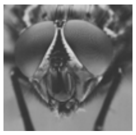
Motion in flight

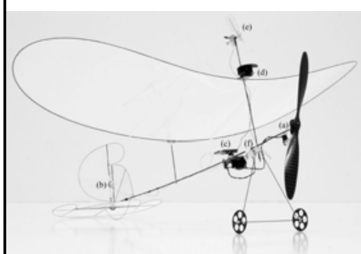
Shih-Chii Liu
Institute for Neuroinformatics
University of Zurich / ETH Zurich
www.ini.uzh.ch/~shih

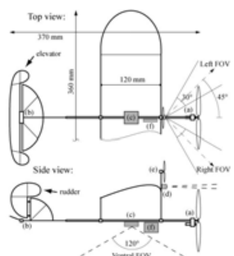


Outline

- Constraints of micro-aerial vehicles
- Choice of aVLSI motion chips
- Behavioral experiments on a robot using motion sensors
- Prototype motion chip for flyer

MC1 Microflyer



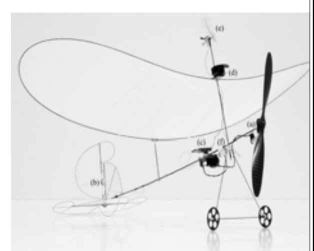


Specs
-65 mAh Li-polymer
-2 linear B/W cameras with 80 pixels covering 120deg FOV, 2 gyros for yaw, pitch, 1 anemometer
-10g, 1.5m/s,
-Optimal latency is 6.4ms, duration is 10mins

(Zufferey, Beyeler, and Floreano, EPFL)

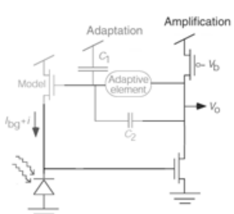
Vision sensor challenges

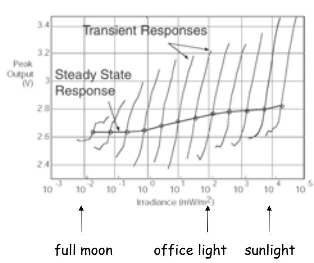
- Operate
  - at low light levels
  - in wide dynamic range scenes
- Low latency
- Low power
- Small and light



- Plus: Offload computation from on-board microcontroller

Photoreceptor circuit in most motion chip front-end

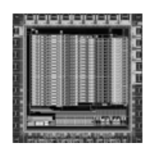




(Delbruck, 1993)

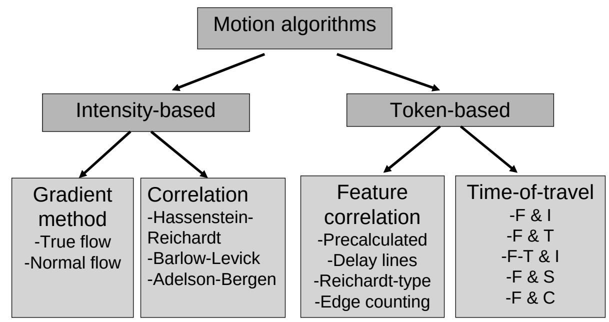
Challenges for neuromorphic vision sensors

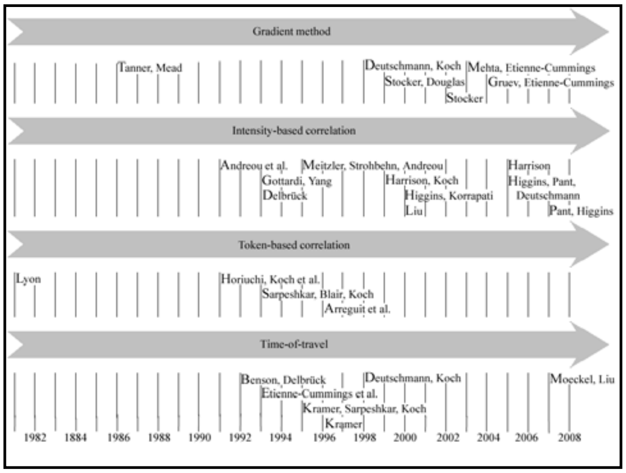
- Presence of across-pixel heterogeneity
- Low precision computation
- Longer development time



Outline

- Constraints of micro-aerial vehicles
- **Choice of aVLSI motion chips**
- Behavioral experiments on a robot using motion sensors
- Prototype motion chip for flyer





Optical flow chips

v=(dI/dt)/(dI/dx)

Brightness constancy equation

$$\frac{dE(x,y,t)}{dt}=0$$

$$\Rightarrow \frac{\partial E}{\partial x}u+\frac{\partial E}{\partial y}v+\frac{\partial E}{\partial t}=0; \quad u=\frac{\partial x}{\partial t}, v=\frac{\partial y}{\partial t}$$

$$\Rightarrow E_x u + E_y v + E_t = 0$$

$$H_{of}=\sum_{ij}\left[\left(E_{xij}u_{ij}+E_{yij}v_{ij}+E_{tij}\right)^2\right]$$

$$\dot{u}_{ij}\propto\left[E_{xij}\left(E_{xij}u_{ij}+E_{yij}v_{ij}+E_{tij}\right)\right]$$

$$\dot{v}_{ij}\propto\left[E_{yij}\left(E_{xij}u_{ij}+E_{yij}v_{ij}+E_{tij}\right)\right]$$

Horn and Schunk (1981), Fenema and Thompson (1979)

Smoothness constraint

$$H_{of}=\sum_{ij}\left[\left(E_{xij}u_{ij}+E_{yij}v_{ij}+E_{tij}\right)^2\right]$$

$$+\rho^x_{ij}\left(\left(\Delta^x u_{ij}\right)^2+\left(\Delta^x v_{ij}\right)^2\right)+\rho^y_{ij}\left(\left(\Delta^y u_{ij}\right)^2+\left(\Delta^y v_{ij}\right)^2\right)$$

Horn and Schunk (1981), Fenema and Thompson (1979)

Bias constraint

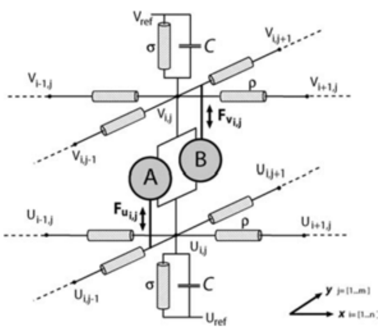
$$H_{of} = \sum_{ij}\left[\left(E_{xij}u_{ij} + E_{yij}v_{ij} + E_{tij}\right)^2\right]$$
$$+\rho_{ij}^{x}\left(\left(\Delta^{x}u_{ij}\right)^2 + \left(\Delta^{x}v_{ij}\right)^2\right) + \rho_{ij}^{y}\left(\left(\Delta^{y}u_{ij}\right)^2 + \left(\Delta^{y}v_{ij}\right)^2\right)$$
$$+\sigma\left(\left(u_{ij} - u_{ref}^{x}\right)^2 + \left(v_{ij} - v_{ref}^{y}\right)^2\right)$$

Stocker (2002)

Update equations

$$\begin{aligned}\dot{u}_{ij} = -\frac{1}{C}[&E_{x_{ij}}(E_{x_{ij}}u_{ij} + E_{y_{ij}}v_{ij} + E_{t_{ij}})\\ &- \rho(u_{i+1,j} + u_{i-1,j} + u_{i,j+1} + u_{i,j-1} - 4u_{ij})\\ &+ \sigma(u_{ij} - u_{\mathrm{ref}})]\\ \dot{v}_{ij} = -\frac{1}{C}[&E_{y_{ij}}(E_{x_{ij}}u_{ij} + E_{y_{ij}}v_{ij} + E_{t_{ij}})\\ &- \rho(v_{i+1,j} + v_{i-1,j} + v_{i,j+1} + v_{i,j-1} - 4v_{ij})\\ &+ \sigma(v_{ij} - v_{\mathrm{ref}})]\end{aligned}$$

Circuit implementation



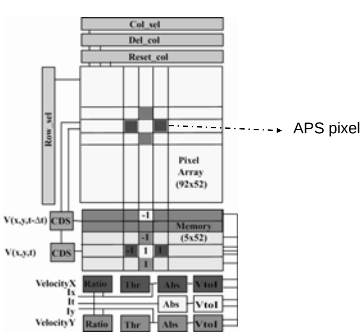
Stocker (2002)

Normal flow chips

$$v_x = -\frac{I_t}{I_x}, v_y = -\frac{I_t}{I_y}$$

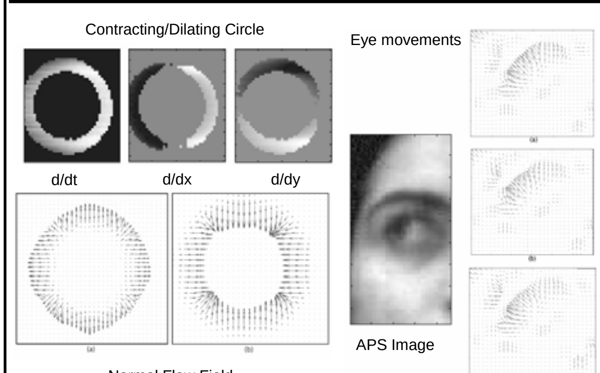
Deutschmann et al (1988), Mehta, Gruev, Etienne-Cummings (2003-)

Visual motion estimation: A normal flow camera

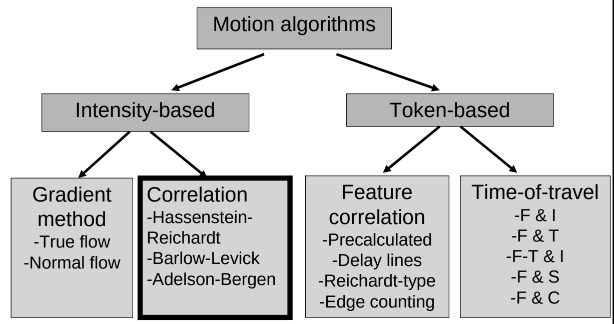


(Mehta and Etienne-Cummings, 2006)

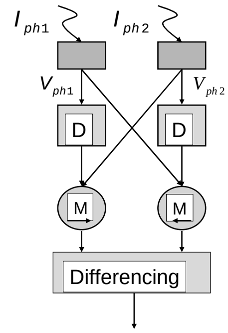
Velocity characterization



(Mehta and Etienne-Cummings, 2006)

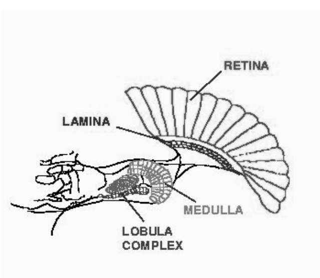


Delay-and-correlate EMD



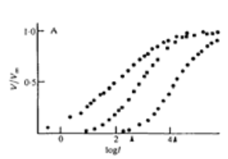
$$R \propto \Delta I^2 \frac{\omega\tau}{1+\omega^2\tau^2} \sin\left(\frac{2\pi a}{\lambda}\right) d$$

(Hassenstein and Reichardt, 1956)

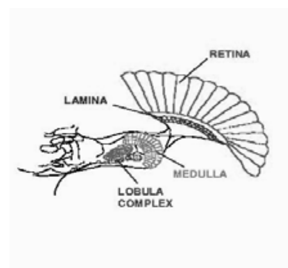


(Hausen, 1982)

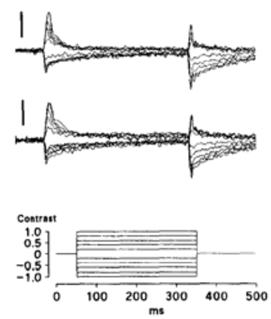
RETINA



(Laughlin, 1989)

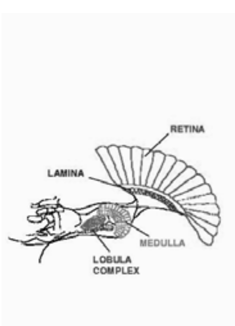


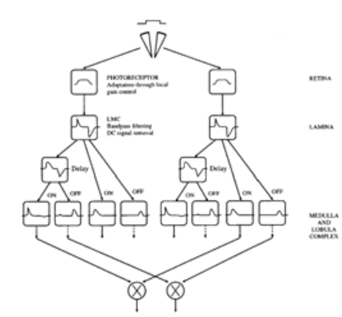
LAMINA



(Juusola et al, 1995)

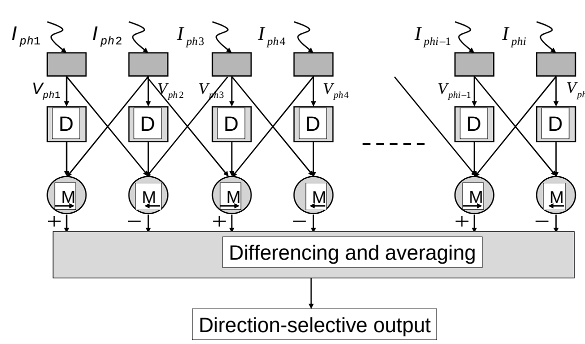
aVLSI EMD model

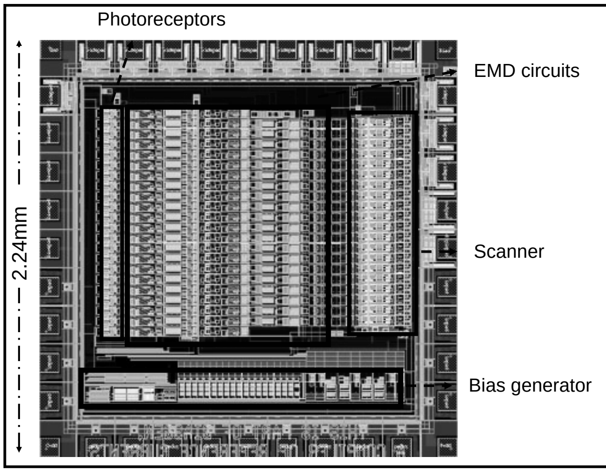




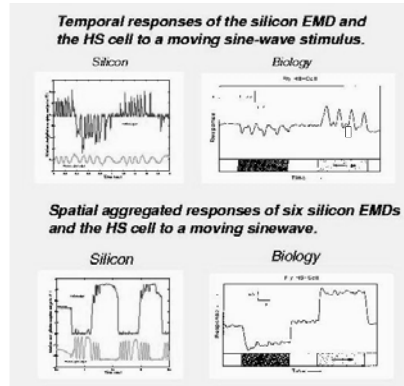
(Liu, 2003)

Motion system on chip



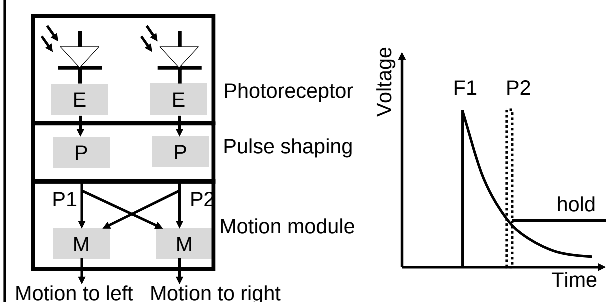


Chip and HS cell responses



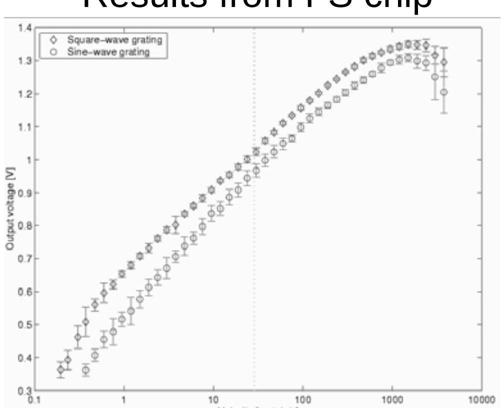
- Motion algorithms
  - Intensity-based
    - Gradient method
      - -True flow
      - -Normal flow
    - Correlation
      - -Hassenstein-Reichardt
      - -Barlow-Levick
      - -Adelson-Bergen
  - Token-based
    - Feature correlation
      - -Precalculated
      - -Delay lines
      - -Reichardt-type
      - -Edge counting
    - **Time-of-travel**
      - -F & I
      - -F & T
      - -F-T & I
      - -F & S
      - -F & C

Facilitate-and-sample algorithm



(Kramer, Sarpeshkar, and Koch, 1997)

Results from FS chip

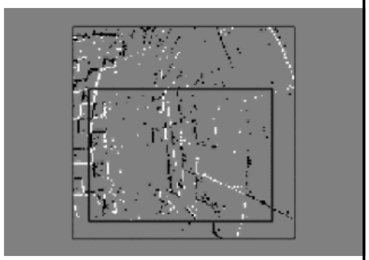


Spike-based approach (more than one chip)

Measuring motion using the temporal contrast silicon retina (Delbruck and Lichtsteiner)

Key specifications: 128x128 pixels, 120dB dynamic range, 2.1%-contrast threshold mismatch, 3kHz pixel bandwidth, 23mW power consumption,15 us-latency

1. Start with raw events that represent temporal contrast
2. Use **spatio-temporal event coincidence** to label events with local edge orientation
3. Label these ***OrientationEvents*** with local direction and speed
4. Integrate these ***DirectionSelectiveEvents*** to compute global translational, rotational, and radial motion



Outline

- Constraints of micro-aerial vehicles
- Choice of aVLSI motion chips
- **Behavioral experiments on a robot using motion sensors**
- Prototype motion chip for flyer

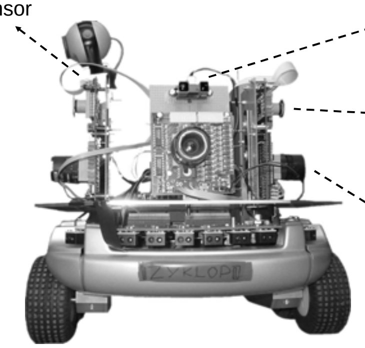
Multi-modal sensors

Photodiode sensor

Range IR sensor

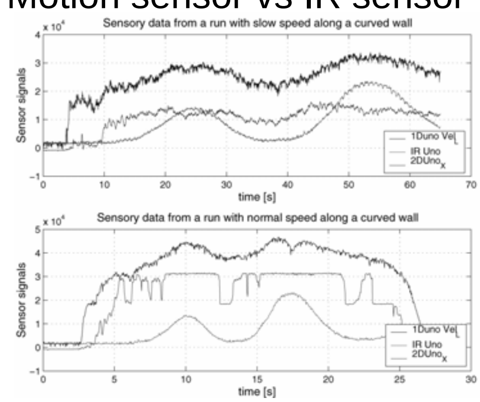
Optical flow motion sensor

Facilitate-and-sample motion sensor



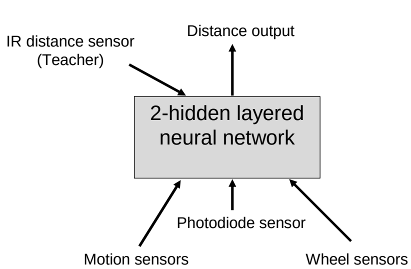
(Kramer et al, 1997; Reichel et al, 2005; Stocker, 2005)

Motion sensor vs IR sensor

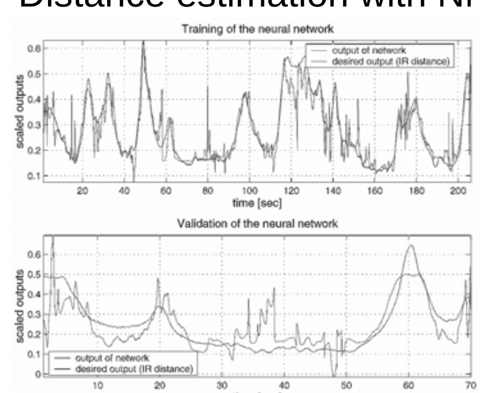


(Reichel et al, 2005)

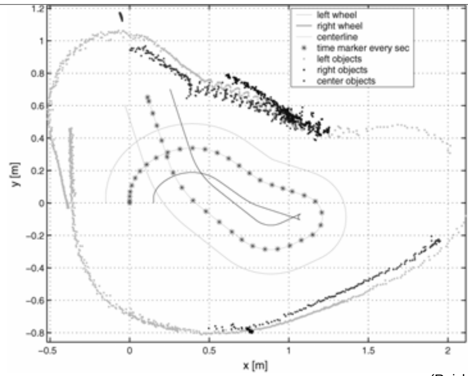
Estimation of distance



Distance estimation with NN



Map of the environment

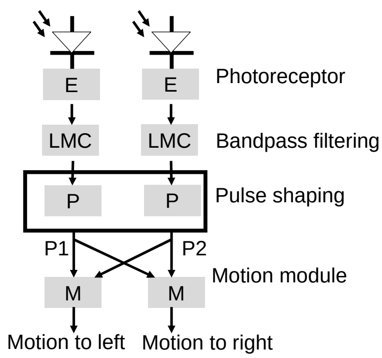


(Reichel et al, 2005)

Outline

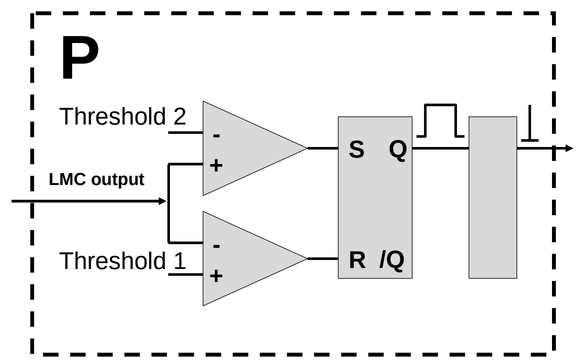
- Constraints of micro-aerial vehicles
- Choice of aVLSI motion chips
- Behavioral experiments on a robot using motion sensors
- **Prototype motion chip for flyer**

Algorithm on MDC2

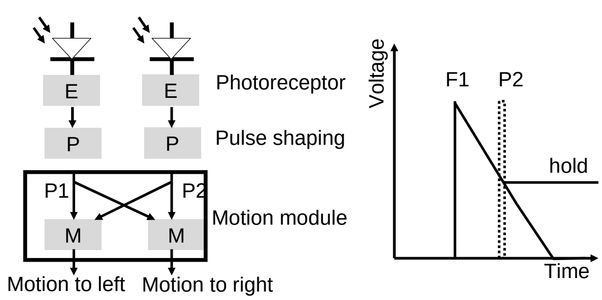


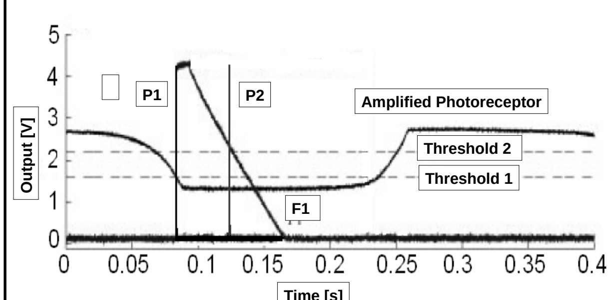
(Moeckel and Liu, 2006)

Pulse-shaping circuit

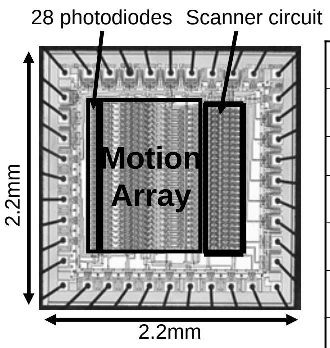


Facilitate-and-sample algorithm



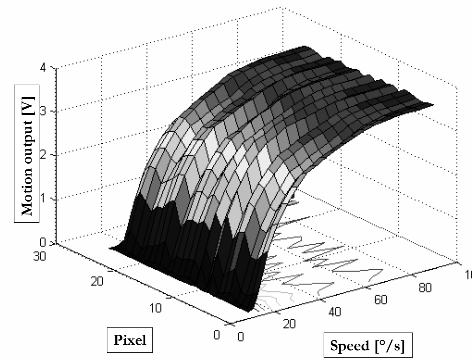


MDC2 Chip

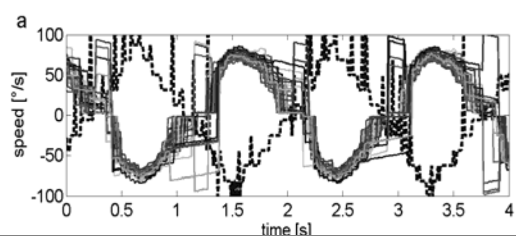


Process	1.5μm 2-poly 2-metal 5V CMOS
Number of motion pixels:	26
Pitch size	68λ=54.4μm
Minimum contrast:	2.5%
Linear motion output:	2 decades
Illumination range:	>3 decades
Power consumption:	5mW

Average response to pattern with different speeds



MDC2 and gyro



Summary

- Micro-aerial vehicles provide a great platform for showing advantages of motion chips.
- Choices for aVLSI motion chips that match the constraints.
- Challenges ahead – how we use reliably the optical flow information on the flyer.

Acknowledgments

Rico Moeckel
Tobi Delbruck

EPFL
J. C. Zufferey
Antoine Beyeler
Adam Klaptocz
Dario Floreano

Joerg Kramer
Samuel Glauser
Karl Presser
David Liechti
Lukas Reichel

- Thanks to Swiss National Foundation, INI

THE END