



Bio-Inspired Odor Source Localization

SOAR2 Review

12-15 JULY 2011

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Report Documentation Page

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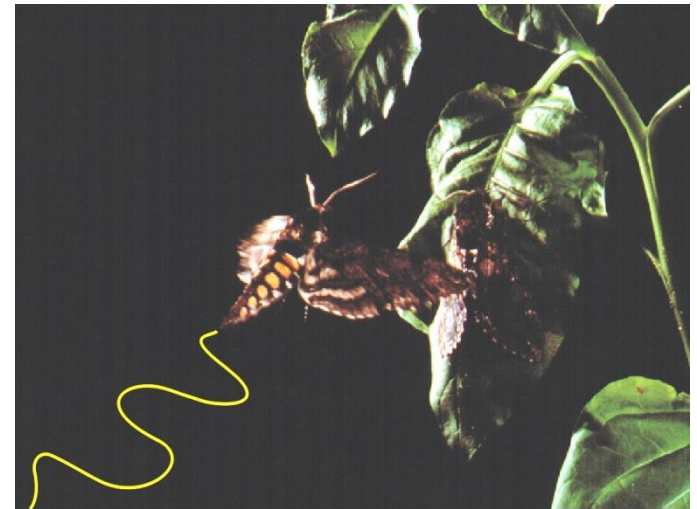
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Why study odor tracking?



- Engineer odor tracking systems
 - Gas leaks
 - Hazardous waste
 - Explosive devices
 - Biological principles
- Understand biological principles
 - Mate/food finding
 - Pest population control
 - Engineered odor tracking systems



Manduca sexta



Odor tracking overview



- Odor plume properties

- carried by wind

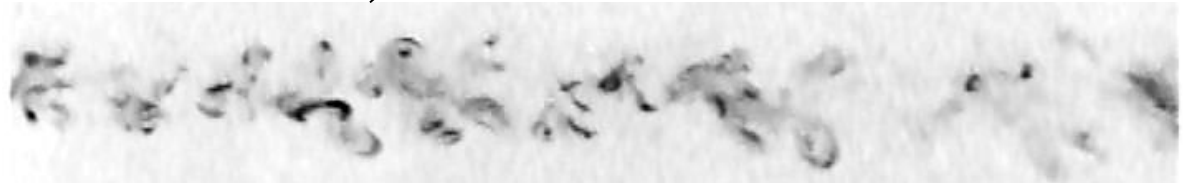
- invisible

- turbulent

- artificial: hazardous waste, explosives

- natural: pheromone, food

no strong gradient



- Tracking agents

- engineered: UAVs, UGVs, AUVs

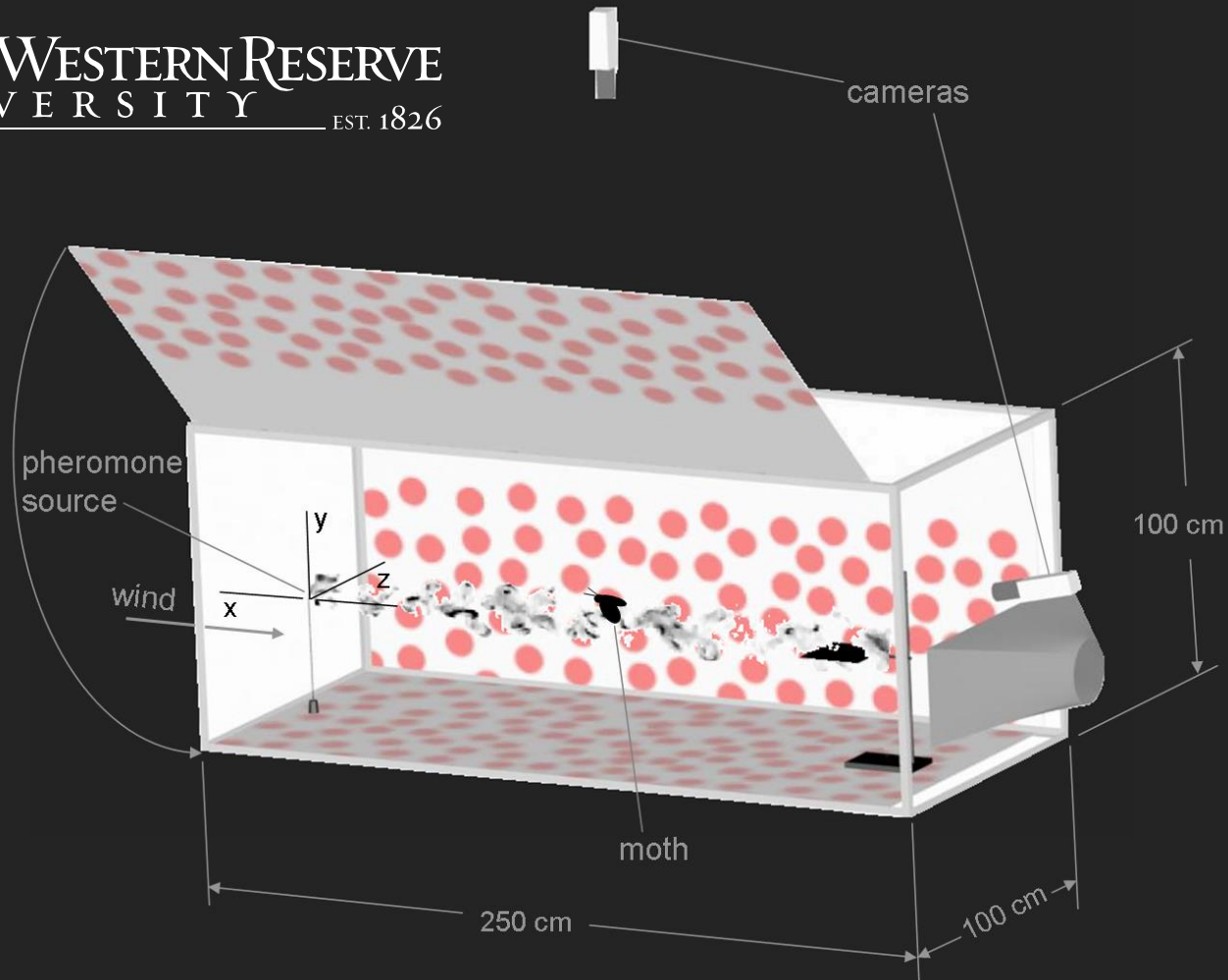
- natural: moths, cockroaches, fish



Moth Odor Tracking Studies

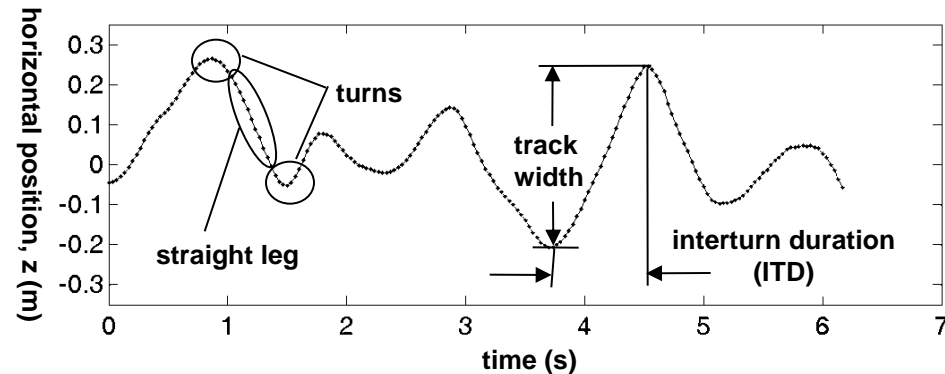
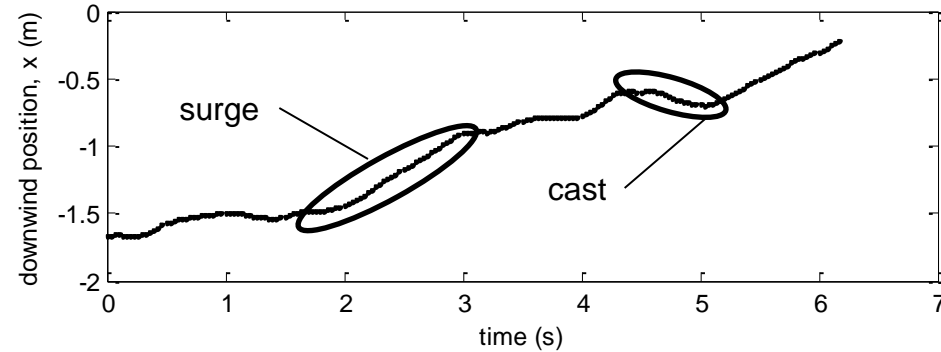
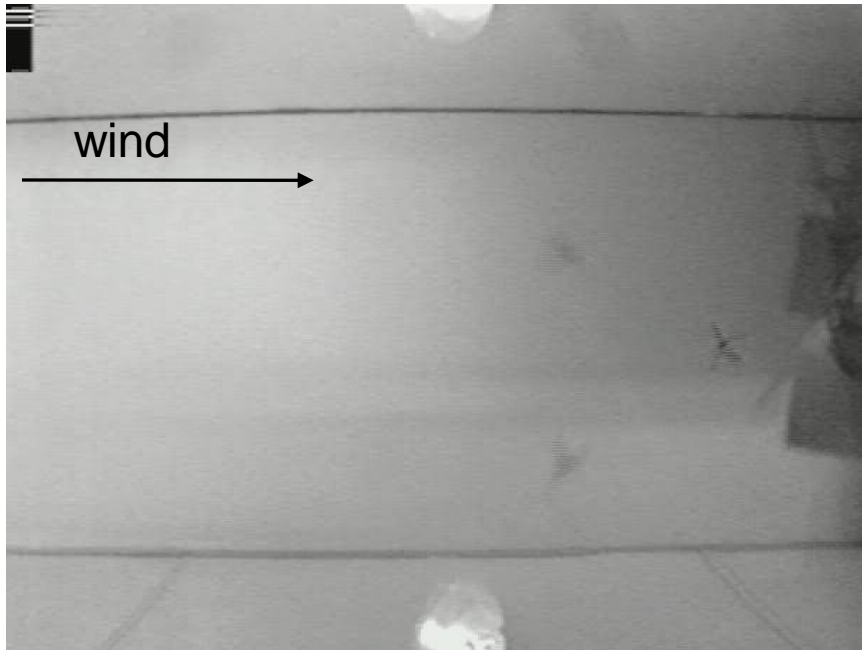


 **CASE WESTERN RESERVE**
UNIVERSITY EST. 1826





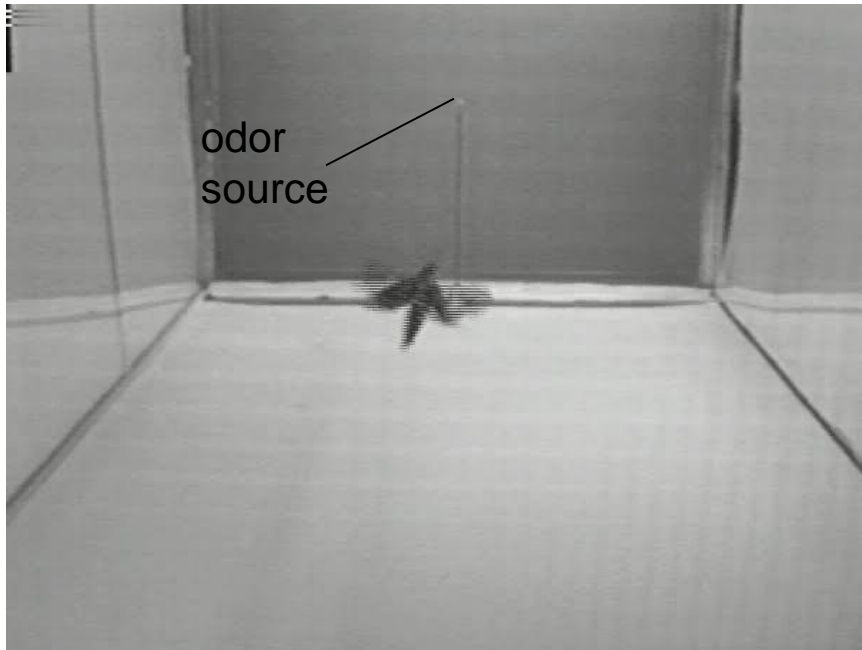
Traditional 2D Analysis



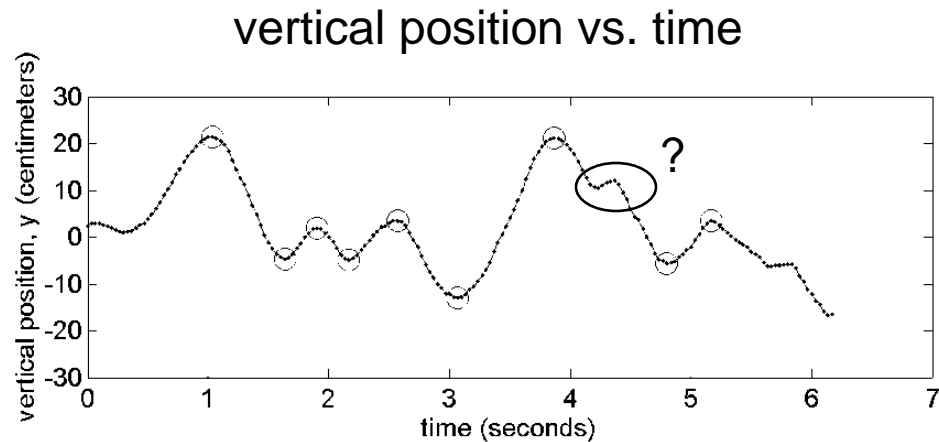
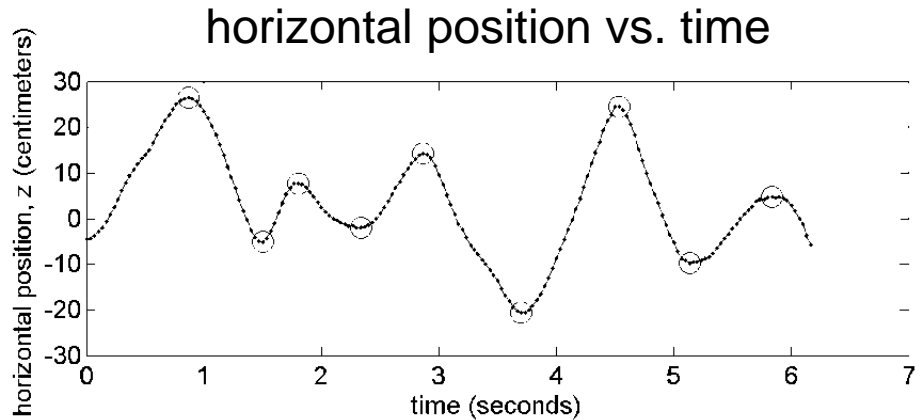
- Odor-modulated anemotaxis
 - Move upwind (surge) when odor detected, move downwind (cast) when odor lost
 - Combination of straight legs and turns (zigzagging)
 - Turning controlled by a timing mechanism (interturn duration of 580 ms)
- Odor plume altitude is maintained



3D Analysis



- Counter-turns vertically with average ITD of 550 ms (90-95% of horizontal ITD)
- Vertical track width 75% of horizontal track width
- Temporal relationship between vertical and horizontal turns is unpredictable
- Turns are ambiguous (in both y and z)



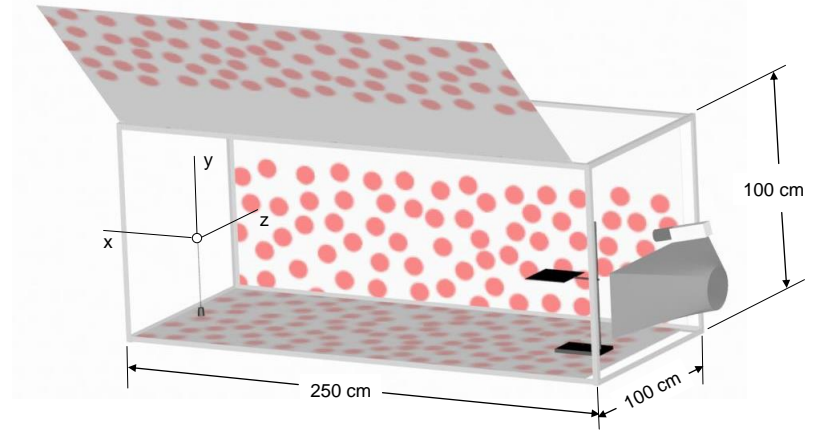
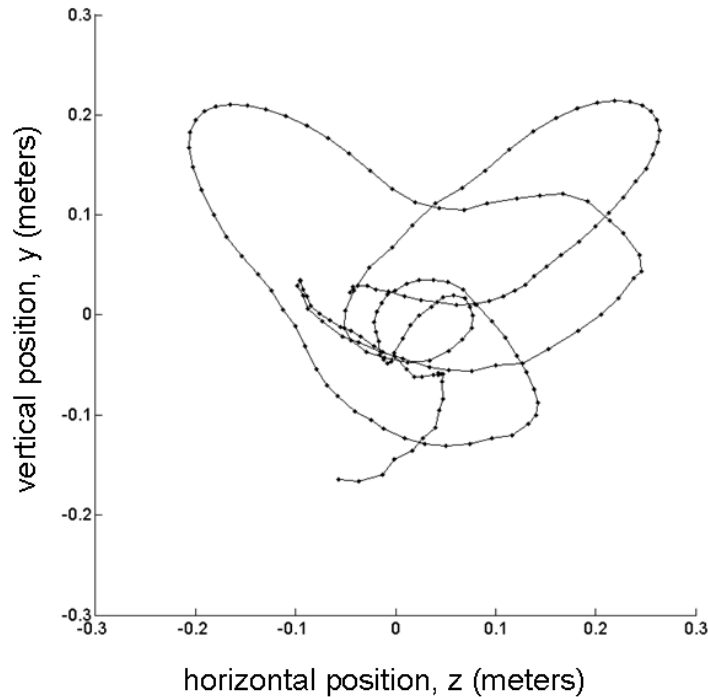
Rutkowski, Quinn, and Willis
J Comp Phys A, 2009



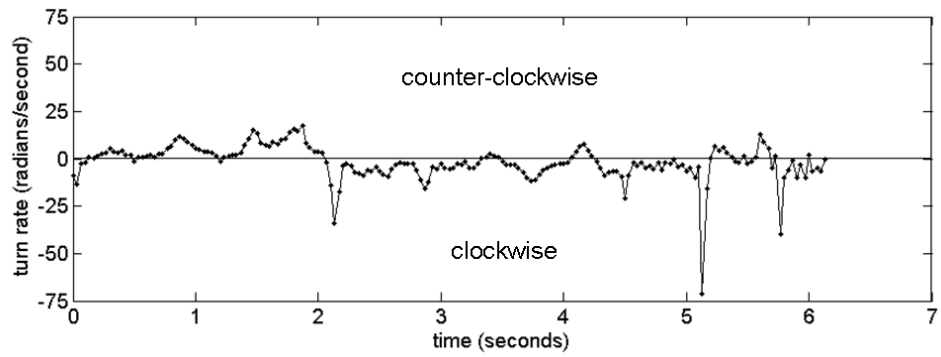
3D Analysis



Downwind View of Moth Track



- Turns continuously as viewed from downwind
- Turn rate varies
- Turn direction varies



Rutkowski, Quinn, and Willis
J Comp Phys A, 2009

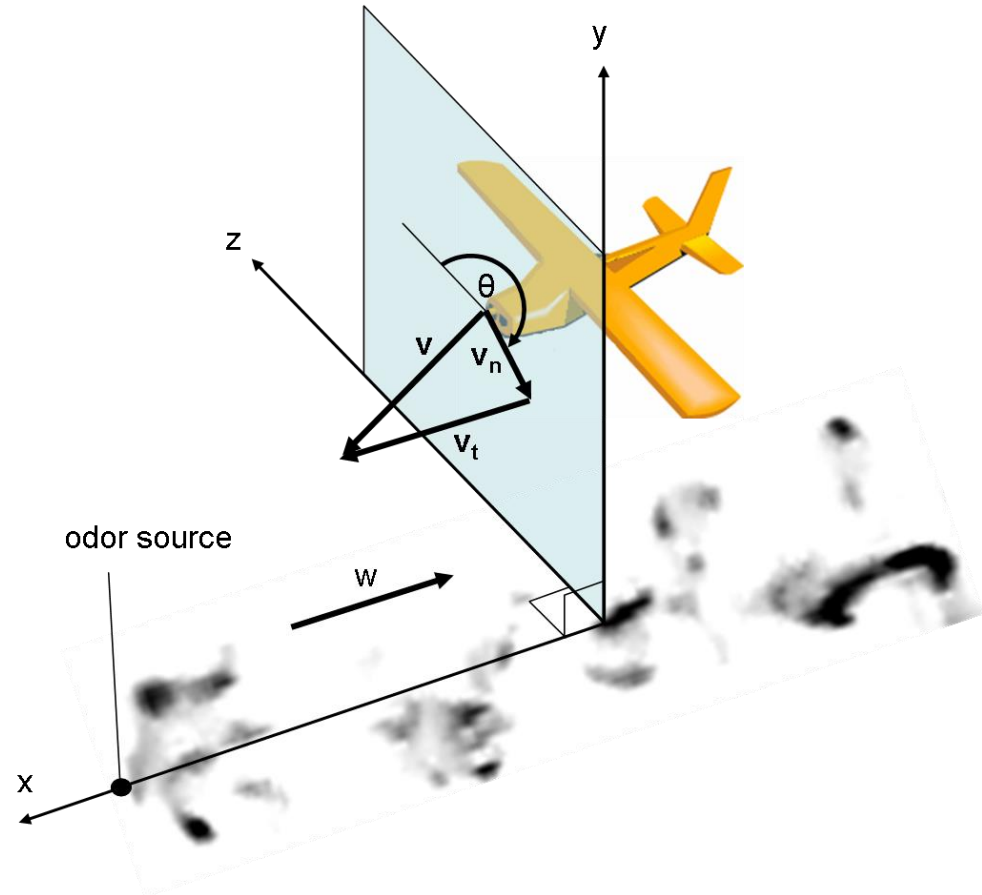


Bio-Inspired Odor Tracking Strategy



Instead of using inter-turn timers to control horizontal and vertical turning behaviors...

- Motion decomposed into normal (\mathbf{v}_n) and tangential (\mathbf{v}_t) components relative to wind
- Turn rate of \mathbf{v}_n $\psi = d\theta/dt$ depends on odor concentration
- Magnitude of \mathbf{v}_t depends on odor concentration



Rutkowski, Quinn, and Willis
ICRA, 2007

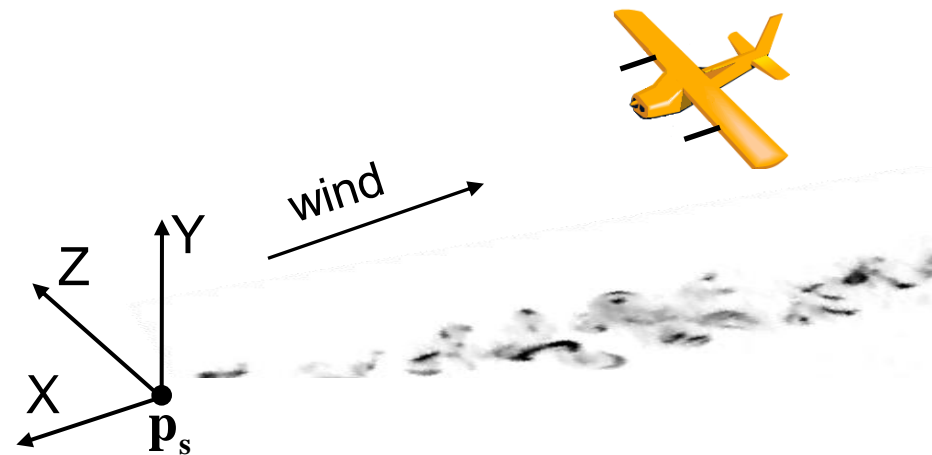


Bio-Inspired Odor Tracking Strategy



1. Measure odor concentration

Two linearly responding odor detectors



Rutkowski, Quinn, and Willis
ICRA, 2007



Bio-Inspired Odor Tracking Strategy

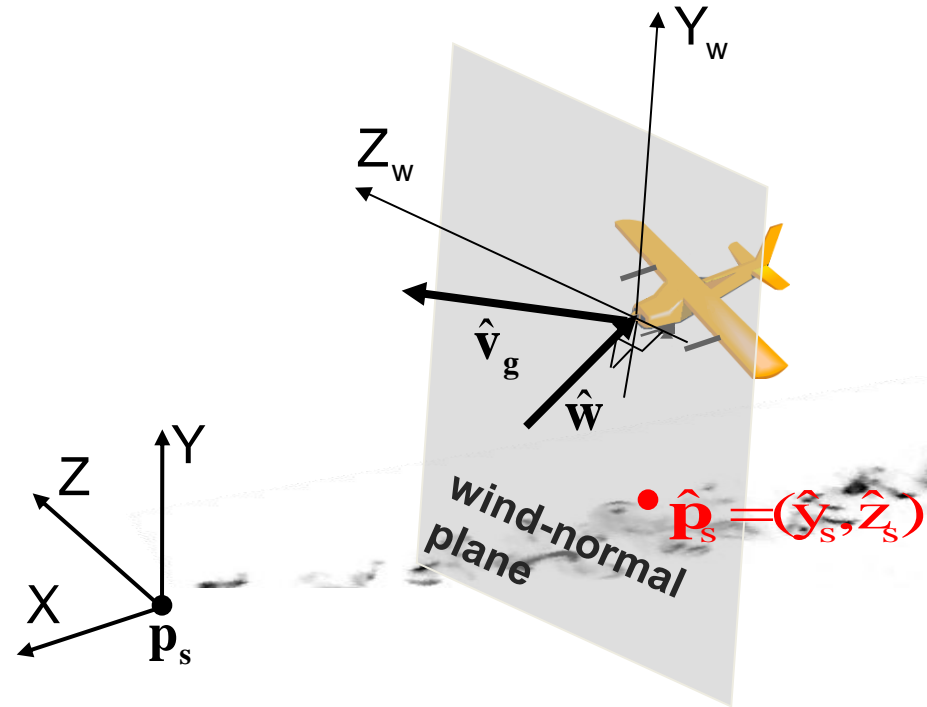


1. Measure odor concentration
2. Determine wind direction (not trivial)
3. Estimate odor plume centerline
Average of antenna position (in wind-normal plane) weighted by concentration and a “forgetting factor”

$$\hat{y}_s(t) = \frac{\alpha_{acy} c_{sur}(t-1) (\hat{y}_s(t-1) - \hat{v}_y(t) \Delta t)}{c_{sur}(t)}$$

$$\hat{z}_s(t) = \frac{\alpha_{acy} c_{sur}(t-1) (\hat{z}_s(t-1) - \hat{v}_z(t) \Delta t) + \epsilon_{right}(t) z_{right}(t) + \epsilon_{left}(t) z_{left}(t)}{c_{sur}(t)}$$

$$c_{sur}(t) = \alpha_{acy} c_{sur}(t-1) + \epsilon_{right}(t) + \epsilon_{left}(t)$$



Rutkowski, Quinn, and Willis
ICRA, 2007



Bio-Inspired Odor Tracking Strategy



1. Measure odor concentration
2. Determine wind direction
3. Estimate odor plume centerline
4. Calculate desired turn rate $\psi = d\theta/dt$

$$c = (c_{\text{right}} + c_{\text{left}}) / 2$$

Turn sharply (6 rad/s) if $c < c_{\text{threshold}}$

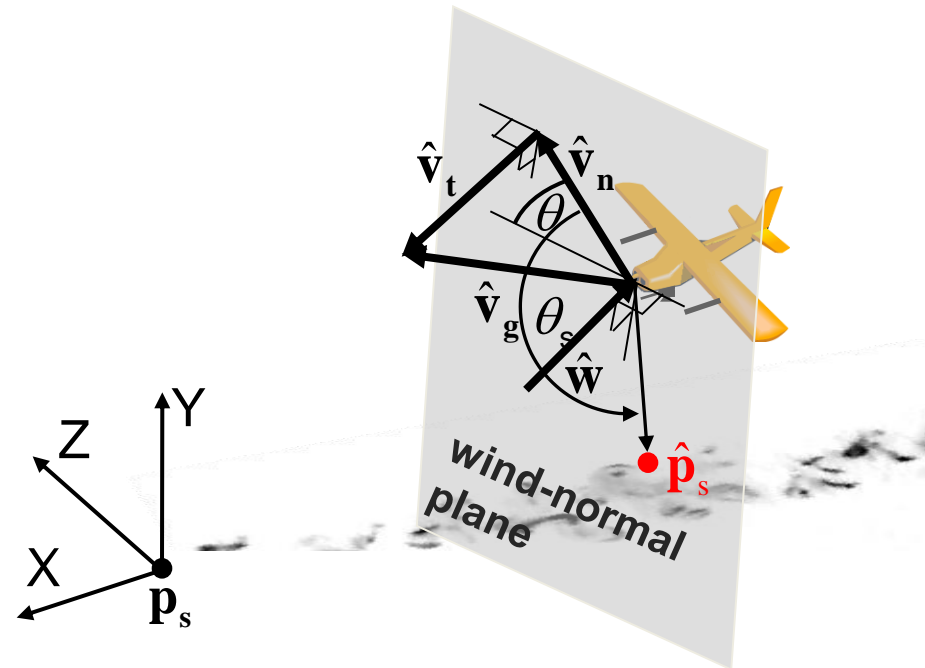
Turn as linear function of concentration if

$$c_{\text{threshold}} < c < c_{\text{saturation}}$$

Turn softly (1 rad/s) if $c > c_{\text{saturation}}$

Turn toward estimated source location

$$\text{sign}(\psi) = \text{sign}(\theta_s)$$



Rutkowski, Quinn, and Willis
ICRA, 2007



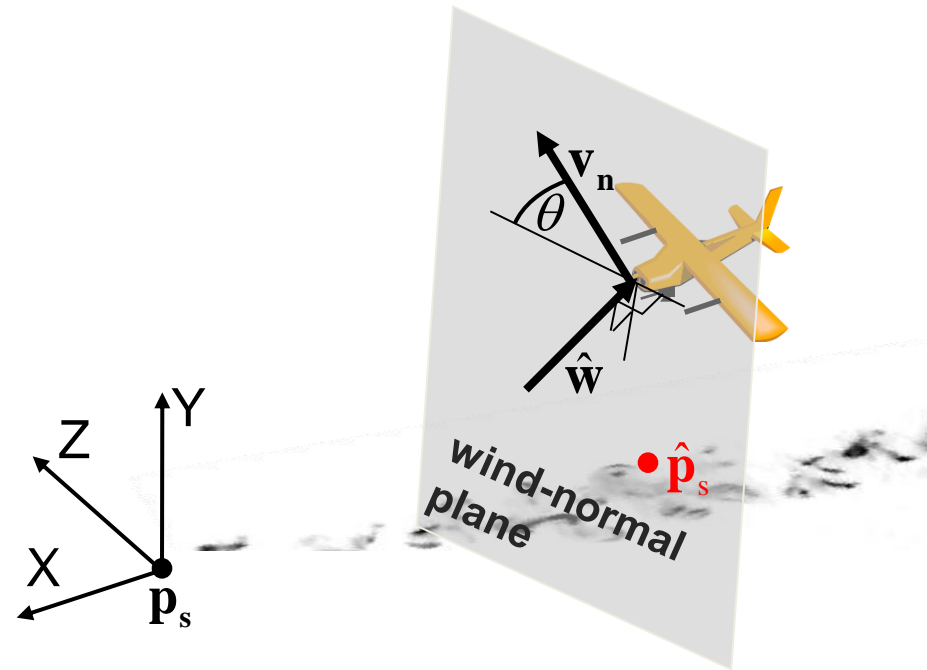
Bio-Inspired Odor Tracking Strategy



1. Measure odor concentration
2. Determine wind direction
3. Estimate odor plume centerline
4. Calculate desired turn rate
5. Calculate desired normal velocity

$$v_n = 30 \text{ cm/s}$$

$$\theta = \int \psi \, dt$$



Rutkowski, Quinn, and Willis
ICRA, 2007



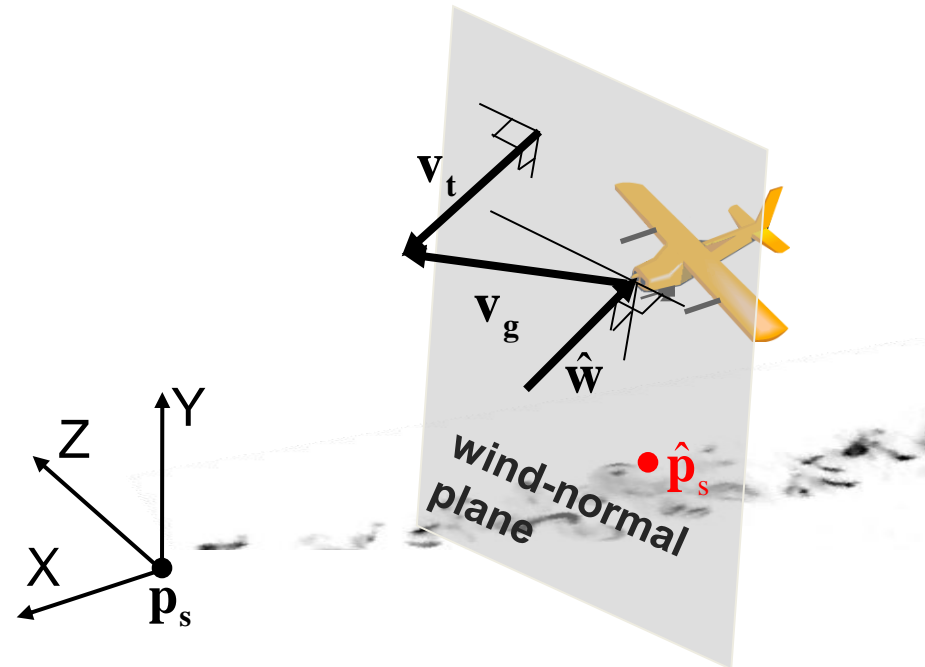
Bio-Inspired Odor Tracking Strategy



1. Measure odor concentration
2. Determine wind direction
3. Estimate odor plume centerline
4. Calculate desired turn rate
5. Calculate desired normal velocity
6. Calculate desired tangential velocity (\mathbf{v}_t)

Surge upwind (30 cm/s) if $c > c_{\text{threshold}}$

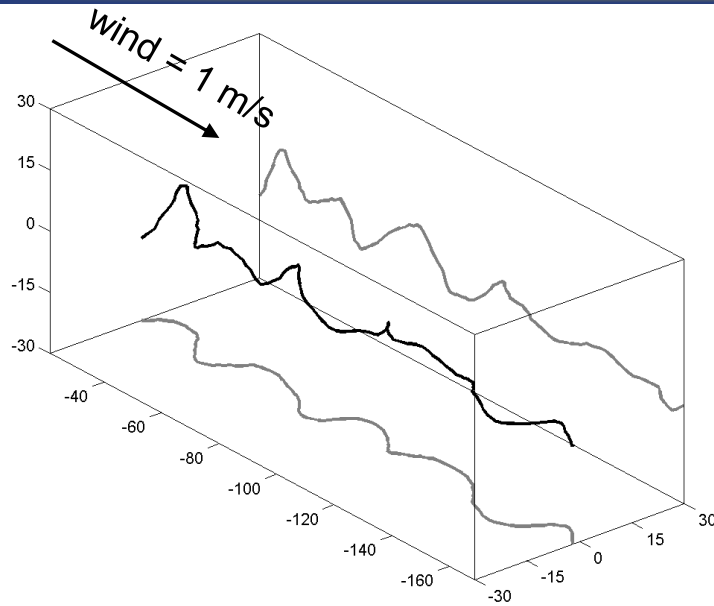
Cast slowly downwind (7 cm/s) if $c < c_{\text{threshold}}$



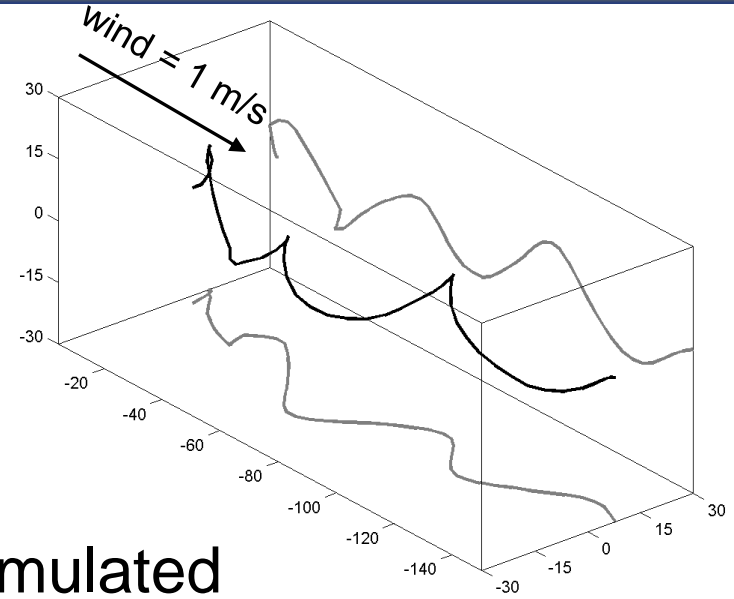
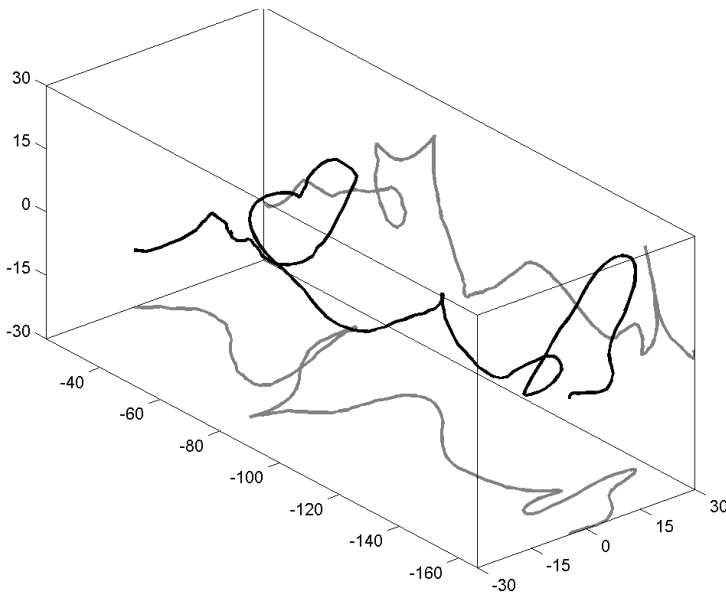
Rutkowski, Quinn, and Willis
ICRA, 2007



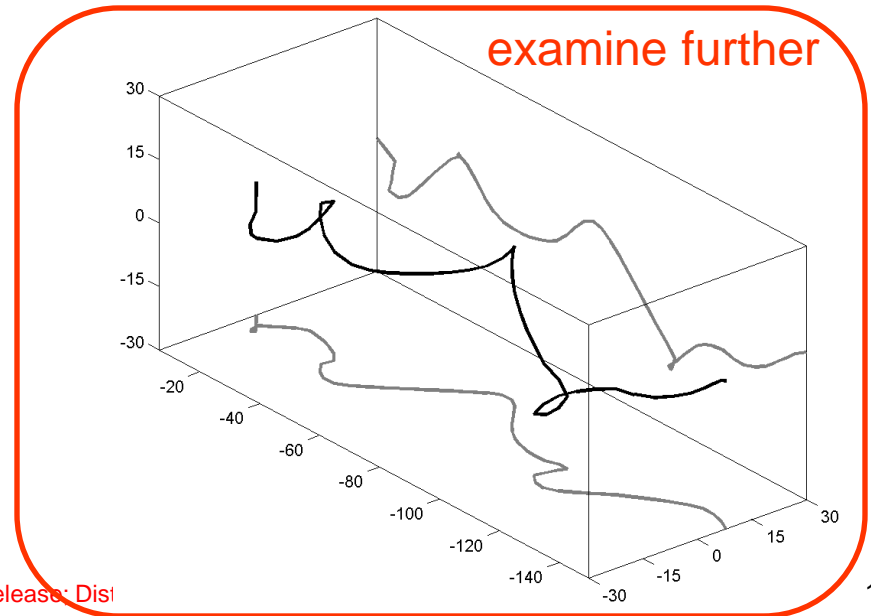
Real vs. Simulated



Real



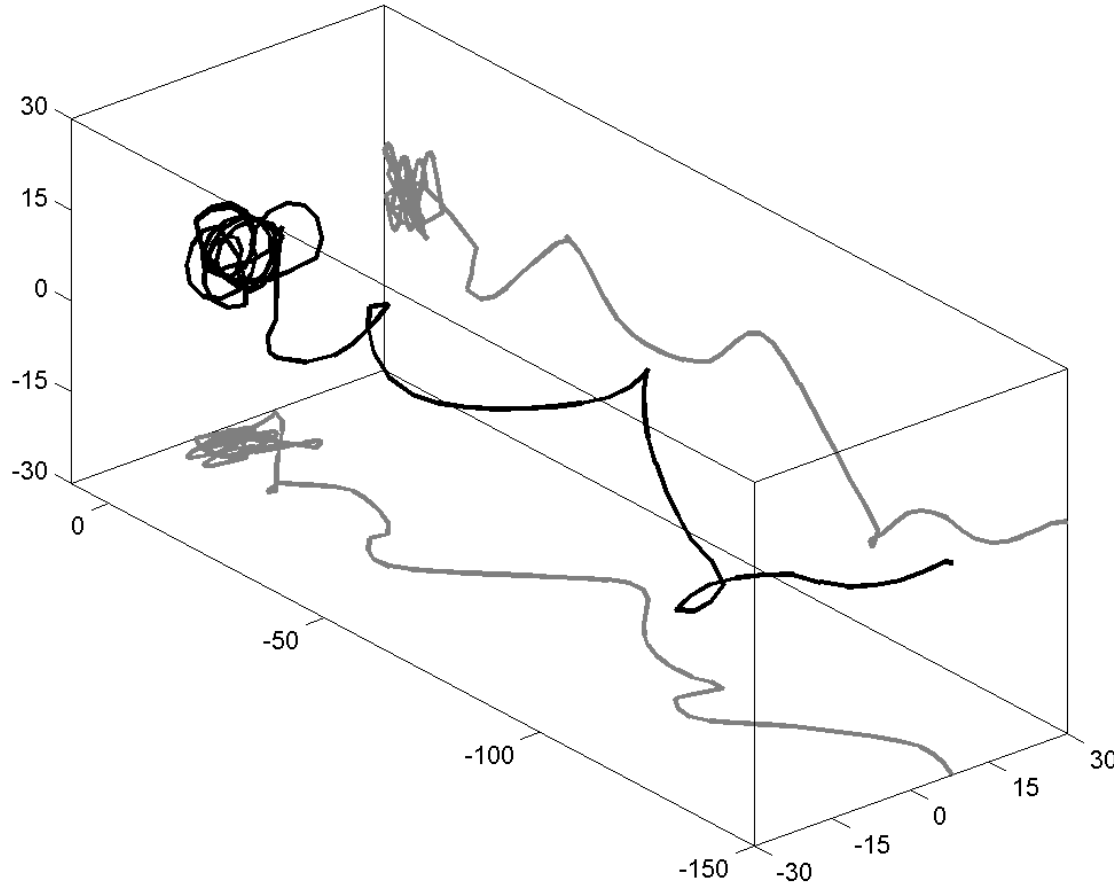
Simulated





Results

What if odor tracking continues after reaching source?



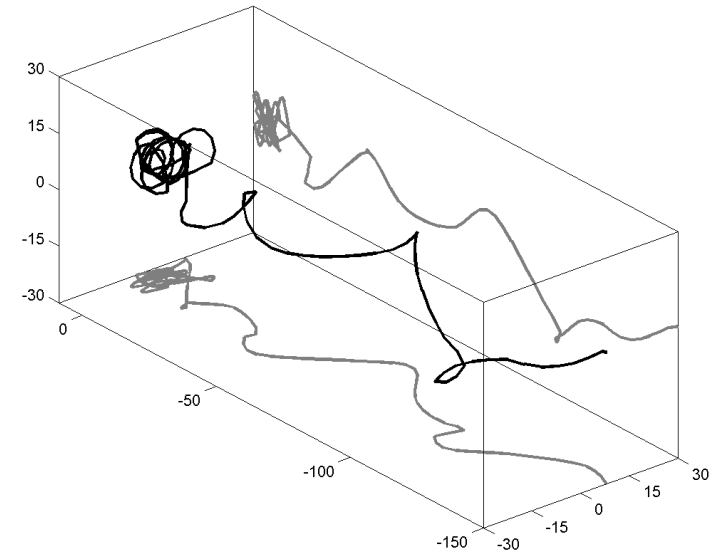
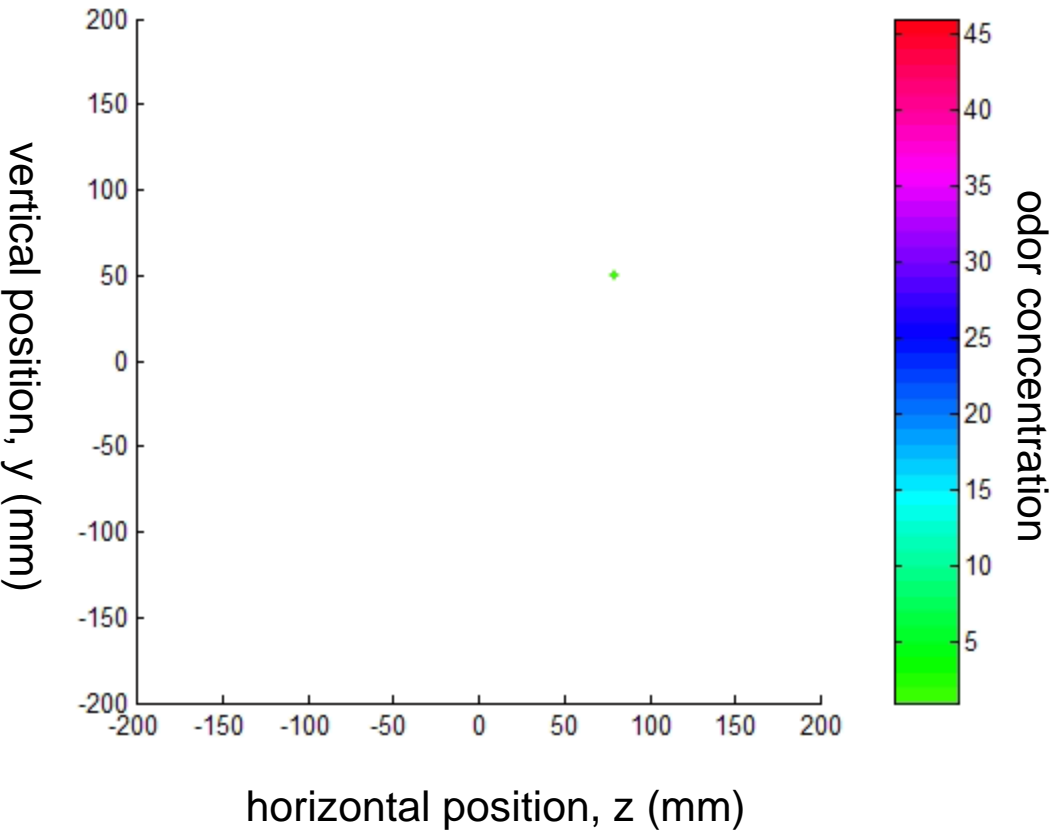
Tracker remains in vicinity of source!



Results

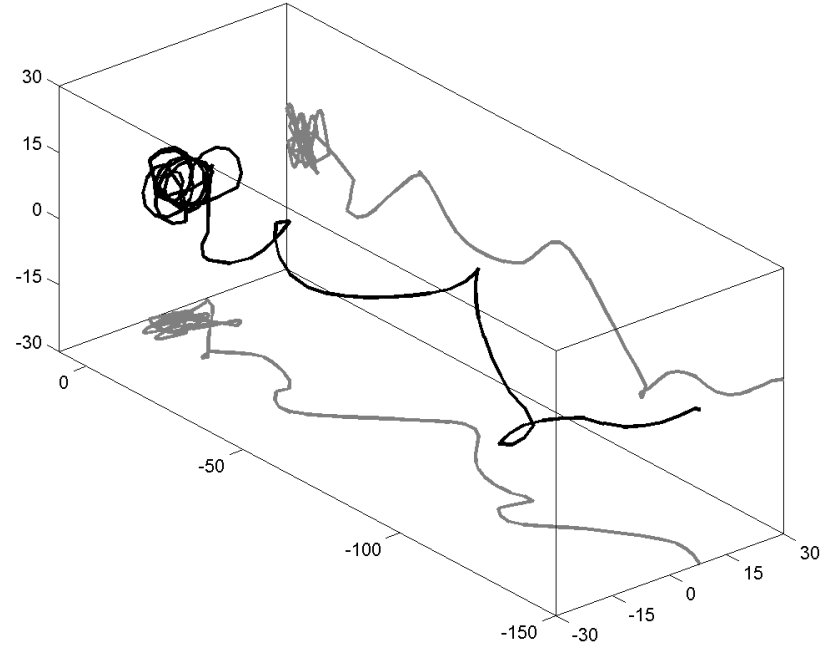
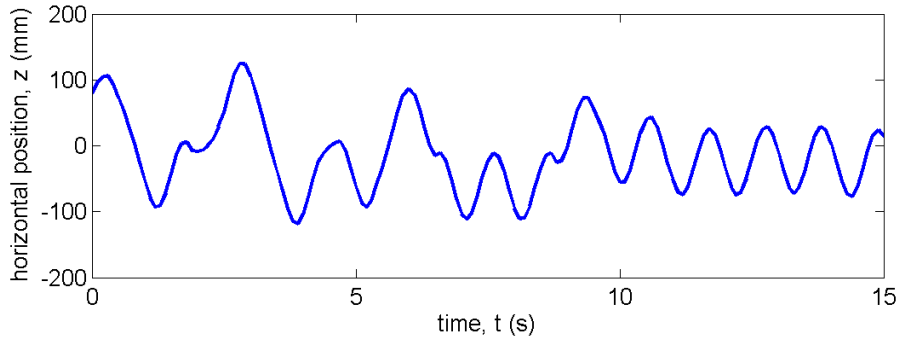
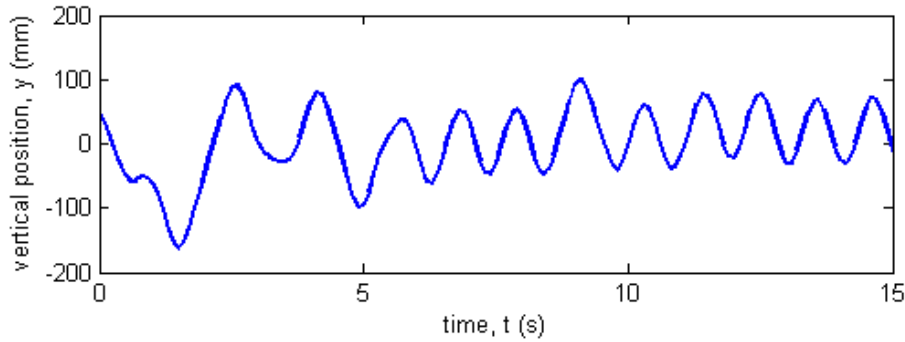
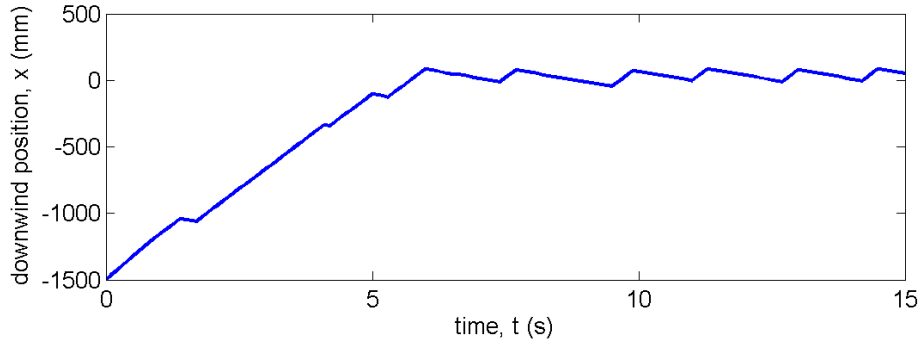


colored dots – tracker position
big black dot - estimated plume centerline





Results



casting and surging

counter-turns without inter-turn timer

“ambiguous” turns



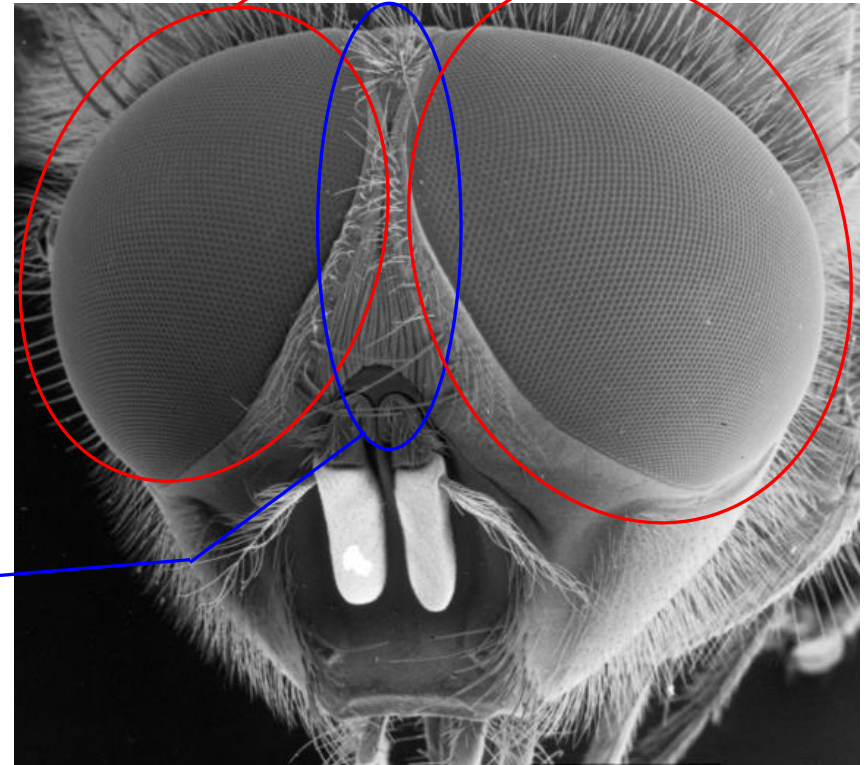
That's great, but how are wind velocity
and self-motion velocity estimated?



Insect Navigation System



- no GPS
- no dedicated accelerometer
- eyes
 - not distance estimators
 - too close together
 - fixed focus
 - small region of overlap
 - optic flow
- head hairs and antennae
 - speed **and direction** of air-current





Egomotion and Wind Velocity Estimation



unique values for

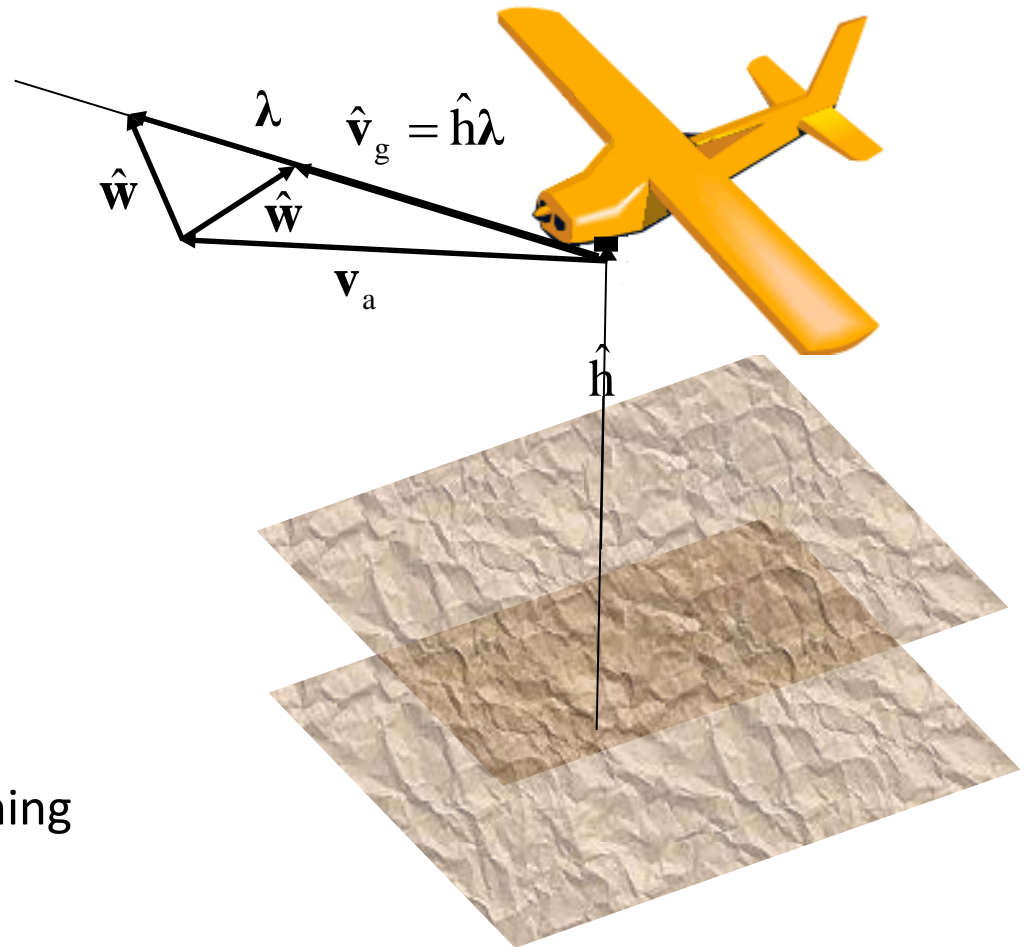
- height (h)
- groundspeed (\mathbf{v}_g)
- wind velocity (\mathbf{w})

cannot be determined from single measurements of

- air-current velocity (\mathbf{v}_a)
- optical flow (λ)

However...

height **can** be estimated by assuming wind is smooth over short time period (~ 1 s)





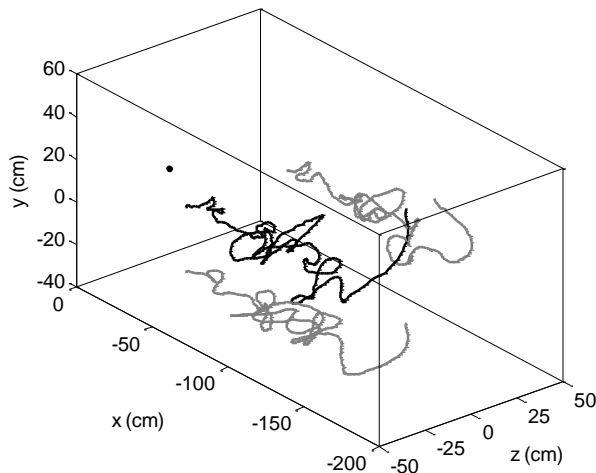
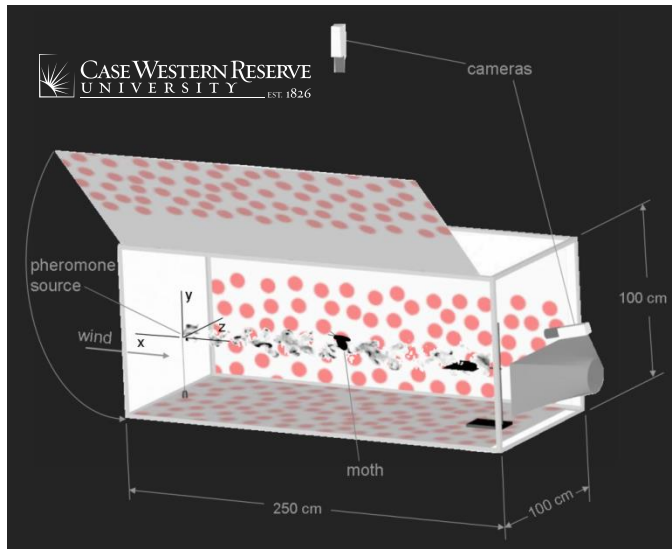




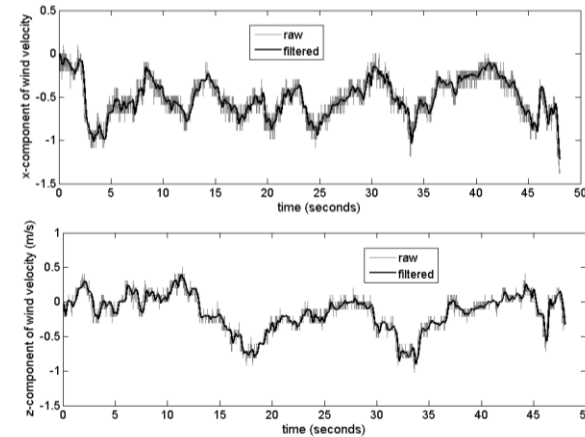
Egomotion and Wind Velocity Estimation



Moth flight track recorded at 30 Hz

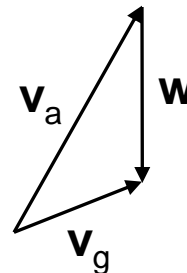


Wind data from open field recorded at 30 Hz



$$\text{Simulated airspeed data : } \mathbf{v}_a = (\mathbf{v}_g - \mathbf{w}) + \eta_a$$

$$\text{Simulated optical flow data : } \lambda = (\mathbf{v}_g / h) + \eta_\lambda$$

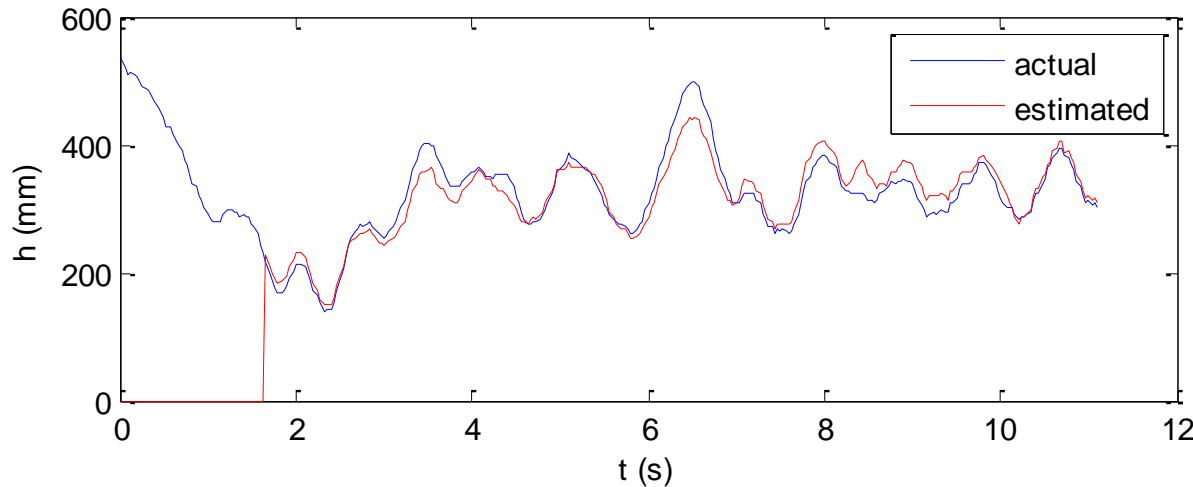


simulated
sensor noise

optical flow: 30 Hz, $\sigma=0.2$ rad/s
airspeed: 30 Hz, $\sigma=100$ mm/s



Height Estimation Results Using Aero/Optical Fusion



$m=2, n=50$

$$e_n = \hat{h} - h$$

$$\text{mean}(e_n) = 0.12 \text{ mm}$$

$$\text{std}(e_n) = 22 \text{ mm}$$

Quality of velocity estimation depends on quality of height estimation







Ground speed Estimation Results Using Aero/Optical Fusion

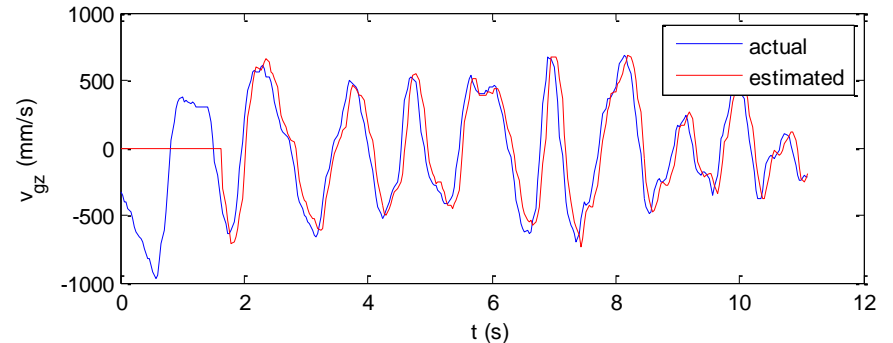
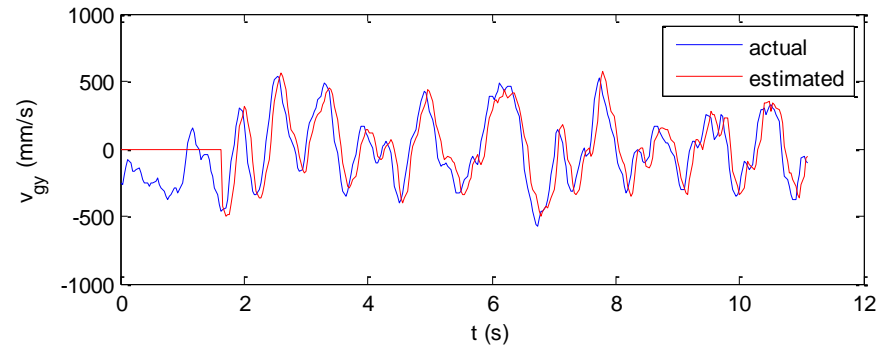
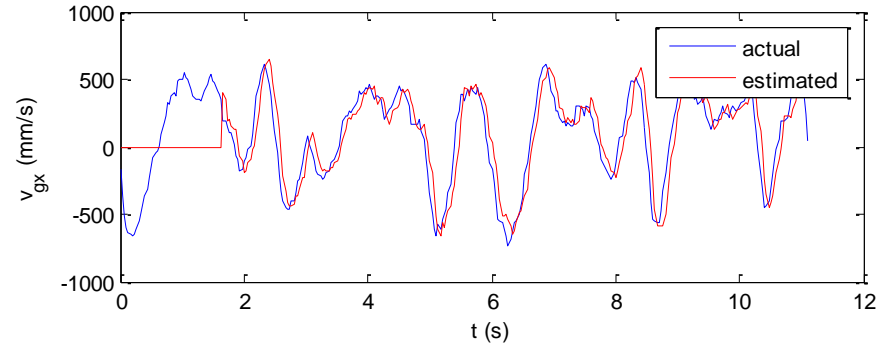


Ground speed (v_g) estimate lags by two timesteps

Lag caused by finite difference approximation of velocity from optical flow

	v_{gx} (mm/s)	v_{gy} (mm/s)	v_{gz} (mm/s)
			
	11	0	5
	10	3	6
	140	144	162
	28	27	28

Rutkowski, Miller, Quinn, and Willis
Biol Cybern, 2011









Wind Estimation Results Using Aero/Optical Fusion

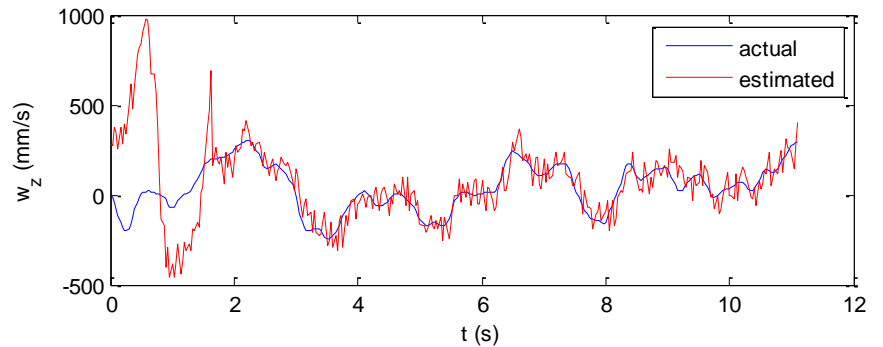
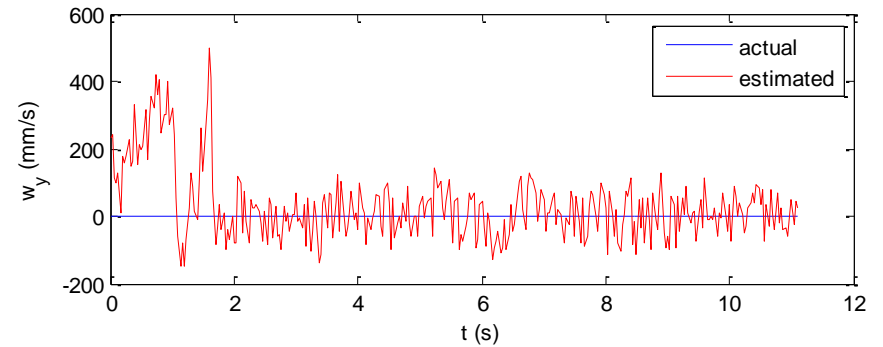
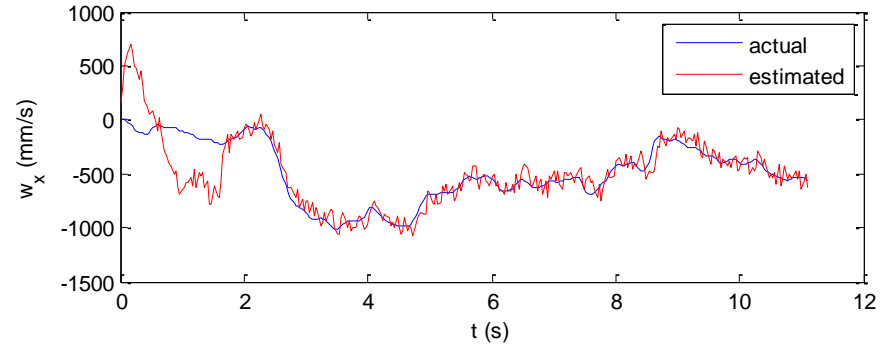


Wind estimate also obtained

Lag also present, but minimal compared to noise

	w_x (mm/s)	w_y (mm/s)	w_z (mm/s)
	12	3	5
	10	3	5
	76	61	68
	64	60	60

Rutkowski, Miller, Quinn, and Willis
Biol Cybern, 2011

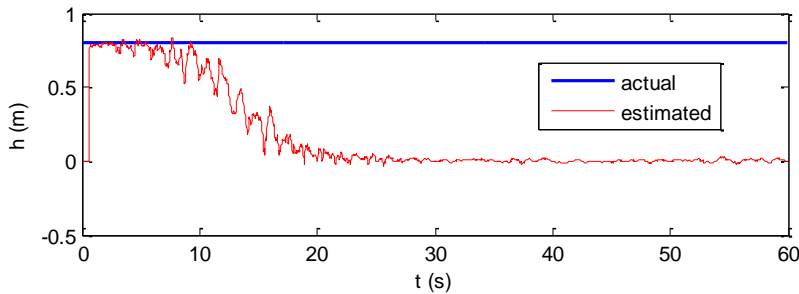




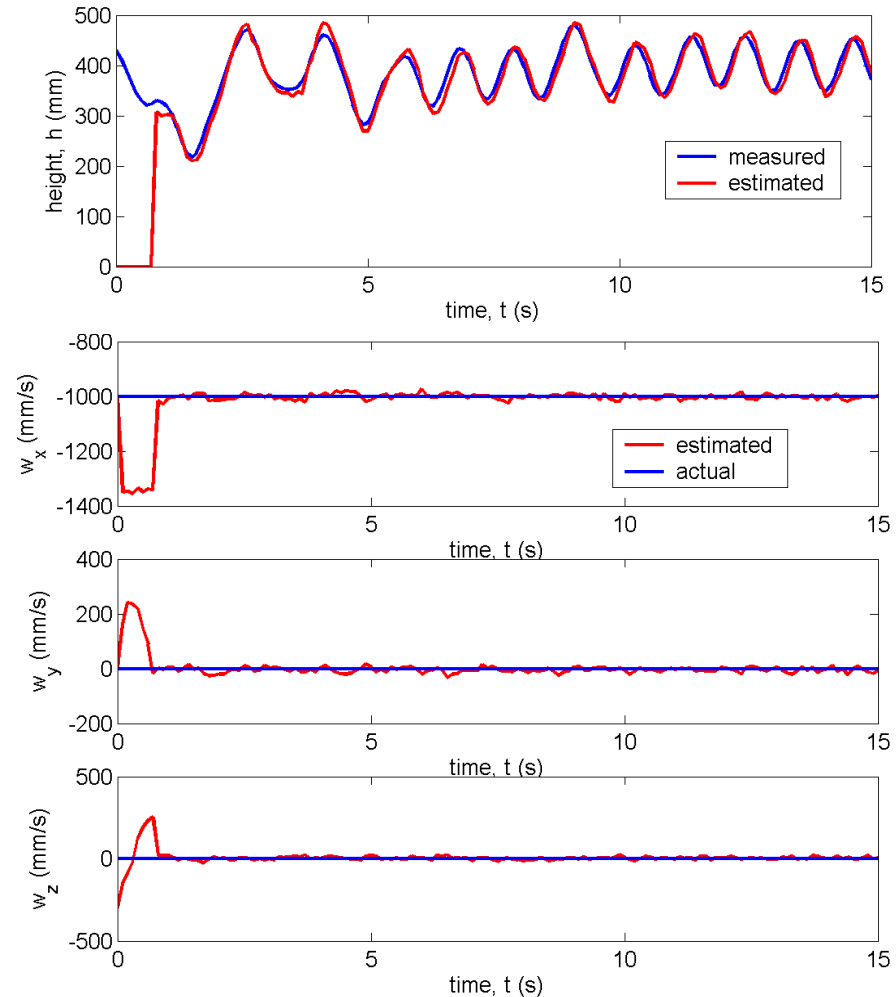
Odor Tracking and Aero/Optical Fusion



- Fusion of vision and airspeed makes odor tracking possible
- Height estimation fails with constant velocity motion



- Motion excitation, as produced by the odor tracking task, allows for state observability

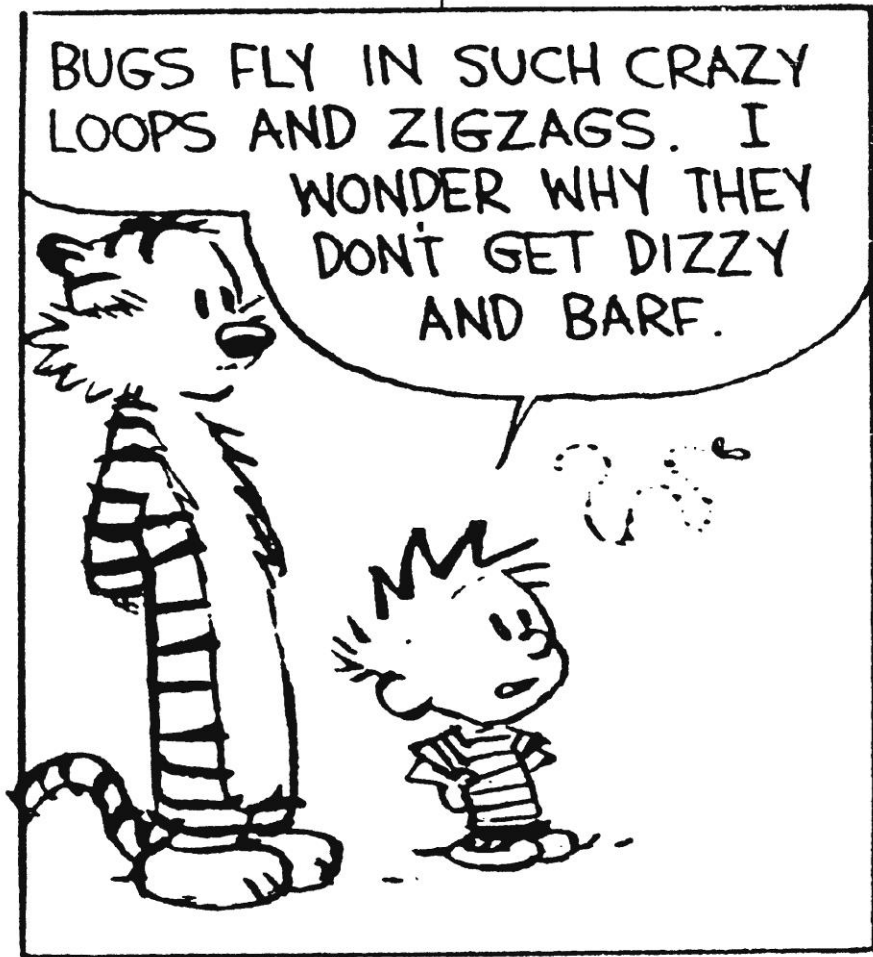




Summary



- Moth odor tracking behavior in 3D is NOT a simple extension of 2D ideas
- Moth-like “counter-turning” behavior can be achieved without inter-turn timers
- State and wind estimation can be performed using insect sensory system
- A “drunken stumble” can actually be beneficial



Thank you for your attention!



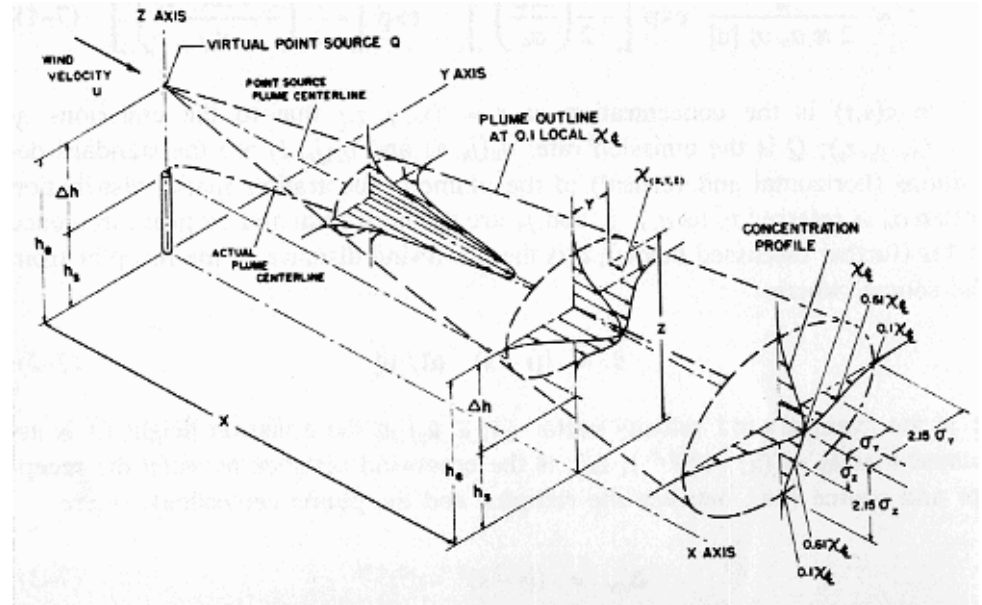
Additional Slides



Odor Plume Model

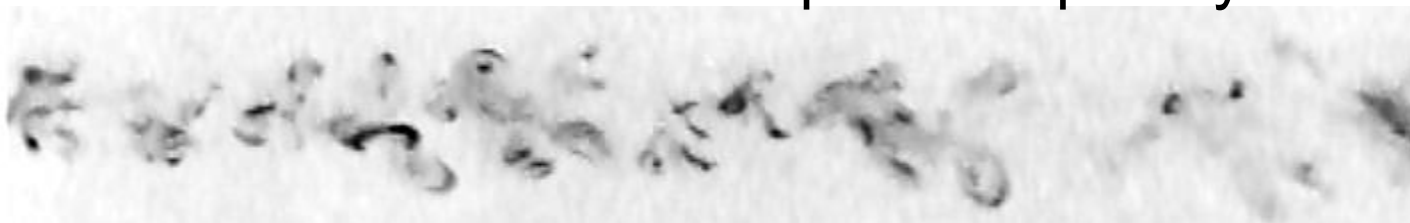


- Normally distributed odor concentration
- Plume narrows with approach to odor source
- Centerline concentration increases with approach to odor source



Zannetti

But remember... odor plume is patchy

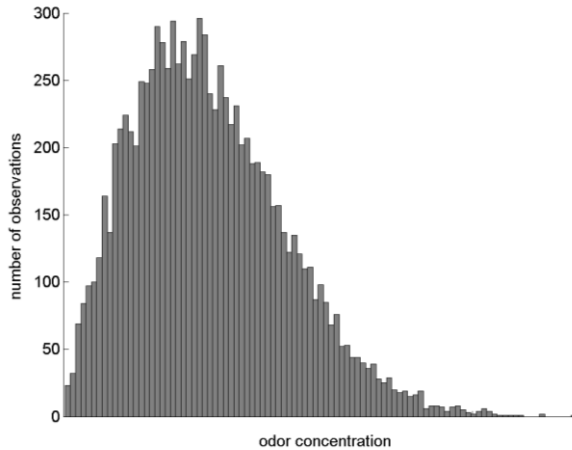




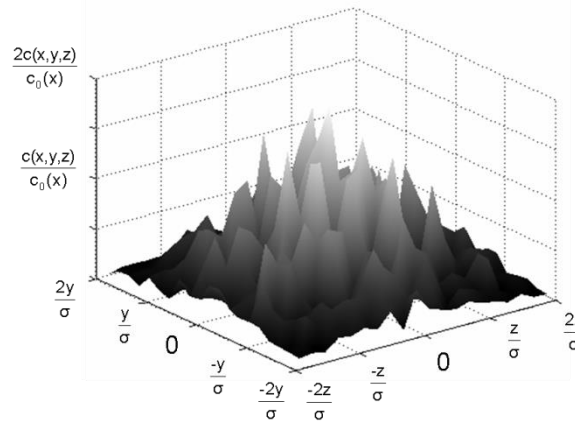
Odor Plume/Sensor Model



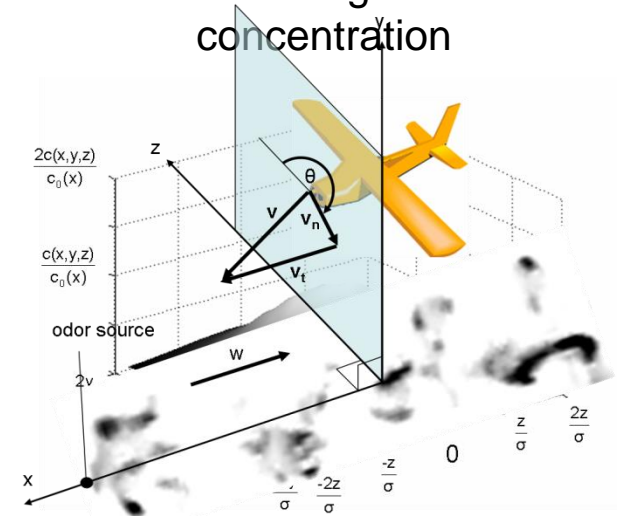
Odor concentration at a single location



Odor concentration at a single timestep

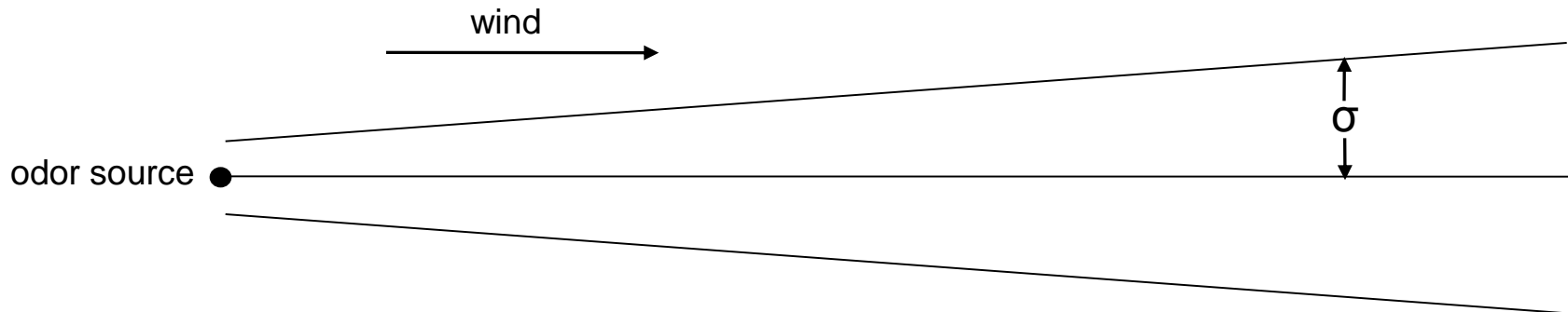


Time-averaged odor concentration



Randomness simulates turbulence

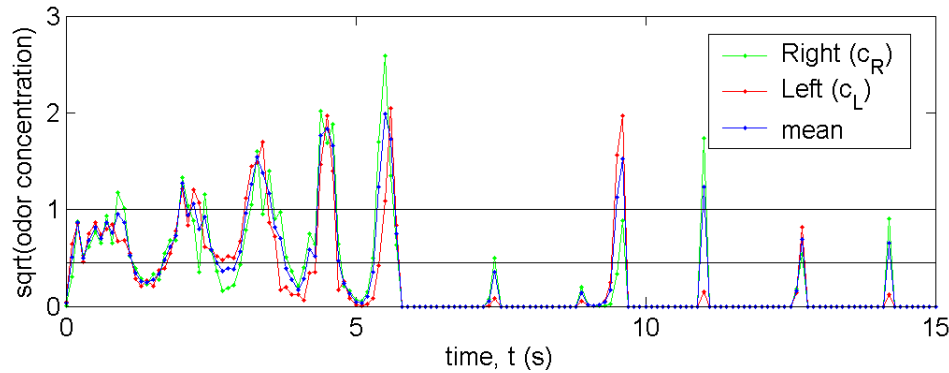
Normally distributed concentration profile



Odor plume narrows with approach to the source

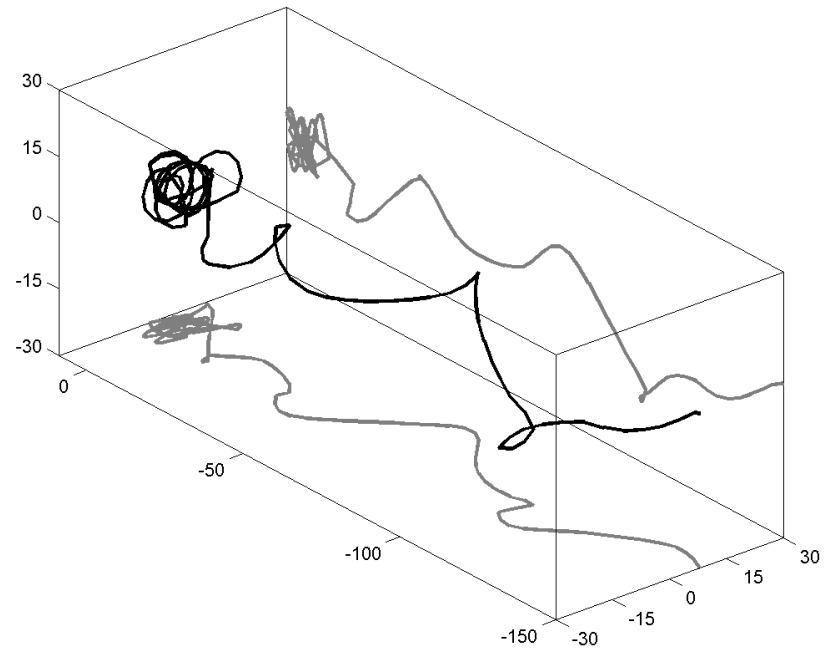
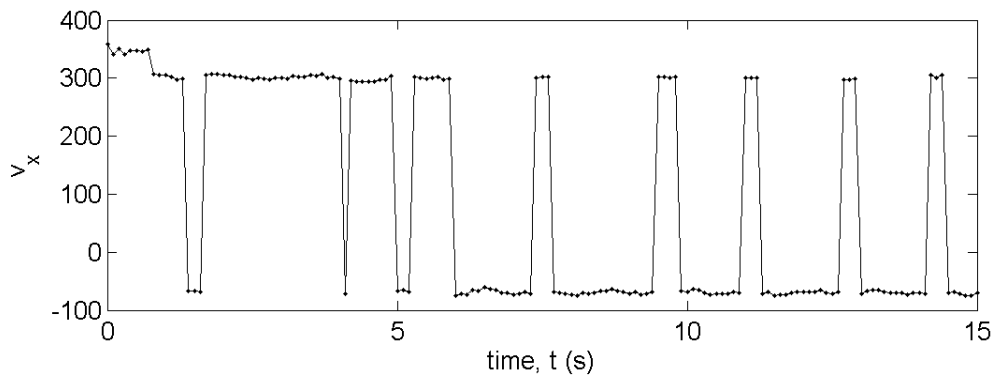
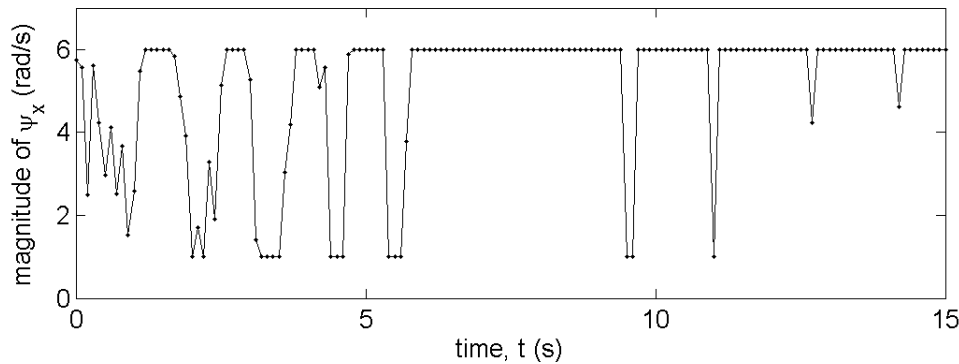


Results



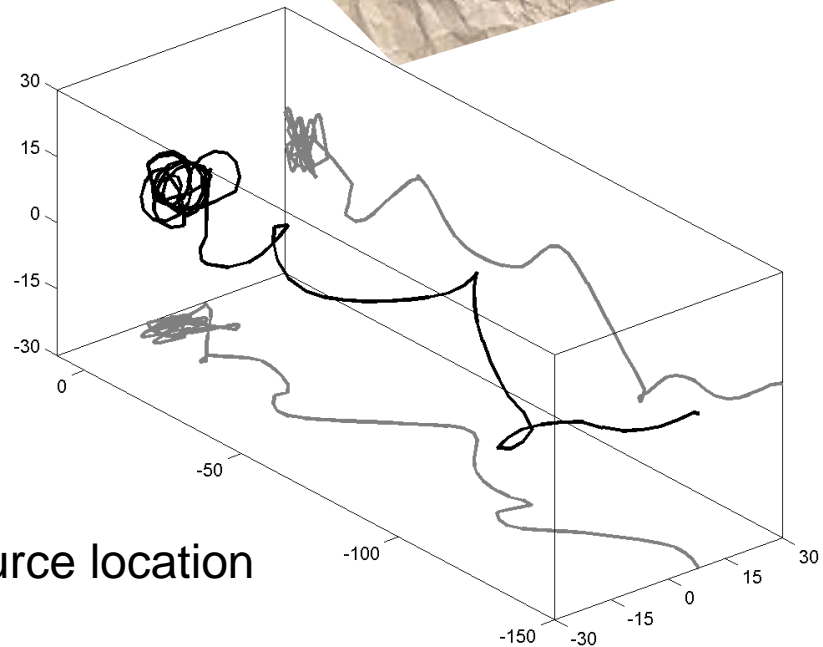
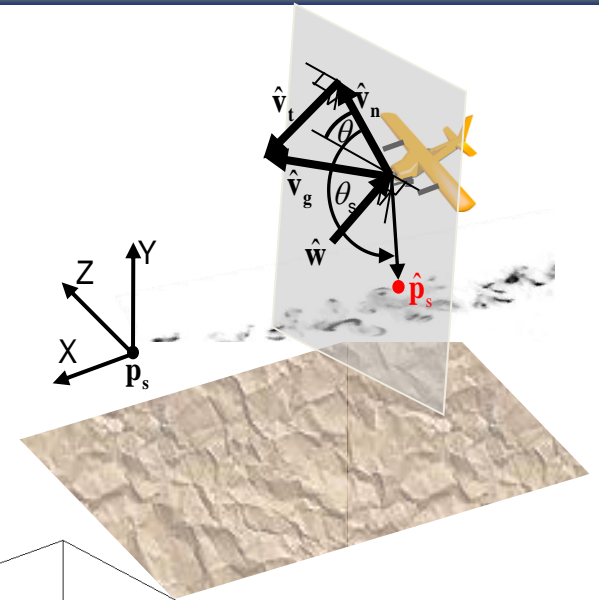
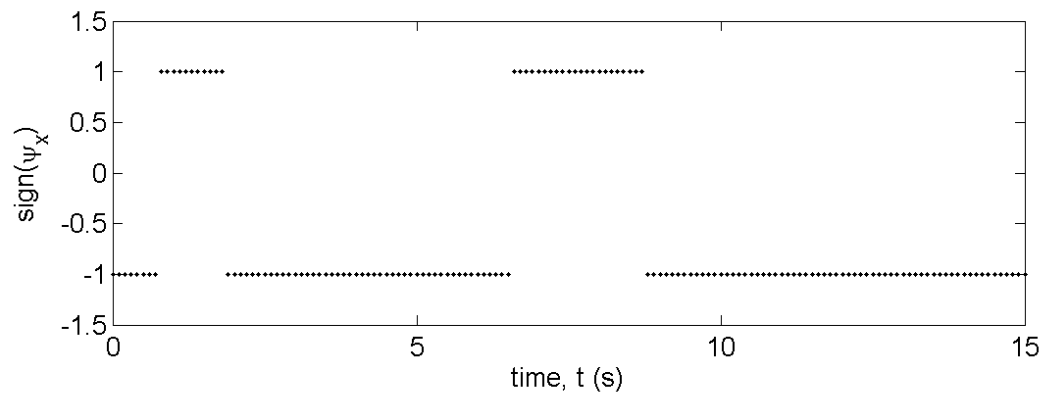
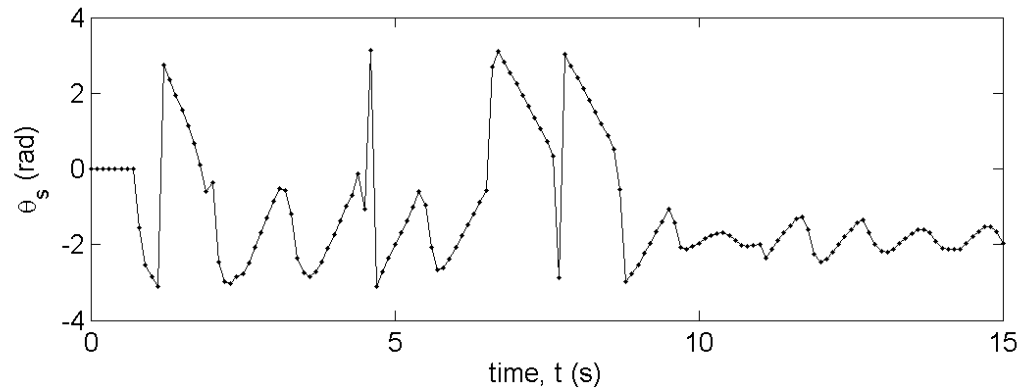
$C_{saturation}$
 $C_{threshold}$

controls
upwind velocity
turn rate
as function of
odor concentration





Spiraling Results



Turns in the direction of the estimated odor source location