Review of different designs of optical payloads for micro-UAV

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EuroSDR/ETH Tutorial on Unmanned Air Vehicles for geomatic

13 september 2011

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OUTLINE

- ❑ Introduction: recall of the different needs of vision for a micro UAV
- ❑ Lesson from Nature
- ❑ Design strategy based on the formalism of third-order Seidel aberrations
- ❑ Co-design (optics with detectors and image processing)
- ❑ Practical case: miniaturization of cooled infrared cameras

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Vision needs

<u>Functional (help for navigation)</u>

- takeoff / landing
- orientation
- obstacle avoidance

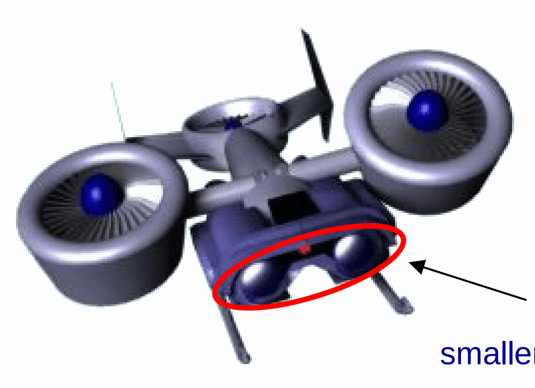
<u>Operational</u>

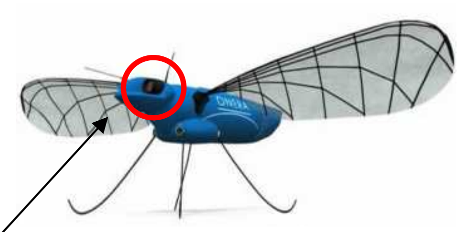
- detection
- recognition
- identification
- pursue of targets
- **<u>geomatic</u>**
- **3D view**
- **Multispectral imagery**
- **Hyperspectral imagery**

⇒ Need of various optical systems to fit all these needs

Optical payloads on micro-UAVs: passive imagery

Compactness





smaller cameras are needed

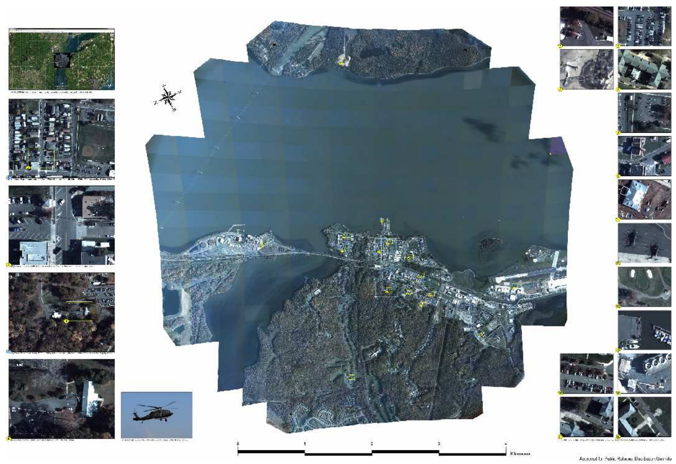
Traditional and/or bulky cameras

Example :

ARGUS-IS gigapixel surveillance sensor :

- 1,8 gigapixel
- 4 optical telescopes
- Each with 92 5-megapixel focal-plane array-cellephone camera chips

ARGUS-DARPA's All-Seeing Eye : AVIATION WEEK Copyright 2011



⇒ Need of breakthroughs in the optical design to fit the payload contraints of small micro-UAV

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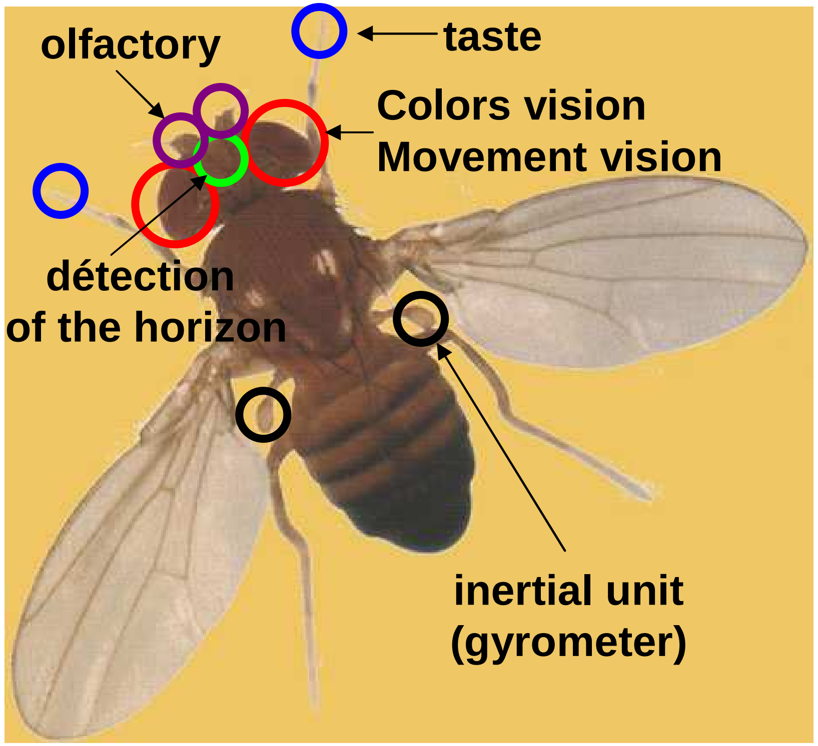
Why studying flying invertebrate ?

Technical sheet:

Mass: 0,1g
Size: 2 cm
Speed: 36 km/h
Acceleration: 2 g
Rotation: 4000°/s

Flying capability:

Obstacle avoidance
Stationary Flying
Control of the height
Landing, takeoff
Pursuit of target at high speed

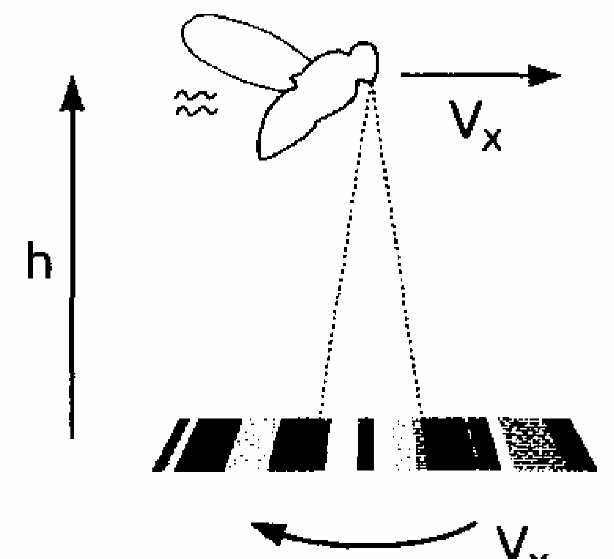


sensory organs aboard

⇒ Vision: the most important sensor for areal attitude

F. Aubépart, de la mouche aux puces !, « Systèmes optroniques intégrés pour l'observation » congress (SOOS), 2009.

Movement detection: Vision with image processing



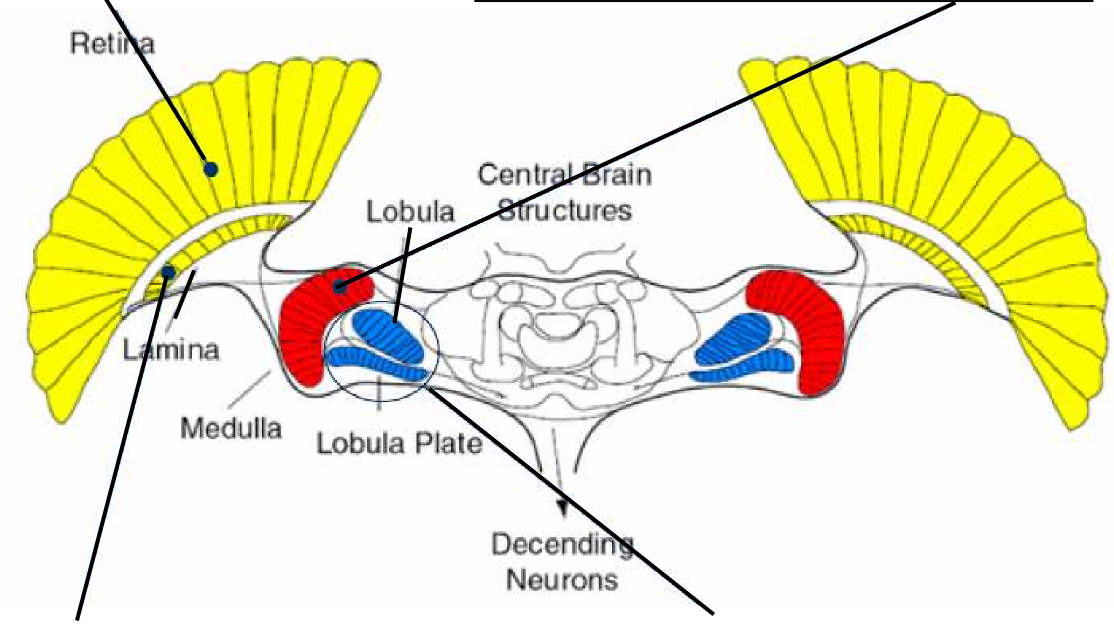
Optical flow: $\omega = \frac{V_x}{h}$

Flying capability :

Obstacle avoidance
Stationary Flying
Control of the height
Landing, takeoff
Pursuit of target at high speed

Sampling and et spatial filtering

Séparation of dark-bright transitions 'ON' and bright-dark transitions 'OFF'



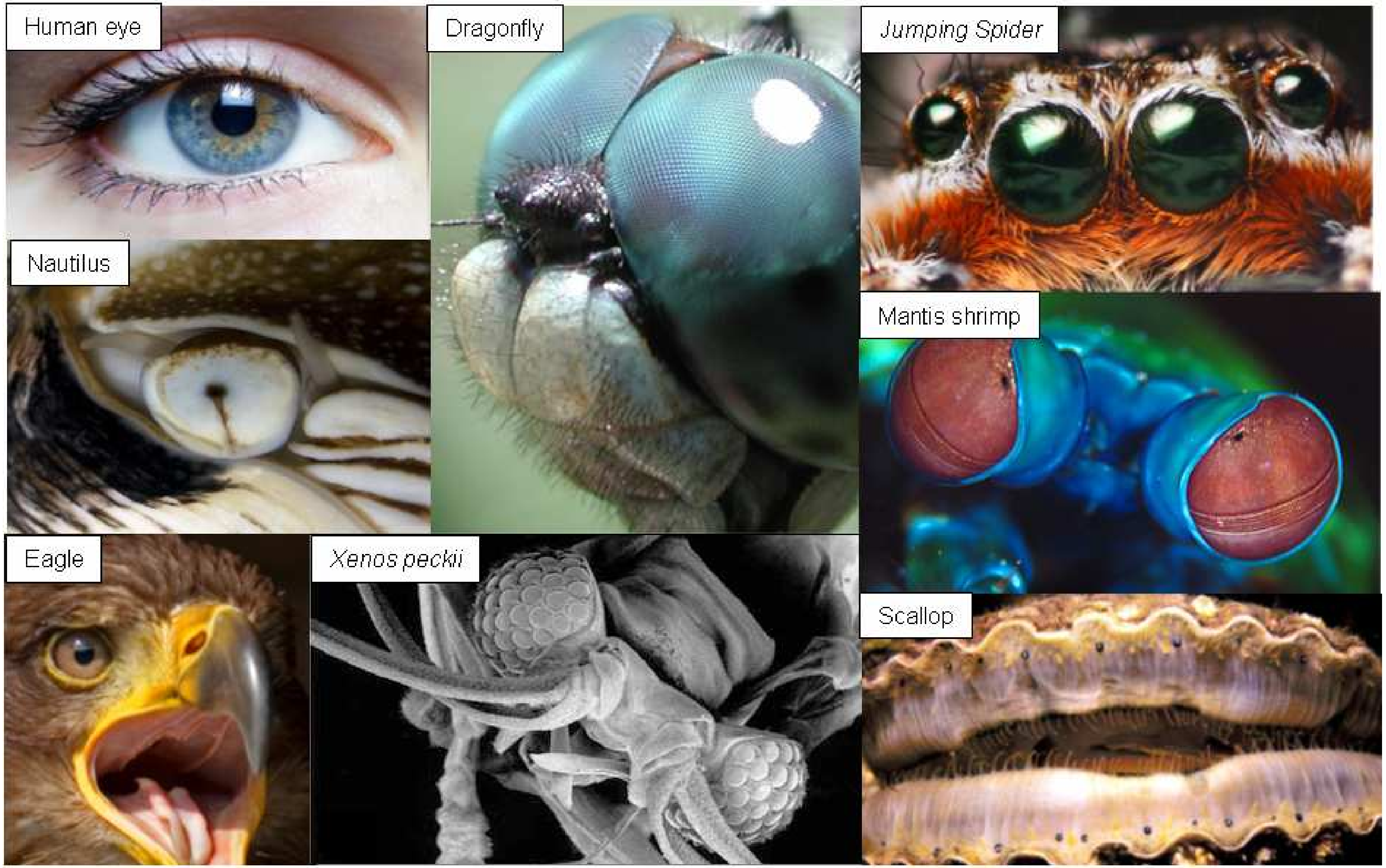
Suppression of the offset and detection of the variations (high-pass filter)

Détection of the direction of the movement (vertical et horizontal) and fusion of the angular speed on small and wide field of view

⇒ Optical flow available at the end of the lobula !

F. Ruffier et al., « Optic flow regulation; the key to aircraft automatic guidance », Robotics and Autonomous Systems, 50, 177-194, 2005
N. Franceschini et al., « a Bio-Inspired Flying Robot Sheds light on Insect Piloting Abilities », Current Biology, 17, 329-335, 2007
F. Aubépart, de la mouche aux puces !, « Systèmes optroniques intégrés pour l'observation » congress (SOOS), 2009.

Animal eyes



<u>Big animals</u>: monochannel optical systems

<u>Small animals</u>: mono and multichannel optical systems and the greatest variety of eyes

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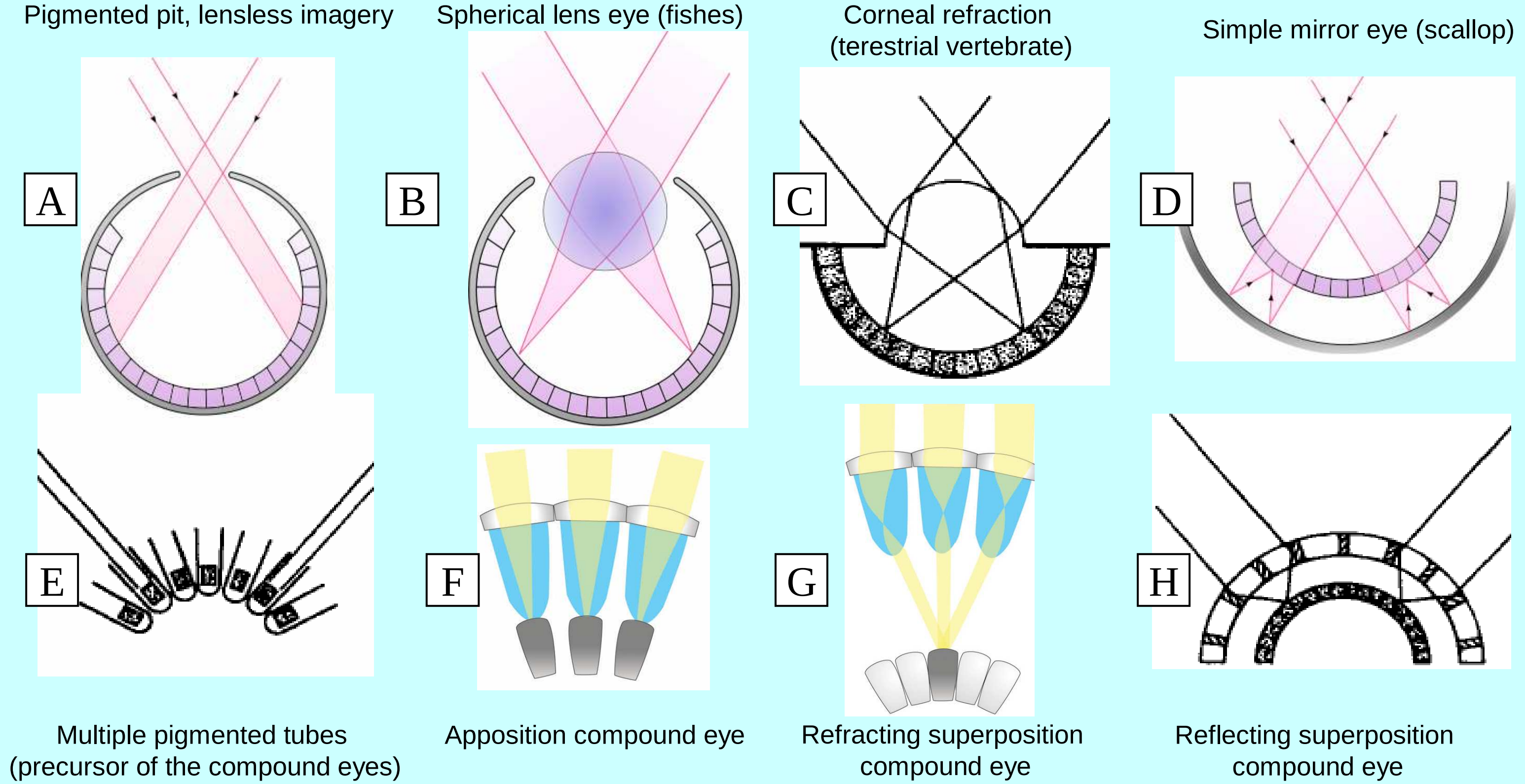
A great variety of eyes

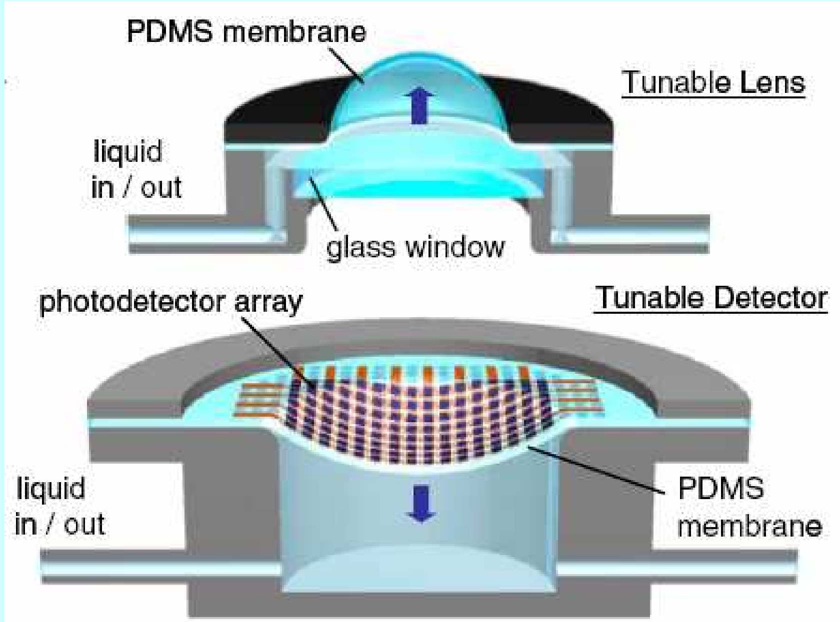


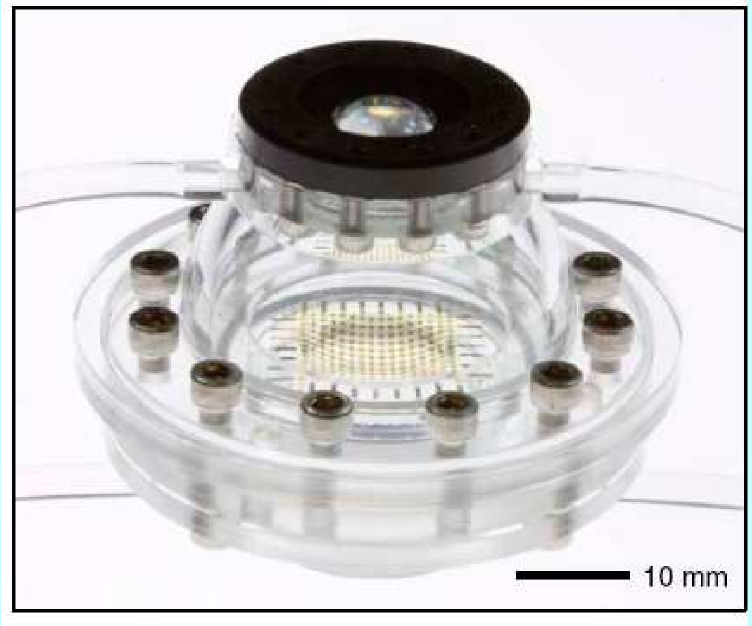
⇒ Various type of mono-channel and multichannel eyes

⇒ Common point: curved retina

M.F. Land, the optics of animal eyes, contemp. Phys, Vol 29, pp 435-455, 1988

Curved detectors





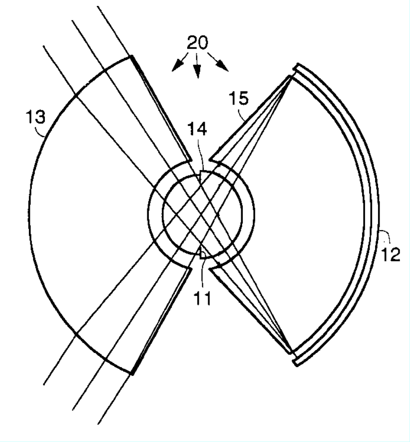
Emergent tecnology

⇒ Opens new ways for designing compact wide field of view optical systems

I.Jung et al. , dynamically tunable hemispherical electronic eye camera system with adjusable zoom capability, PNAS Applied Physical Sciences
H. Cho Ko et al. ,A hemispherical electronic eye camera based on compressible silicon optoelectronics, Nature, Vol 454, pp748-753, 2008
S.-B. Rim et al, The optical advantages of curved focal plane arrays, Opt. Express, Vol 16, pp 4965-4971, 2008

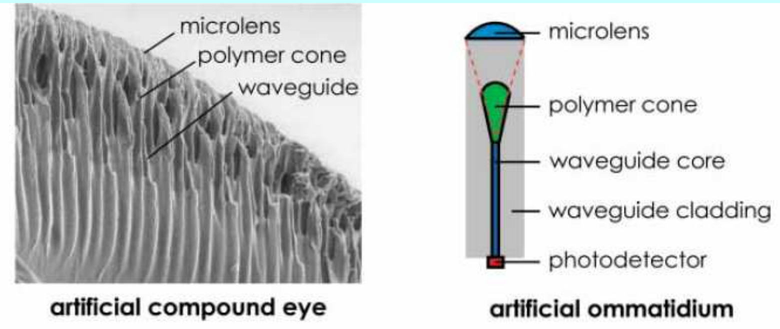
Original optical designs based on curved detectors

Wide field of view cameras



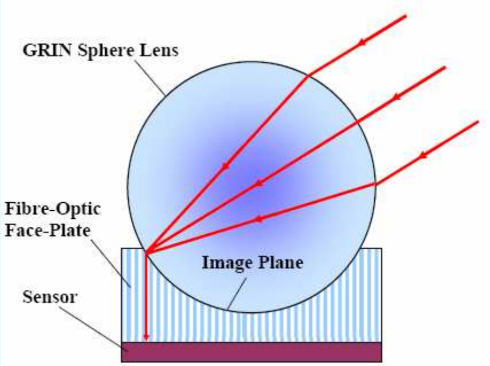
C. W. Chen and J. Steve, Ultra wide field of view concentric sensor system, Patent, US6320703

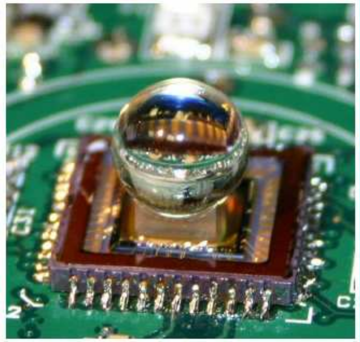
Artificial insect eyes



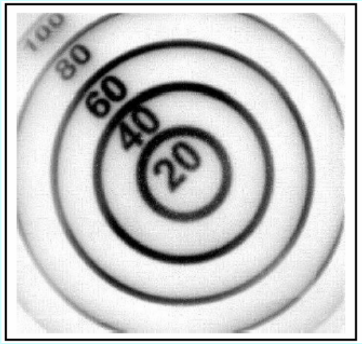
K.-H. Jeong et al, biologically inspired artificial compound eyes, SCIENCE, Vol 312, pp 557-561

Concept of a foveated camera using a GRIN sphere lens





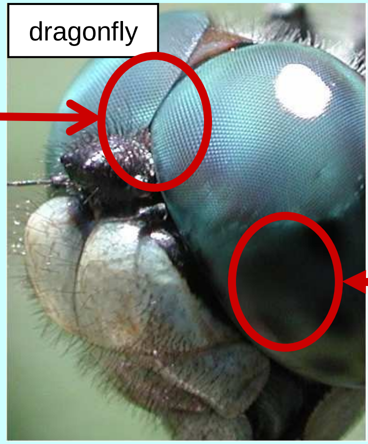
Assembled sphere lens camera.



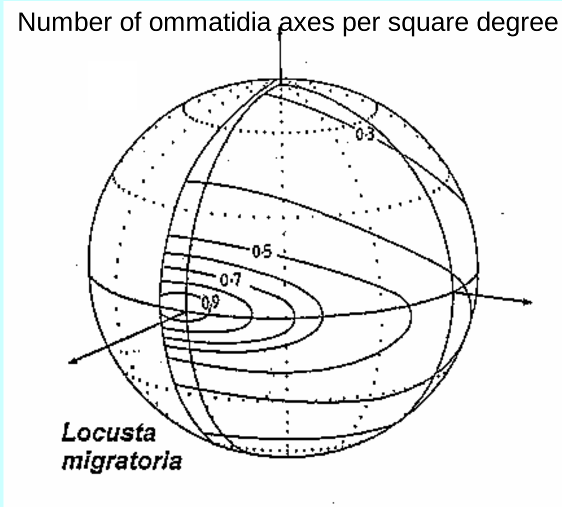
L.C. Laycock et al., miniature imaging devices for airborne platforms, SPIE, Vol 7113, 71130M, 2008

Variation of the angular resolution in the field of view

Identification:
high resolution



Detection:
small resolution
optical flow

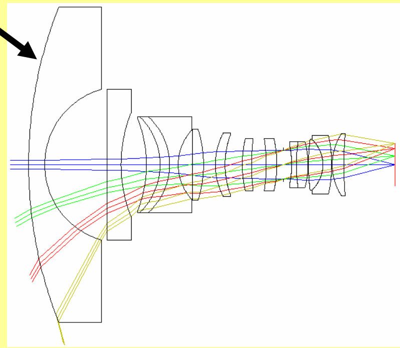


The resolution is decreasing from front to back and from the equator to the dorsal and ventral

M.F. Land & D-E Nilsson, animal eyes, oxford animal biology series, p146.

ImmerVision Enables 360°

Control of the distortion of a fish-eye lens by aspherising and anamorphosing the lens



S. Thibault et al., « enhanced optical design by distortion control », SPIE Vol. 5962, 596211, 2005.

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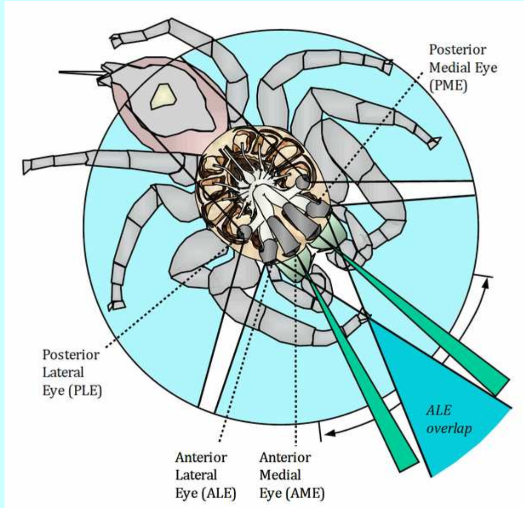
Multi-aperture imaging device

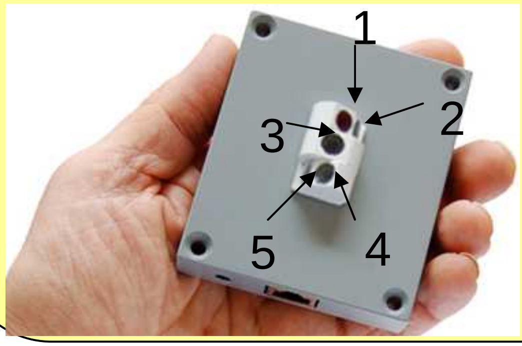
Identification:
high resolution
small field of view

Detection:
small resolution
high field of view



Combinaison of various cameras for identification or surveillance applications

Scallop imaging



Field of view of 180° obtained by 5 camera modules with an elementary field of view of 20°x36°

180°

http://www.scallopimaging.com/

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Advanced imagery functions

3D view
Stereo vision

Multispectral imagery
Polarimetric imagery

$\Rightarrow$ A lot of image processing before interpreting the scene

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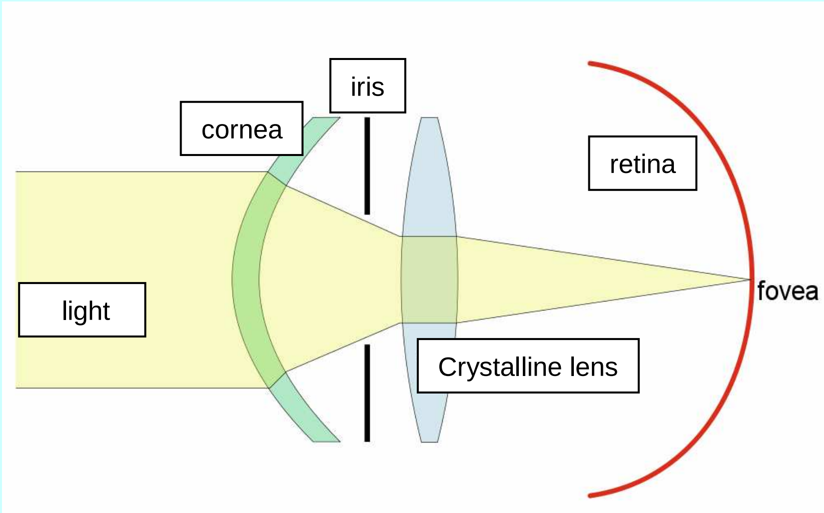
Design strategy

A simple optical system inspired from the nature and composed of less than 4 elements :

Scheme of an human eye



- <2 optical componants
- 1 diaphragme
- 1 detector

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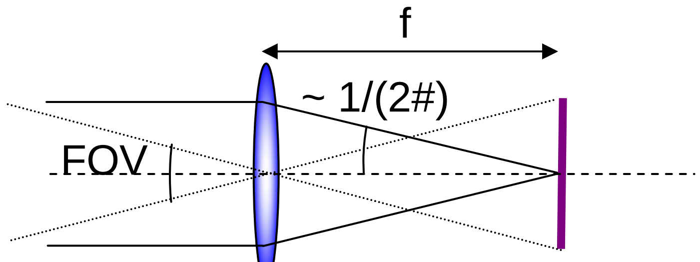
Aberrations of a simple optical system



f : Focal length

: f - number

FOV : Field of view

A_3, A_4, A_5, A_6 : Seidel coefficients

Maximal wave aberrations (at the edge of the exit pupil and for a maximal field of view):

$$W^{(4)}{}_{max} = A_3 \frac{f^4}{\#^4} + A_4 FOV \frac{f^4}{\#^3} + A_5 FOV^2 \frac{f^4}{\#^2} + A_6 FOV^3 \frac{f^4}{\#}$$

Spherical aberration | Coma | Field curvature and astigmatism | Distortion

The amount of aberrations decreases when

- A_3, A_4, A_5, A_6 decreases
- f decreases
- FOV decreases
- # increases

F. De la Barrière et al. , design strategies to simplify and miniaturize imaging systems, Appl. Opt., Vol 50, pp 943-951, 2011

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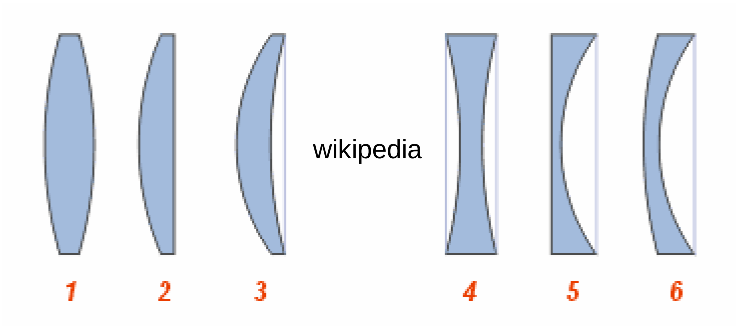
Traditional design: playing on the Seidel coefficients

Seidel coefficients (for instance A_3,A_4,A_5,A_6) depends on:

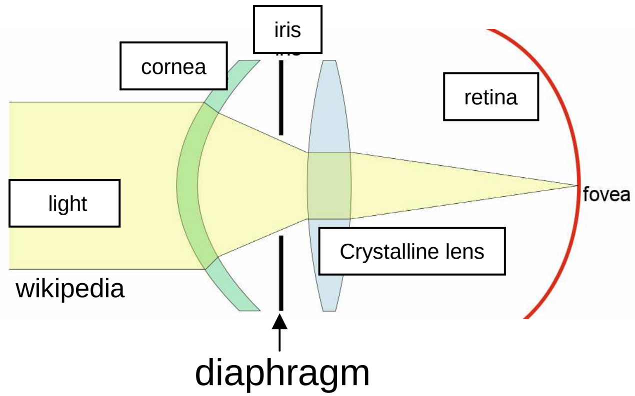
- ❑ The optical power of the lens
- ❑ The bending of the lens



Convergent Lenses
1. Biconvex lens
2. Plano-convex lens
3. Convergent meniscus

Divergent Lenses
4. biconcav lens
5. Plano-concav lens
6. Divergent méniscus

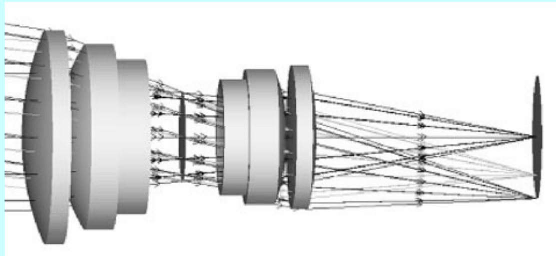
- ❑ The materials that make the optics (Glass such as BK7, Plastic, Germanium, Silicon…)
- ❑ The position of the diaphragm



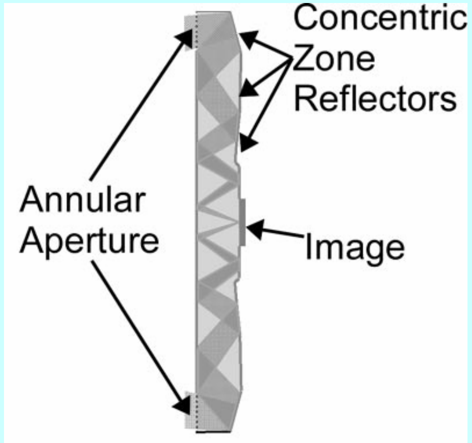
⇒ If a single lens is not sufficient then add more lenses to add more lenses !

Catadioptric lenses (small field of view)

Mixing transmissive and reflective surfaces on a single componant

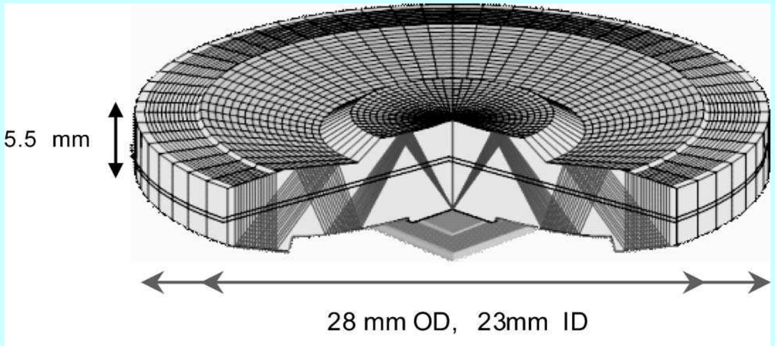


Conventional refractive lens.



Annular folded

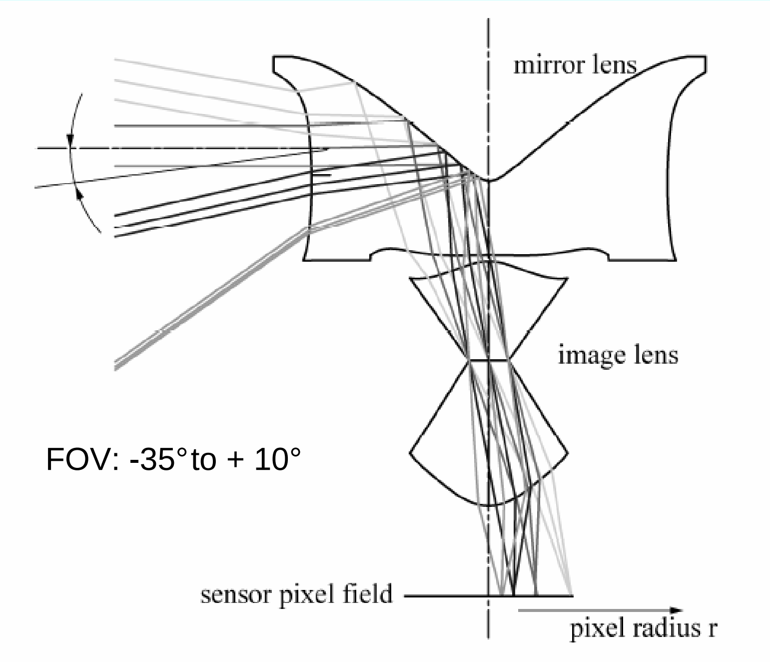
Exemple



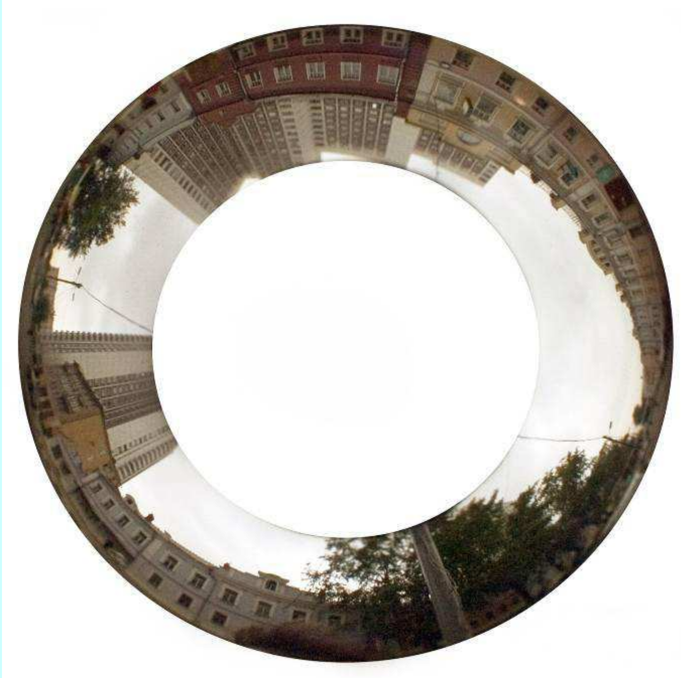
<u>Focal lens</u>: 38mm
<u>Field of view</u>: 6,7°

E. J. Tremblay et al., Ultrathin cameras using annular folded optics, Appl. Opt., Vol 46, pp 463-471, 2007.
E. J. Tremblay et al., Ultrathin four-reflection imager, Appl. Opt., pp 343-354, 2009.

Catadioptric lenses (panoramic field of view)



FOV: -35° to + 10°



Example of an image obtained from a panoramic annular lens

C. Gimkiewicz et al., Ultra-Miniature Catadioptrical System for an Omnidirectional Camera, SPIE micro-optics 2008, Vol 6992, 69920J, 2008.
V. N. Martynov et al., New constructions of panoramic annular lenses: design principle and output characteristics analysis, SPIE Optical Design and Engineering III, Vol 7100, 71000O-1, 2008.

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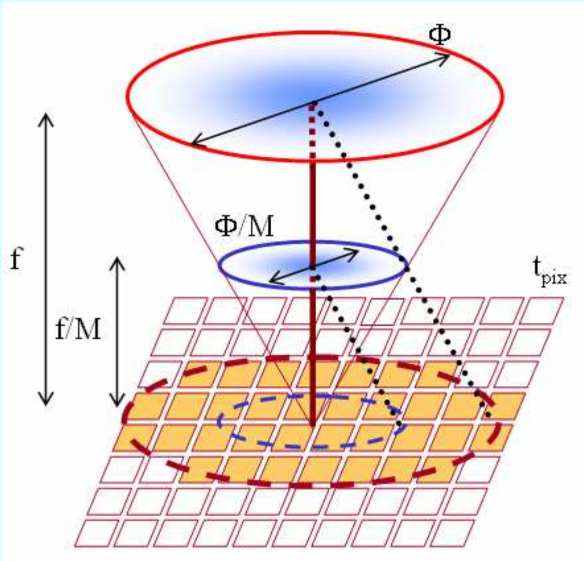
Decreasing the focal length f

Miniaturization while keeping a F-number and a FOV constant



$\Rightarrow$ Decrease of the number of resolved points if the same detector is kept

A. W. Lohmann, "Scaling laws for lens systems", Appl. Opt. **28**, pp. 4996-4998 (1989).

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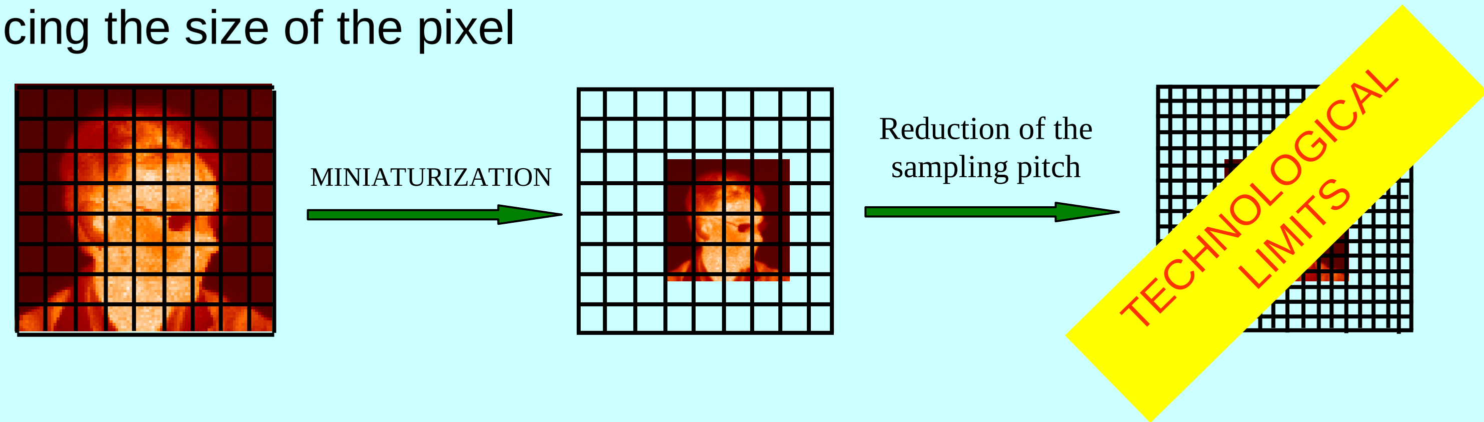
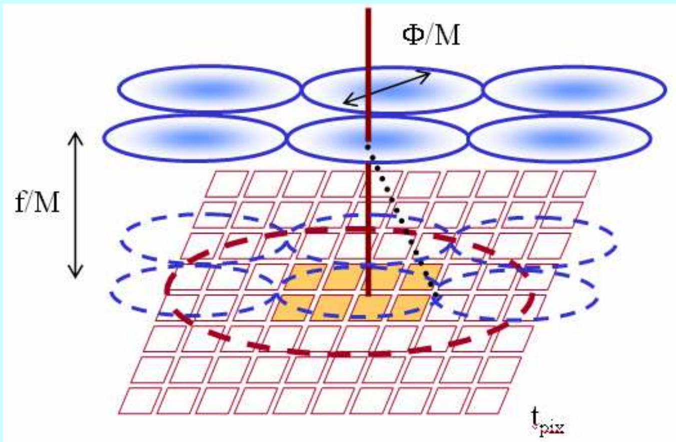
Solution to maintain the number of resolved points

Reducing the size of the pixel



Dividing the sampling of the scene in several optical channels and reducing the fill-factor of the pixel

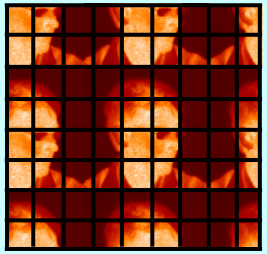


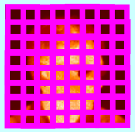
J. Tanida et al, “Thin observation module by bound optics (TOMBO): concept and experimental verification”, Appl. Opt. **40**, pp. 1806-1813 (2001).

Interest of replicating a miniaturized optical system in terms of sampling of the scene

Subpixel shifts between the subimages ($t_{pix}/2$)

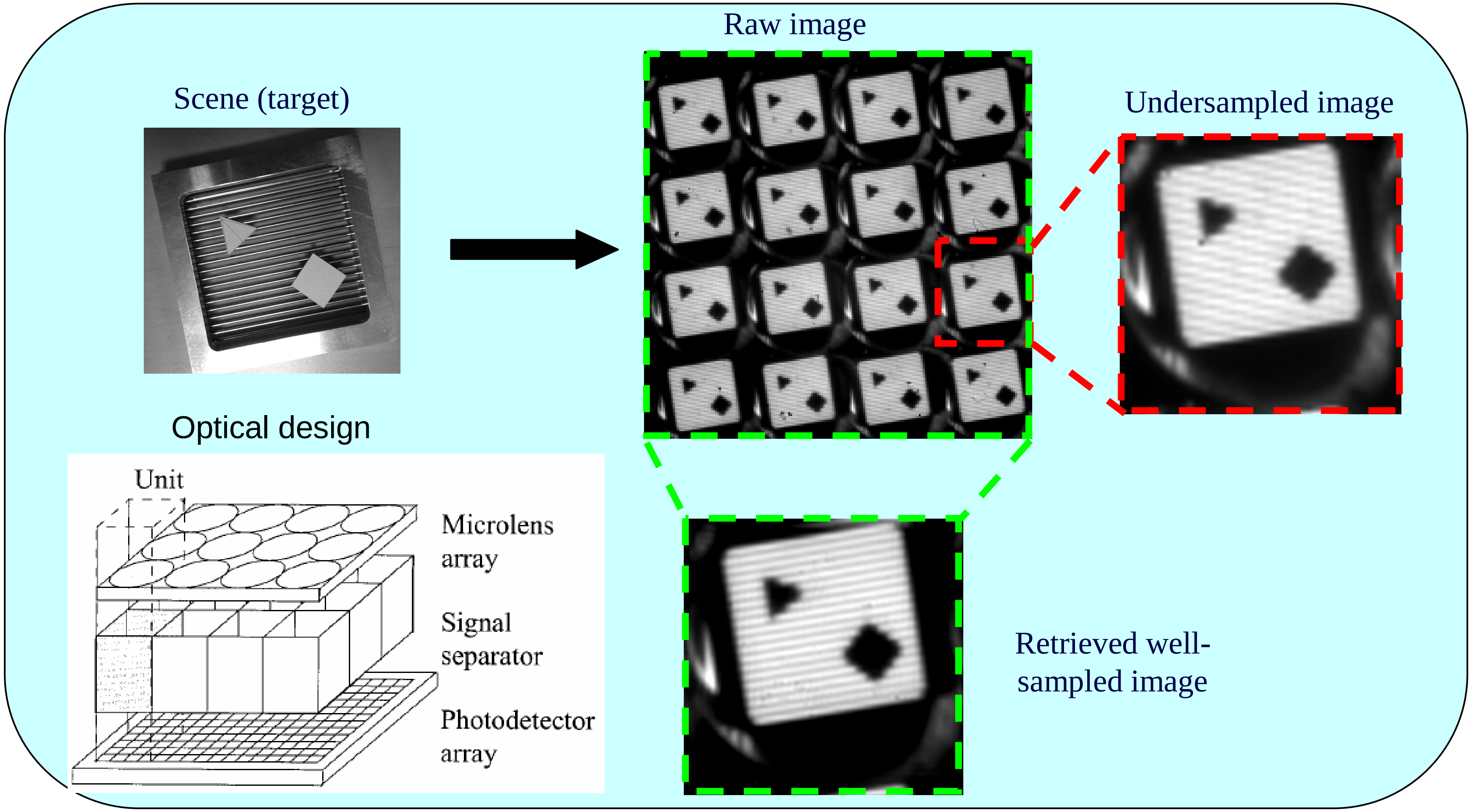
Sampling of the subimage by a scanning monodetector of size t_{pix} and which is scanned with a pitch equal to $t_{pix}/2$





F. de la Barrière et al, “Modulation transfer function measurement of a multichannel optical system”, Appl. Opt. **49**, 2879-2890 (2010).

TOMBO principle

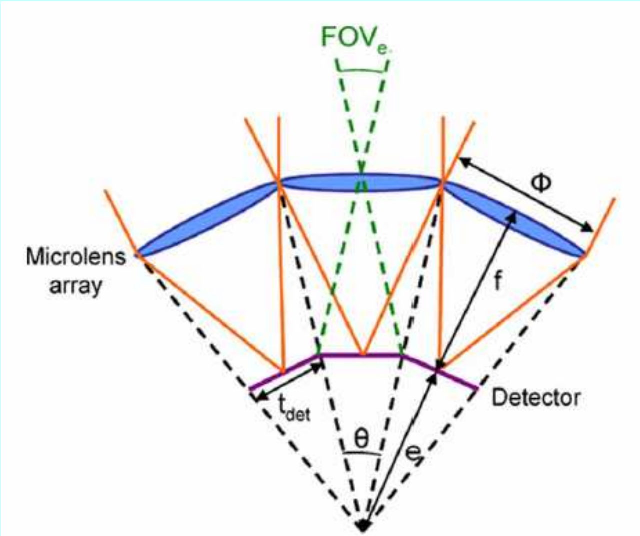


⇒ Reduction of the focal length without loosing angular resolution

Y. Kitamura, Reconstruction of a high-resolution image on a compound-eye image-capturing system, Appl. Opt., 43, pp 1719-1727, 2004.
F. De la Barrière et al., Modulation transfer function measurement of a multichannel optical system, Appl. Opt., 49, pp 2879-2890, 2010

Decreasing elementary FOV: Multichannel Insect's Eyes

Principle:



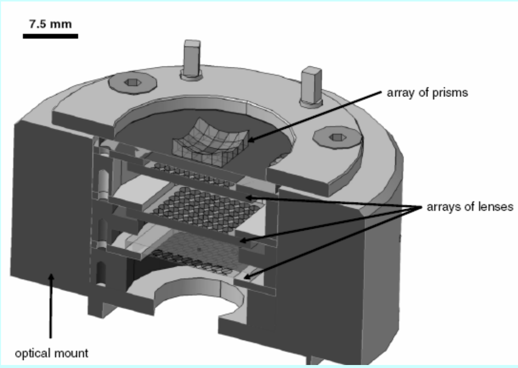
Raw image

Restored image

G. Druart and al., Demonstration of an infrared microcamera inspired by Xenos peckii vision, Appl. Opt., Vol 48, pp 3368-3374, 2009.

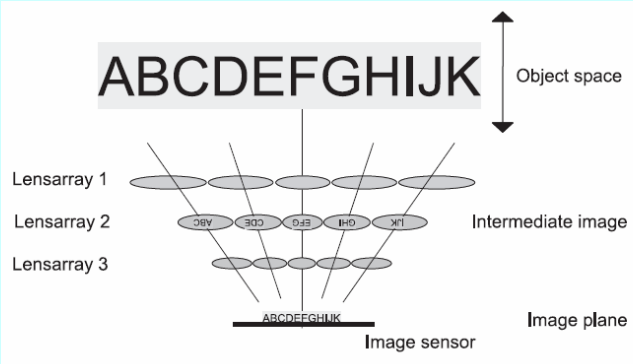
Examples of Multichannel Insect's Eyes

Deflector at the front of the optical design



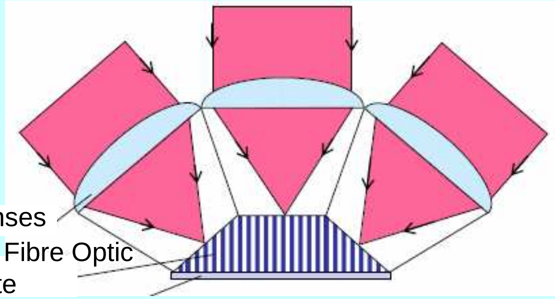
G. Druart and al., Demonstration of an infrared microcamera inspired by Xenos peckii vision, Appl. Opt., Vol 48, pp 3368-3374, 2009.

Arrays of lenses with different pitches



J. Duparré, Microoptical telescope compound eye, Opt. Express, Vol 13, pp 889-903, 2005

Deflector on the detector



L.C. Laycock et al., Multi-aperture imaging device for airbone platforms, SPIE, Vol 6737, 673709, 2007
L.C. Laycock et al., Miniature imaging devices for airborne platforms, SPIE, Vol 7113, 71130M, 2008

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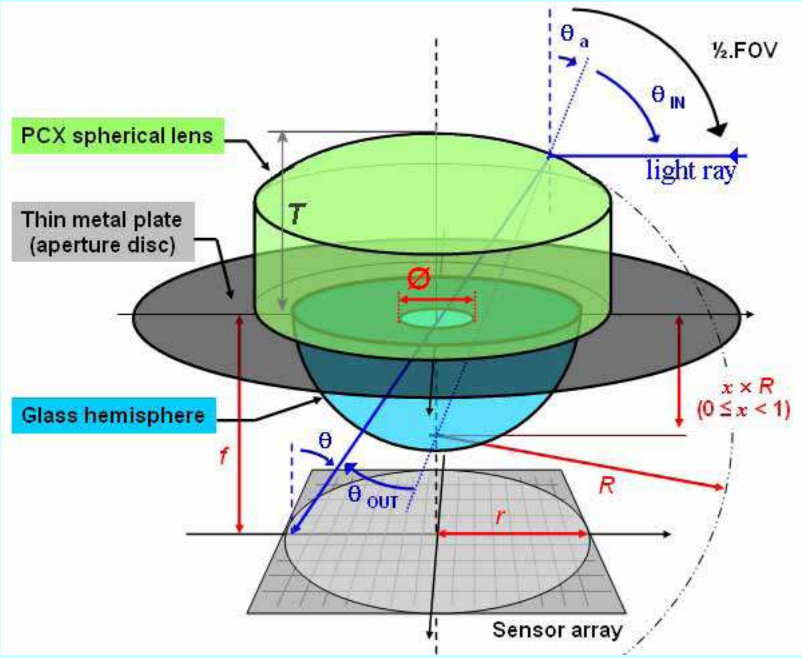
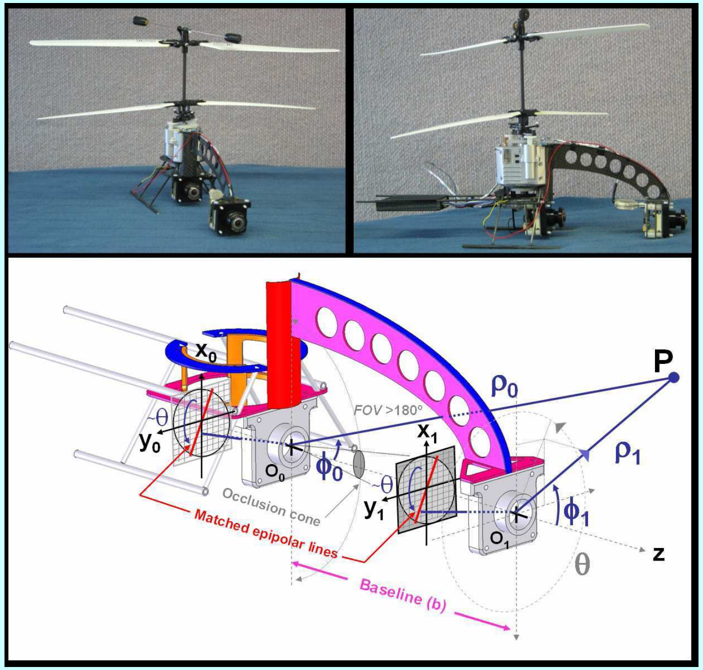
Decreasing #: Lensless imagery

Back to the camera oscura (camera with a pinhole)

Wide field of view Pinhole camera





C.-L. Tisse, Low-cost miniature wide angle imaging for self motion estimation, Opt. Express, Vol 13, pp 6061-6072, 2005.
C.-L. Tisse, Hemispherical Depth Perception for slow-Flyers using coaxially aligned fisheye cameras, Flying Insects and Robot Symposium, 2007

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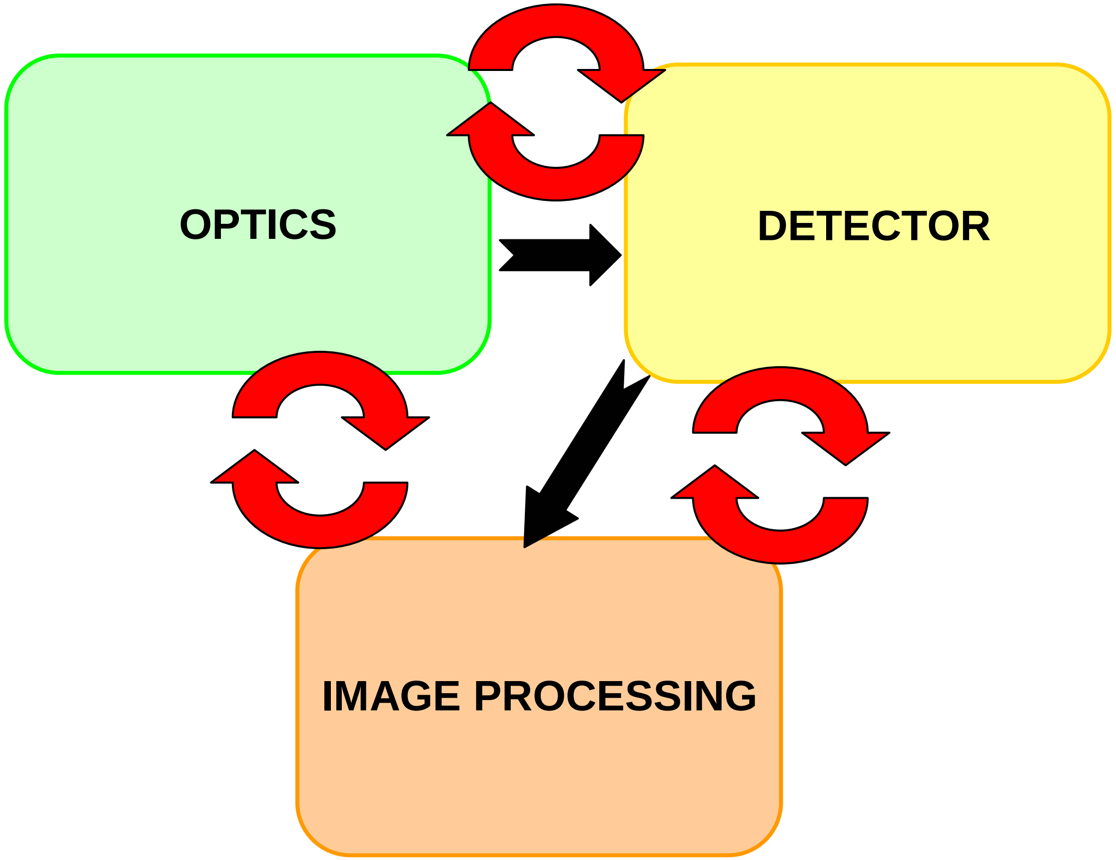
Working on the interfaces



⇒ Co-design between Optics, Detector and Image Processing

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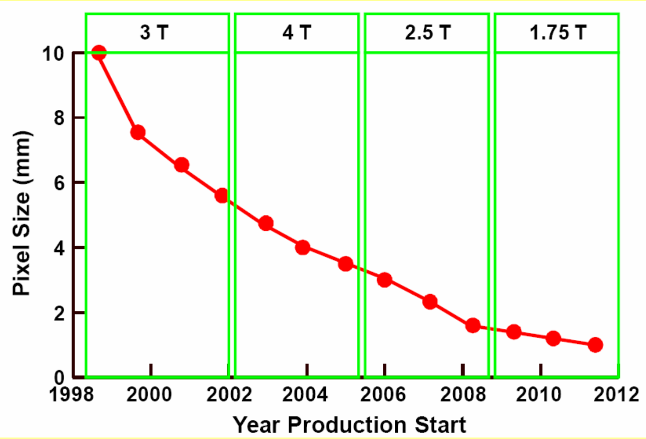
Troughputs on detectors influence the optical design

Decrease of the pixel pitch

⇒ smaller cameras

Challenges :
-Get as many as possible photons/electrons in these tiny pixels
-Optical system with better throughput without increasing its volume.

Trends for visible detectors:

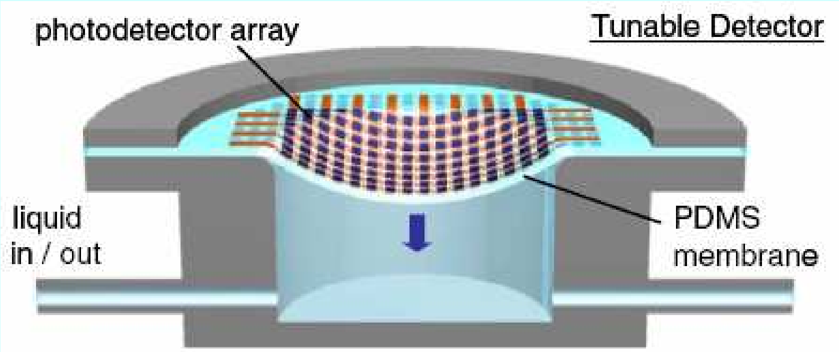


A. Theuwissen, "Imagers getting worse, images getting better", Harvest Imaging 2011.
After : Jean-Luc Jaffard : "CMOS Image Sensor for Mobile Phone Camara : Past and Trends", MINATEC Crossroads, Grenoble, June 26, 2008.

Curving the detector

⇒ Simplifying optical design

Challenge :
-Same amount of pixels as planar detectors



I.Jung et al. , dynamically tunable hemispherical electronic eye camera system with adjusable zoom capability, PNAS Applied Physical Sciences

⇒ Technological breakthroughs are still expected on detectors !

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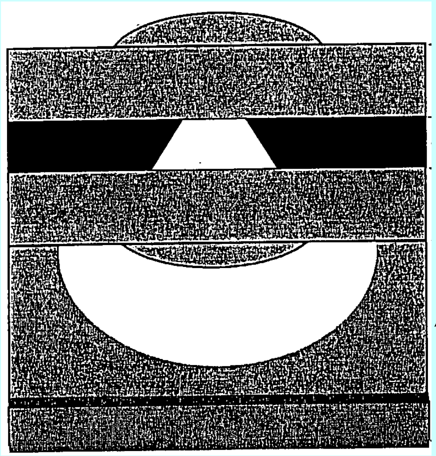
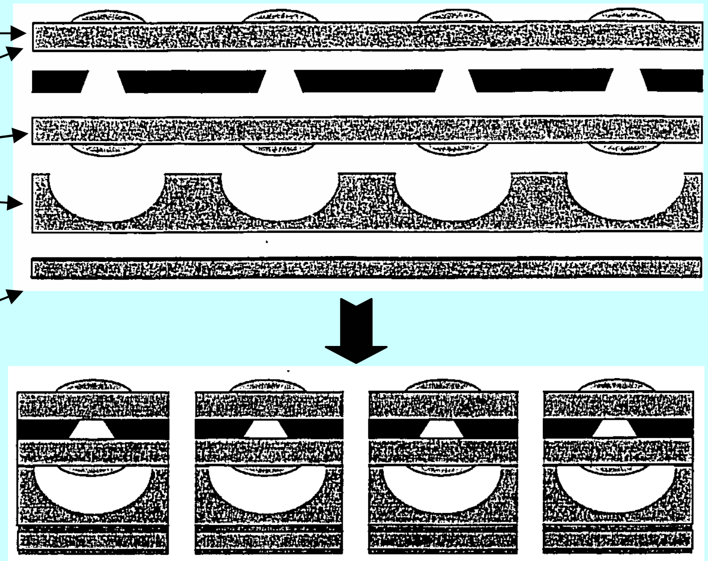
Optics on detectors : toward on chip cameras



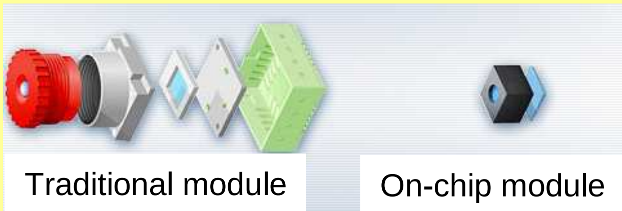
wafer

optics

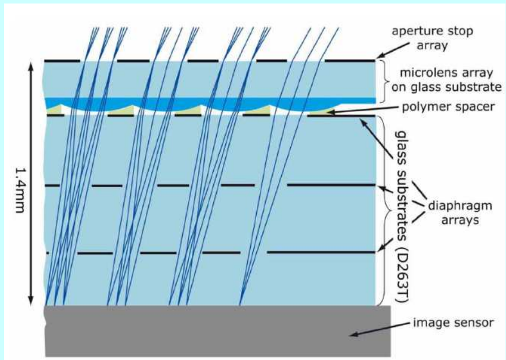
detector

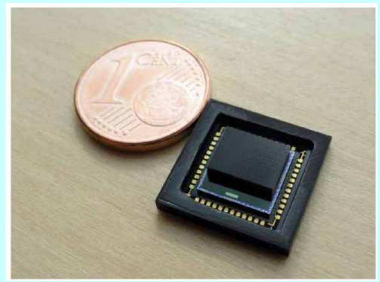


J. Duparré et al., « camera module, array based thereon and method for the production thereof », patent, WO2006010622A1



http://www.ovt.com/

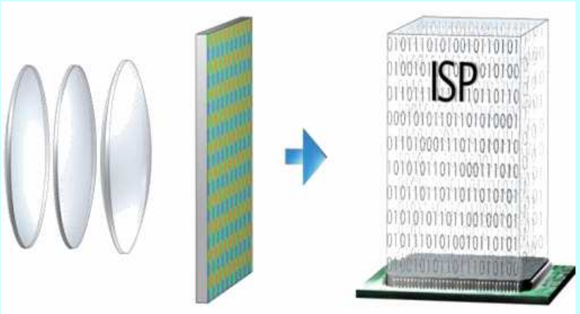




A. Brückner et al., « Thin wafer-level camera lenses inspired by insect compound eyes », Opt. Express **18**, 24379-24394 (2010)

Computational imaging: an important part for modern optical device

A digital camera :



1 2 3

1: Lens
2 : Sensor
3 : Embedded Image processing (ISP)

- Correction of lens and sensor flaws and improvement of image capability
- Extraction of information and addition of advanced applications

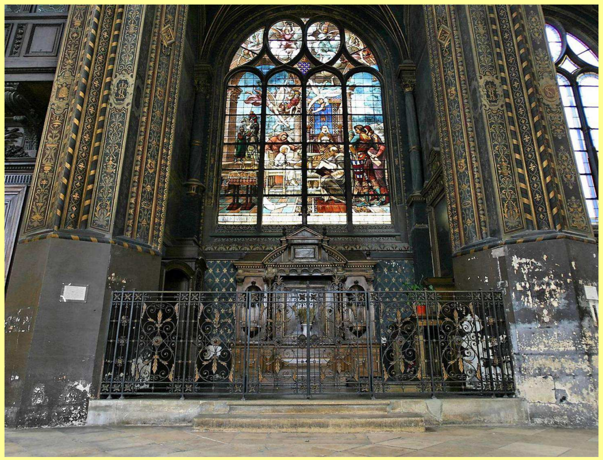
Correction

Contrast and distortion correction

DXO Image Science

http://www.dxo.com

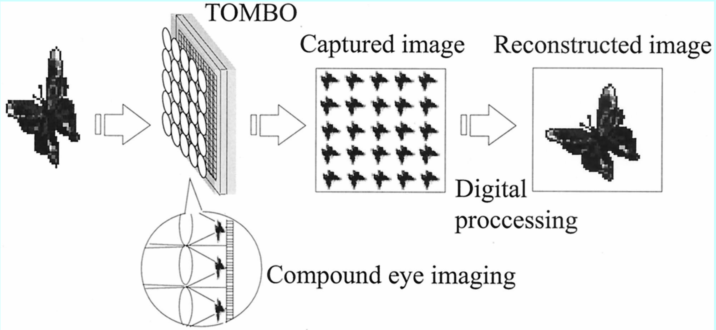
(ISP)



H.-P. Nguyen, Pourquoi le numérique révolutionne l'appareil photo ?, « Systèmes optroniques intégrés pour l'observation » congress (SOOS), 2009.

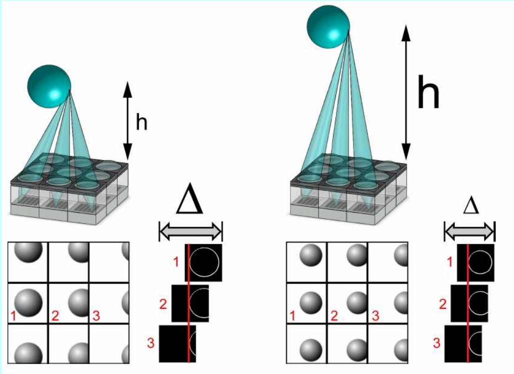
application to multichannel cameras

Improvement superresolution



Y. Kitamura and al., « Reconstruction of a high-resolution image on a compound-eye image-capturing system », appl. Opt., 43, pp 1719-1727, 2004

Extraction 3D view



R. Horisaki et al., « three-dimensional Information acquistion using a compound imaging system », Opt. Rev., 14, pp 347-350, 2007.

http://pelicanimaging.com/

Thinner imaging system with advanced applications :

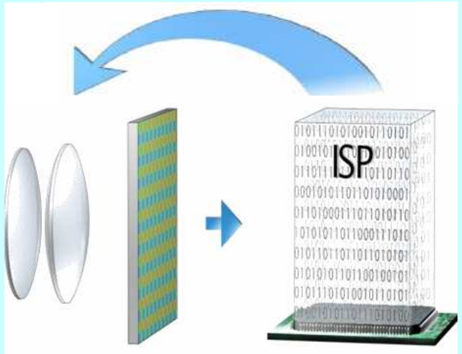
- 3-D depth
- Gesture control
- Interaction with the image before and after capturing the shot

B. Willburn et al., « High performance Imaging Using large camera Arrays », ACM Transactions on Graphics, 24, pp 222-235, 2005

Computational imaging: a way to simplify optical systems

<u>Codesign:</u> ISP, lens, sensor are co-optimized to achieve new performances

« Computational Imaging » (Nayar)
« Wavefront coding » (Dowski, Harvey)



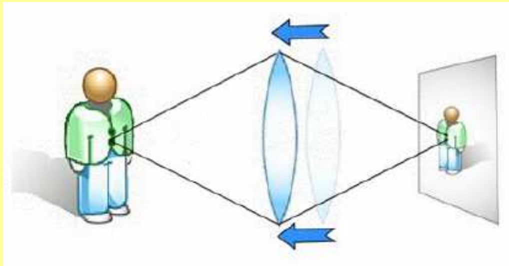
1 2 3

1: Lens
2 : Sensor
3 : Embedded Image processing (ISP)

❑ Simplification of the optical design

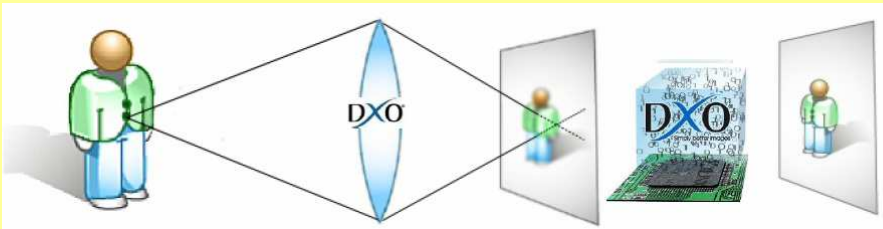
Getting ride of the autofocus

<u>A traditional autofocus</u>:
Move/reshape lenses for focusing

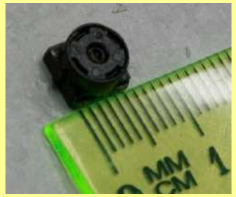


3Mpix AF f/2.8

<u>Digital autofocus (or EDoF):</u>
A special fix focus lens and a digital correction of the image



http://www.dxo.com



3Mpix DxO EDoF f/2.4

H.-P. Nguyen, Pourquoi le numérique révolutionne l'appareil photo ?, « Systèmes optroniques intégrés pour l'observation » congress (SOOS), 2009.

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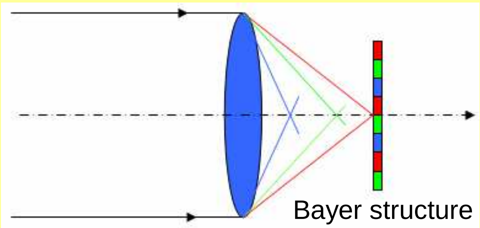
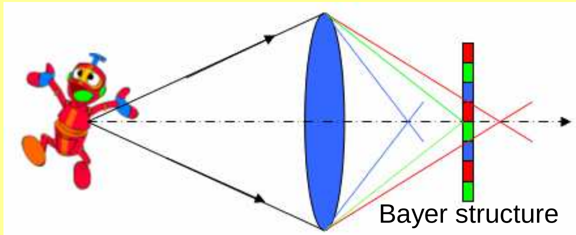
Exemple of a digital autofocus

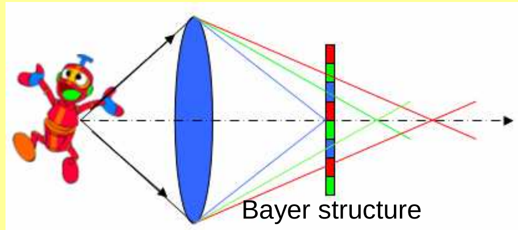
A fixed focus lens with longitudinal chromatic aberrations



red at infinity (landscape)



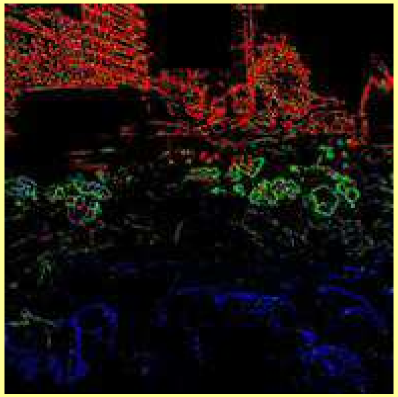
green at 50 cm (portrait)



blue at 20 cm (macro)

Depth Estimation

determines sharpest channel



Sharpness Transport

Reconstructs the colors channels from the sharpest one

Both foreground and background are sharp: long depth of focus

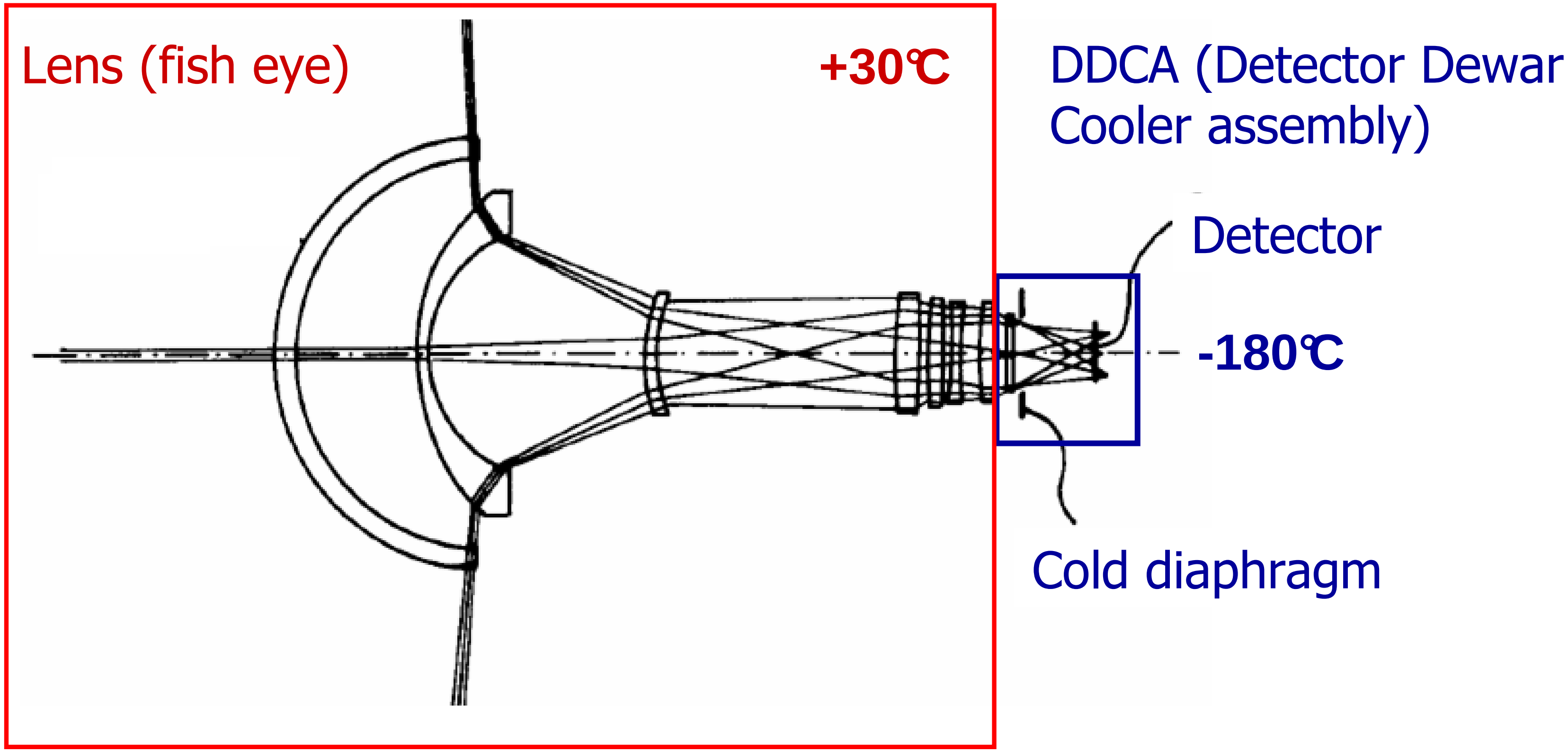
L. Chanas & al. WO095110 patent -2005
L. Jaeguyn & al. Electronics Imaging -2008

H.-P. Nguyen, Pourquoi le numérique révolutionne l'appareil photo ?,
« Systèmes optroniques intégrés pour l'observation » congress (SOOS), 2009.

OUTLINE

- Introduction: recall of the different needs of vision for a micro UAV
- Lesson from Nature
- Design strategy based on the formalism of third-order Seidel aberrations
- Co-design (optics with detectors and image processing)
- Practical case: miniaturization of cooled infrared cameras

Description of a cooled infrared optical system

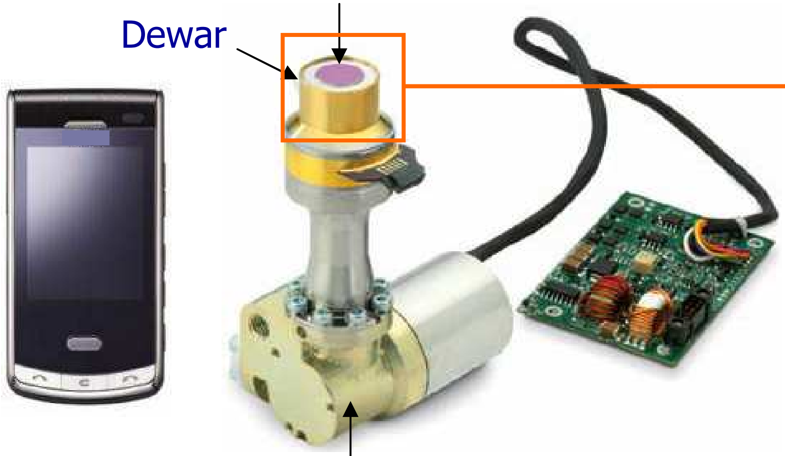


Patent, « Tête optique pour détecteur de départ de missile ou autre équipement de veille », FR2885702 (B1), 2006.

Description of a DDCA

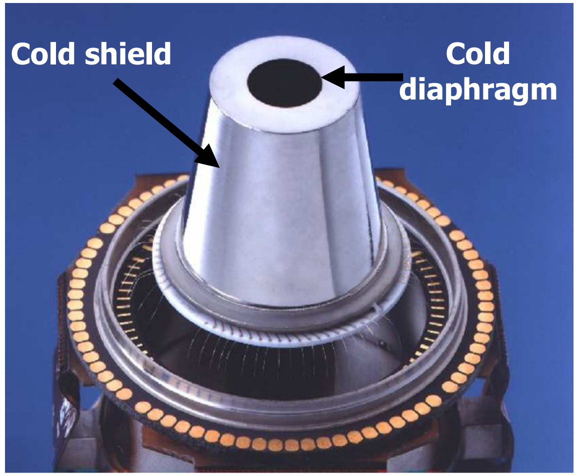
SOFRADIR DDCA (Epsilon)

+30℃



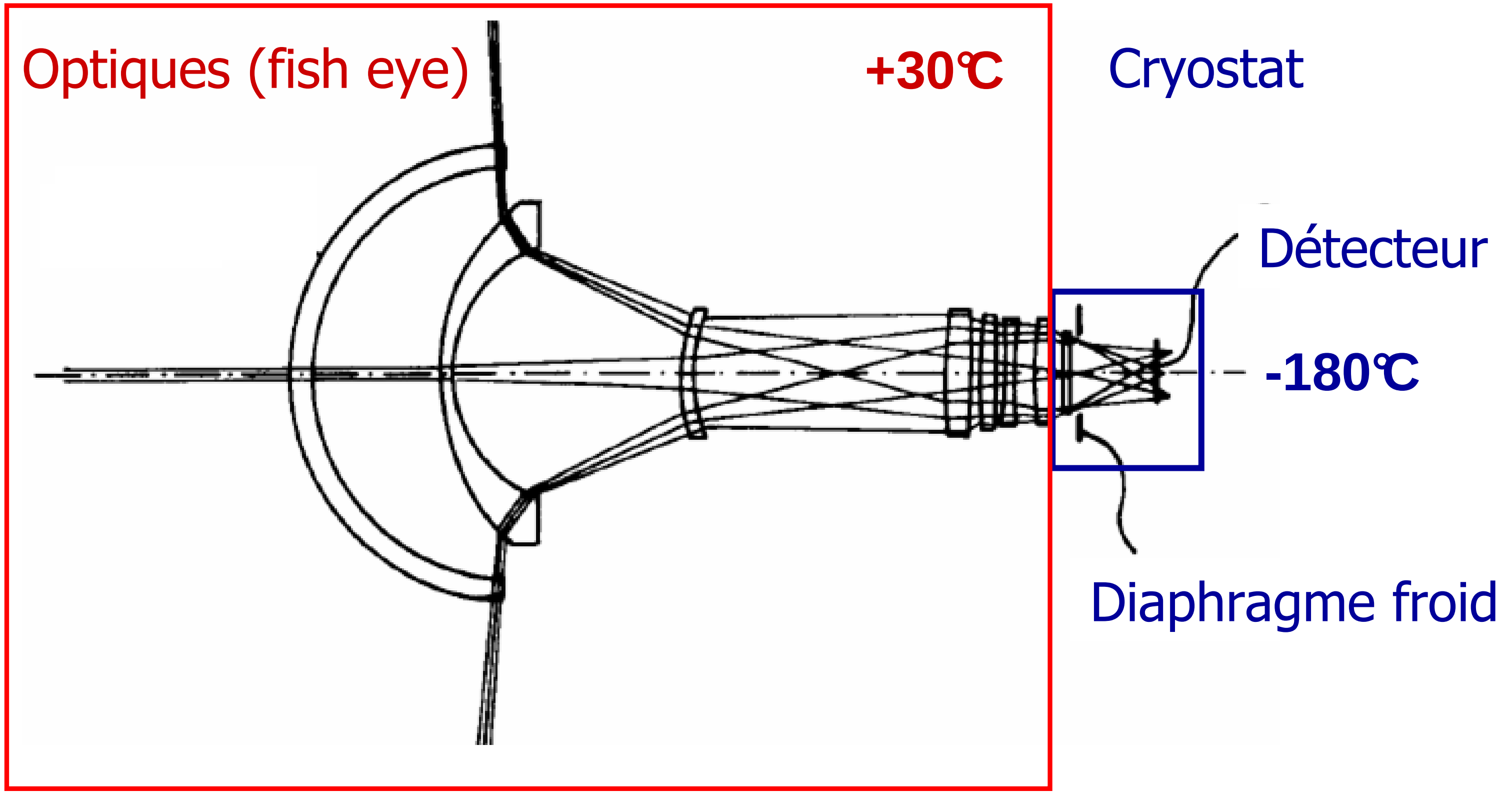
Inside the dewar

-180℃



SOFRADIR

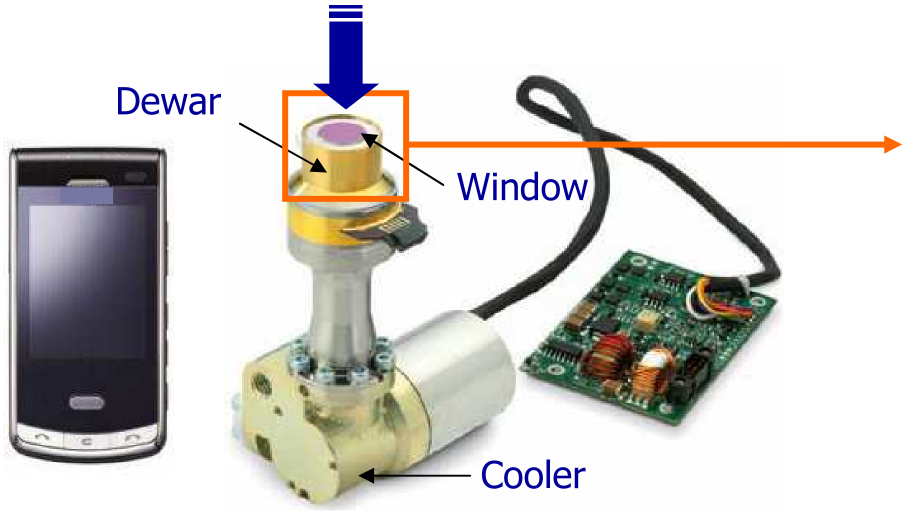
Description of a cooled infrared optical system



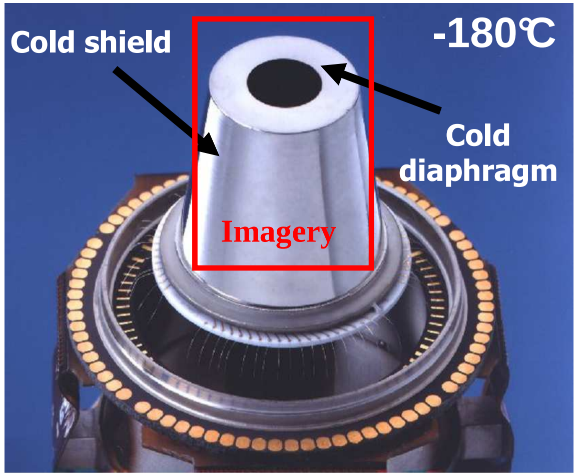
Brevet, « Tête optique pour détecteur de départ de missile ou autre équipement de veille », FR2885702 (B1), 2006.

Imaging DDCA

SOFRADIR DDCA (Epsilon)



Inside the dewar



- ❑ Minimal size for optical system.
- ❑ Guaranteed cooled pupil.

Design compatible with cryogenic environment.

=> co-design optics with the detector area

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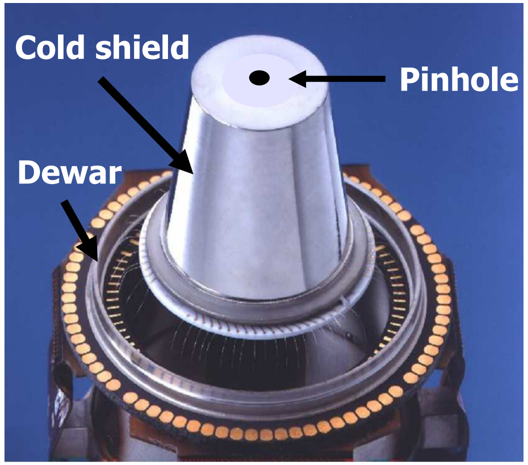
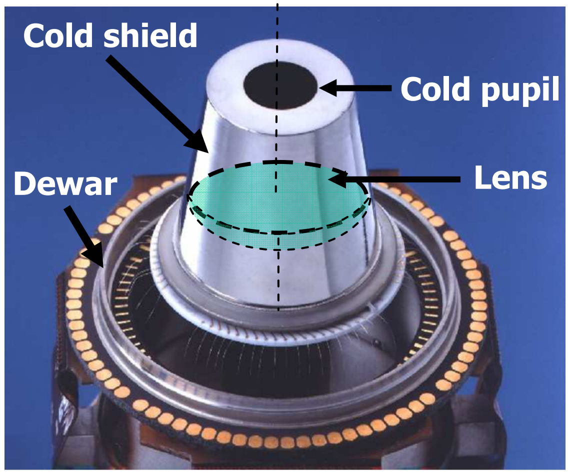
Strategies of integration

1.
Minimalist approach



2.
Dewar integration



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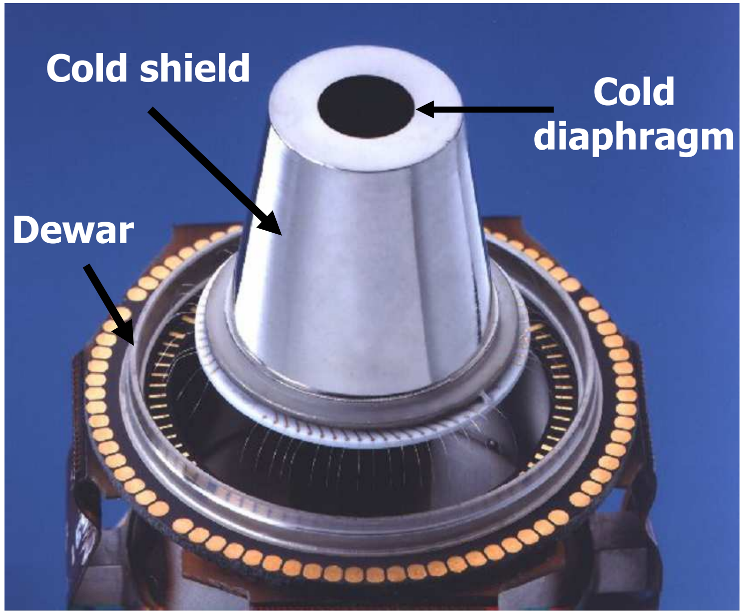
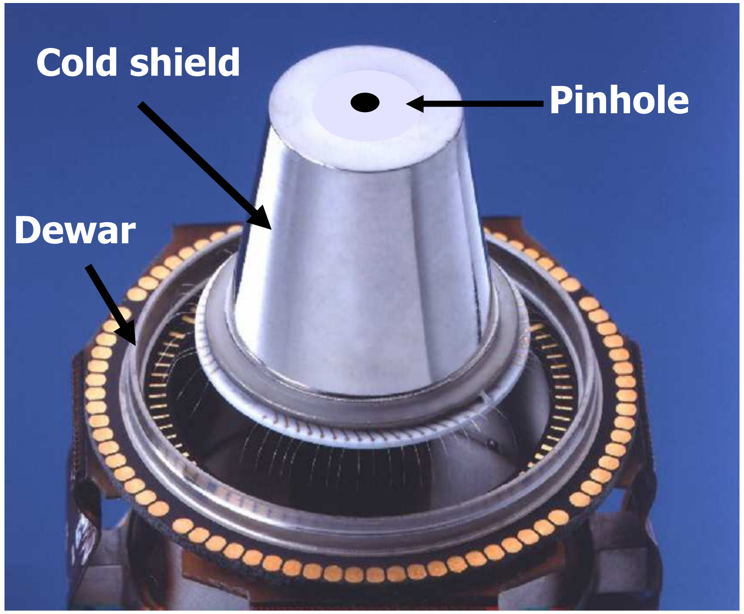
Minimalist approach (Increasing #)

A design that doesn't change the dewar structure





The DDCA becomes a *camera obscura* !

G. Druart *et al*, « Compact infrared pinhole fisheye for wide field applications, » Appl. Opt., Vol. 48, pp. 1104-1113, 2009.

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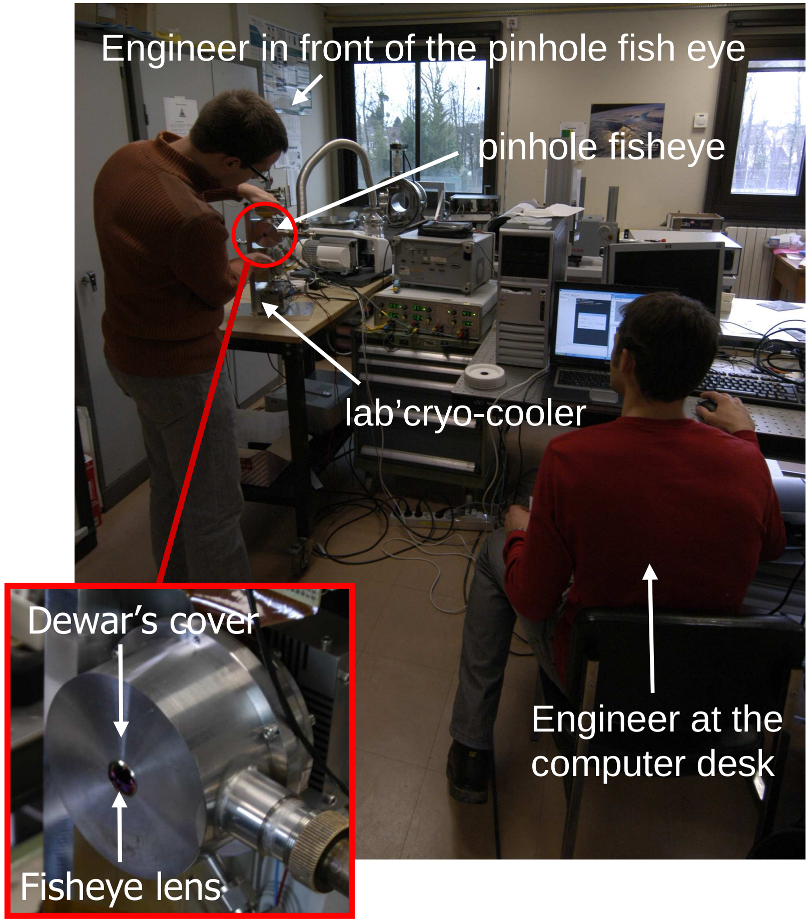
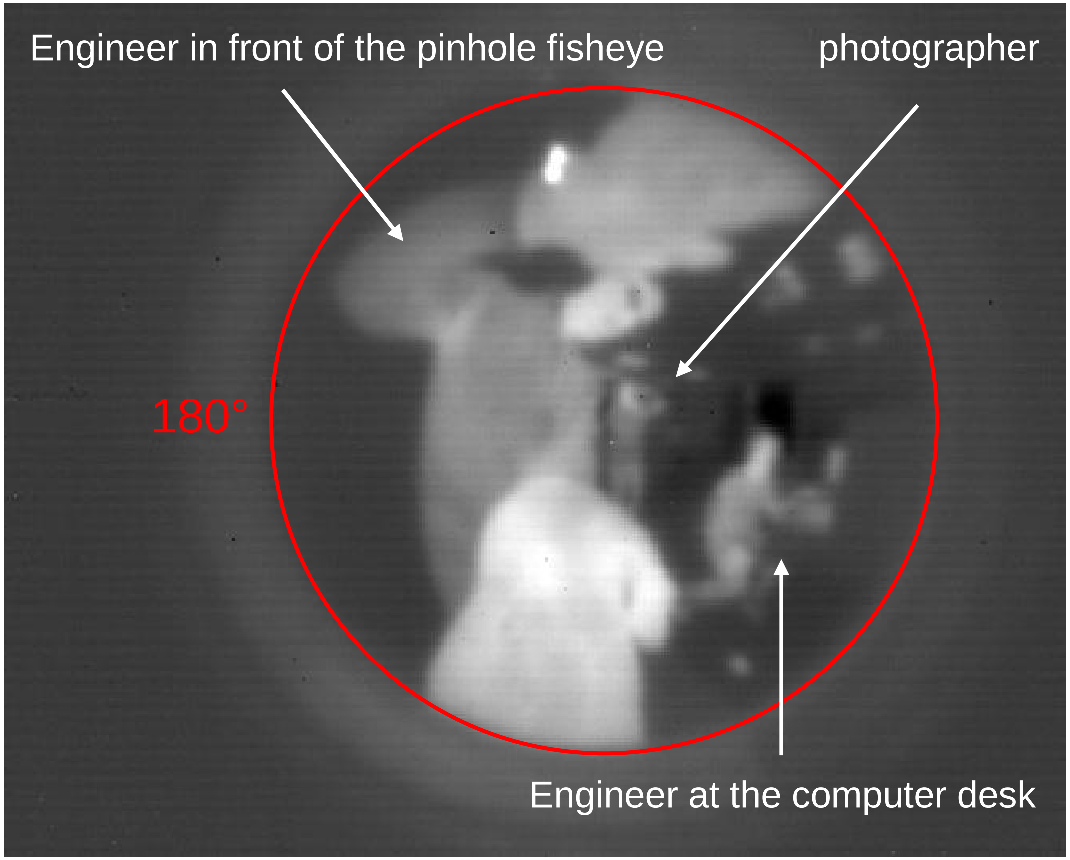
The pinhole fisheye

Implementation of the pinhole fisheye

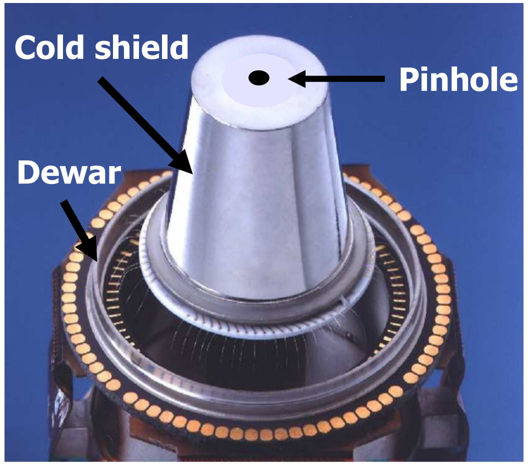




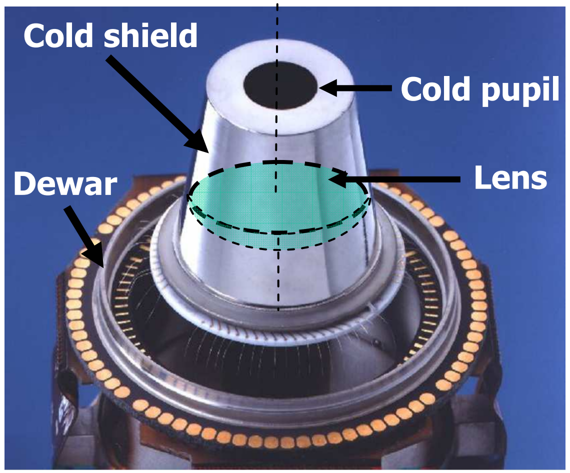
G. Druart *et al*, « Compact infrared pinhole fisheye for wide field applications, » Appl. Opt., Vol. 48, pp. 1104-1113, 2009.

Strategies of integration

1.
Minimalist approach

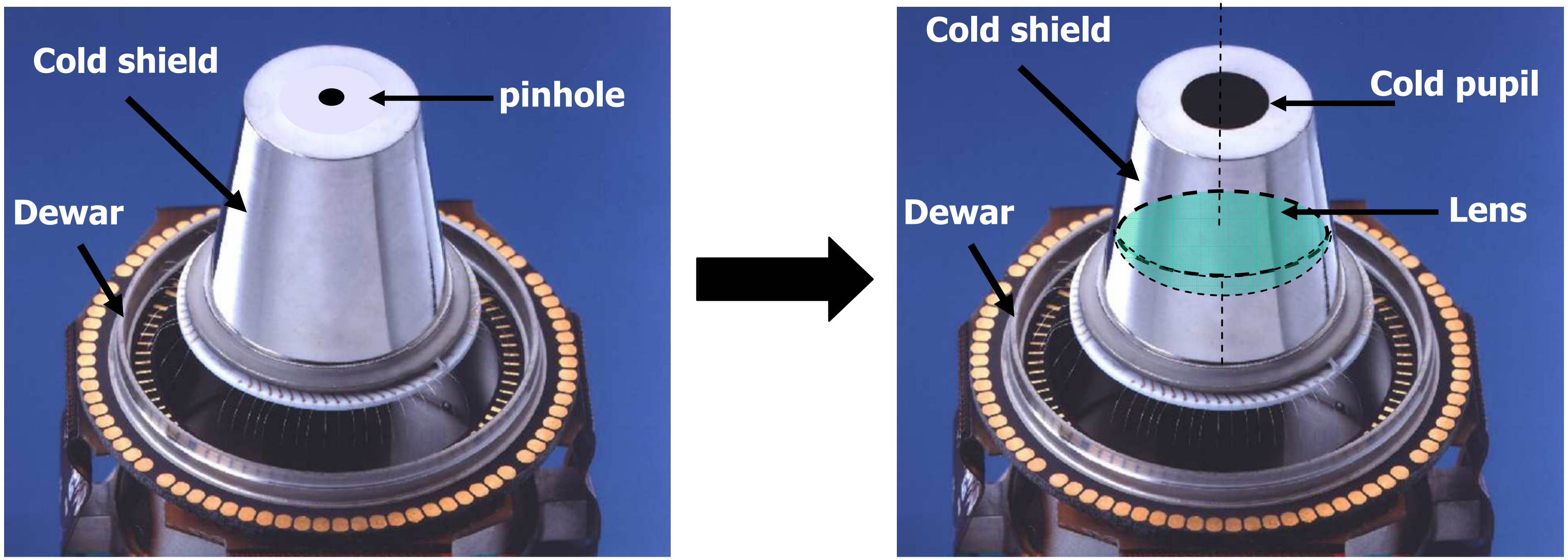


2.
Dewar integration



Dewar integration (Decreasing Seidel coefficients)

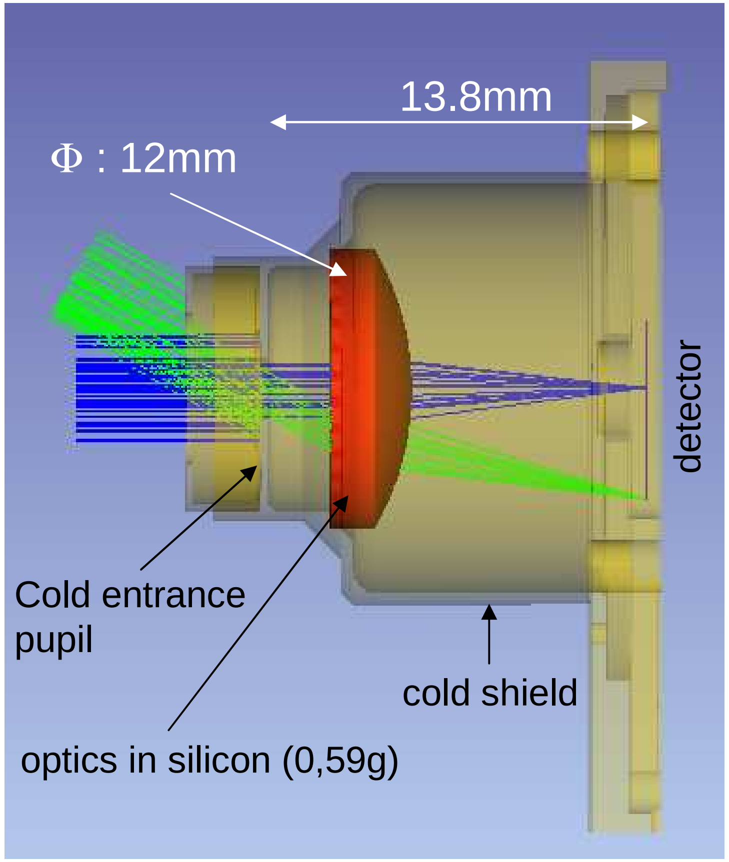
Improvement of angular resolution and throughput



<u>Optimisation</u> : choosing the right optic shape, the right cold pupil position and the right material

G. Druart *et al*, « Système d'imagerie grand champ infrarouge à chambre obscure intégrant une lentille », FR 2 936 878 – A1, 2008 .
G. Druart *et al*, « Infrared wide field imaging system integrated in a vacuum housing », WO 2010/040914 A2.

DDCA with a single integrated optics




Detector of 320×256 pixels (pitch of 30µm)

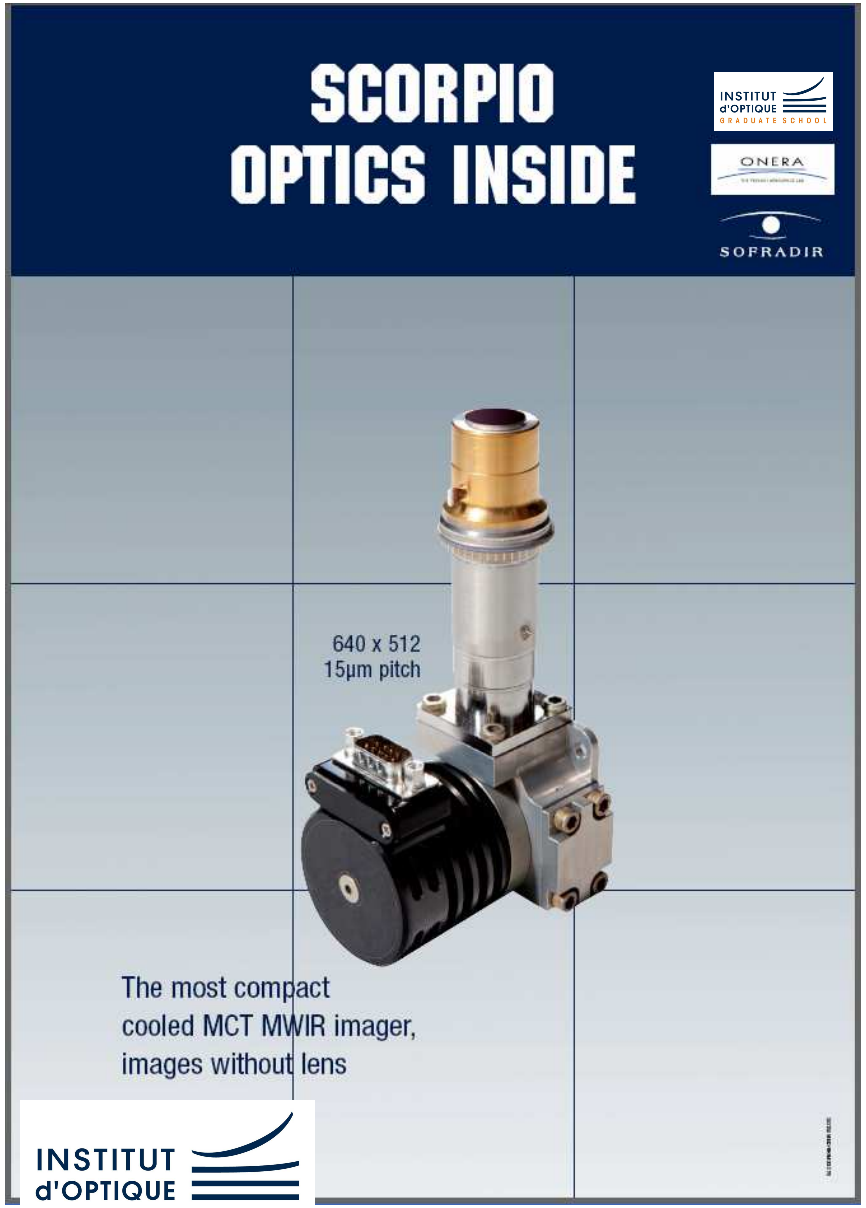

Detector of 640×512 pixels (pitch of 15µm)

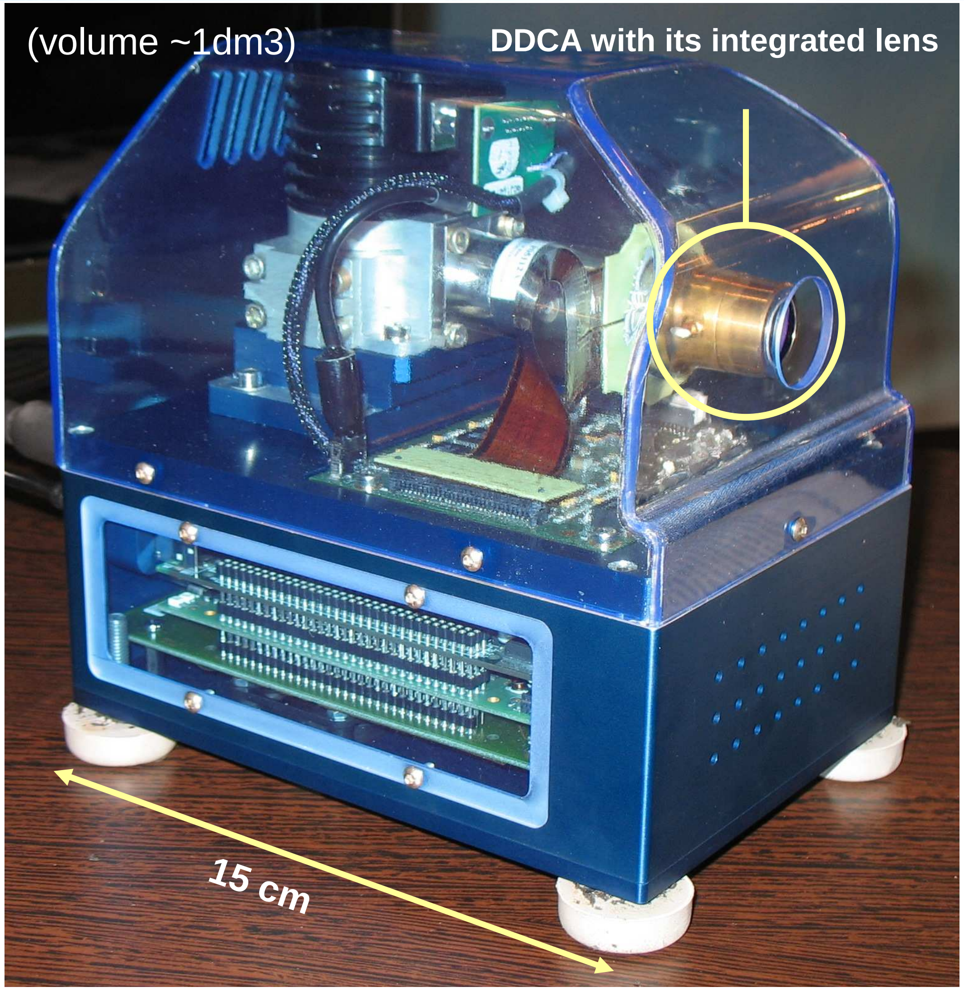
FOV=60° (On the length of the detector)
F#=4 (spherical lens)

G. Druart *et al*, « Infrared wide field imaging system integrated in a vacuum housing », WO 2010/040914 A2.

First prototype of 60° FOV micro-camera (SOIE)

SOFRADIR





Présent at SPIE Orlando 2010, SPIE Orlando 2011 and at Eurosatory 2010

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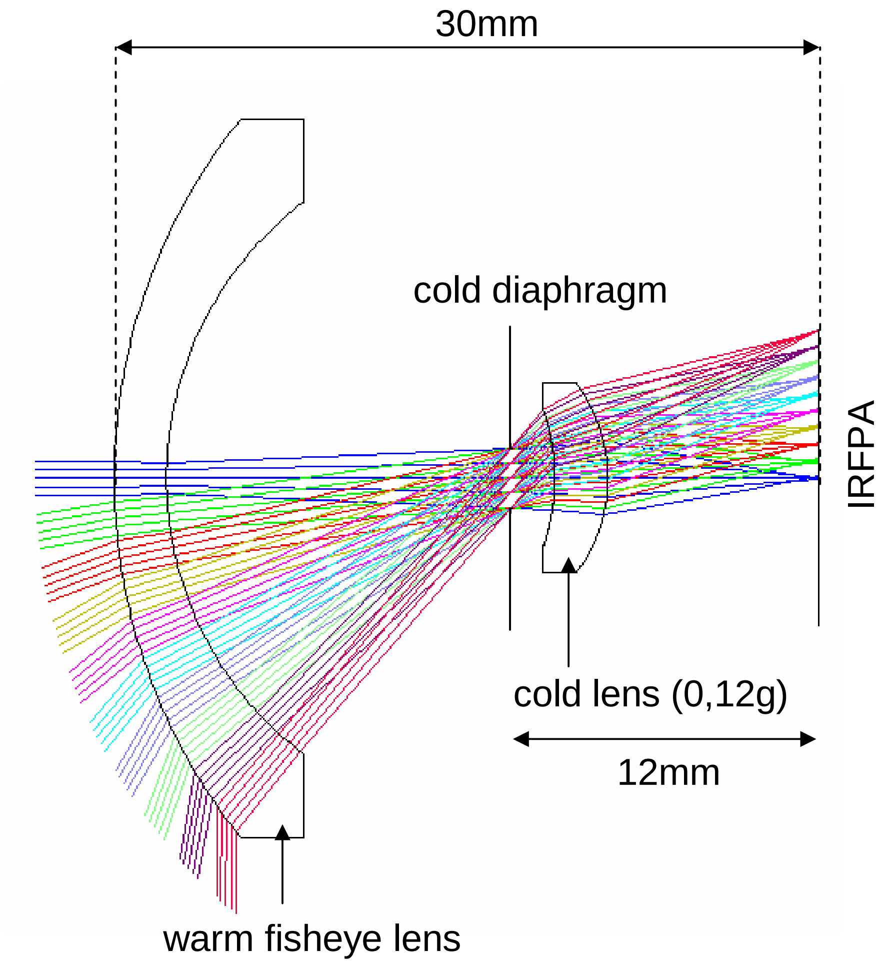
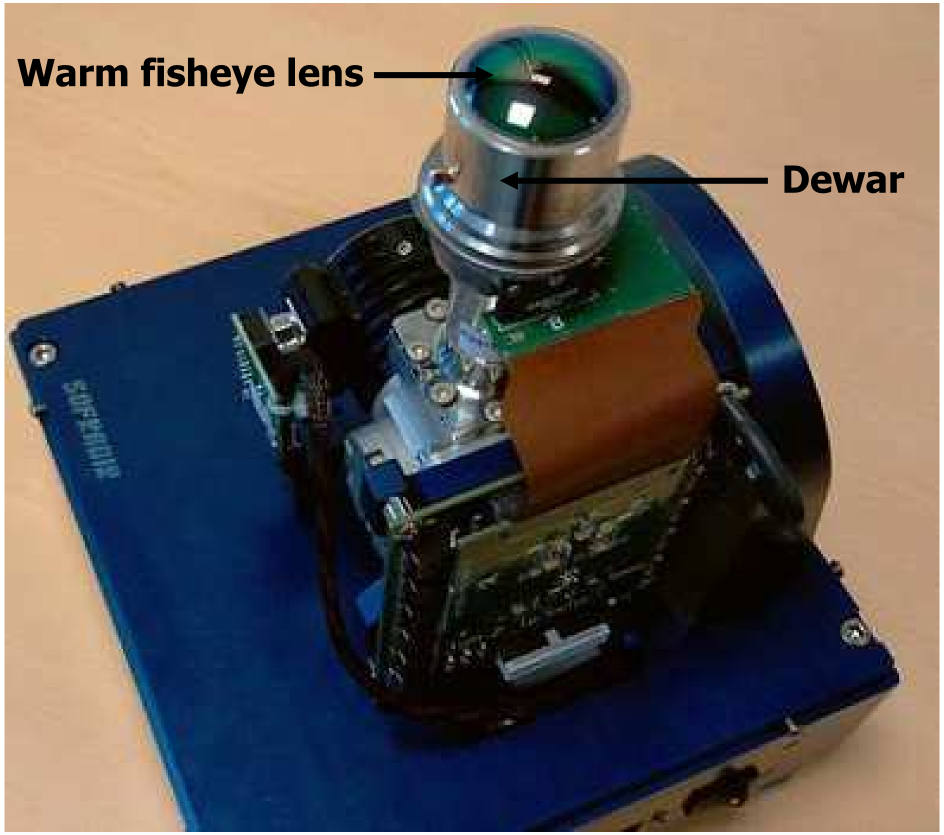
Second prototype of 180° FOV micro -camera (FISBI)





FOV=180° (On the width of the detector)
F#=2,8 (spherical lenses)

SOFRADIR

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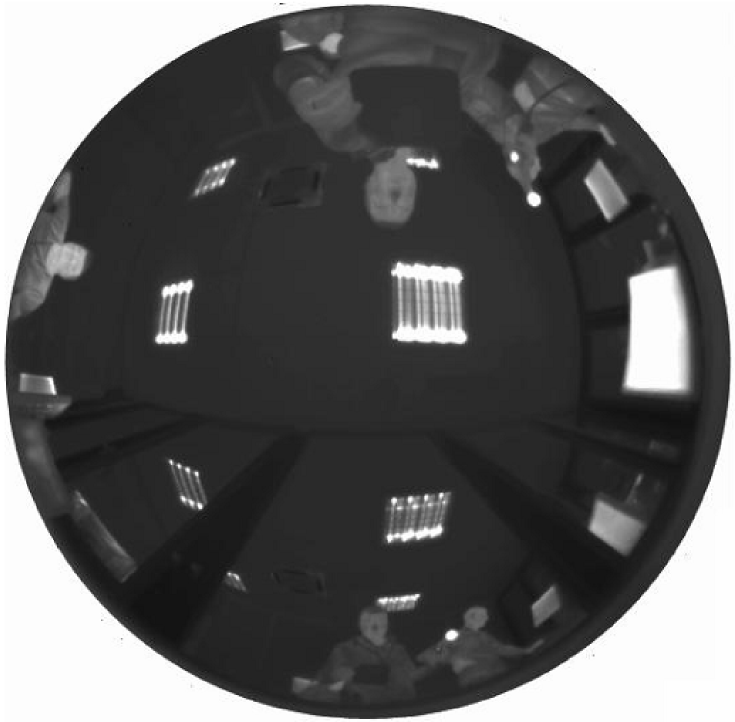
Images obtained from FISBI

In a fish eye configuration

In a panoramic configuration



CONCLUSION

There exist a lot of solutions for micro cameras

- ❑ Vision has to be adapted to your needs
- ❑ Do you really need the best camera ever seen for your application ?
- ❑ What are your tradeoff ?

- ➢2 eyes
- ➢3000 ommatidia per eyes
- ➢8 photoreceptors per ommatidia

Only 48000 pixels !!!

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