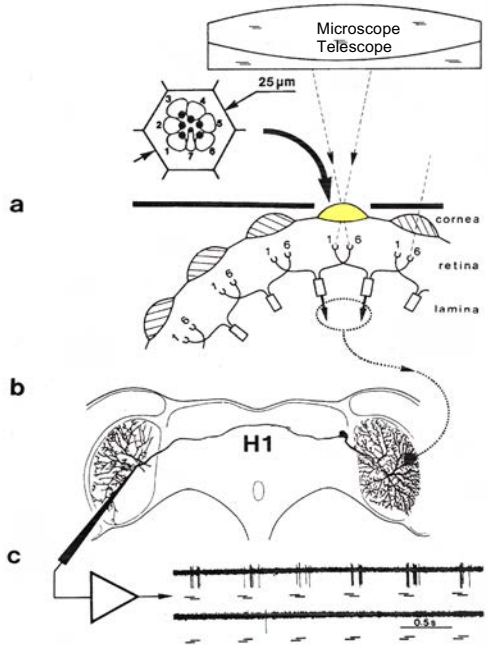
Neurons sensible to preferred directions

Hausen, 1984

Response of large-field motion-sensitive neurons to large-field motion



Riehle & Franceschini, 1984



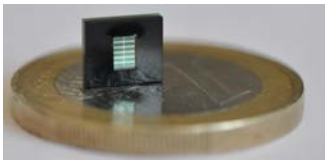
Response of large-field motion-sensitive neurons to local motion

=> to a sequential illumination of two neighboring photoreceptors R1-R6

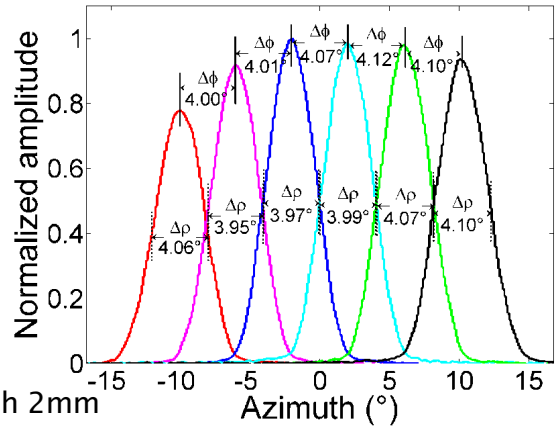
Franceschini et al. 1989

Lens/photodiode assembly

Linear array of 6 photodiodes Gaussian angular sensitivities



- Linear on-chip current preamplification circuit



Plastic Lens

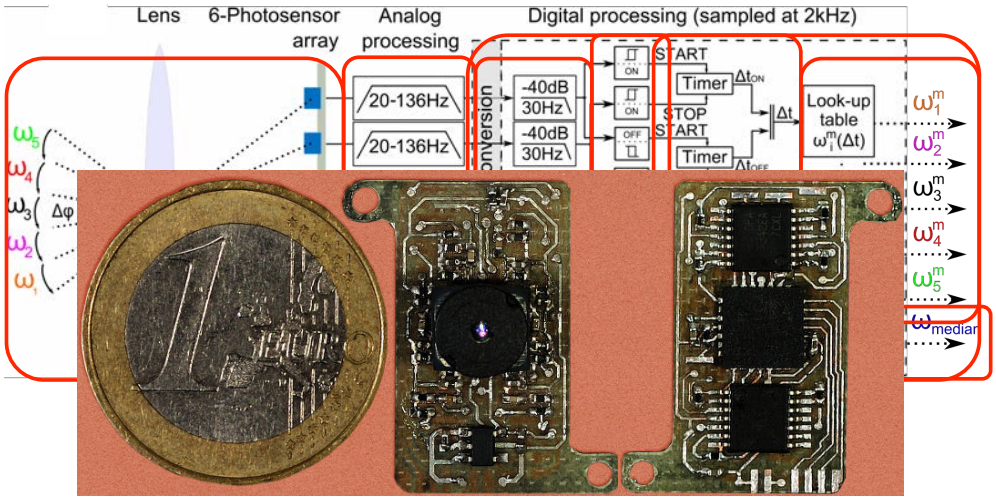
- Focal length 2mm
- f-number 2.8

F. Roubieu *et al., IEEE Sensors Journal, 2013*

Local motion processing

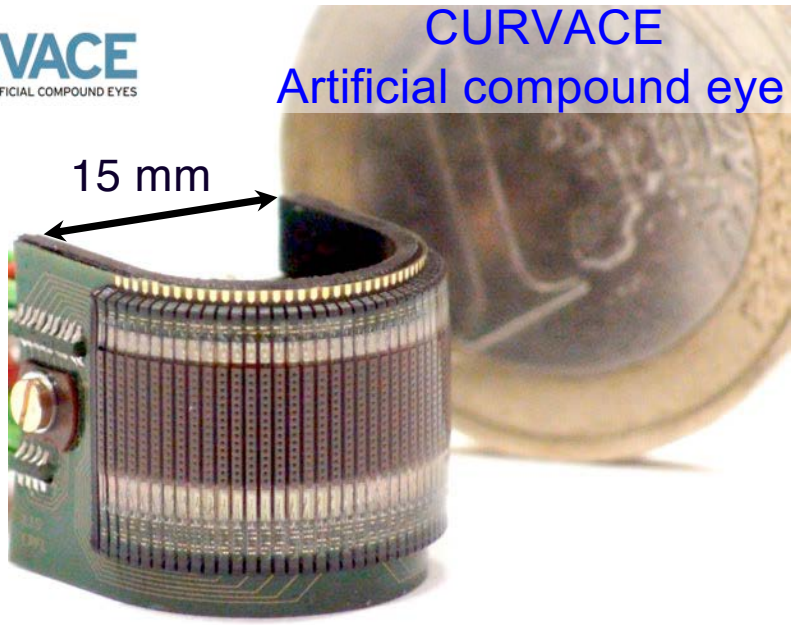
Time of travel scheme : 6 processing steps

$$\omega_i^m = \frac{\Delta\varphi}{\Delta t_i}$$



F. Roubieu *et al., IEEE Sensors Conf., 2011.*

CURVACE
Artificial compound eye



1st programmable artificial compound eye

630 Delbrück pixels (42x15)

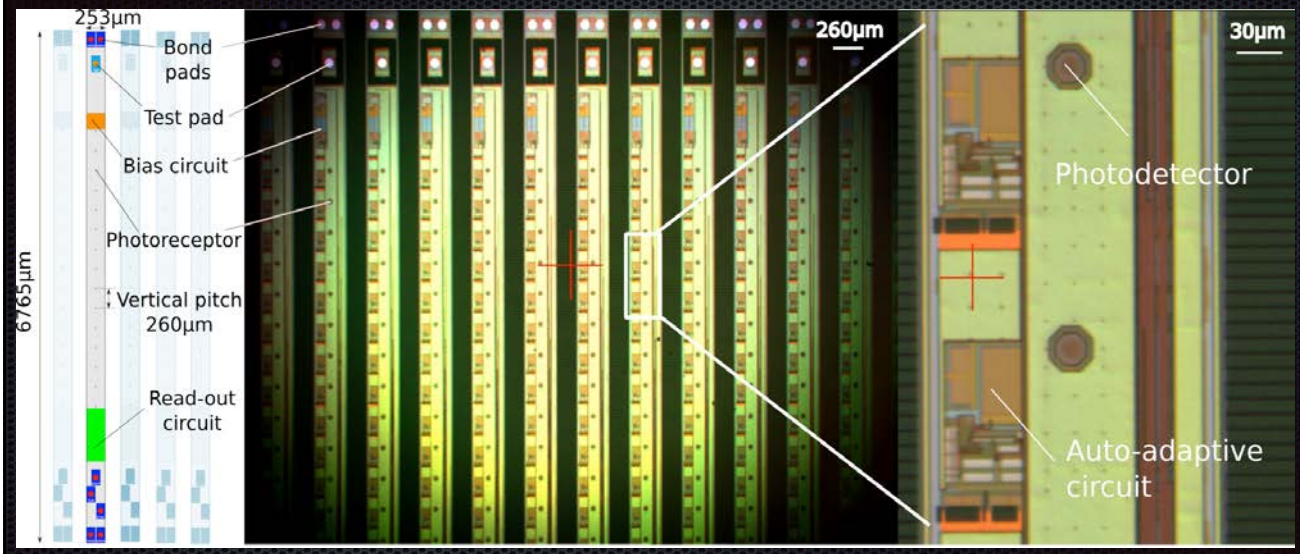
Mass:
2 grams

Field Of View:
180° x 60°

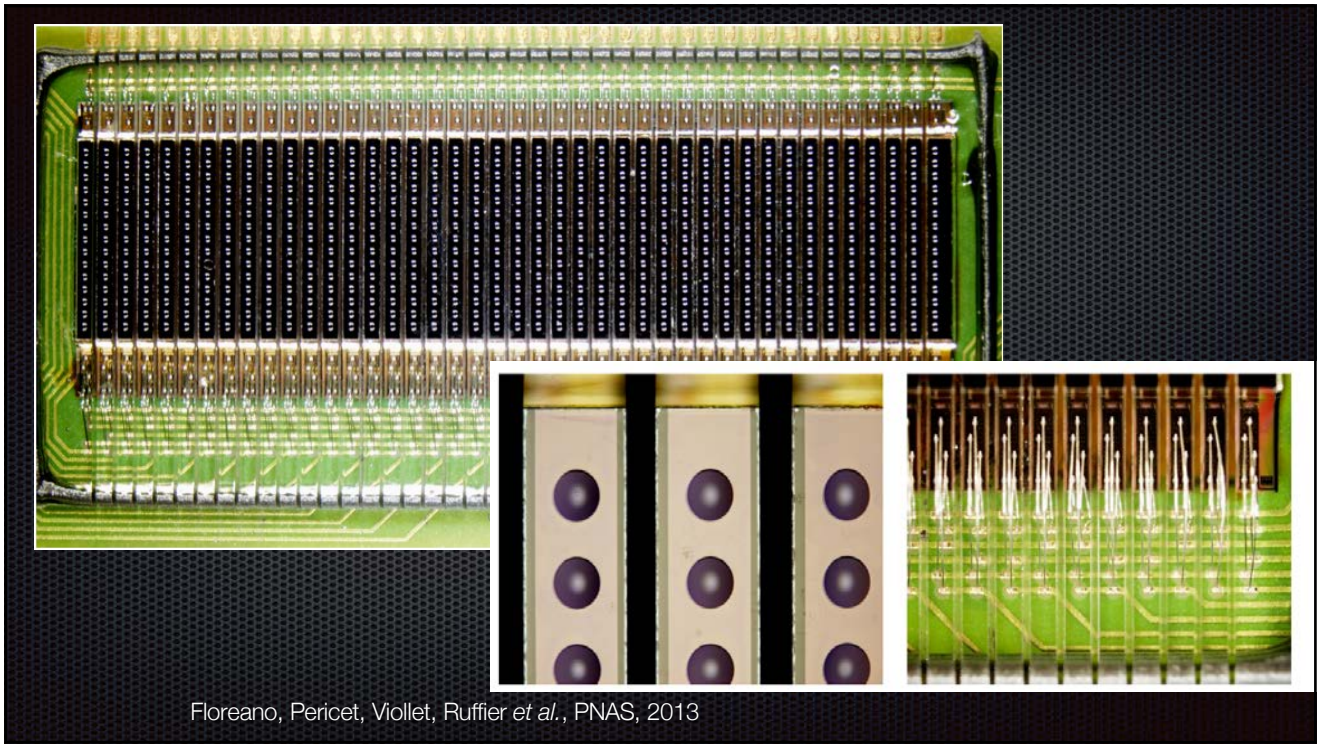
Floreano *et al. (2013) PNAS*

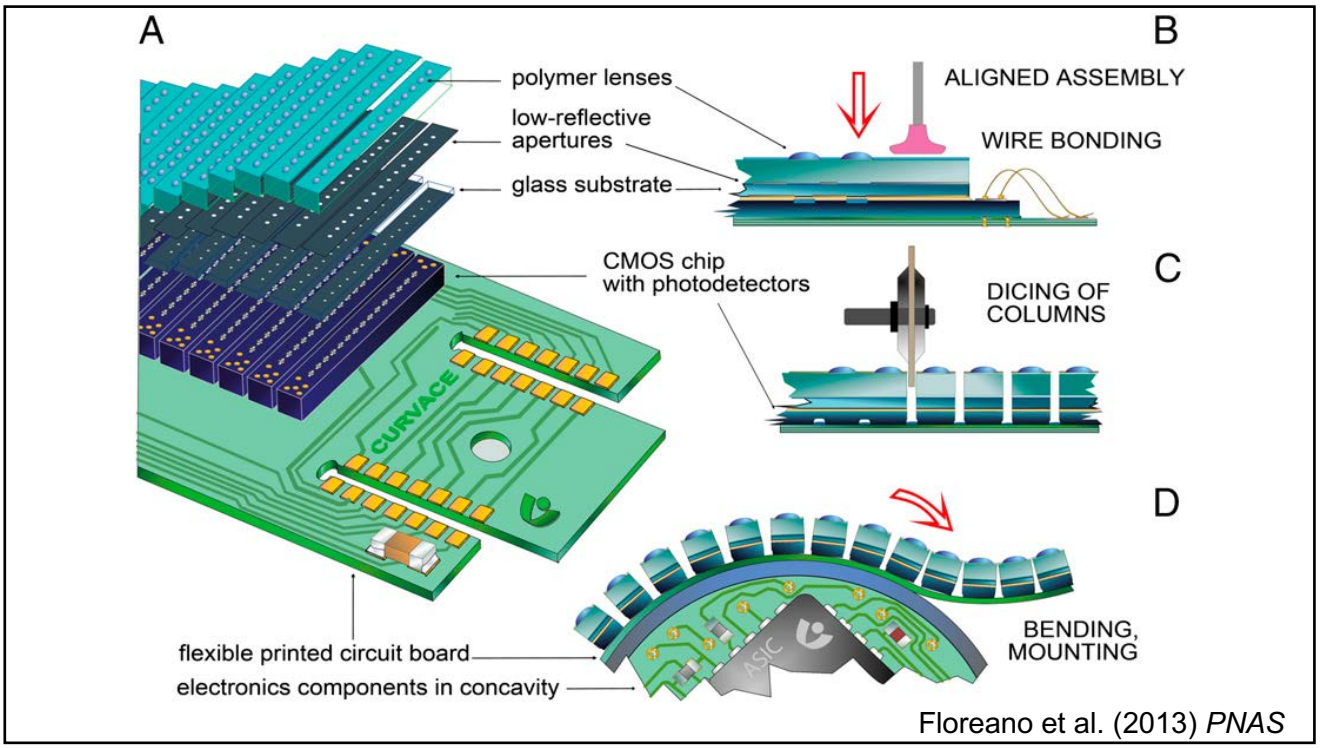
CURVACE (ICT/FET) European project

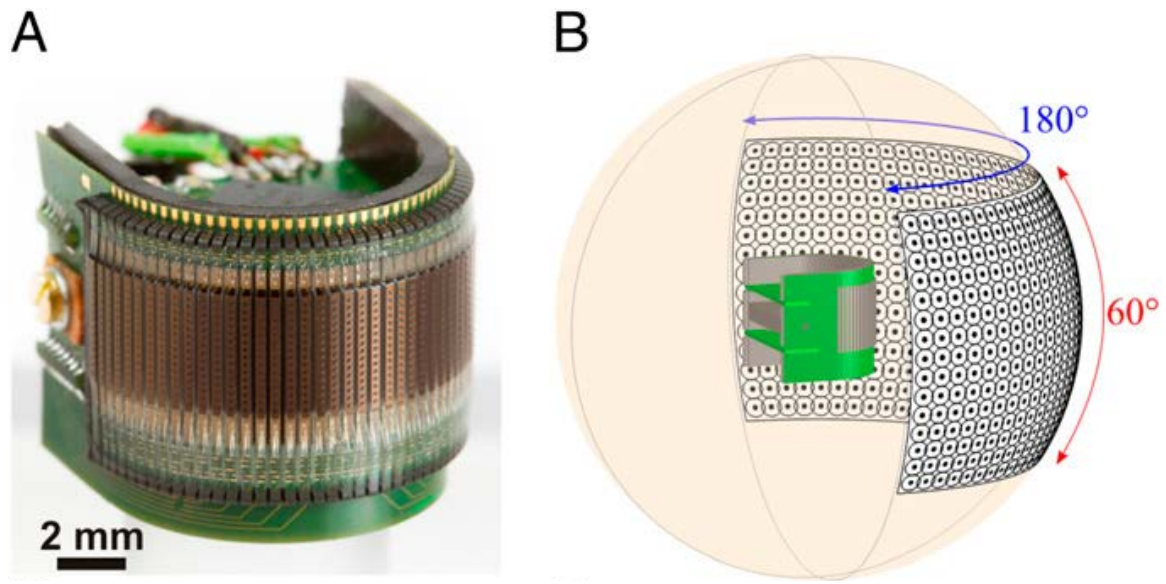
www.curvace.org



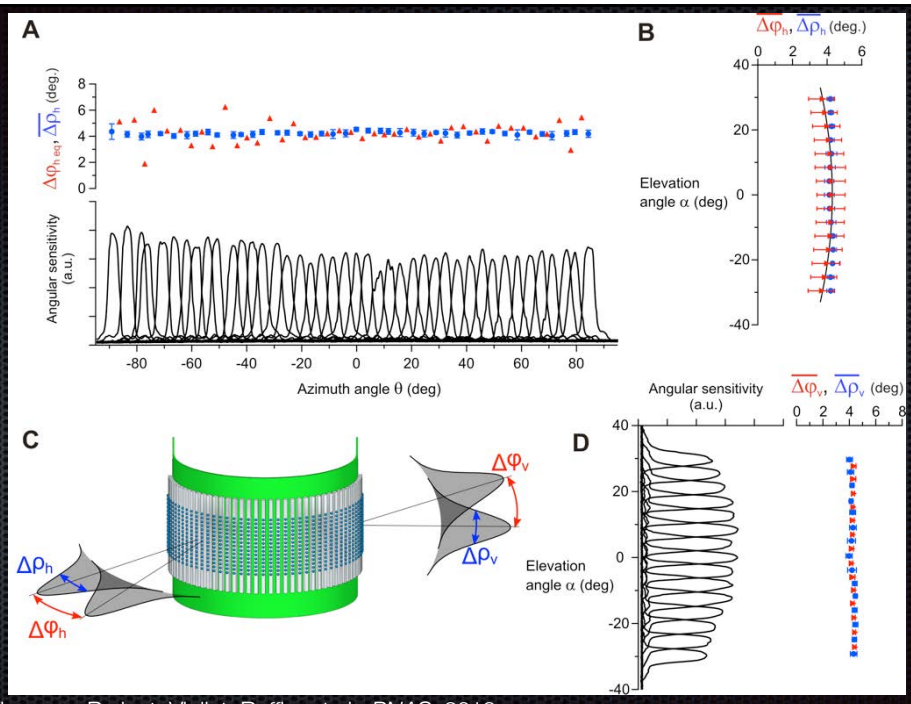
Floreano, Pericet, Viollet, Ruffier et al., *PNAS*, 2013


Floreano, Pericet, Viollet, Ruffier *et al.*, PNAS, 2013

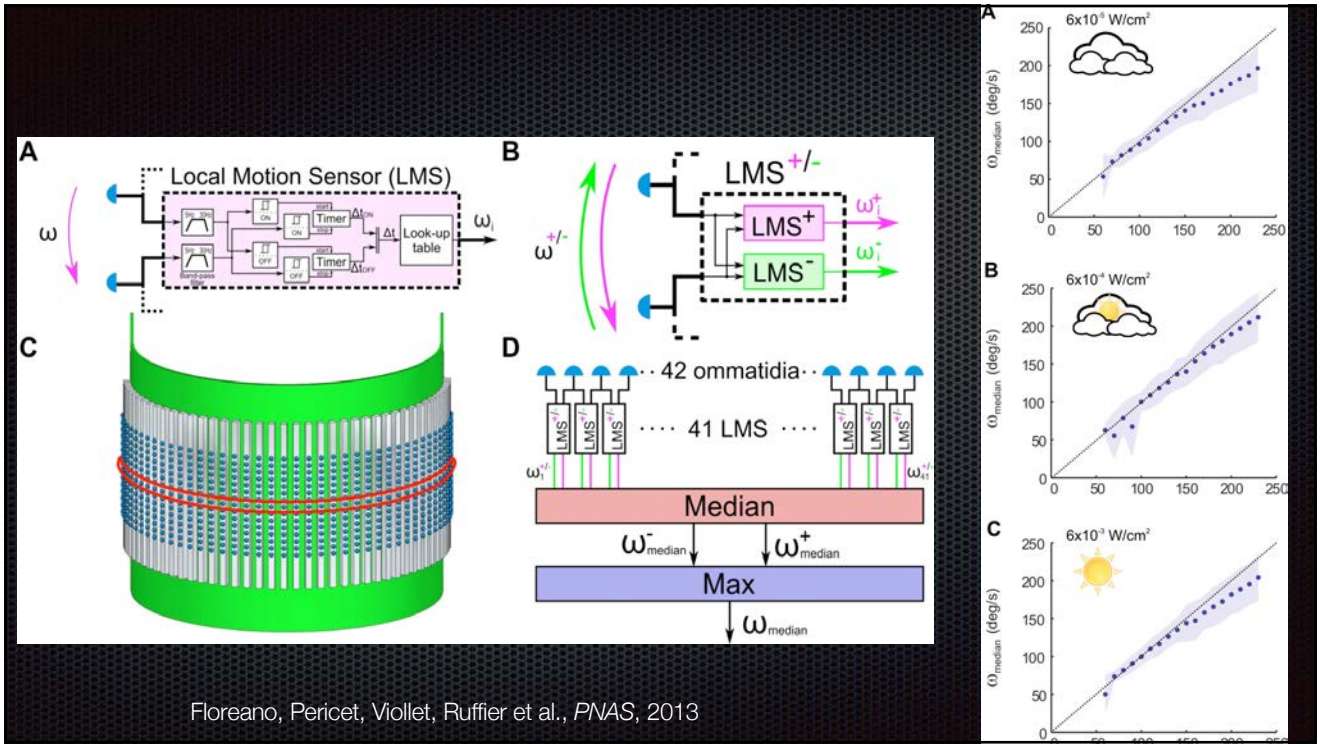

A
B
polymer lenses
low-reflective apertures
glass substrate
ALIGNED ASSEMBLY
WIRE BONDING
CMOS chip with photodetectors
C
DICING OF COLUMNS
CURVACE
D
BENDING, MOUNTING
ASIC
flexible printed circuit board
electronics components in concavity
Floreano et al. (2013) *PNAS*



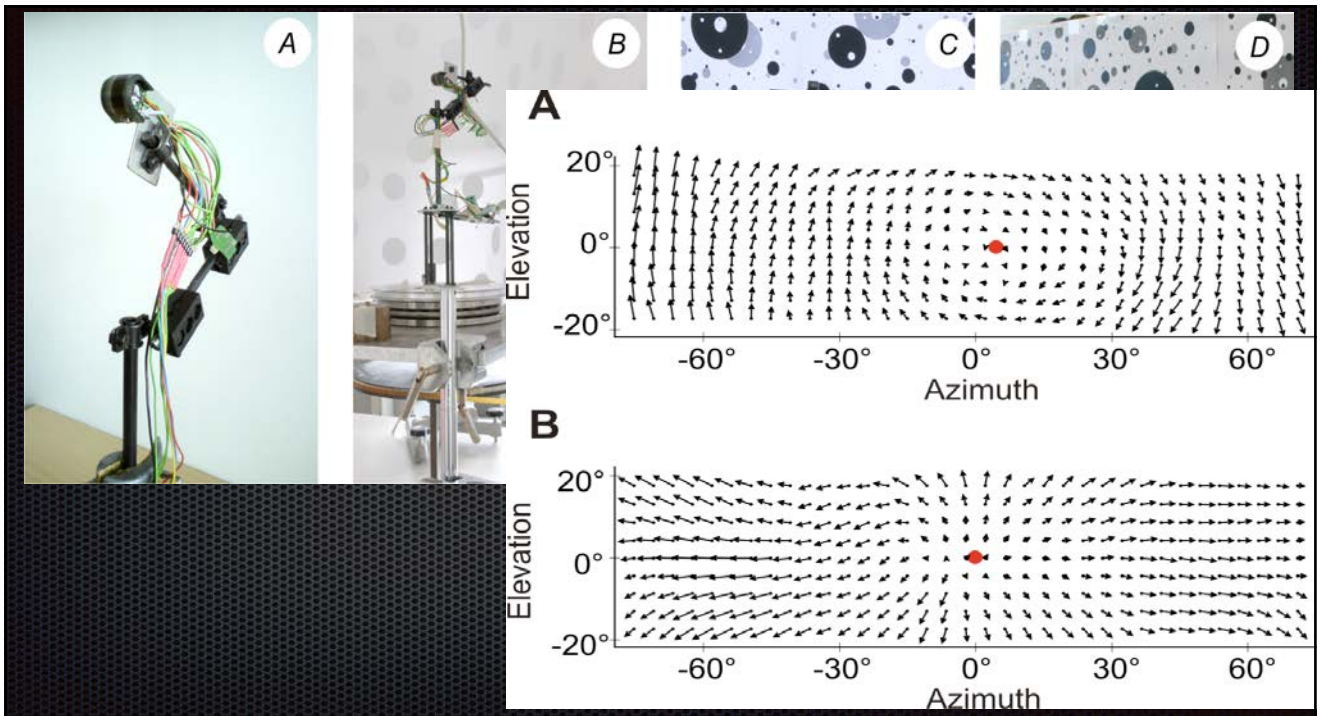
Floreano et al. (2013) *PNAS*



Floreano, Pericet, Viollet, Ruffier et al., *PNAS*, 2013



Floreano, Pericet, Viollet, Ruffier et al., *PNAS*, 2013



Floreano, Pericet, Viollet, Ruffier et al., *PNAS*, 2013

CurvACE prototype compared with the Drosophila melanogaster compound eye

	CurvACE	*Drosophila* eye [Ref(s).]
Number of ommatidia	630	600–700
Facet diameter, μm	172	16 (42)
Eye diameter, mm	12.8	0.36 (42)
Facet diameter/eye diameter, %	1.3	4.4
Interommatidial angle, $\Delta\varphi$; deg.	~4.2	~4.7–5.5 (42)
Acceptance angle, $\Delta\rho$; deg.	4.2	~4.5 (24)
FOV, deg.	180 × 60	160 × 180 (43)
Signal acquisition bandwidth, Hz	300	<100 (28)
Adaptability to illuminance	Yes	Yes (4)
Crosstalk prevention	Yes	Yes (24)

deg., degree.

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deg., degree.

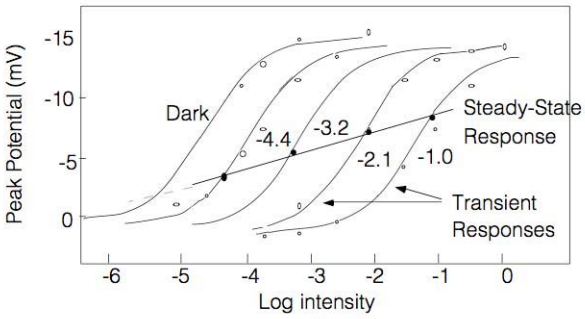
CURVACE

Viollet et al (2014) *Sensors*

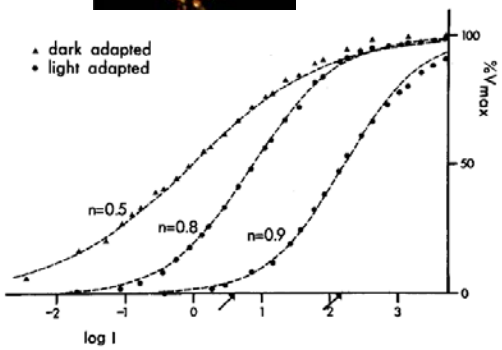
[redacted]

M²APIX :
Michaelis-Menten auto-adaptive pixels

Light Adaptation in Animal Photoreceptors



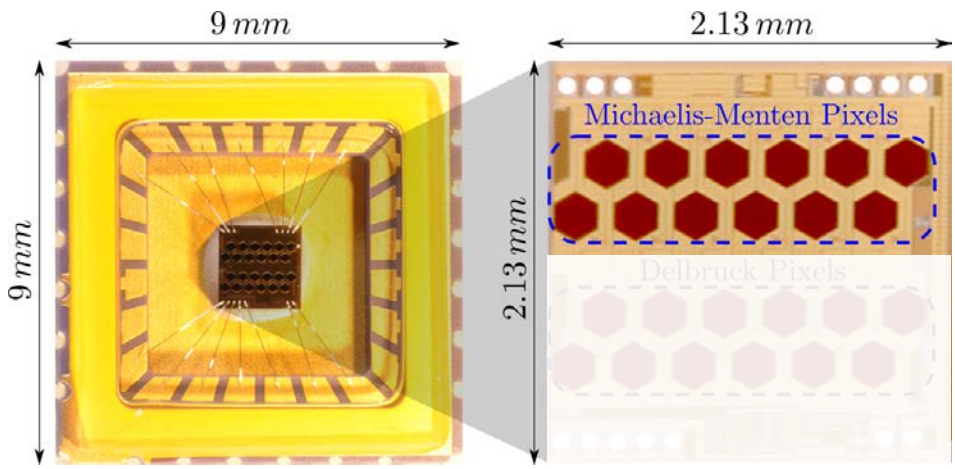
Normann and Perlman – J. Physiol. London – 1979



Matic and Laughlin – J. Comp. Physiol. – 1981

22

New Auto-Adaptive Silicon Retina: M²APIX



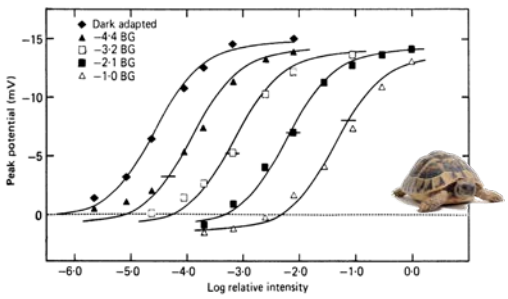
S. Mafrica et al., *Optics Express*, 2015

New Auto-Adaptive Silicon Retina: M²APIX

$$V_{out} = \frac{I_{ph}}{I_{ph} + I_0}$$

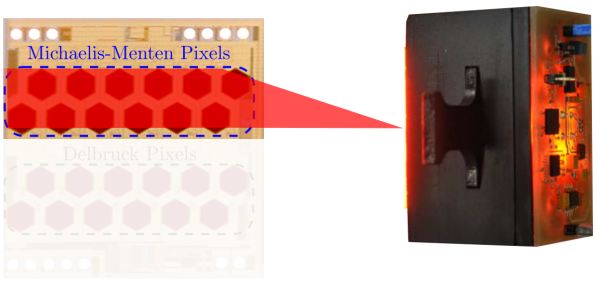
I_{ext} or I_{mean}

$\frac{1}{12}\sum_{i=1}^{12} I_{ph_i}$ low-pass filtered

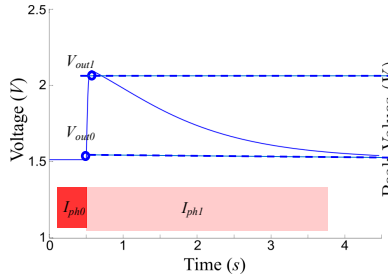


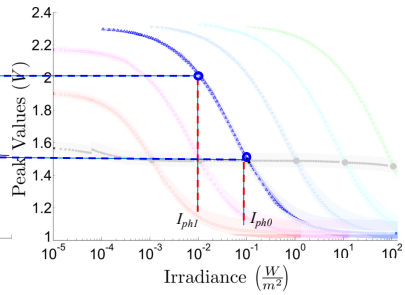
Red cone of a turtle (R. A. Normann & I. Perlman, 1979)

New Auto-Adaptive Silicon Retina: M²APIX



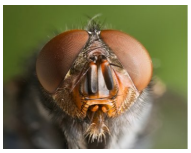
Lighting Box

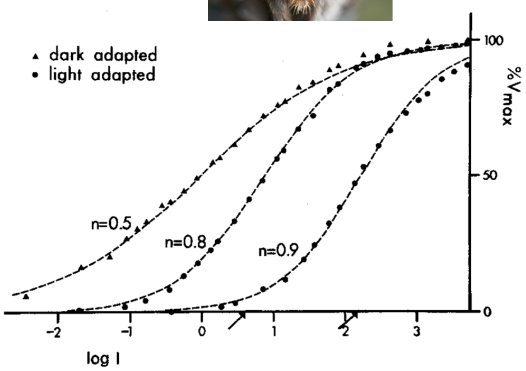




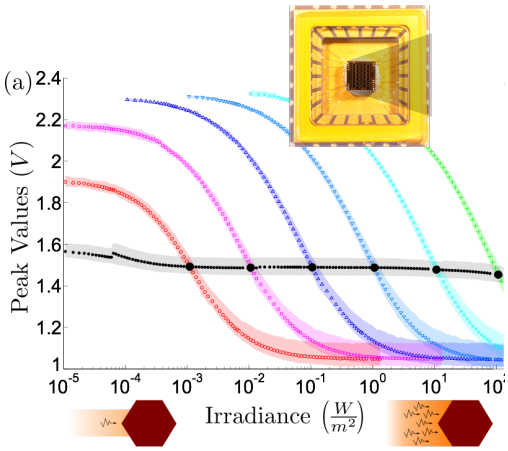
Mafrica *et al.*, Optics Express, Vol. 23, 2015.

Bio-inspired auto-adaptive pixels





S. Laughlin and M. Weckstrom 1993



Mafrica *et al.*, Optics Express, Vol. 23, 2015.

Bio-inspired auto-adaptive pixels

Auto-adaptation in 7-decade range

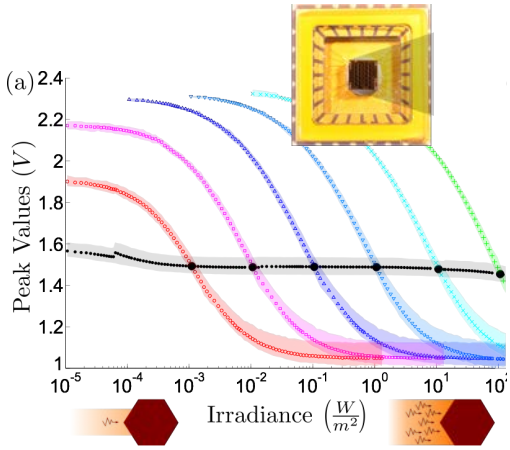
Contrast sensitivity in 2-decade dynamic range

Minimum detectable contrast of 2% (after ADC)

Consistent monotonic response in ±3 decades

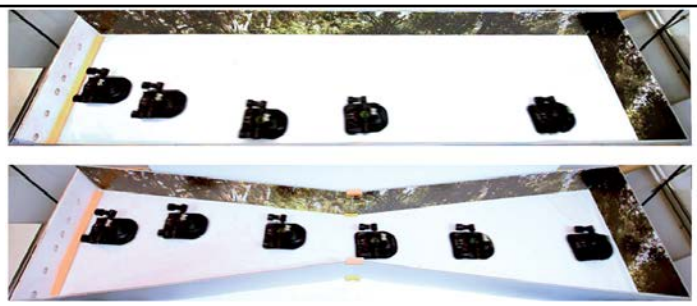
Constant steady-state response (resting point)

→ same contrast resp. at any light level



Mafrica *et al.*, Optics Express, Vol. 23, 2015.

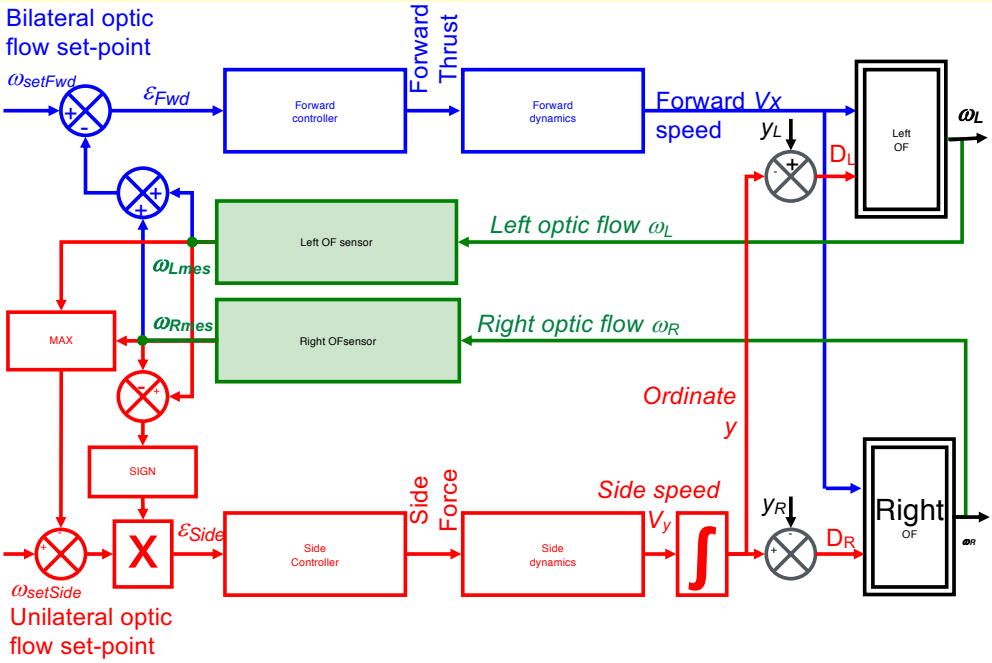
Biomimetic Robotics



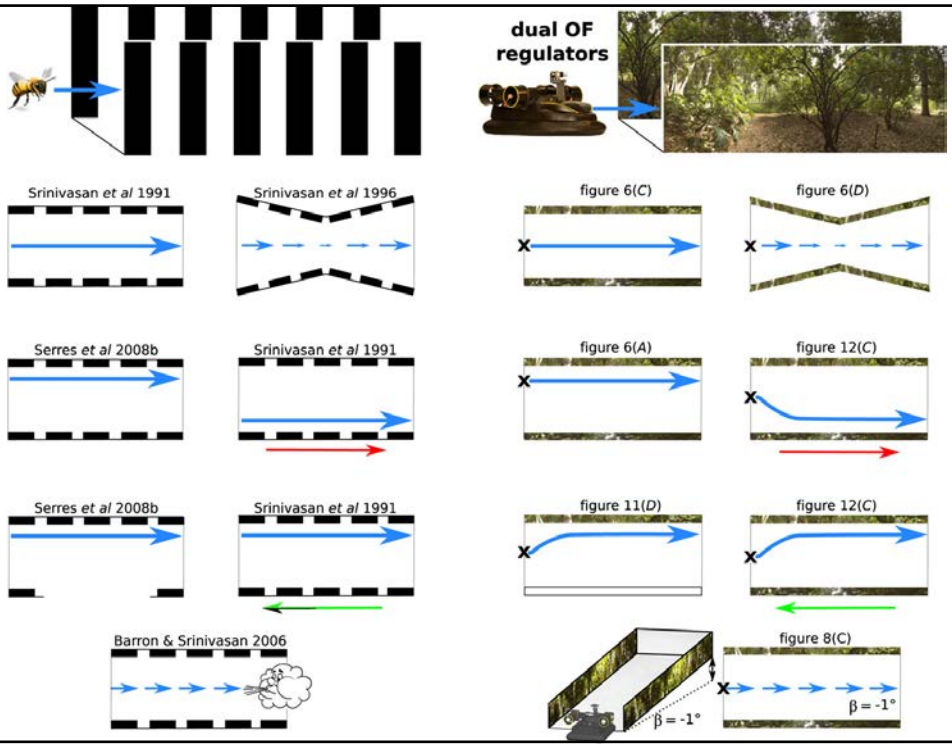
The robot LORA

Roubieu et al. (2014)
Bioinspir. Biomim.

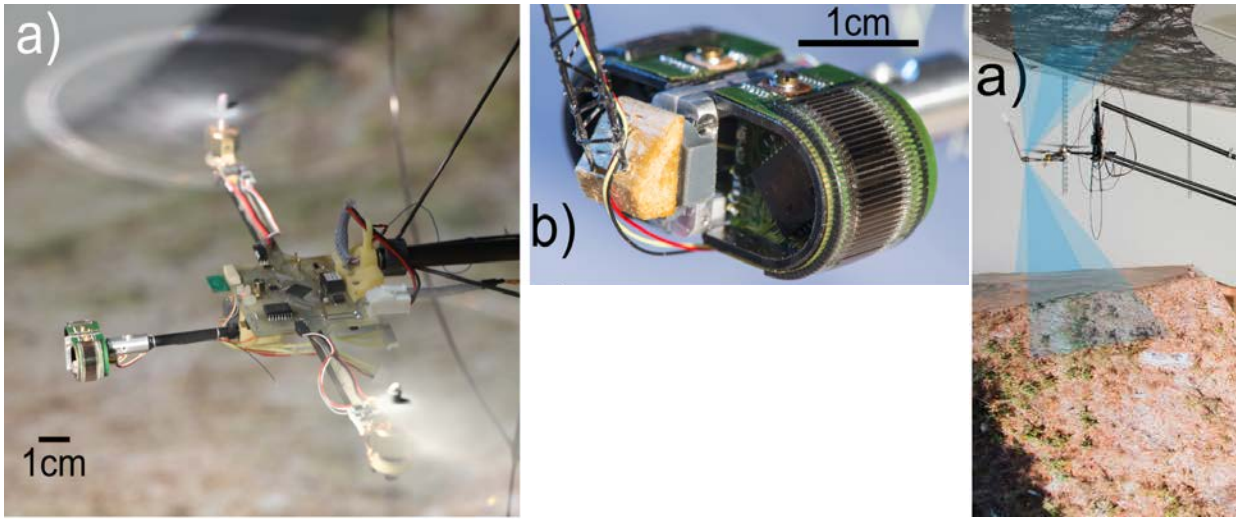
LORA III: Forward control loop+Side control loop



Roubieu et al. (2014) *Bioinspir. Biomim.*

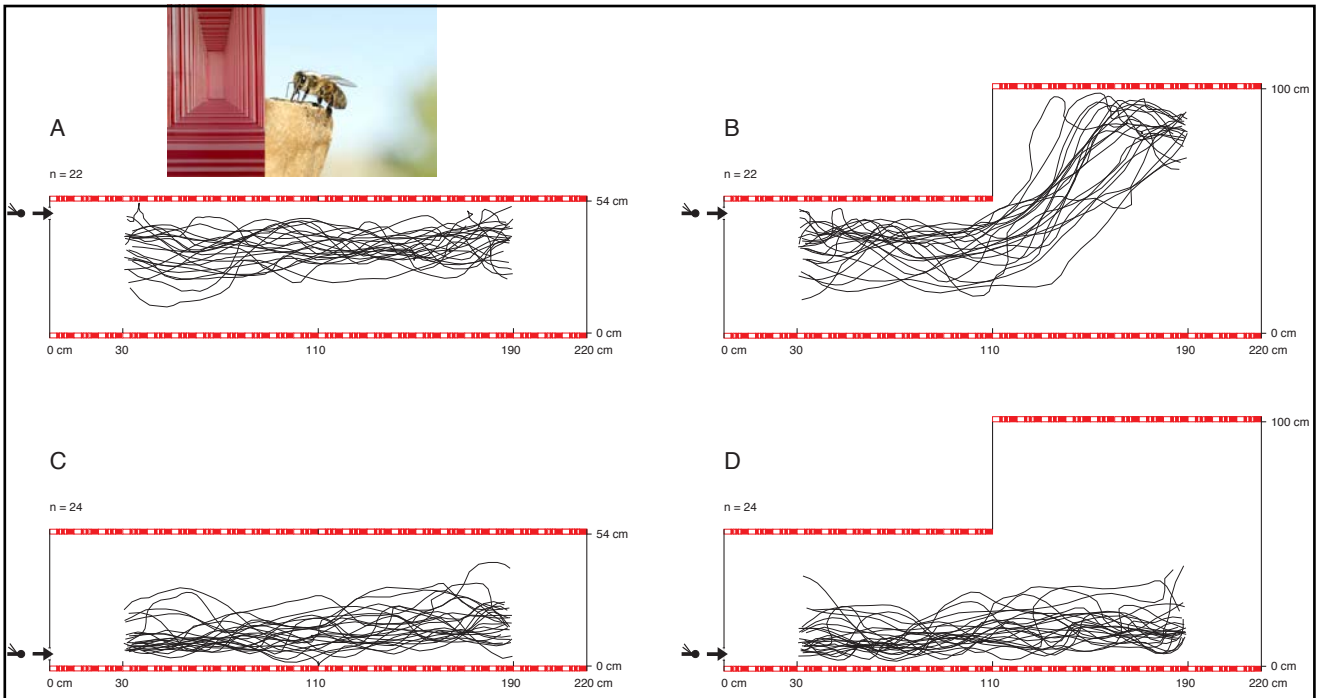


Beerotor: Flying over uneven moving terrain based on optic-flow cues

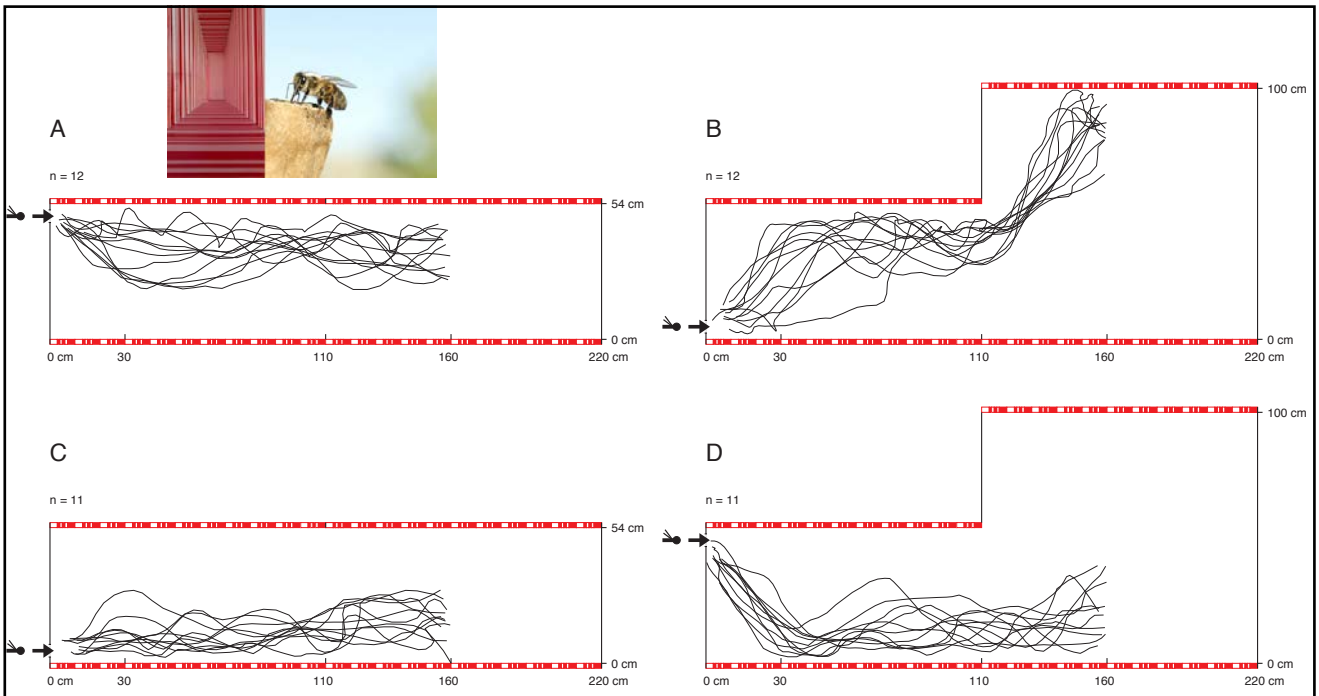


Expert, Ruffier (2015) *Bioinsp & Biomim*

Portelli Serres Ruffier (2017) *Scientific Reports*

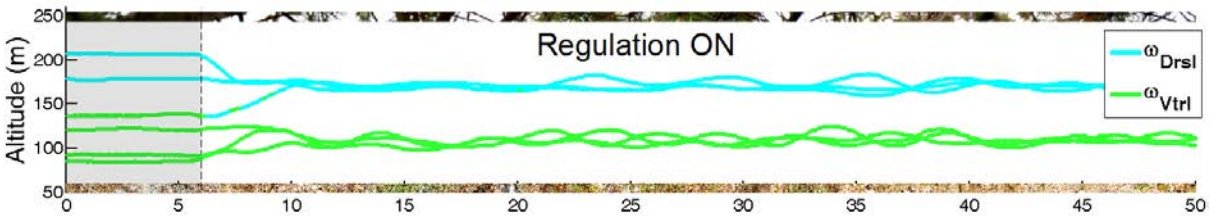


Portelli Serres Ruffier (2017) *Scientific Reports*



Portelli Serres Ruffier (2017) *Scientific Reports*

Results : Influence of the initial altitude



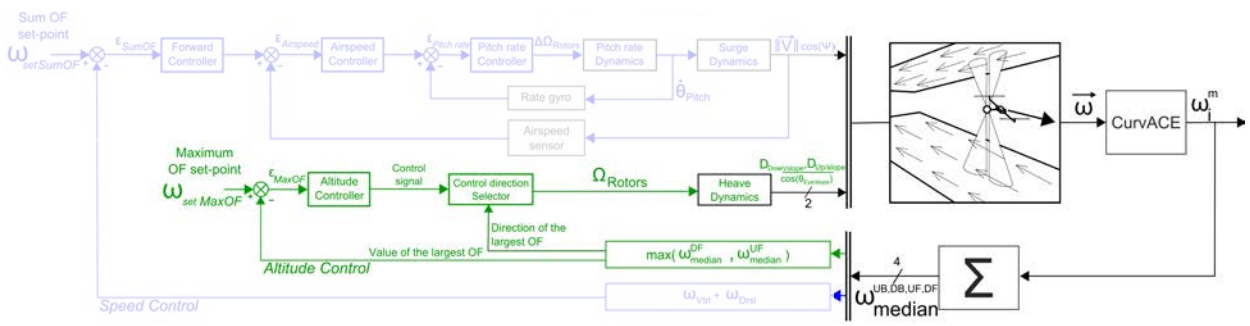
Expert and Ruffier - IROS - 2012

- Initial altitude ranging from 80 to 220cm.
- The robot followed the nearest wall.
- Same final altitude in the cases the robot is following the ceiling and in the cases the robot is following the ground.

1st control law:

To regulate the maximum optic flow (ventral or dorsal)

=> by acting upon the rotors' speed

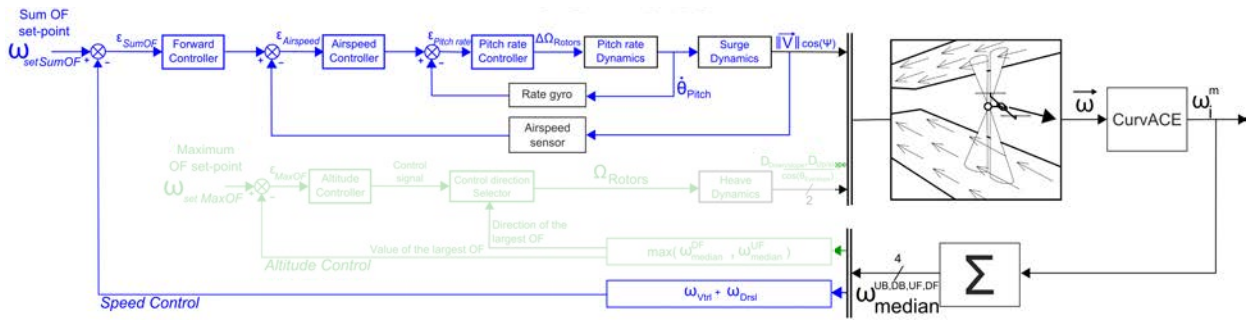


Expert, Ruffier (2015) *Bioinsp & Biomim*

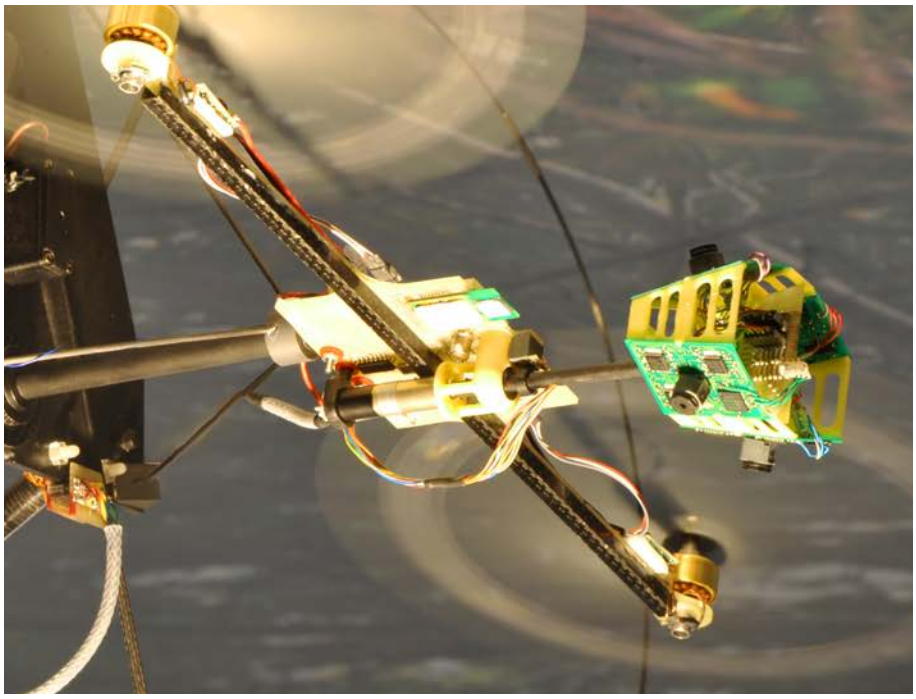
2nd control law:

To regulate the sum of ventral + dorsal optic flow

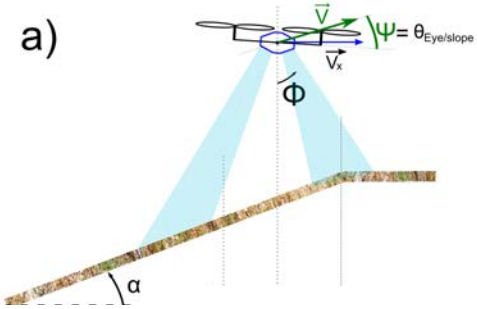
=> by acting upon the rotors differentially



Expert, Ruffier (2015) *Bioinsp & Biomim*



Without eye reorientation, the OF depends on the angle between the eye and the slope which causes the crash



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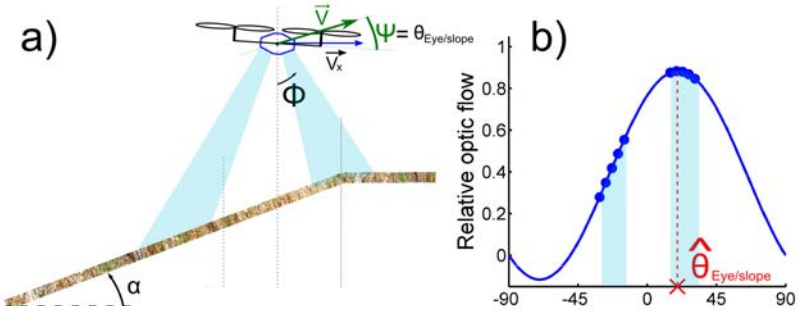
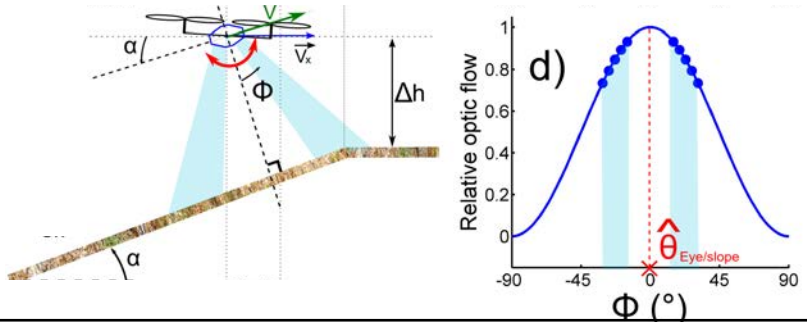


3rd control law:

To orient the OF sinus profile toward surface below

=> by acting upon the eye's pitch



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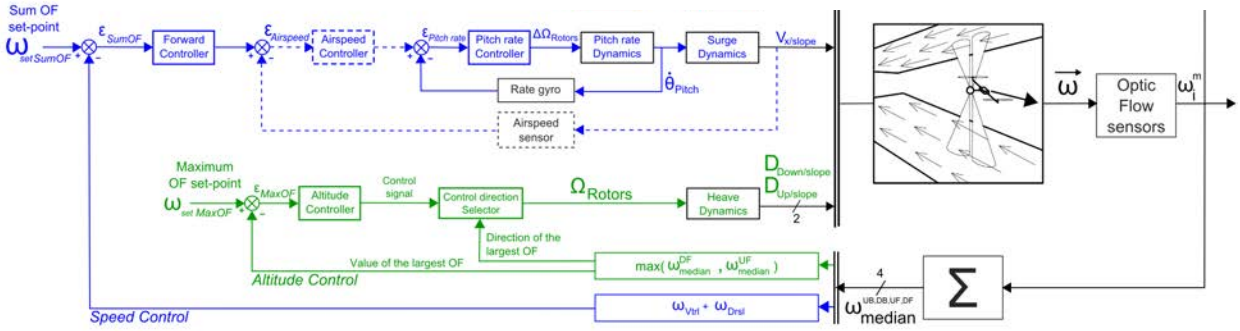

Expert, Ruffier (2015) *Bioinsp & Biomim*

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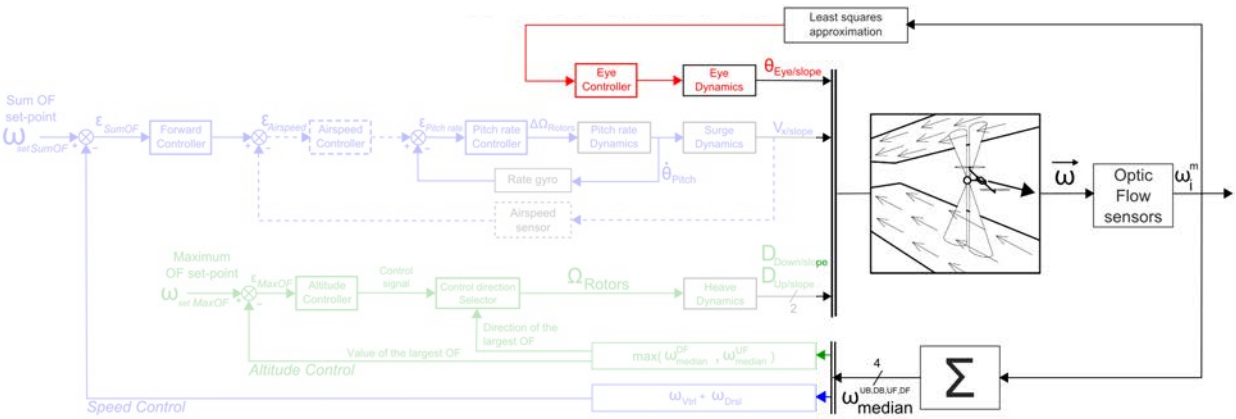
To orient the OF sinus profile toward surface below

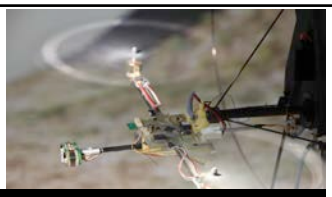
=> by acting upon the eye's pitch



Expert, Ruffier (2015) *Bioinsp & Biomim*

Beerotor

(Expert, Ruffier 2015 *Bioinsp. Biomim.*)

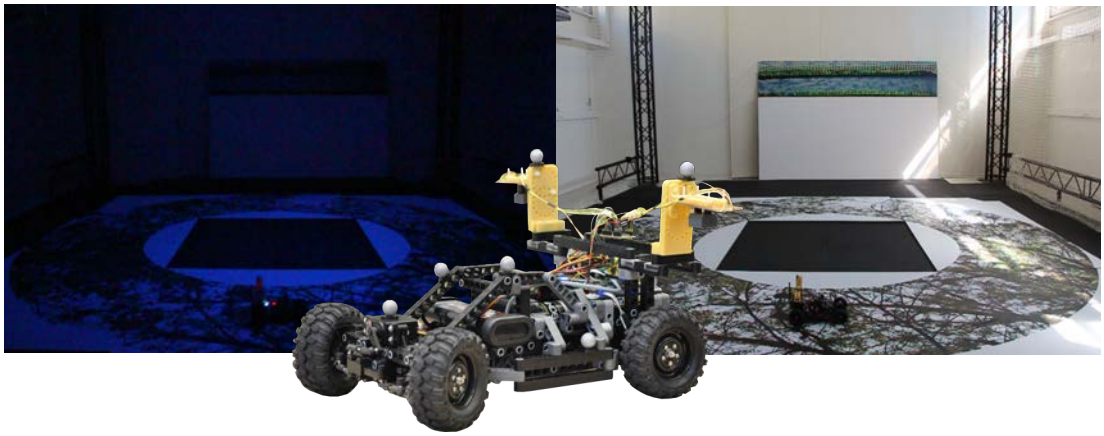


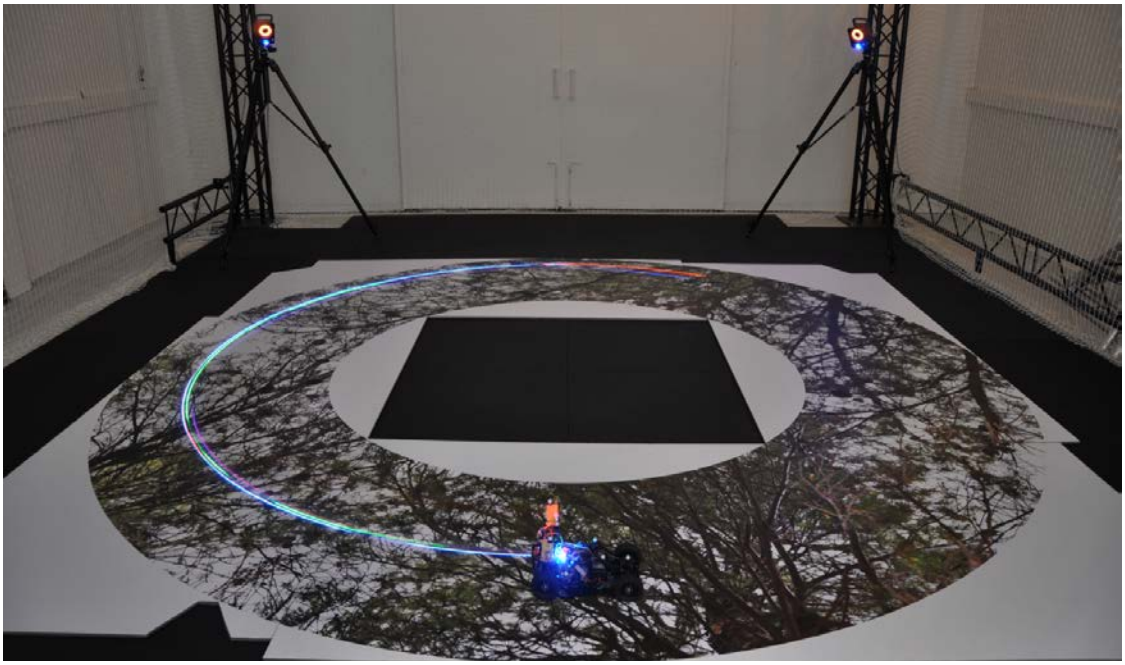
Moving terrain + up and down oscillation

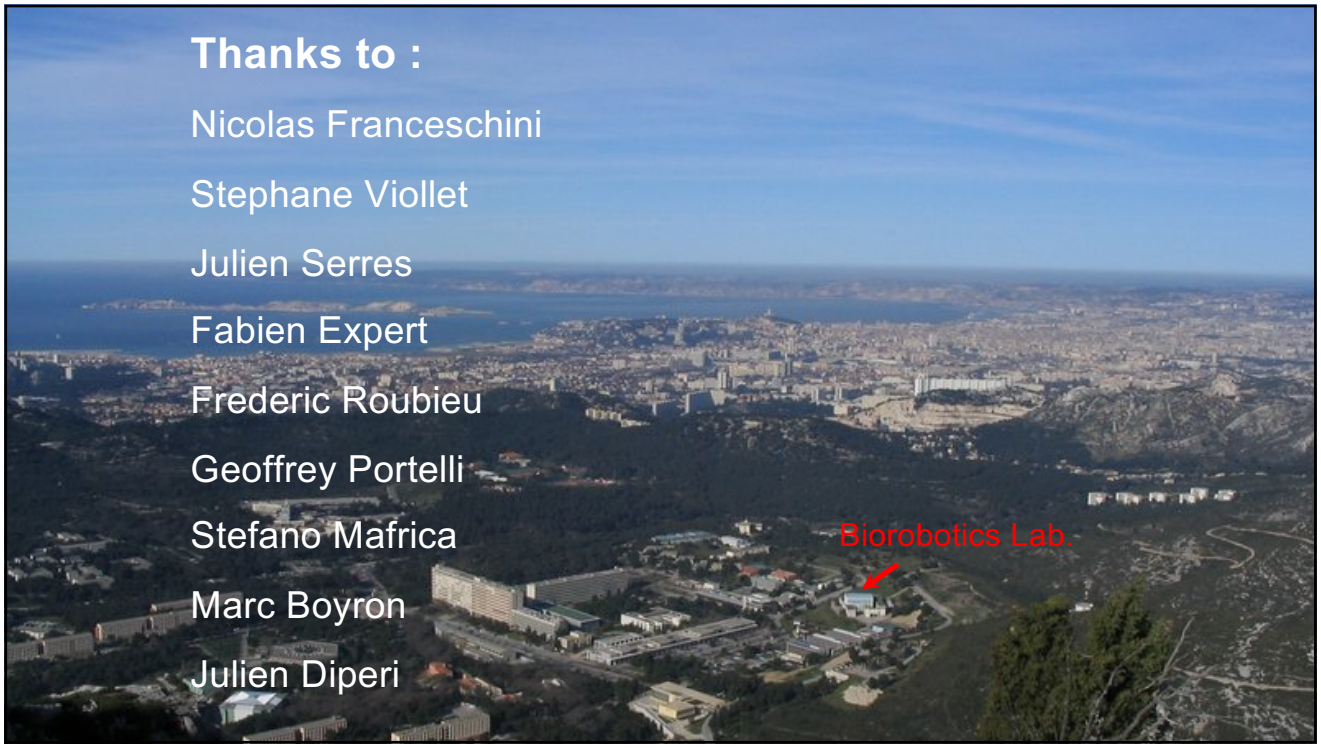
Expert, Ruffier (2015) *Bioinsp & Biomim*

Optic-Flow Based car-like guidance and odometry

PSA PEUGEOT CITROËN



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