Vision and Navigation in Honeybees and Applications to Flying Machines

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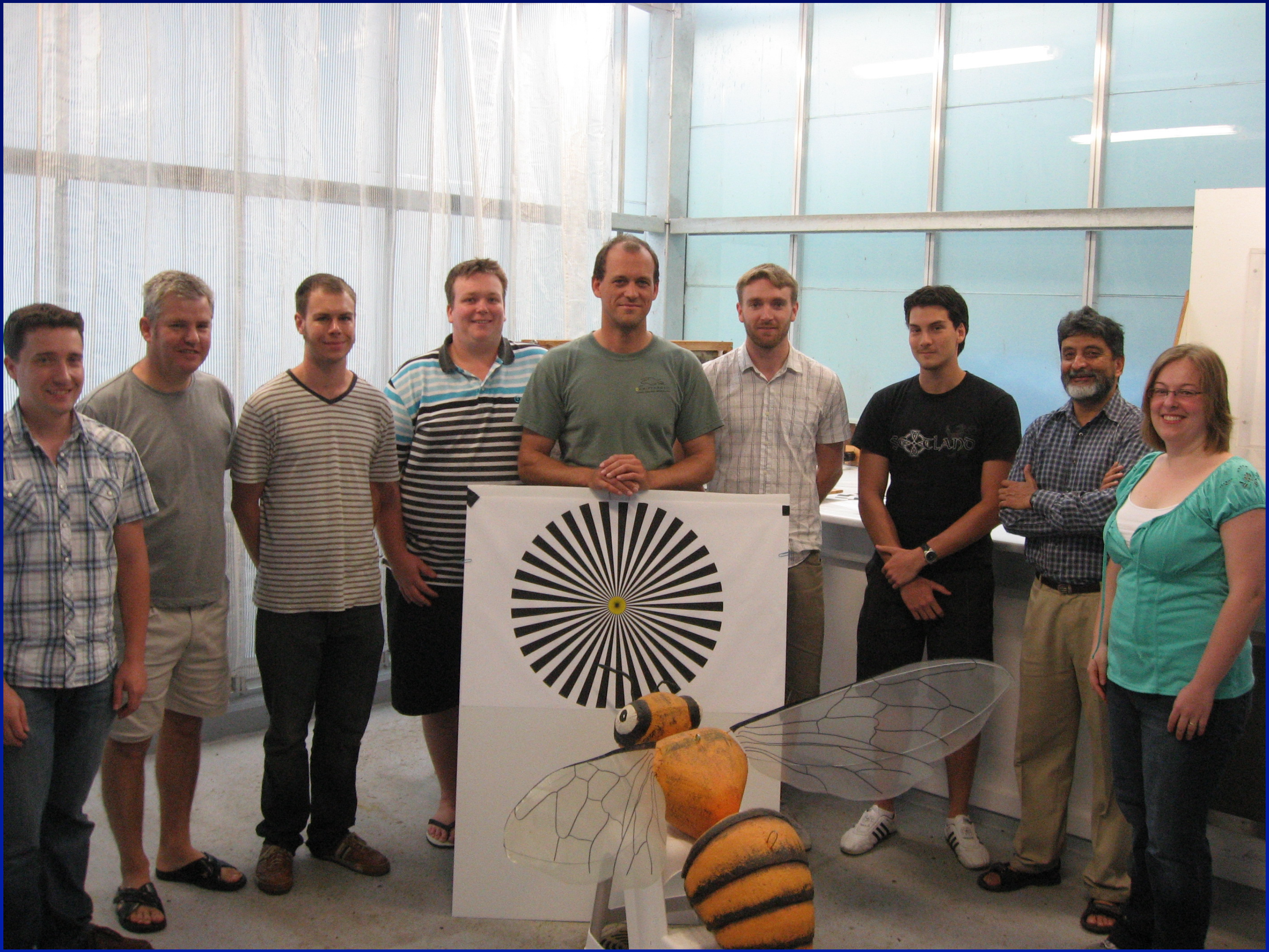
Sam Baker, Daniel Bland, Natalie Bland, Nikolai Liebsch,
Richard Moore, Gavin Taylor, Saul Thurrowgood, Dean Soccol



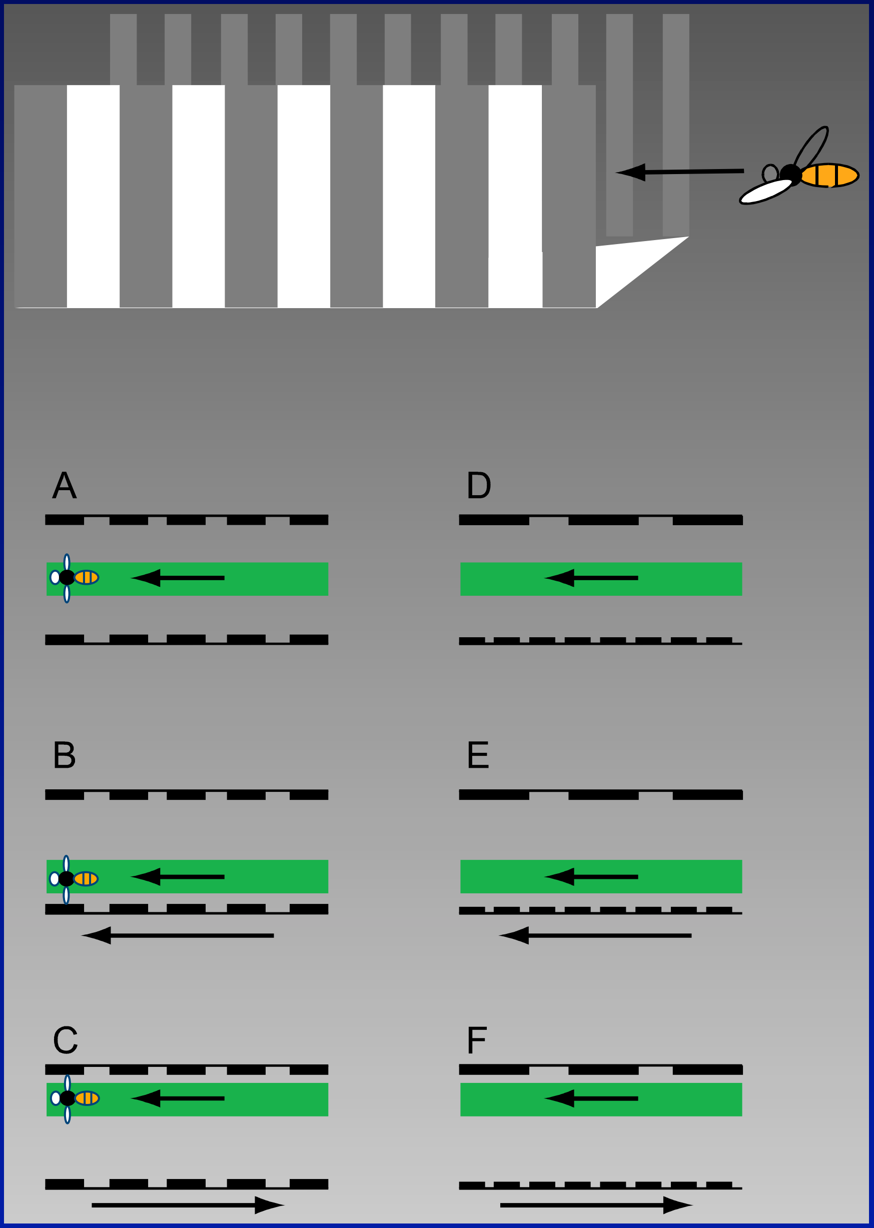
Peculiarities of insect vision

Small interocular separation

Therefore, stereo vision is difficult

→ Insects rely heavily on image motion cues to infer object distance, perceive the world in 3-D and navigate in it

Bees negotiate narrow gaps by balancing the image velocities in the two eyes

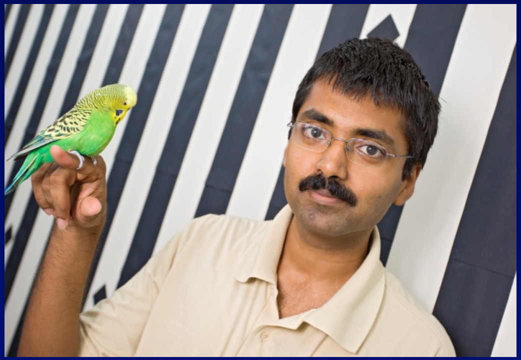


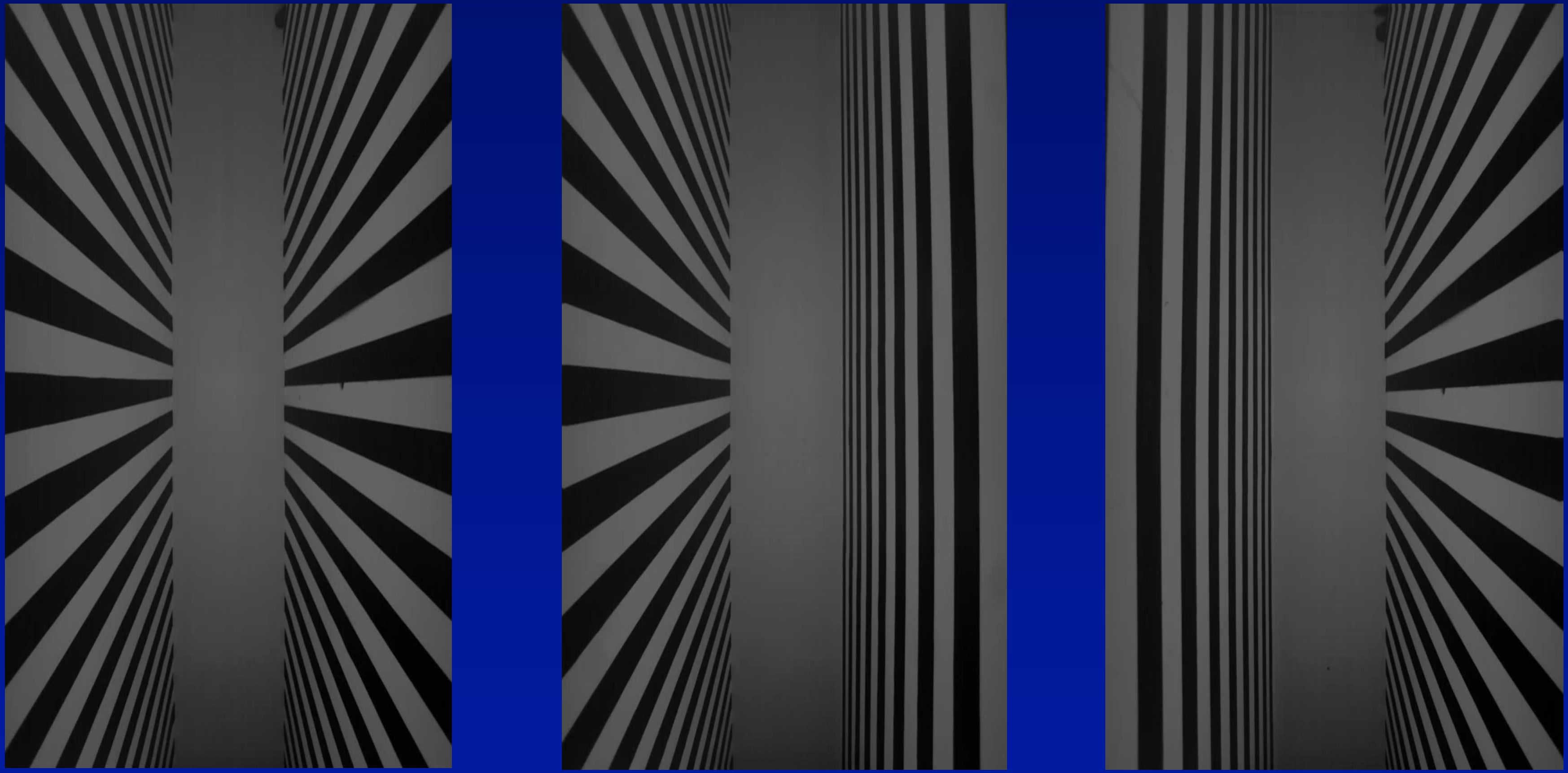
Kirchner & Srinivasan
Naturwissenschaften (1988)

Srinivasan, Lehrer, Kirchner & Zhang
Vis. Neurosci. (1991)

Centering response in budgerigars

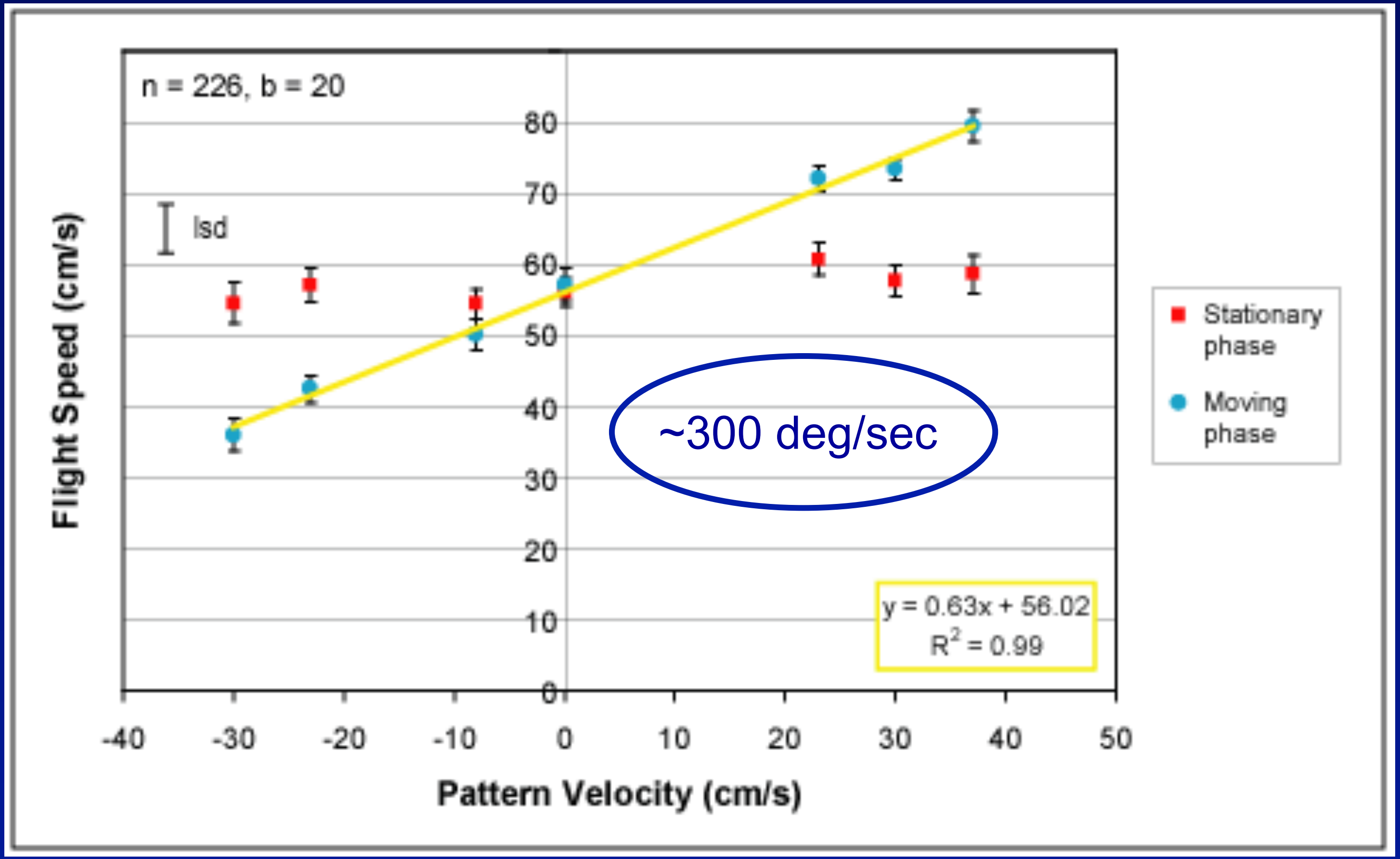
P. Bhagavatula, C. Claudianos, M. Ibbotson, M.V. Srinivasan
Current Biology (2011)

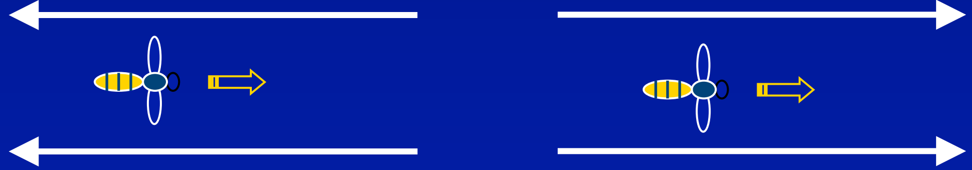




N.S.

Visual control of flight speed - bees

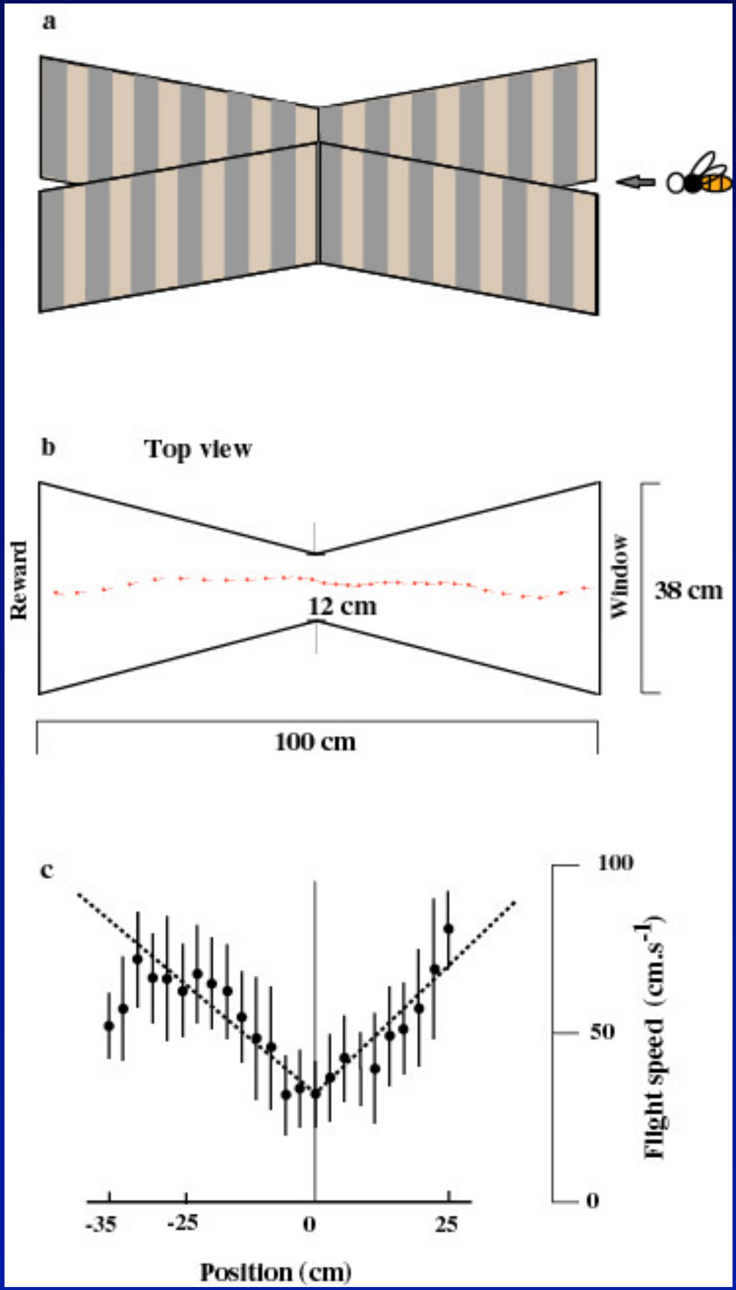




Baird, Srinivasan, Zhang and Cowley, J Exp Biol (2005)

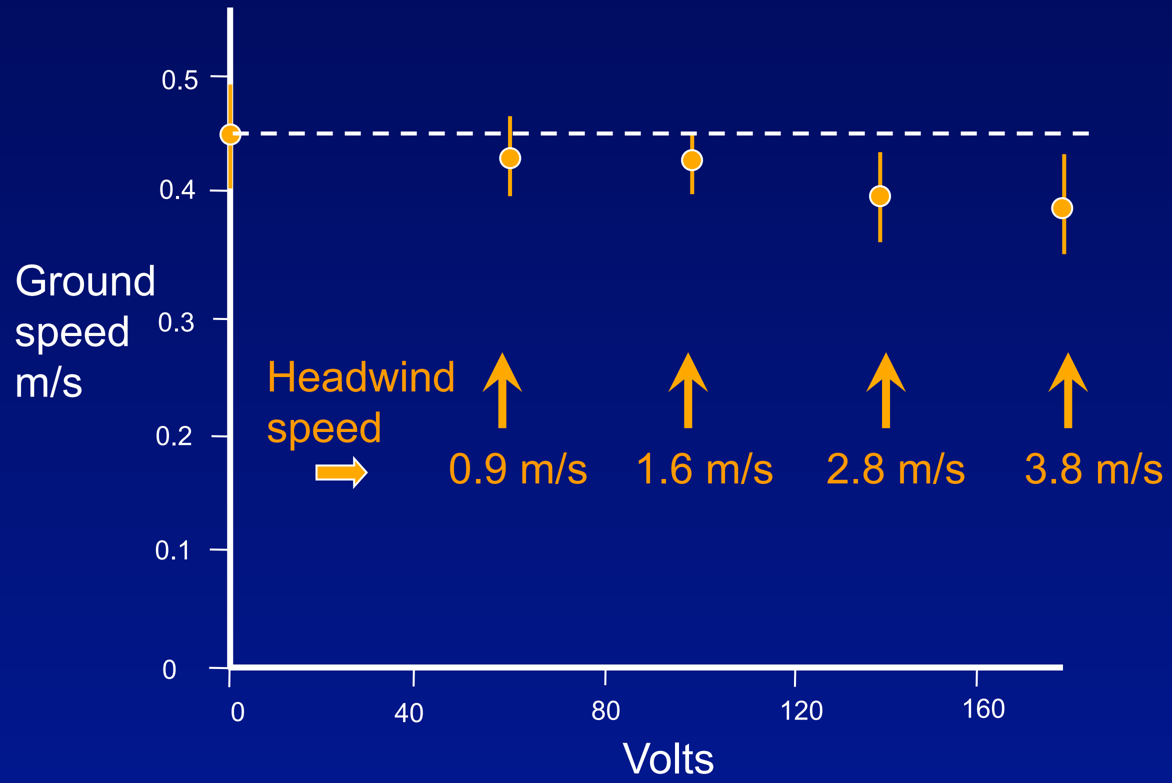
Control of flight speed

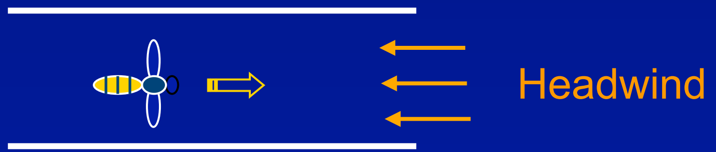
Speed of flight is regulated by holding the global image velocity constant



Srinivasan, Zhang, Lehrer & Collett
J. Exp. Biol. (1996)

Battling headwind



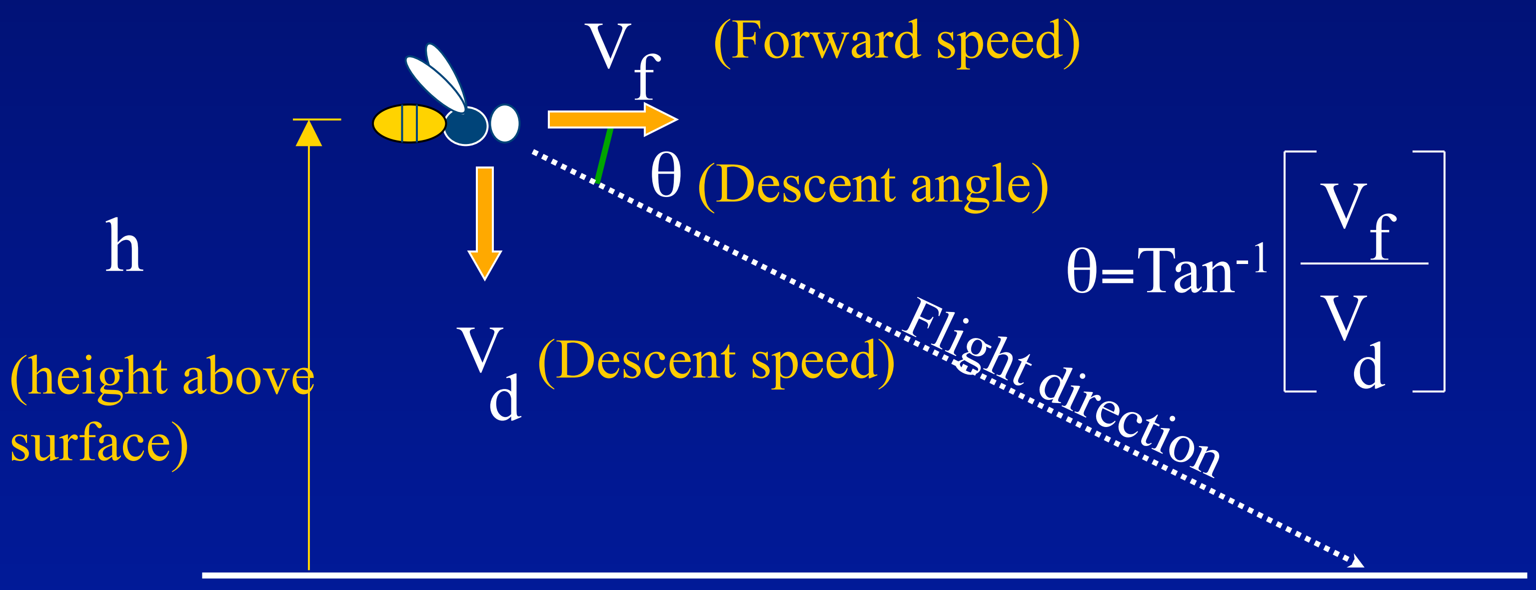


Barron and Srinivasan, *J. Exp. Biol.* (2006)

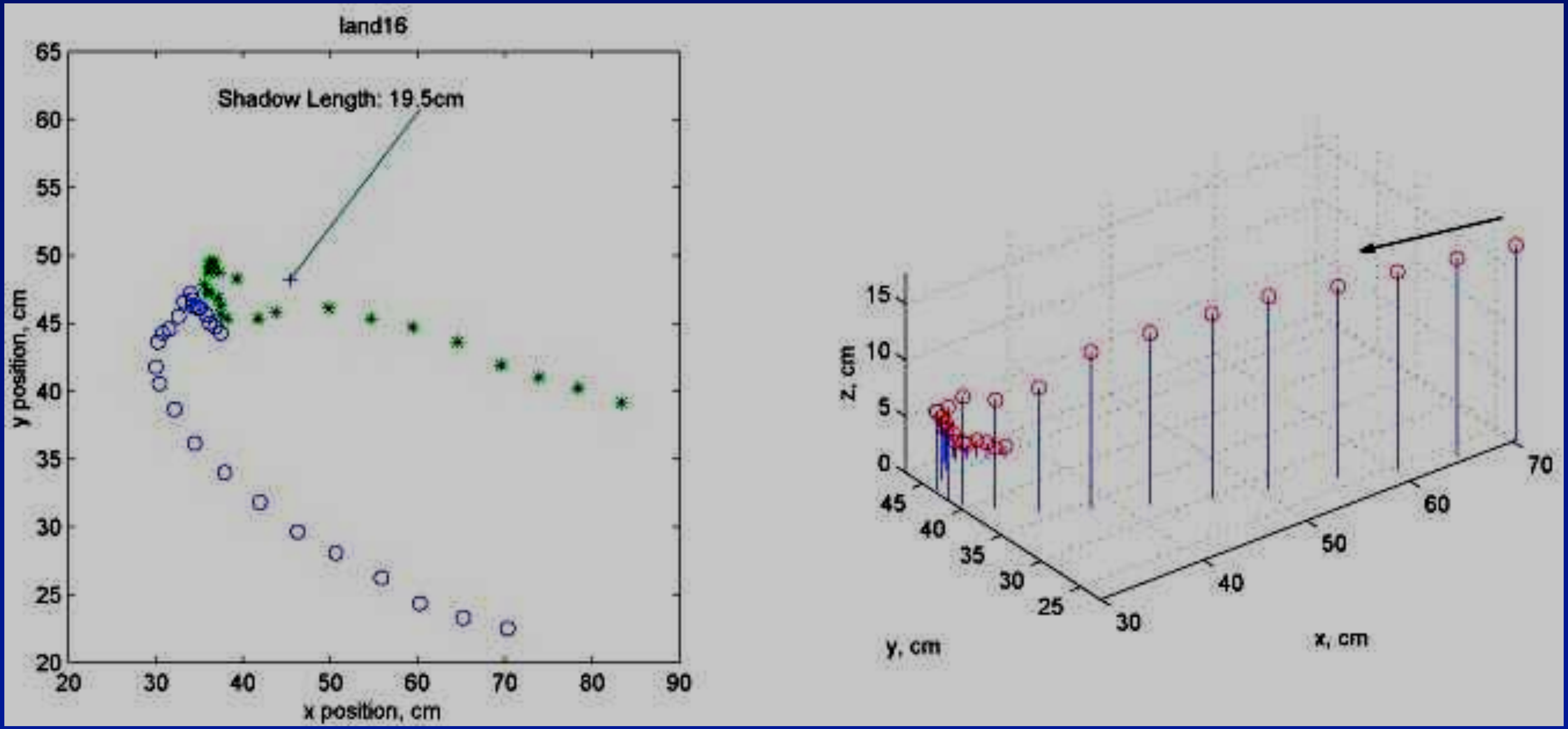
Landing

How does a bee perform a smooth, grazing landing ?

Landing parameters

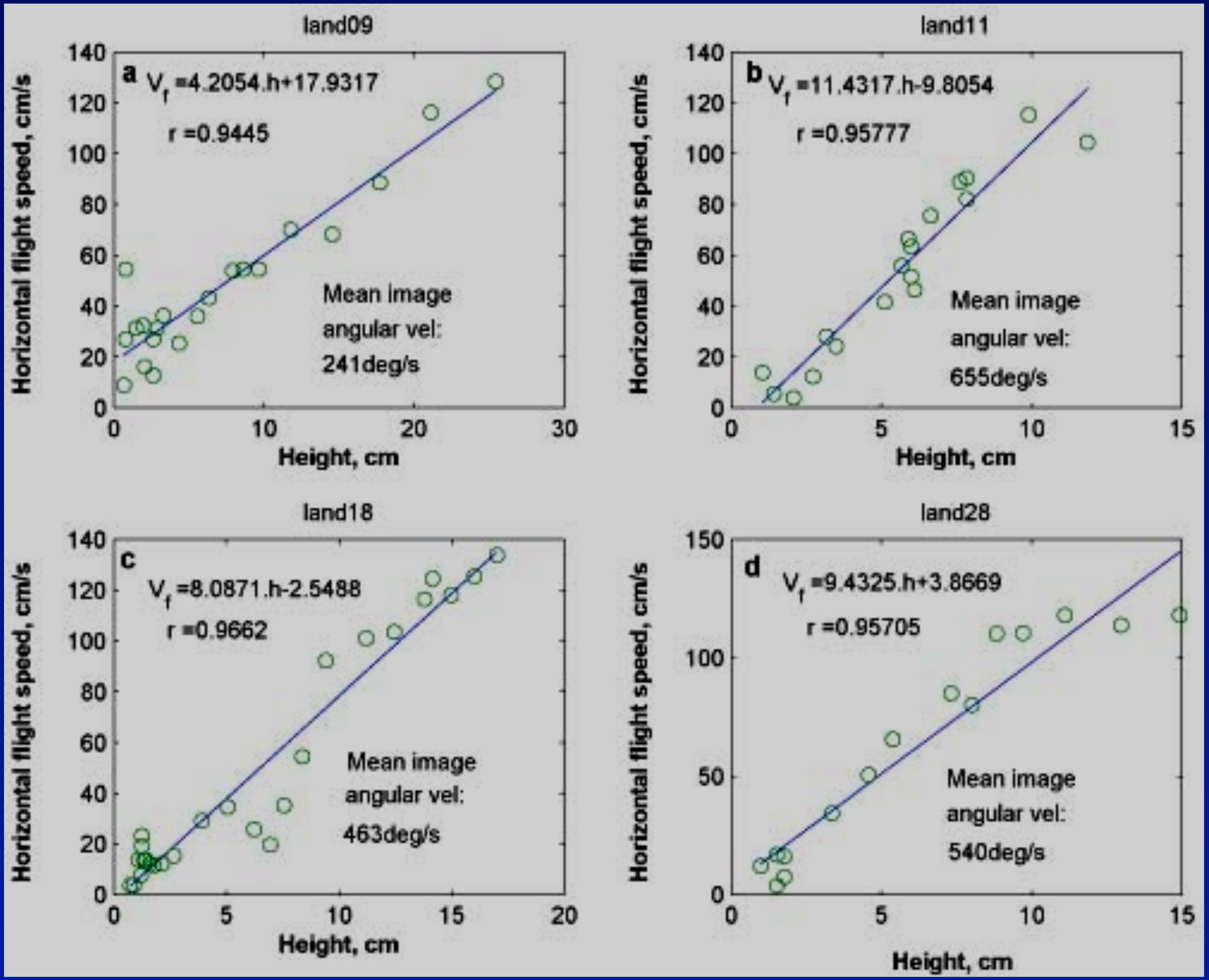


Reconstruction of landing trajectories in 3d

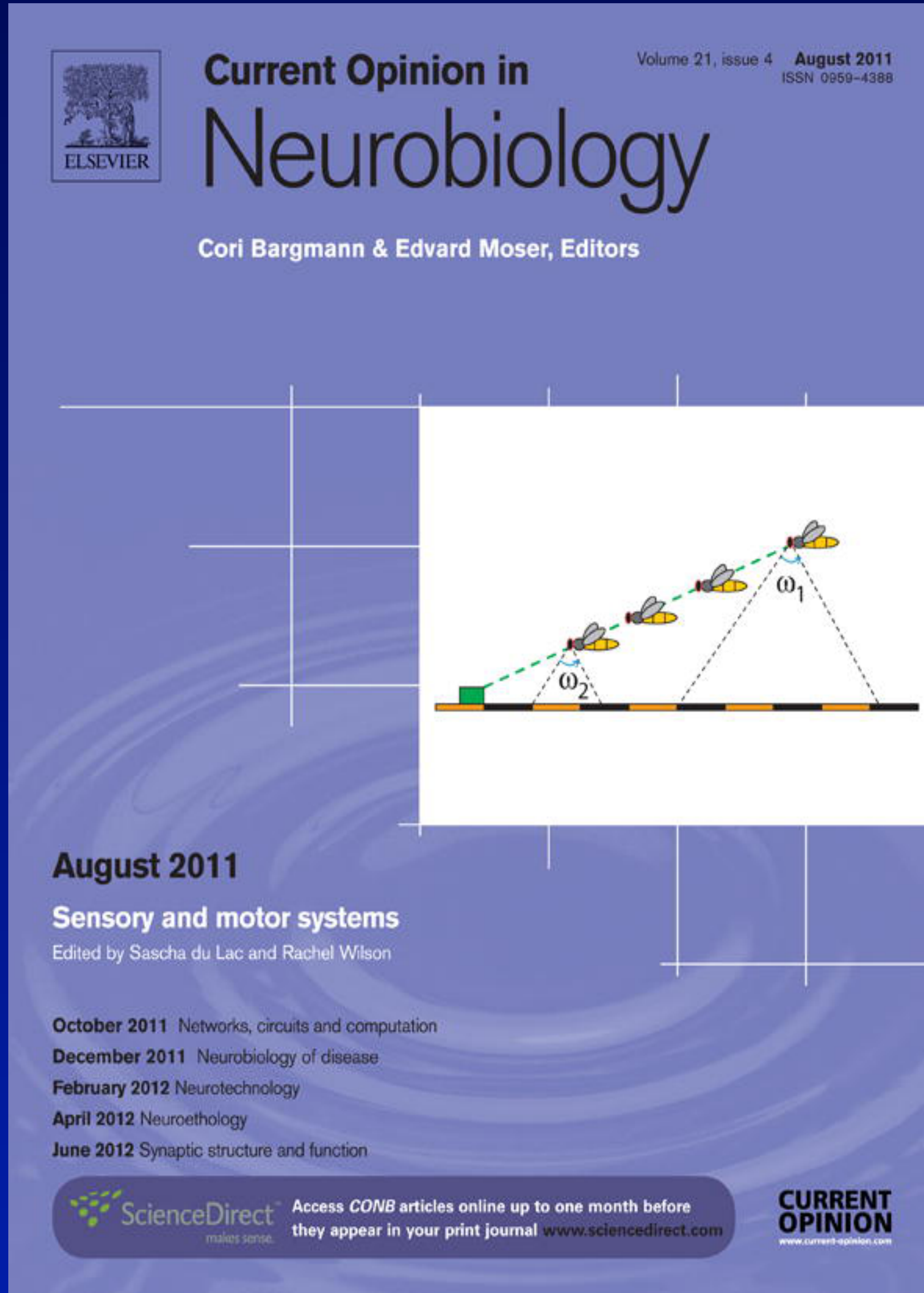


Srinivasan, Zhang, Chahl, Barth & Venkatesh, *Biol. Cybern.* (2000)

Horizontal flight speed versus height



Srinivasan, Zhang, Chahl, Barth & Venkatesh, *Biol. Cybern* (2000)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Cori Bargmann & Edvard Moser, Editors

ω_1
ω_2

August 2011

Sensory and motor systems
Edited by Sascha du Lac and Rachel Wilson

October 2011 Networks, circuits and computation
December 2011 Neurobiology of disease
February 2012 Neurotechnology
April 2012 Neuroethology
June 2012 Synaptic structure and function

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Rules for landing

1. Ground image speed is held constant

$$V_f(t) = \omega . h(t)$$

2. Instantaneous descent speed $V_d(t)$ is coupled to instantaneous forward flight speed $V_f(t)$:

$$V_d(t) = -\frac{dh(t)}{dt} = B.V_f(t)$$

Rules for landing

- Forward flight speed $V_f(t)$ is proportional to instantaneous height $h(t)$ above ground:

$$V_f(t) = \omega.h(t) \qquad (1)$$

where ω is the angular velocity of the image in radians/sec.

- Make descent speed $V_d(t)$ proportional to forward flight speed $V_f(t)$:

$$V_d(t) = -\frac{dh(t)}{dt} = B.V_f(t) \qquad (2)$$

Inserting (1) into (2),

$$B.\omega.h(t) + \frac{dh(t)}{dt} = 0 \qquad (3)$$

which can be solved for $h(t)$ to yield

$$h(t) = h(t_0).e^{-\omega.B.(t-t_0)} \qquad (4)$$

where $h(t_0)$ is the height at the initial time $t = t_o$.

$\Rightarrow$ ***Height decreases exponentially with time***

Inserting (4) into (1),

$$V_f(t) = \omega.h(t_0).e^{-\omega.B.(t-t_0)} \qquad (5)$$

$\Rightarrow$ ***Forward speed decreases exponentially with time***

Inserting (5) into (2),

$$V_d(t) = B.\omega.h(t_0).e^{-\omega.B.(t-t_0)} \qquad (6)$$

$\Rightarrow$ ***Descent speed also decreases exponentially with time***

Dividing (6) by (5),

$$\frac{V_d(t)}{V_f(t)} = B \qquad (7)$$

as required by the descent constraint.

- Cumulative horizontal distance travelled $(Hordist)$:

$$Hordist = \int_{t_0}^{t} V_f(t).dt = \int_{t_0}^{t} \omega.h(t_0).e^{-\omega.B.(t-t_0)}.dt \qquad (8)$$

Integrating, we get

$$Hordist = \frac{h(t_0)}{B}.\left[1 - e^{-\omega.B.(t-t_0)}\right] \qquad (9)$$

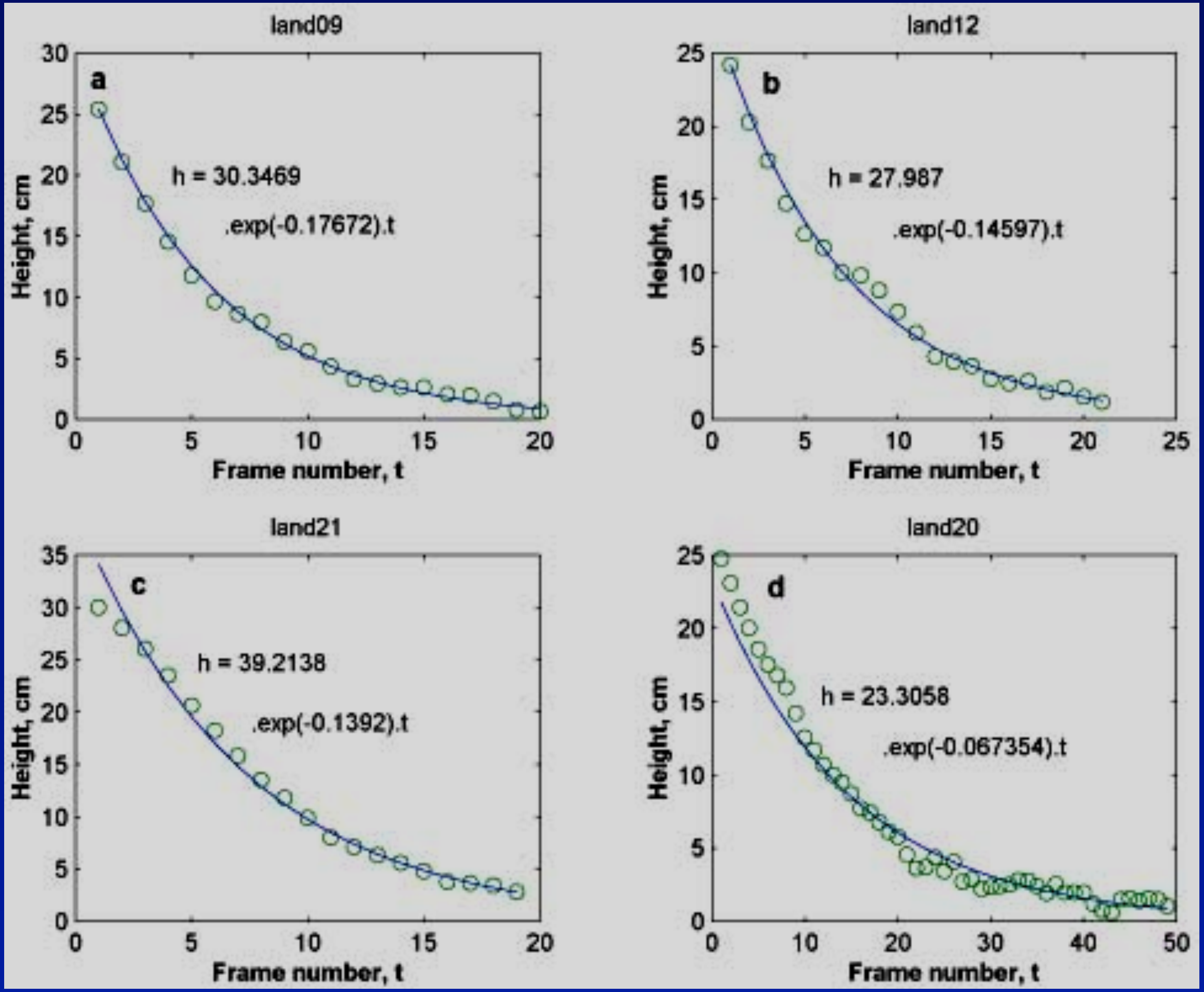
$\Rightarrow$ ***Horizontal distance travelled is a saturating exponential function of time***

Model prediction 1:

$$h(t) = h(t_0).e^{-\omega.B.t}$$

$\Rightarrow$ Height decreases exponentially with time

Test of prediction 1



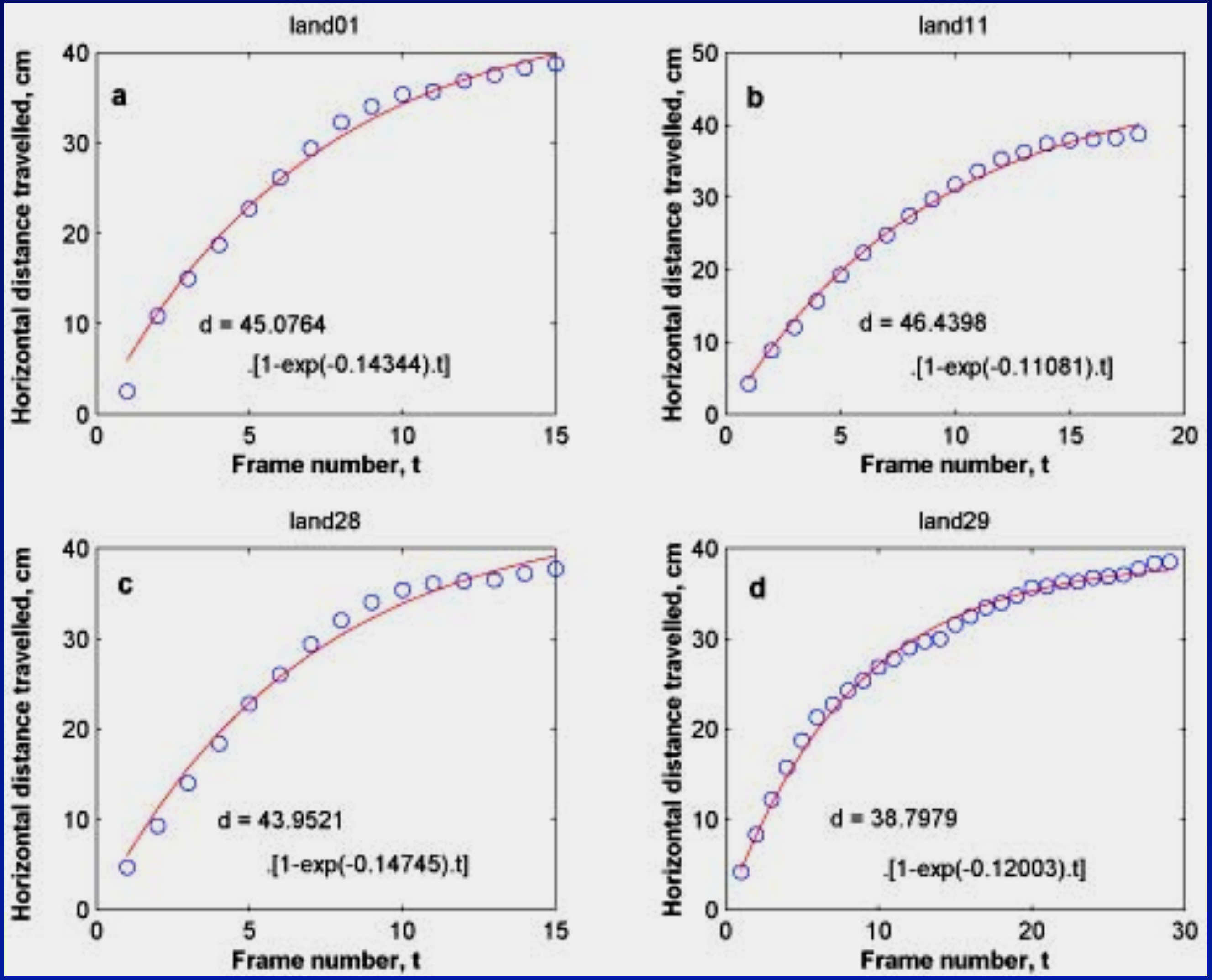
Srinivasan, Zhang, Chahl, Barth & Venkatesh, *Biol. Cybern* (2000)

Model prediction 2:

$$Hordist = \frac{h(t_0)}{B}.\left[1 - e^{-\omega.B.t}\right]$$

$\Rightarrow$ Cumulative horizontal distance travelled is a saturating exponential function of time

Test of Prediction 2



Srinivasan, Zhang, Chahl, Barth & Venkatesh, *Biol. Cybern* (2000)

Projected time to touchdown

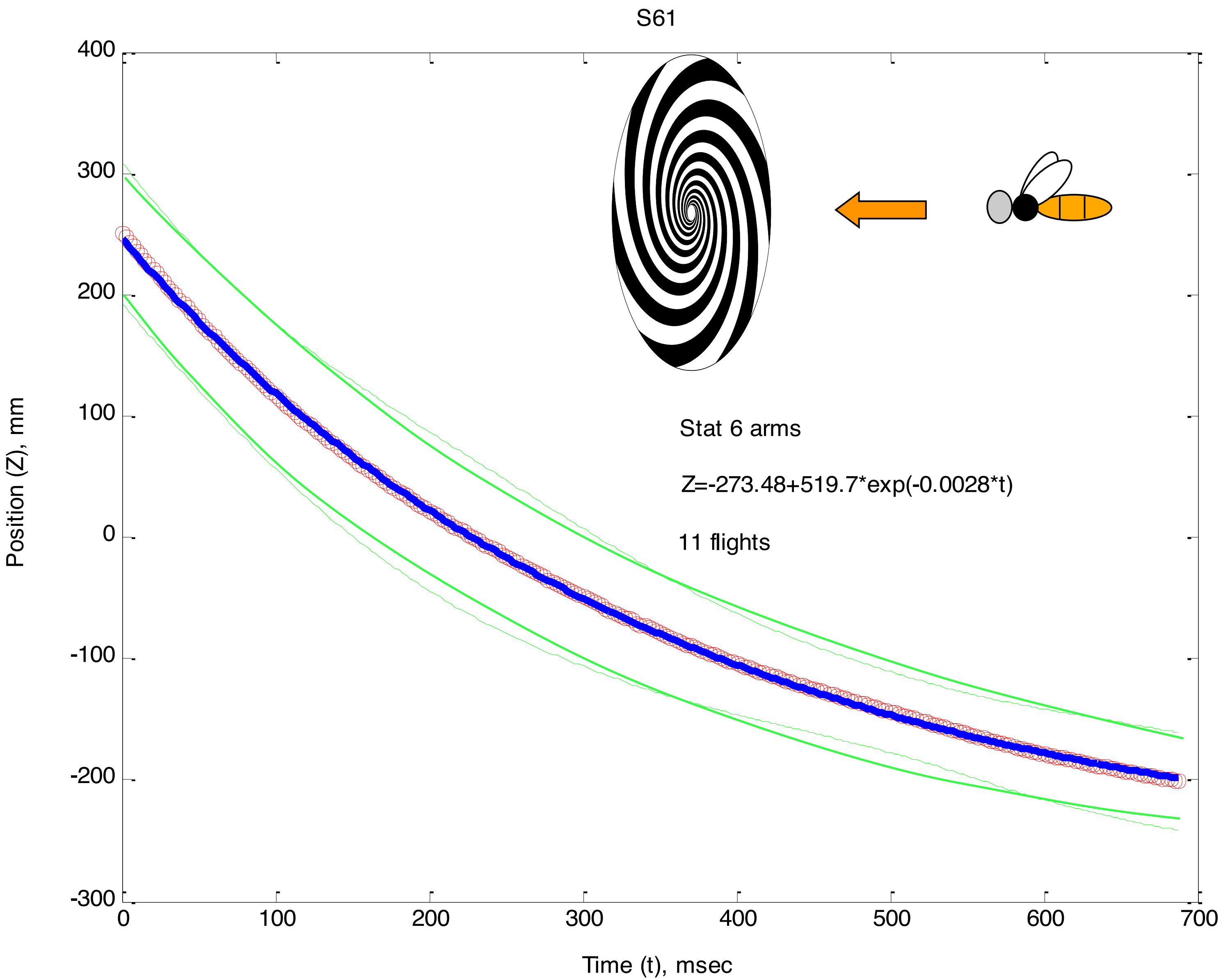
$$TTT = \frac{1}{B.\omega}$$

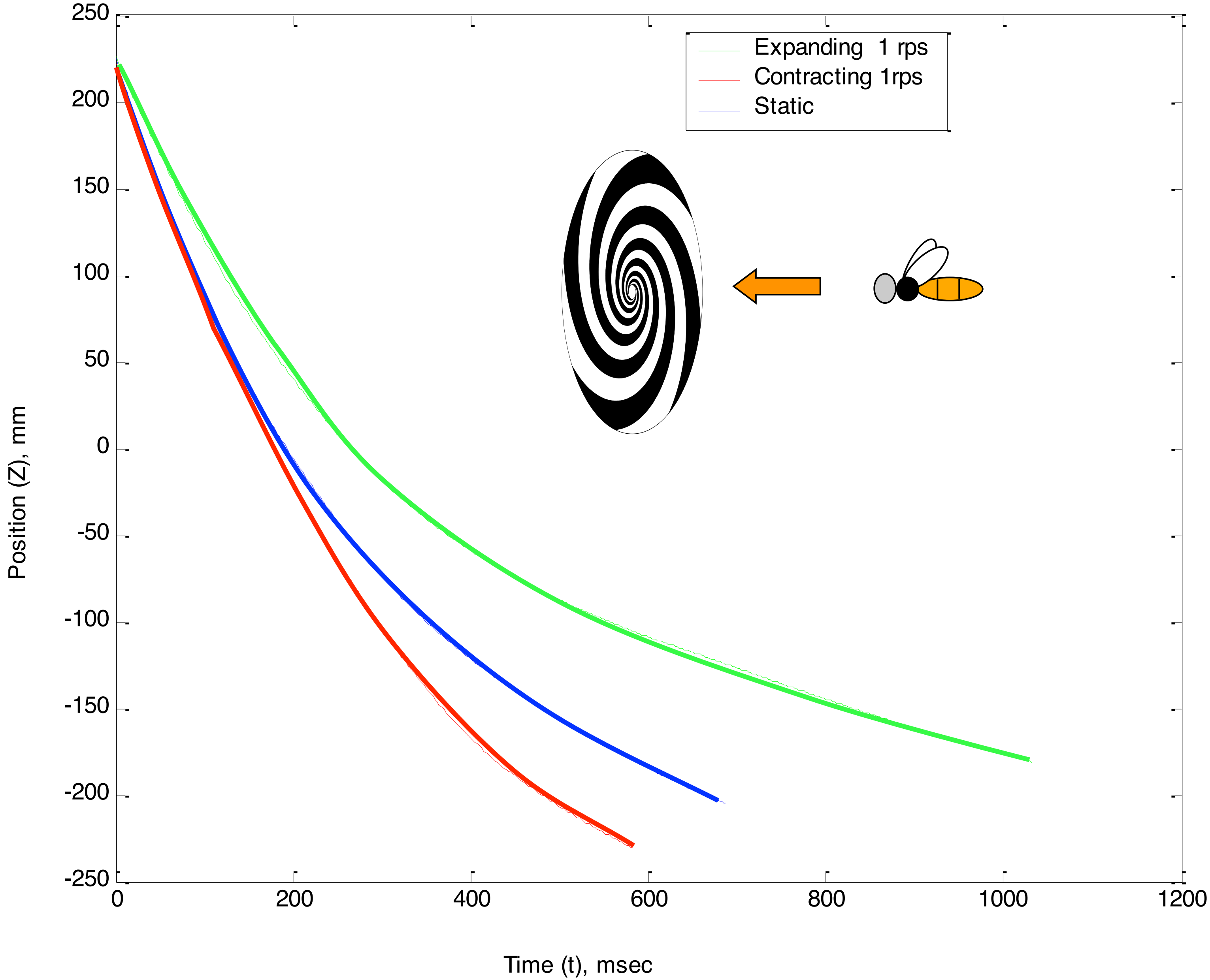
$\cong$ 0.22 sec

Is constant through the landing process!

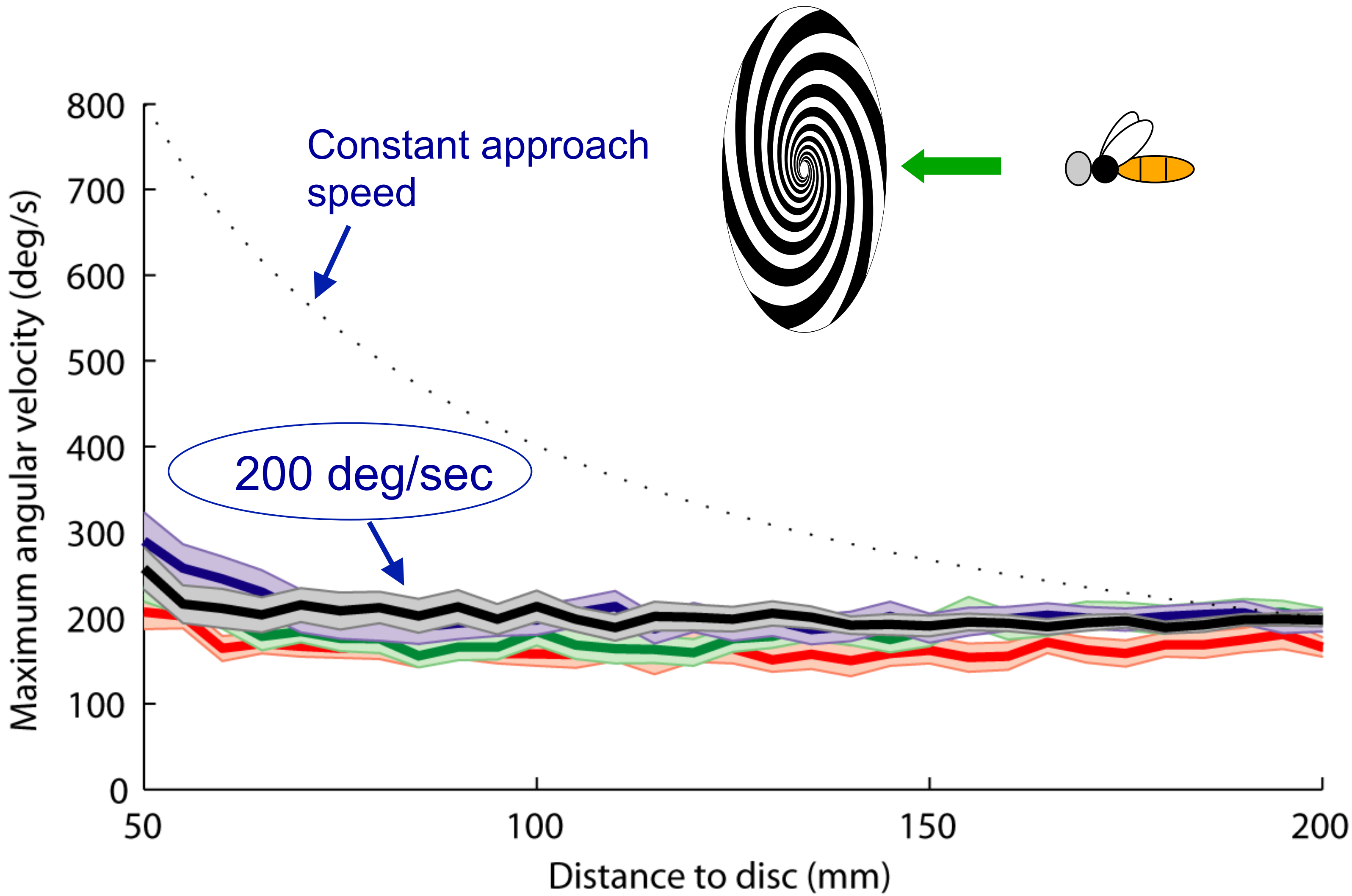
Work with Emily Baird, Norbert Boeddeker

Distance decreases exponentially as a function of time



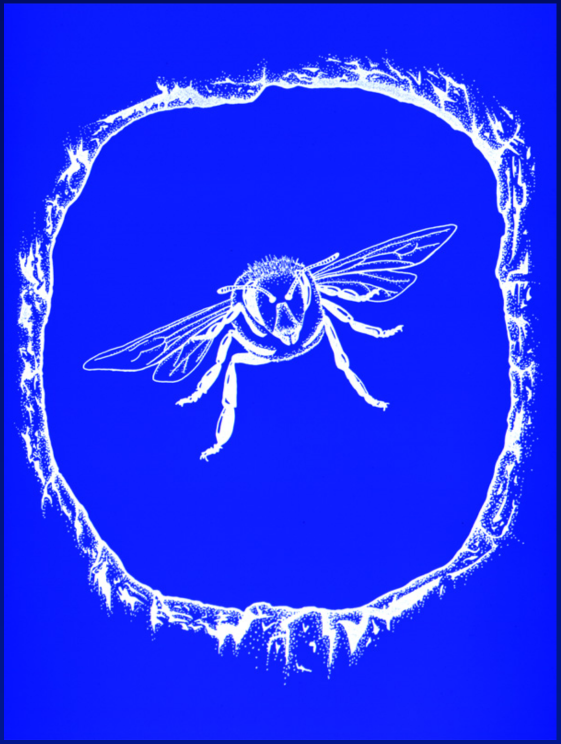


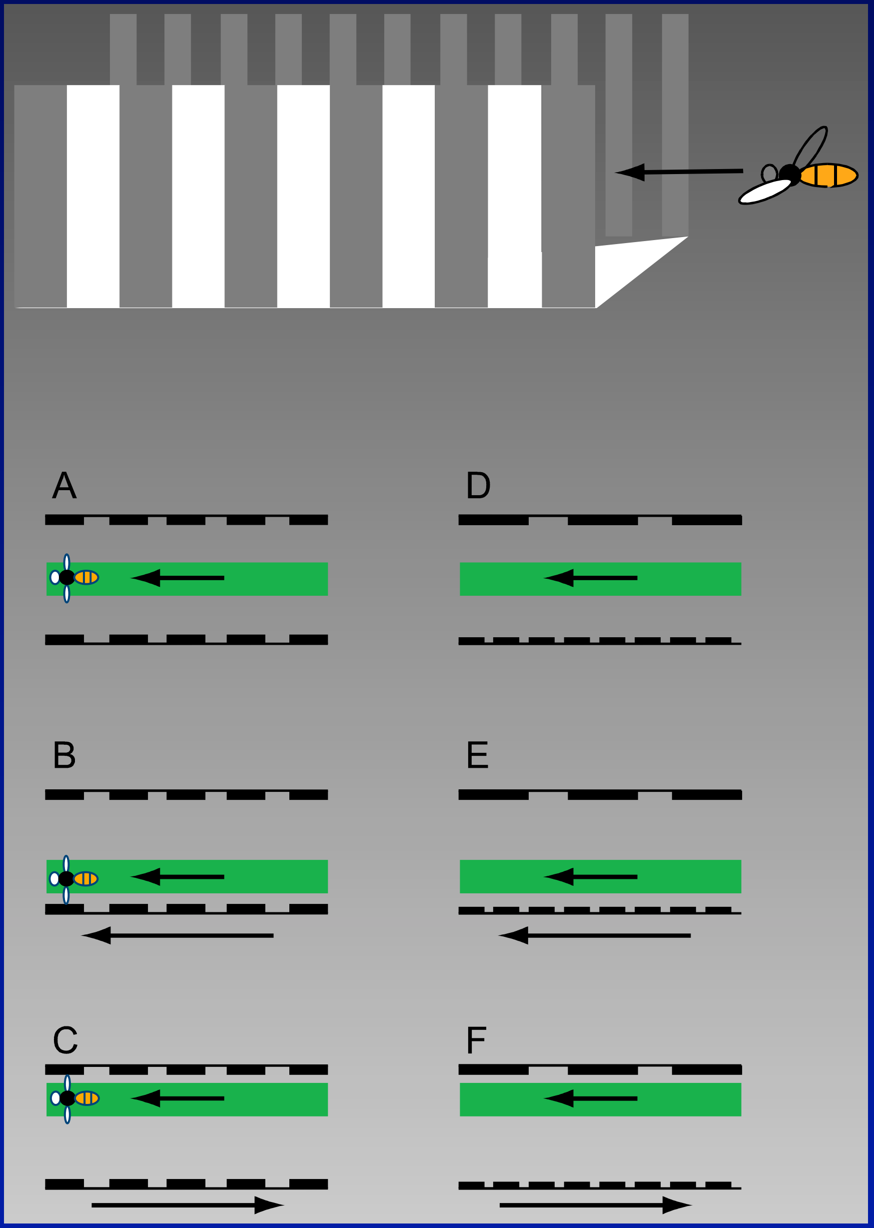
Expanding 1 rps
Contracting 1rps
Static
Position (Z), mm
Time (t), msec
250
200
150
100
50
0
-50
-100
-150
-200
-250
0
200
400
600
800
1000
1200


Constant approach speed
200 deg/sec
Maximum angular velocity (deg/s)
800
700
600
500
400
300
200
100
0
50
100
150
200
Distance to disc (mm)

Biologically inspired robotics

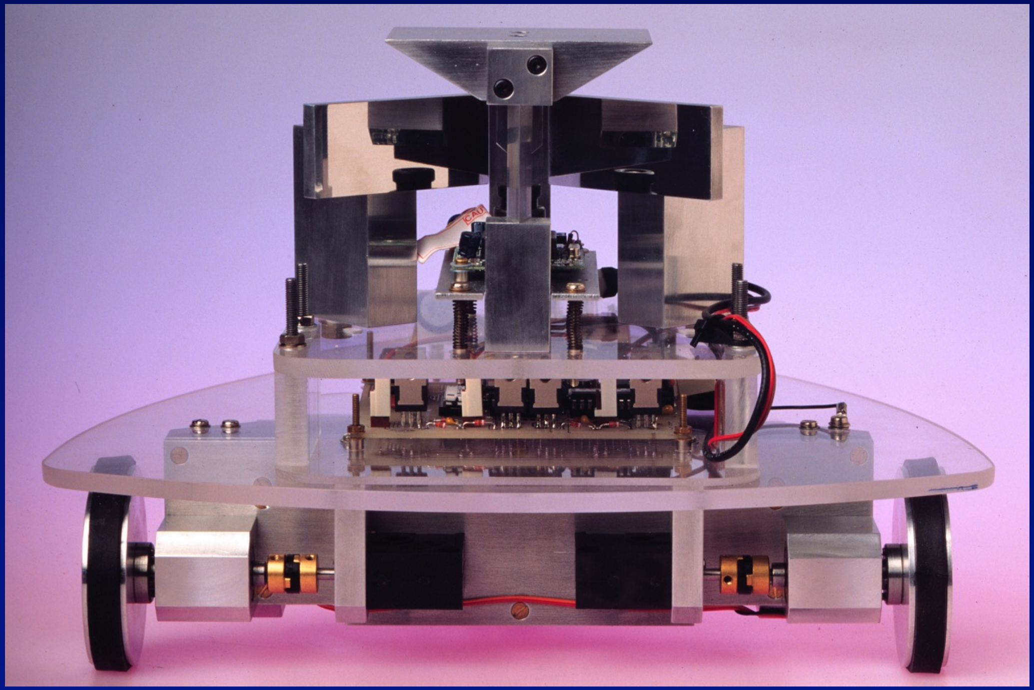
Bees negotiate narrow gaps by balancing the image velocities in the two eyes

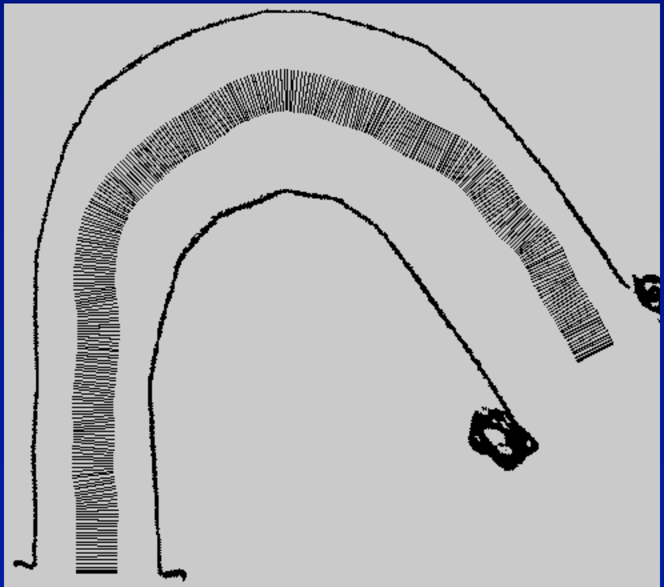




Kirchner & Srinivasan
Naturwissenschaften (1988)

Srinivasan, Lehrer, Kirchner & Zhang
Vis. Neurosci. (1991)





This robot, about the size of a skateboard, navigates along corridors by balancing optic flows on the left and the right

Weber, Chahl, Srinivasan & Venkatesh (1997)

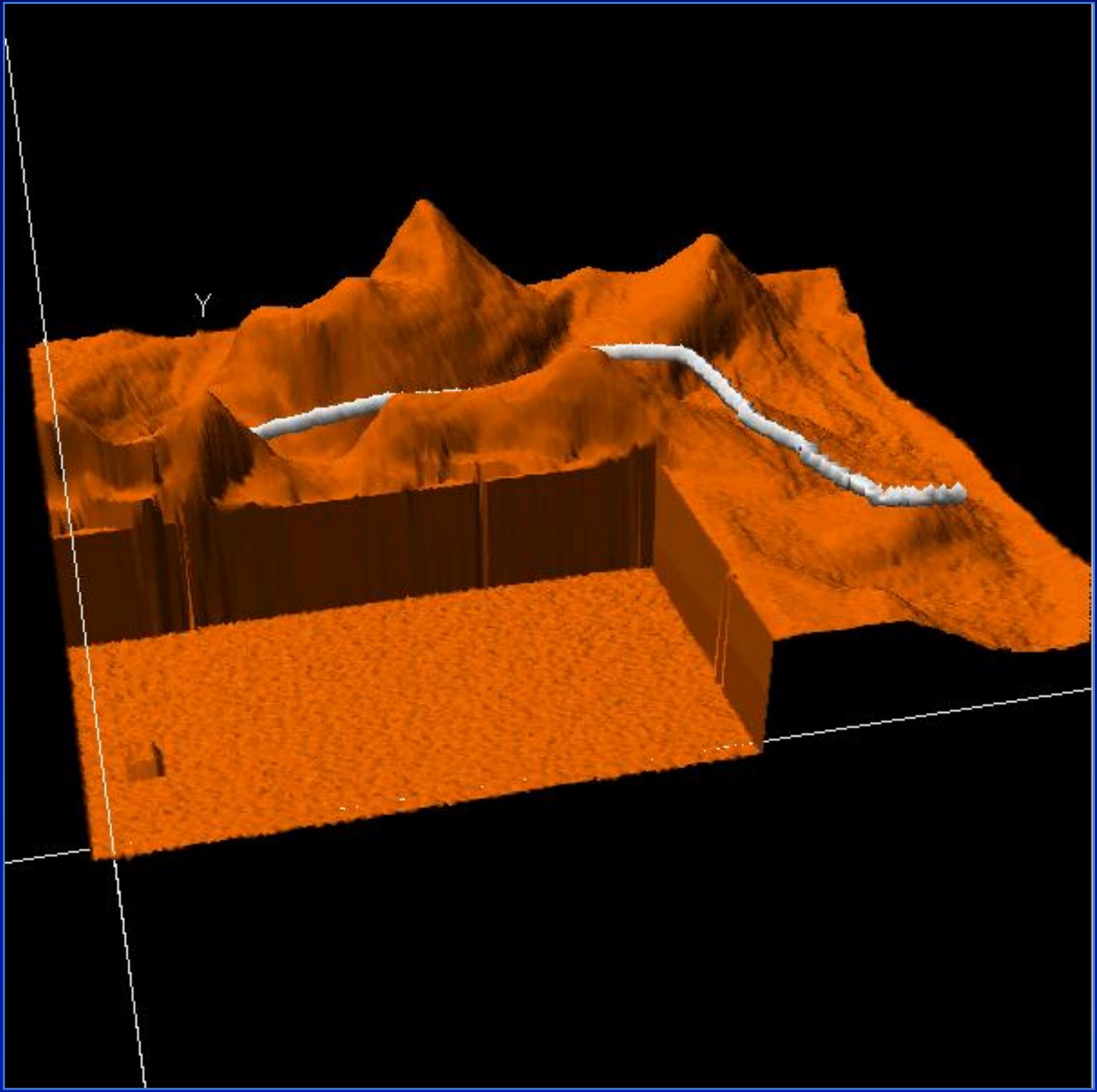
Navigation in 3-D

Gantry -based, insect-inspired navigation system emulates flight in realistic terrain

Navigation in 3-D(contd.)

Development and testing of algorithms for landing, terrain following, gorge following, obstacle avoidance and point-to-point navigation

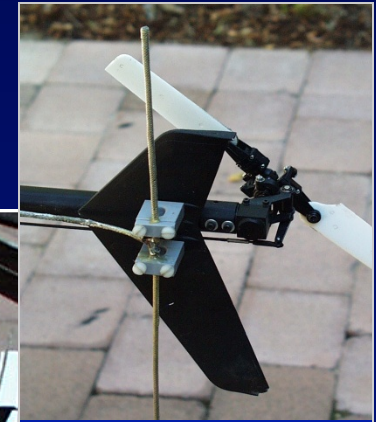
Chahl & Srinivasan (2000b)

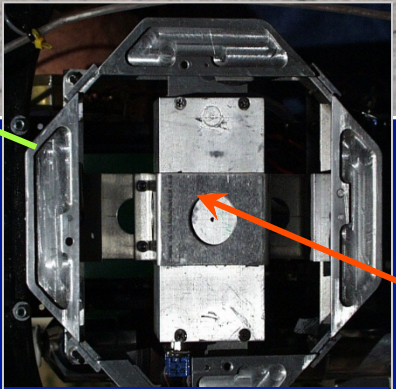



Commands
Alt
50
200
700
Start

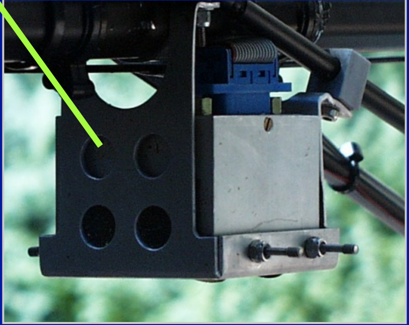
Helicopter System Overview

(Hirobo Eagle-X)

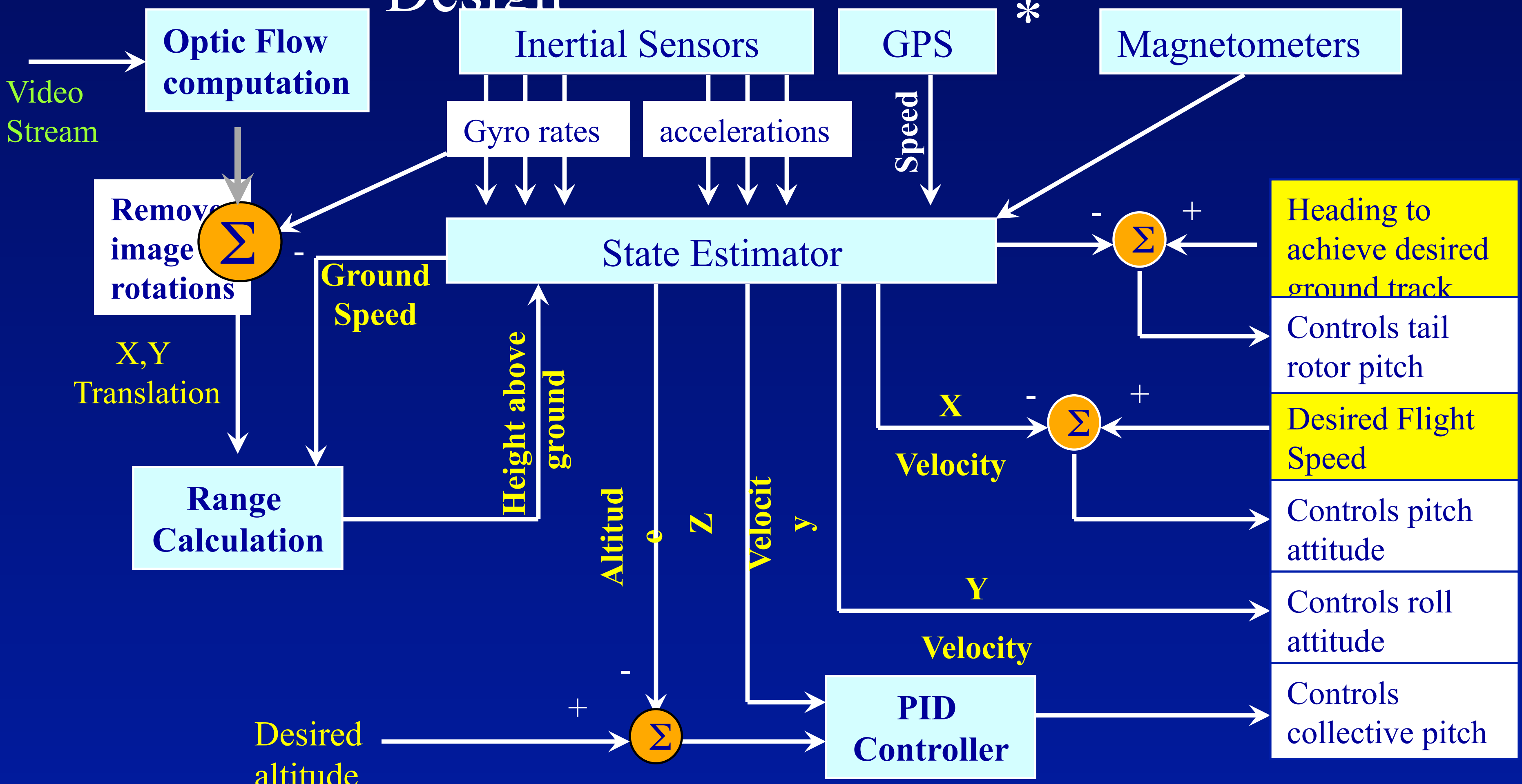

Video Antenna



Vibration Isolator

Magnetometers


Forward Flight Controller Design



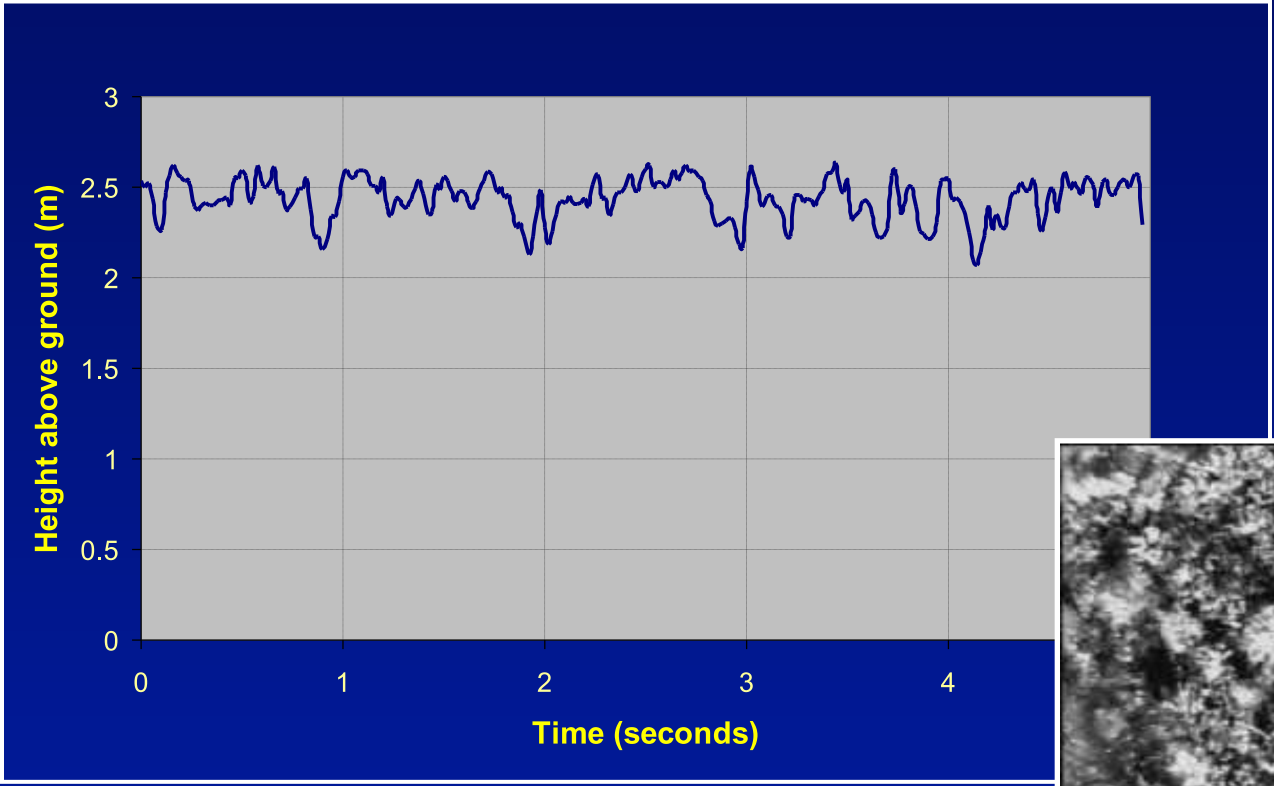
* GPS can be replaced with any suitable ground speed measure.

Field testing of forward flight controller

View from helicopter

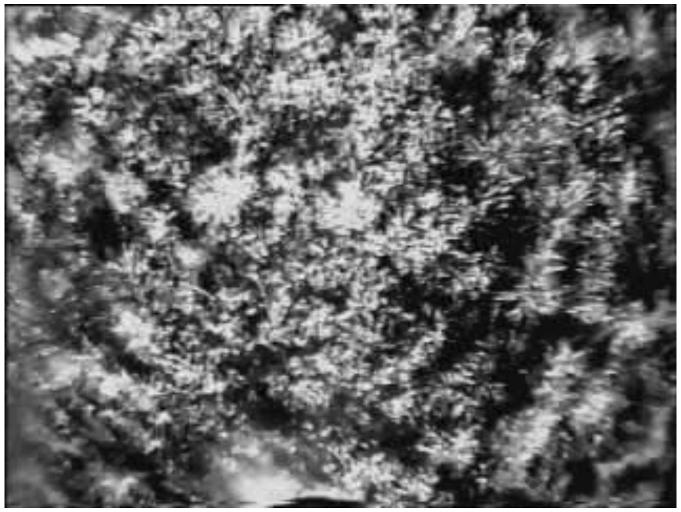
Method adopted for testing forward flight algorithms on actual helicopter. A safety pilot observes from the back of the chase vehicle, poised to take control from the automatic controller for take off, landing and in case of an emergency.

Flight test results for helicopter at 50 km/hr



Height above ground calculated by optic flow

Image from downward looking camera



Measurement of image motion:
Feature tracking

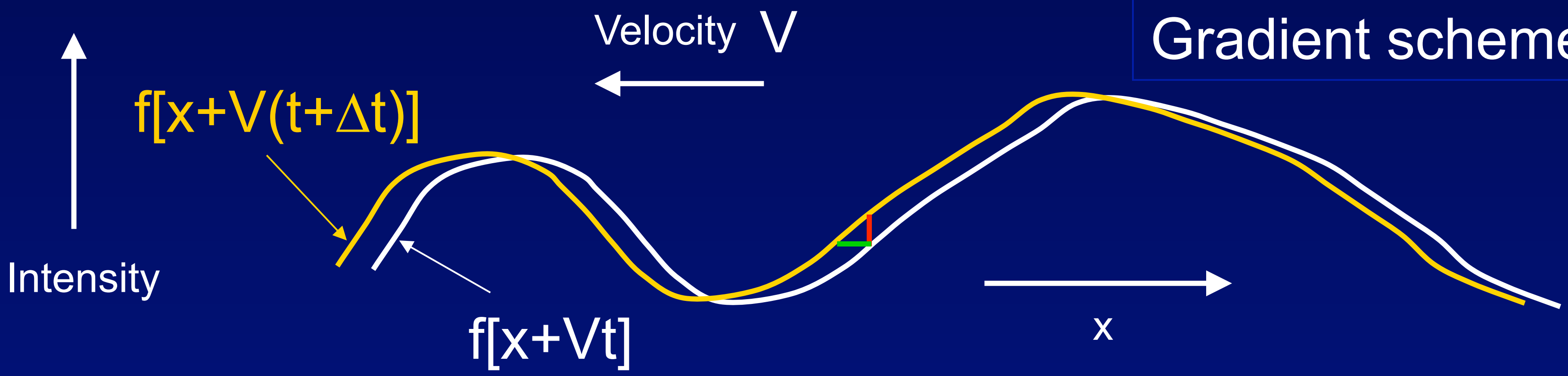
Frame 1

Frame 2

Measurement of image motion:

Correlation/Image matching

Gradient scheme



$$f(x+V.t)$$

$$\frac{\partial f}{\partial t} = V.f'(x+V.t)$$

$$\frac{\partial f}{\partial x} = f'(x+V.t)$$

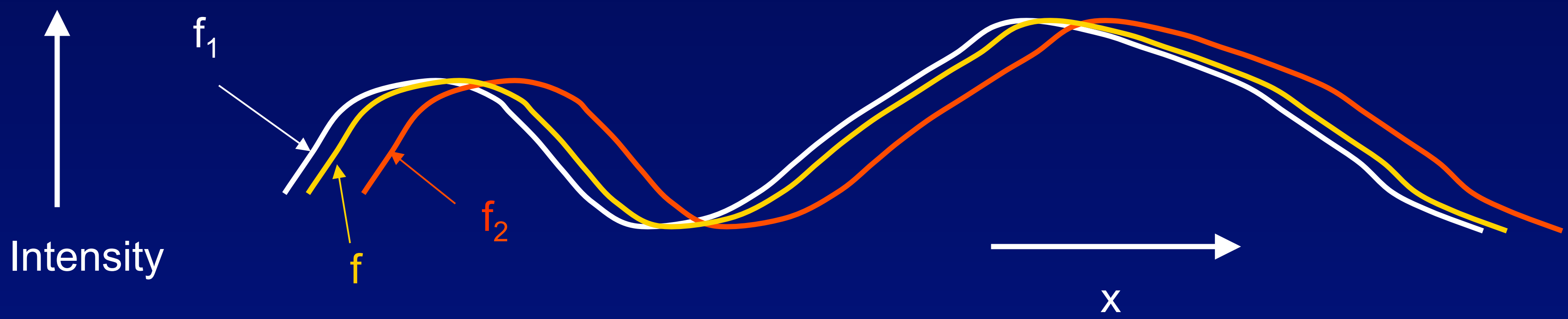
$$\frac{\partial f}{\partial t} / \frac{\partial f}{\partial x} = \frac{V.f'(x+V.t)}{f'(x+V.t)} = V$$

$$V = \frac{Local\_temporal\_derivative}{Local\_spatial\_derivative}$$

Limb JO & Murphy JA: Comput Graph Image Process (19
Horn BKP & Schunck: Artif Intell (1981)

Image Interpolation Scheme

MV Srinivasan: Biol. Cybern. (1994)



$$\hat{f} \cong (1-\alpha).f_1 + \alpha.f_2$$

$$\underset{\alpha}{Minimize}..E = \int \psi.(f - \hat{f})^2.dx$$

$$\underset{\alpha}{Minimize}..E = \int \psi.(f - (1-\alpha).f_1 - \alpha.f_2)^2.dx$$

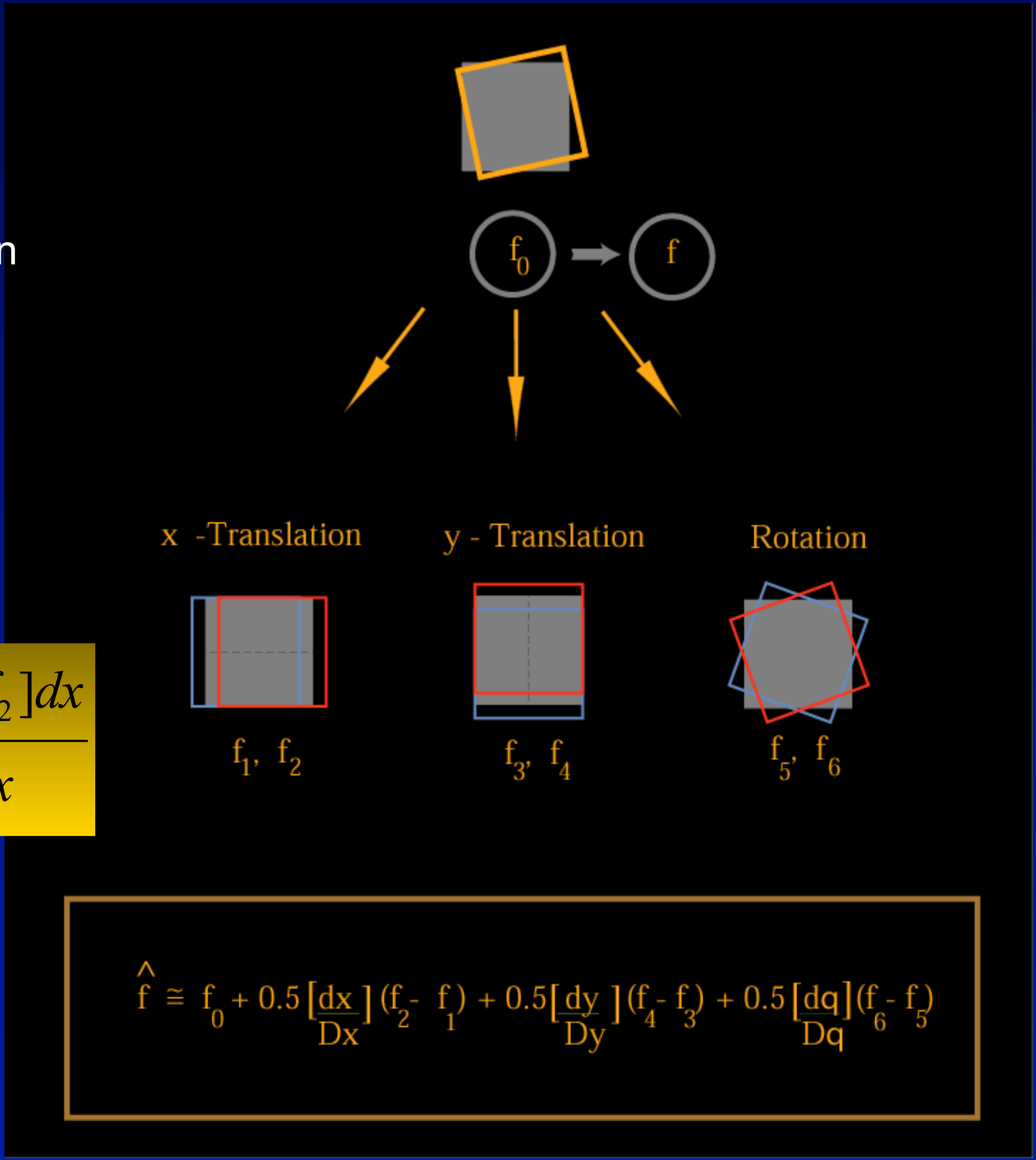
$$\frac{dE}{d\alpha} = 0 \Rightarrow \int \psi.(f - f_1).(f_2 - f_1).dx = \alpha.\int \psi.(f_2 - f_1)^2.dx$$

$$\alpha = \frac{\int \psi.(f - f_1).(f_2 - f_1).dx}{\int \psi.(f_2 - f_1)^2.dx}$$

Image Interpolation
Algorithm – 2D image motion

Min $\iint \psi (f - \hat{f})^2 dx.dy$

$$\frac{dx}{Dx} = 2\frac{\iint \psi.[f - f_1][f_1 - f_2]dx}{\iint \psi.[f_1 - f_2]^2 dx}$$



MV Srinivasan: Biol. Cybern. (1994)

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