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Optic-flow-based Navigation for Ultra-light Indoor Aircraft

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Introduction

Goal

The goal of this project is to develop an autonomous micro-flyer capable of navigating within houses or small built environments using vision as main source of information.

The Problem at Hand

Flying indoor implies a number of challenges that are not found in outdoor autonomous flight. These include small size and slow speed for maneuverability, light weight to stay airborne, low-consumption electronics, and smart sensing and control to fly in textured environments. Sensors commonly employed in robotics, in particular range finders, are too heavy and energy consuming for very light flying platforms. Moreover classical model-based approaches for signal processing and control usually require much more computing power than low-power embedded processors are able to deliver. Therefore, we take inspiration from flying insects (in particular the flies[1]) for the selection of sensory modalities, the design of signal processing, and for the choice of control strategy.

Fly's Navigational System

Usually flies move through their environment using a series of straight flight segments separated by rapid turns, known as saccades. Recently, scientists[2] have studied the visual cues that control steering behavior in the fruit fly by reconstructing 3D trajectories from images taken by stereo infrared video cameras. They found that

(1) image expansion (or divergence) is responsible for triggering saccades,
(2) the direction of the saccades (left versus right) is such to turn away from the side experiencing faster image motion or optic flow (OF), and
(3) the magnitude of those rapid turns (roughly 90 deg) is independent of visual feedback.

Aside from visual sensors, flies can estimate angular velocities by the mean of mechanoreceptors at the base of its halteres, tiny club-shaped organs derived through evolutionary transformation from the hind wings. The working principle of this biological sensor is much like the one of piezo-electric gyroscopes, which sense Coriolis forces acting on oscillating mechanical parts. Halteres have been shown to play an important role in gaze stabilization as well as pitch and yaw control in the fly.

Biological Principles applied to Flying Robot

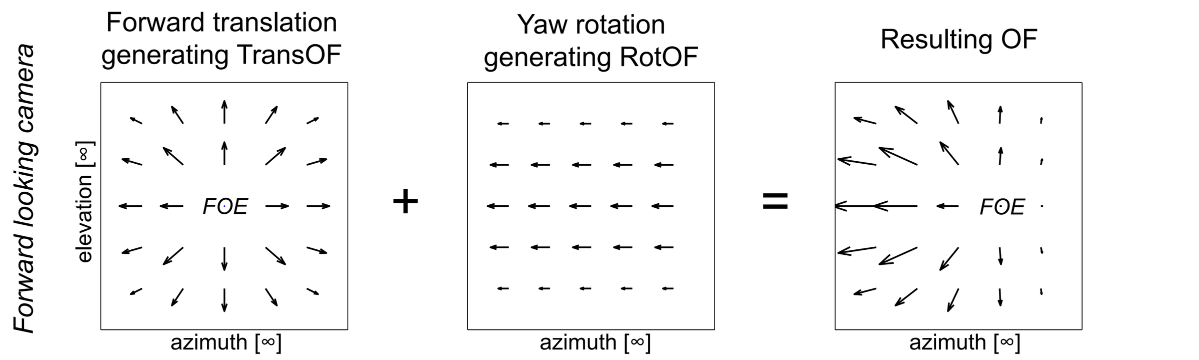
Within our experiments, we take inspiration from the aforementioned fly characteristics. First at the sensory level, the flying robot is equipped only with visual and gyroscopic sensors, and neither distance nor position sensors are available. At the vision processing stage, then, we do estimate OF in order to provide the behavior controller with a mean of measuring image expansion. Finally at the behavioral level, the plane follows the straight-flight-and-saccade strategy, described above.

The milestone that has been reached so far consists in **autonomous steering of a 30-gram indoor airplane capable of stabilizing its course and avoiding imminent collisions** in a square textured arena of 16 by 16 meters.

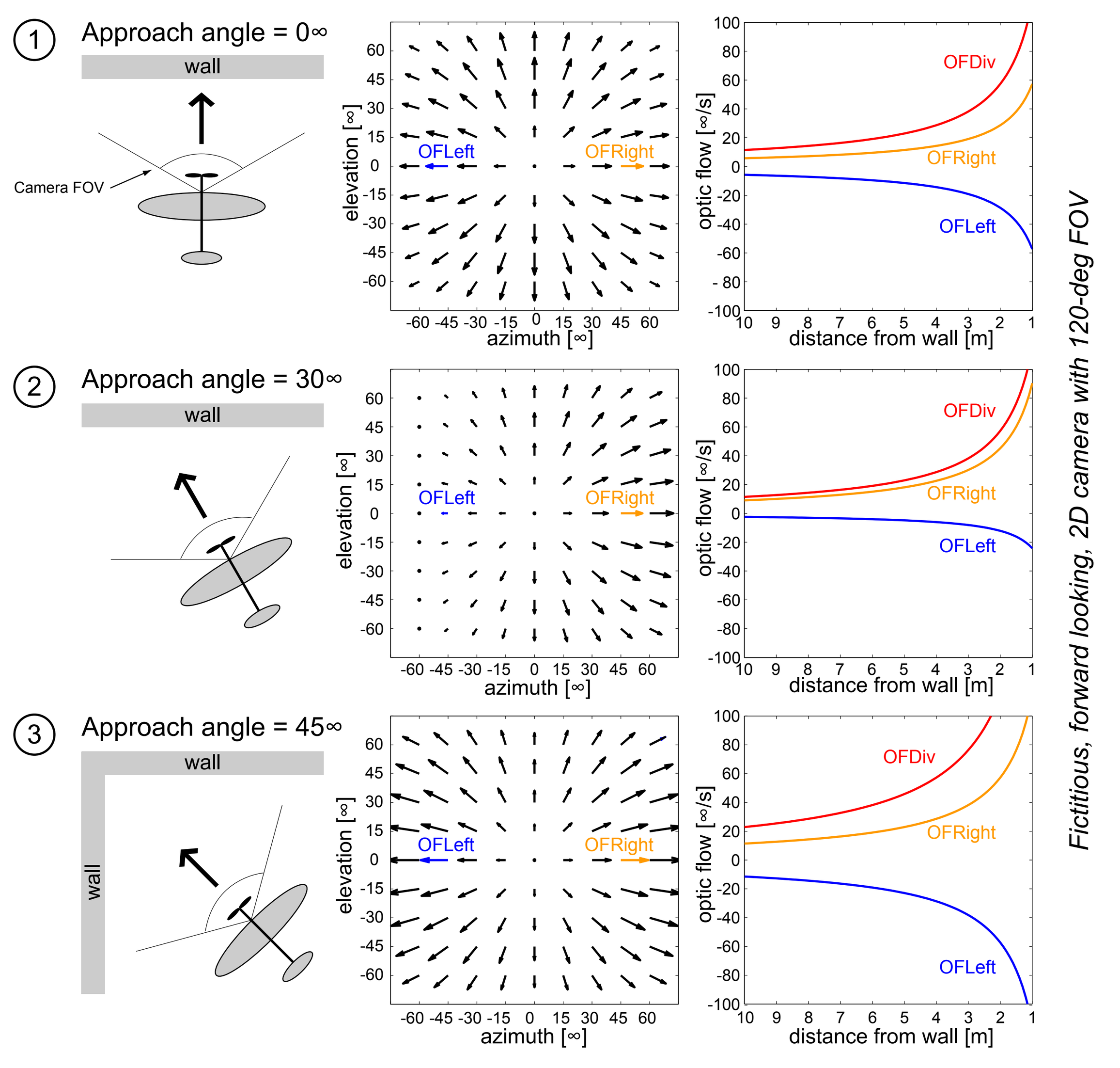
[1] Egelhaaf, M., Borst, A. (1993) A Look into the Cockpit of the Fly: Visual Orientation, Algorithms, and Identified Neurons. The Journal of Neuroscience, 13(11), pp. 4563-4574.
[2] Tammero, L.F., Dickinson, M.H. (2002) The influence of visual landscape on the free flight behavior of the fruit fly Drosophila melanogaster. The Journal of Experimental Biology, 205: 327-343

Ideal Optic Flow

Translational and Rotational Optic Flow[3]



Typical Patterns of Optic Flow



Control Criteria

Image divergence (or expansion) is estimated from the following difference:

OFDiv = OFRight - OFLeft

Side experiencing higher OF is given by the difference of absolute values:

OFDiff = |TransOFRight| - |TransOFLeft|

Note: OFDiff is not independant of RotOF, therefore, OFRight and OFLeft must be cleaned from their rotational component using gyroscopic information.

[3] Koenderink, J.J., van Doorn, A.J. (1987) Facts on Optic Flow. Biological Cybernetics 56: 247-254.

Glossary

OF	=	optic flow	OFDiv	=	divergence of OPF
TransOF	=	OPF due to translation	OFDiff	=	difference of TransOPF
RotOF	=	OPF due to rotation	FOE	=	focus of expension
OFLeft	=	OPF at -45-deg azimuth	FOV	=	field of view
OFRight	=	OPF at +45-deg azimuth	LPF	=	low pass filter

Estimation of 1D Optic Flow

Simplified Image Interpolation Technique

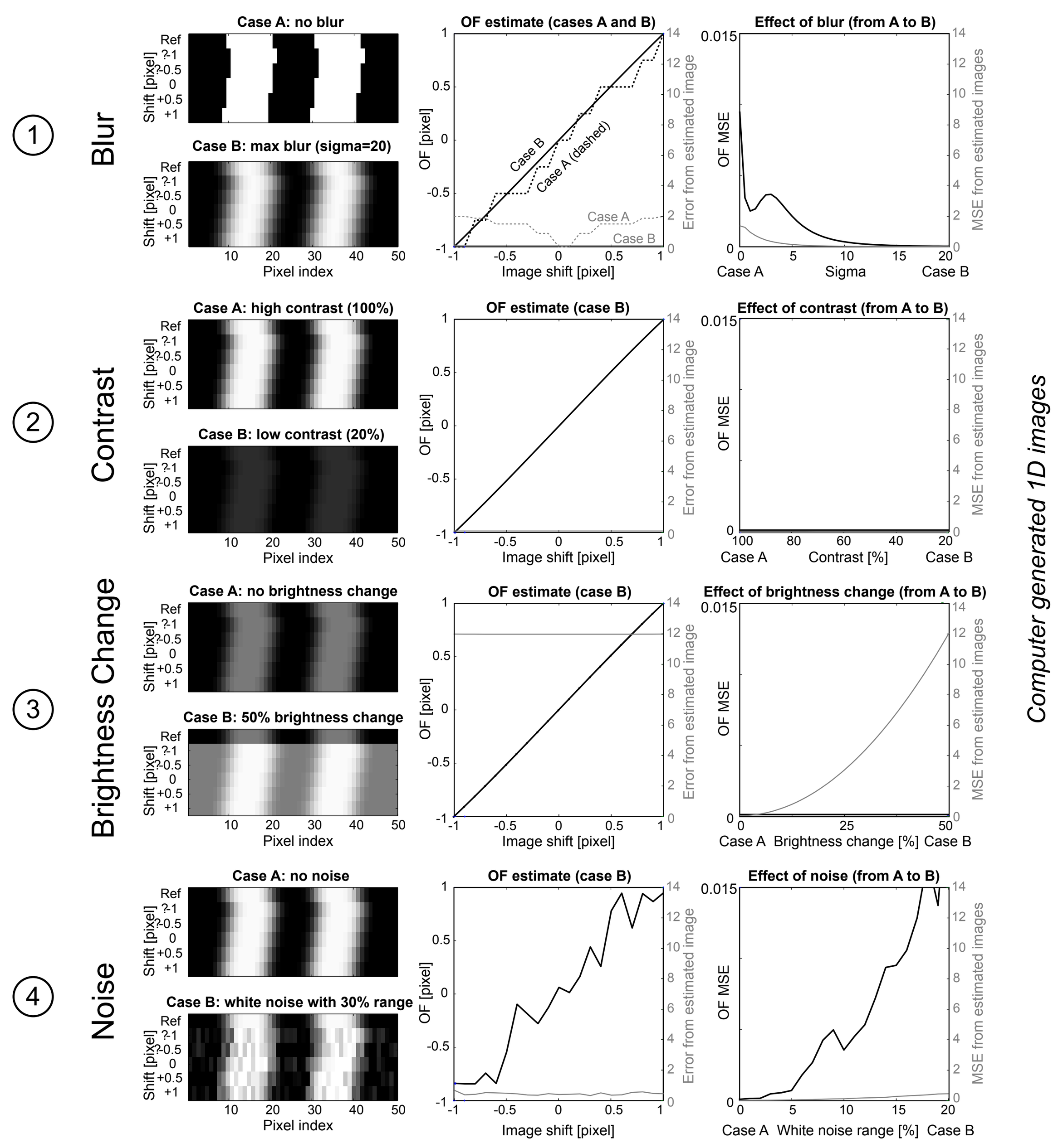
The 1D image interpolation technique[4] computes the shift s in pixels that provides the best fit between a recently acquired image $I_{t+1}(n)$ and the linear combination of two shifted versions of a reference image $I_t(n)$.

$$\hat{I}_{t+1}(n) = I_t(n) + s\frac{I_t(n-k) - I_t(n+k)}{2k} \qquad E = \sum_n \left[I_{t+1}(n) - \hat{I}_{t+1}(n)\right]^2$$

$$\frac{dE}{ds} = 0 \Leftrightarrow s = 2k\frac{\sum_n [I_{t+1}(n) - I_t(n)]\,[I_t(n-k) - I_t(n+k)]}{\sum_n [I_t(n-k) - I_t(n+k)]^2}$$

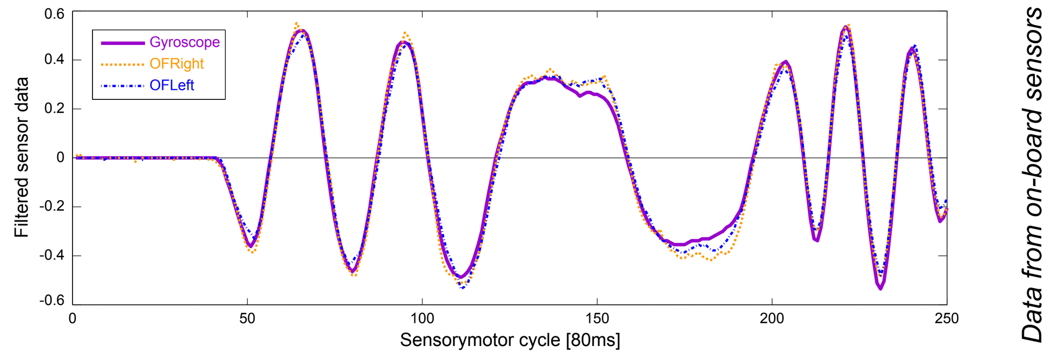
where n is the pixel index in the image, and k a reference shift in number of pixels ($k=1$ in our implementation). The shift s is interpreted as the 1D OF estimate in the FOV corresponding to the image $I(n)$.

Effects of Image Perturbations on Optic Flow Estimates



Actual Optic Flow Estimation compared to Yaw Gyroscope

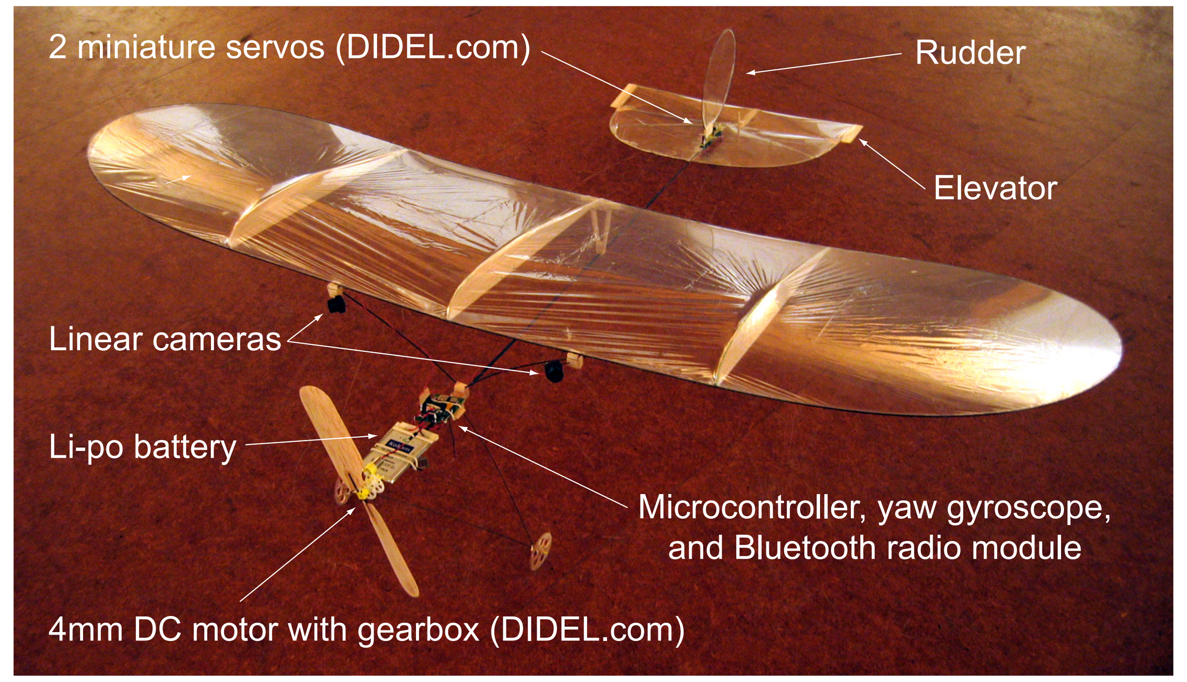
The robot is hold by hand in the test arena while subjected to yaw rotation:

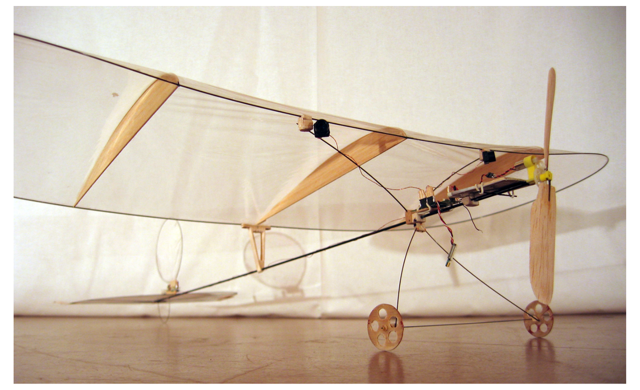


[4] Srinivasan, M.V. (1994) An image-interpolation technique for the computation of optic flow and egomotion. Biological Cybernetics 71: 401-416.

Flying Platform

The 30-gram Indoor Slow-flyer (model F2)





Weight Budget

Fuselage with rudder & elevator:	4.7 g
Wing:	4.5 g
Landing gear:	1.2 g
Motor, gearbox, and propeller:	2.7 g
Two servos:	2.7 g
Lithium-polymer battery:	6.9 g
Electronic board with gyroscope and radio module:	4.0 g
Two linear cameras:	2.2 g
Miscellaneous (cables, glue):	1.1 g
Total weight:	**30.0 g**

Main Characteristics

Speed Range:	1.2 to 2.5 m/s
Electronic consumption:	300 mW
Overall peak consumption:	2 W
Energetic autonomy:	30 minutes
Sensory-motor cycle:	80 ms

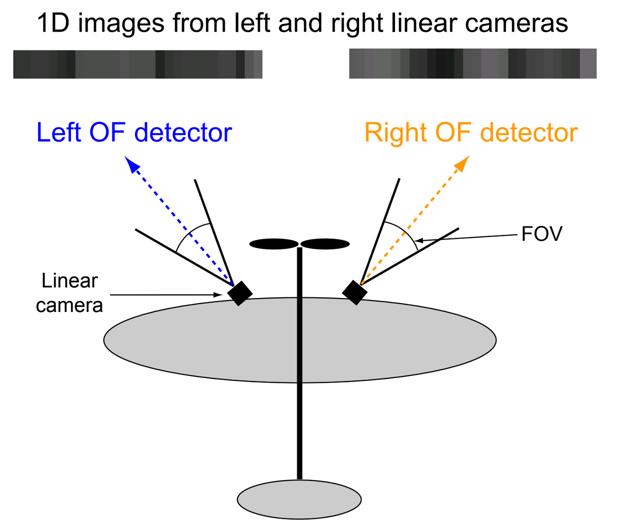
Microcontroller

Type:	Microchip PIC18LF6720
Frequency:	20 MHz
Floating-point:	none

Optic Flow Detector

Linera cameras:	Taos TSL3301
Number of pixels:	28
Field of view (FOV):	40 deg
Image acquisition:	3.5 ms
OF computation:	0.9 ms

Camera Orientation and FOV



Test arena (16 by 16 meters)

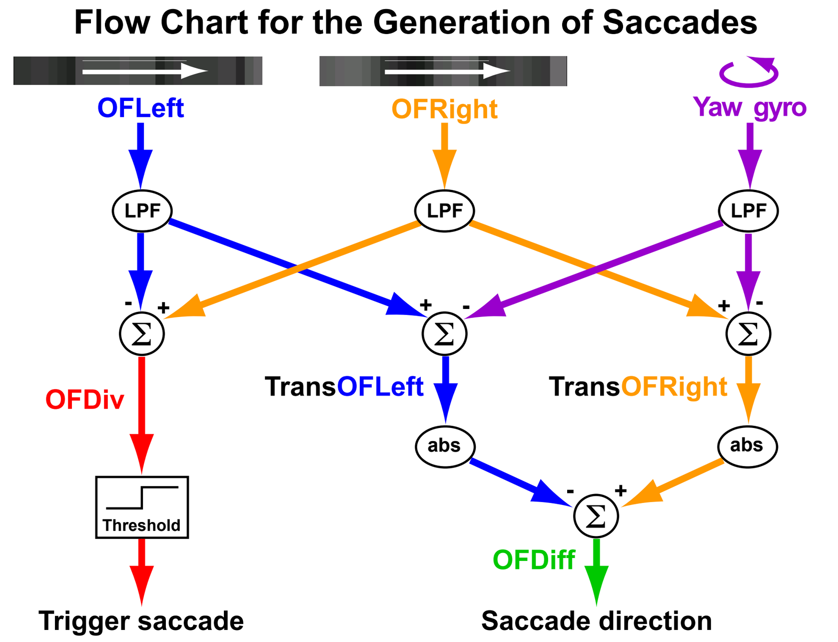
Experiments & Results

Control Strategy

Like the fly, the aerial robot is intended to fly along straight trajectories interspersed with predefined turning actions (saccades), whenever necessary. The behavior is thus divided into two states: (1) maintain heading, (2) turn away as quickly as possible.

State (1) is readily implemented by the mean of a proportional feedback loop connecting the yaw gyroscope to the rudder servomotor. State (2), i.e. the saccade itself, is programmed as a series of motor commands during a predefined amount of time.

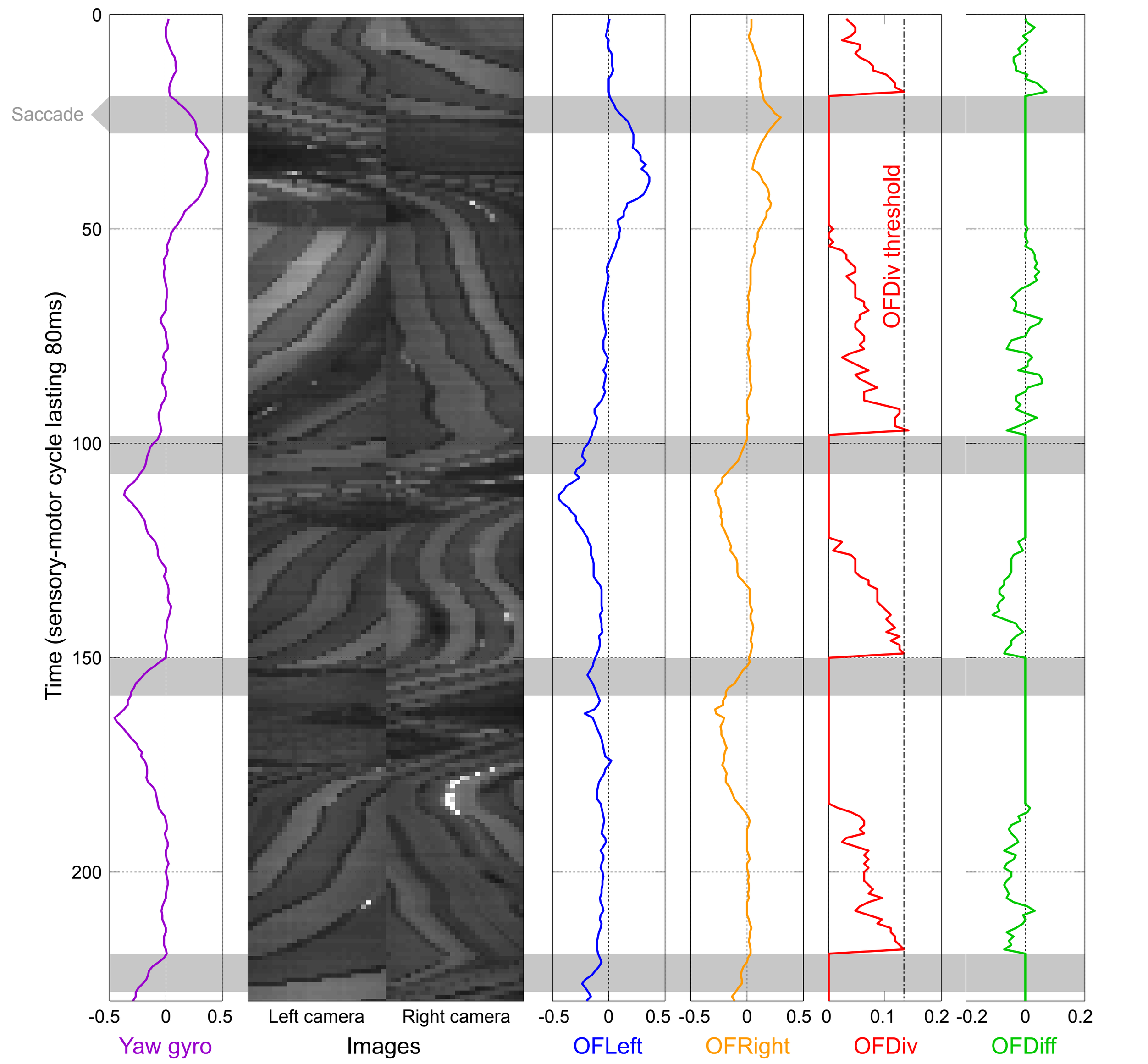
Flow Chart for the Generation of Saccades



Results

So far, the 30-gram robot has been able to fly collision-free for more than 4 minutes without any interventions regarding its steering. Only 20% of the time was engaged in saccades, which suggests that very few turning actions were triggered when no collision was imminent. During 4 minutes, the plane generated 50 saccades, and covered about 300m in straight motion.

Sample of Sensor Data during Autonomous Flight



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