Bio-Inspired Odor Source Localization

SOAR2 Review
12-15 JULY 2011
Adam J Rutkowski, Ph.D.
Research Engineer
AFRL/RWGIA

Air Force Research Laboratory

Integrity ▪ Service ▪ Excellence
Bio-Inspired Odor Source Localization

Air Force Research Laboratory

Approved for public release, distribution unlimited

See also ADM202973. BioMav SOAR 2. Held at Chilworth Manor, United Kingdom on July 12-15, 2011. Supporting documents are attached to the report as separate files (WMV; AVI). The original document contains color images.
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

• Tracking agents
  – engineered: UAVs, UGVs, AUVs
  – natural: moths, cockroaches, fish

no strong gradient
Moth Odor Tracking Studies

CASE WESTERN RESERVE UNIVERSITY

Bio-Inspired Odor Source Localization

Distribution A: Approved for Public Release; Distribution Unlimited
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
Instead of using inter-turn timers to control horizontal and vertical turning behaviors...

- Motion decomposed into normal ($v_n$) and tangential ($v_t$) components relative to wind
- Turn rate of $v_n \psi = d\theta/dt$ depends on odor concentration
- Magnitude of $v_t$ depends on odor concentration

Rutkowski, Quinn, and Willis
ICRA, 2007
1. Measure odor concentration

Two linearly responding odor detectors

Rutkowski, Quinn, and Willis
ICRA, 2007
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”

$$\hat{z}_{i} = \frac{a_{\text{de}} c_{\text{sun}} (t_i - 1) \left(\chi_i \frac{\chi_i}{c_{\text{sun}} (t_i)} \right)}{c_{\text{sun}} (t_i)}$$

$$\hat{z}_{i} = \frac{a_{\text{de}} c_{\text{sun}} (t_i - 1) \left(\chi_i \frac{\chi_i}{c_{\text{sun}} (t_i)} \right) e_{\text{right}} (t_i) e_{\text{right}} (t_i) + e_{\text{right}} (t_i) e_{\text{right}} (t_i) + e_{\text{right}} (t_i) e_{\text{right}} (t_i) + e_{\text{right}} (t_i) e_{\text{right}} (t_i) + e_{\text{right}} (t_i) e_{\text{right}} (t_i)}{c_{\text{sun}} (t_i)}$$

$$c_{\text{sun}} (t_i) = \text{dec} \cdot c_{\text{sun}} (t_i) + e_{\text{right}} (t_i) e_{\text{right}} (t_i) + e_{\text{right}} (t_i) e_{\text{right}} (t_i) + e_{\text{right}} (t_i) e_{\text{right}} (t_i)$$

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 ($v_t$)
   - 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

wind = 1 m/s

examine further
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 airflow
unique values for
- height \( (h) \)
- groundspeed \( (v_g) \)
- wind velocity \( (w) \)
cannot be determined from single measurements of
- air-current velocity \( (v_a) \)
- optical flow \( (\lambda) \)

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

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

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

Simulated sensor noise

optical flow: 30 Hz, \( \sigma = 0.2 \text{ rad/s} \)
airspeed: 30 Hz, \( \sigma = 100 \text{ mm/s} \)
Quality of velocity estimation depends on quality of height estimation.

\[ e_h = \hat{h} - h \]
\[ \text{mean}(e_h) = 0.12 \text{mm} \]
\[ \text{stdv}(e_h) = 22 \text{mm} \]

\( m = 2, n = 50 \)
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

<table>
<thead>
<tr>
<th></th>
<th>$v_{gx}$ (mm/s)</th>
<th>$v_{gy}$ (mm/s)</th>
<th>$v_{gz}$ (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>actual</td>
<td>11</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>actual</td>
<td>10</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>actual</td>
<td>140</td>
<td>144</td>
<td>162</td>
</tr>
<tr>
<td>actual</td>
<td>28</td>
<td>27</td>
<td>28</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>w_x (mm/s)</th>
<th>w_y (mm/s)</th>
<th>w_z (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>76</td>
<td>61</td>
<td>68</td>
</tr>
<tr>
<td>64</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>

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

But remember… odor plume is patchy
Odor Plume/Sensor Model

Odor concentration at a single location

Randomness simulates turbulence

Wind

Odor source

Odor plume narrows with approach to the source

Time-averaged odor concentration

Normally distributed concentration profile

Odor plume narrows with approach to the source

Bio-Inspired Odor Source Localization
Results

controls upwind velocity turn rate as function of odor concentration
Spiraling Results

Turns in the direction of the estimated odor source location