Searching In Random Environments

Jean-Baptiste Masson
Physics of Biological Systems, Institut Pasteur, CNRS UMR 3525, Paris, France
Janelia Research Campus, HHMI, Ashburn, USA.
Laboratoire Physico-Chimie, Institut Curie, CNRS UMR168, Paris France.

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• **Scale:** nm, µm, mm, m, \(10^{th} m\), km.

• **Cue (if any) propagation:** Diffusion, ballistic, turbulence.

• **Statistics of the environment:** homogeneous, heterogeneous, disappearing probability.

• **Searcher motion dynamics:** velocity, run-tumble, crawl-headcast, fly-walk etc.

• **Computation capacities of the searcher:** Biochemistry, few neurons, numerous neurons.

• **Representation of the environment:** Space perception, statistics of environment, other searchers.
• **Biomolecules Random Walks**
  
  Large knowledge, Models
  Strategies and Bayesian Inference

• **Bacteria** (*E. coli*), *C. elegans*, Neutrophils

• **Larva**

• **Robots**
  
  Heterogeneity, Intermittency, turbulence
  Less knowledge (growing)

• **Insects**


M. Sarris *et al*, Current Biology, 22, p2375-2382, (2012)


Exploration/Exploitation

• Searching is an information game

• Source sends noisy message that the searcher attempts to decode

• for all searchers there is a balance in decision making
  – Explore the environment to acquire more information
  – Exploit accumulated information to make decision
2-Armed Bandit: explore-exploit Games

- Multi-Armed Bandit Game
  - N “Bandit” machines with unknown paying probabilities, $p_i$
  - Operator sequentially plays bandit to find the best one
  - Goal: efficient strategies to have the smallest regret

- Explore/Exploit
- Playing the same machine increase information on the machine
- Playing another machine: it might a better one

- Hard decision Making: Pain/Threat (Low level) ppk

Drosophila Larval

- 3 instar (3 days after hatching)
- 2-5mm
- Start development on their food
- No Food: immediately start to search
- 10000 neurons
- Genetic targeting of individual neurons
- Optogenetic Stimulation of identified neuron/s with chrimson

Playing the Bandit Game

• We need a close-loop system:
  – Assessing behaviour live
  – Stimuli depending on behaviour

• Increasing attempt to quantify Behaviour from video

• Large number of features extracted + Data Tagging

• JAABA based on GentleBoost

• The larva is complex
  – Large variance in images.
  – Deformable object, multiscale dynamics.

• Limited number of features

• Features are accessible up until time t

• Image analysis with OpenCV

• 15ms data acquisition and basic processing

• 5ms features + classification

Setup

- C++, Qt and OpenCV

A. Schulze et al, eLife 2015;4:e06694
Features

• Angle \( \theta = \cos(\vec{u} \cdot \vec{v}) \)

• Nematic spline \( S = \frac{1}{N-1} \left( 3 \sum_{i=1}^{N-1} \vec{u}_i \cdot \vec{w}_i - \frac{1}{2} \right) \)

• Reduced eigenvalues \( \hat{\lambda} = \frac{\lambda_1 - \lambda_2}{\lambda_1 + \lambda_2} = \sqrt{1 - \frac{4 \left( \langle x^2 \rangle \langle y^2 \rangle - \langle xy \rangle^2 \right)}{\left( \langle x^2 \rangle + \langle y^2 \rangle \right)^2}} \)

• Agitation velocity \( \langle \| \vec{V} \| \rangle = \frac{1}{3} (\| \vec{V}_{\text{neck}} \| + \| \vec{V}_{\text{top neck}} \| + \| \vec{V}_{\text{down neck}} \|) \)

• Asymmetry factor \( As = \vec{u} \cdot \vec{v} \)

• Damped distance \( d = \sum_{i=0}^{t} \gamma_i d_{t-i} \quad d_{t-i} = \| \vec{r}^{t-i}_{\text{neck}} - \vec{r}^{t-i}_{\text{neck}} \| \)

• Negative velocity \( \vec{V}_{\text{neg}} = \vec{V}_{\text{neck}} \cdot \vec{u} \)

• Squared Smoothed delayed derivatives

\[ F'(t) = \left| \int_{\infty}^{t} K(t-s) F(s) ds \right|^2 \]

\[ K(t) = e^{-\lambda t} (1 - \lambda t) \]
Custom tagging software

- **Matlab Gui**
- Replay experimental data
- Evaluate features at all time
- Trajectory + specific points
- \{+1;0;-1\} tagging
- **Issue with Ground-Truth-ing**
  - No easy agreement on some behaviour
  - Tagging extreme state
  - 2-3 larvae tagging
- Save features + states
Classifying

- Simple Neural Network
- Pre-structure architecture
- Small data set
- New Version: Random Forest

Diagram:

- \(\theta, \theta'\)
- \(s, s'\)
- \(\lambda, \lambda'\)
- \(<v>, <v'>\)
- \(d, d'\)
- \(v_{neg}, v'_{neg}\)
- \(A_s\)
- \(<<v>>\)

Connections:

- 10 connections to 5
- 5 connections to 1
- 1 connection to Crawl and Cast
- 5 connections to 1
- 1 connection to Curl
- 5 connections to 1
- 1 connection to Stop
- 5 connections to 1
- 1 connection to Back
- 1 connection to 1
- 1 connection to Left and Right
- 1 connection to Slow and Fast

Output:

- Weird
Live Behaviour

- 40-50 Hz recording
- Live behaviour assessment
- No fast oscillations between Behaviour
- 2 larvae tagging
- Save videos
- Save features + contour in text files
- 5min-5hours recording
Larva Playing The Bandit Game

- 2-Armed Bandit
- The Game starts when the larva starts Head-Casting
- Each Side Is associated to a stimulus
- The Game is finished when the Larva choses a side and crawl

- 2 Games
- Game 1: $S_0 = 0$, $S_1 = 50\% - S_2 = 100\%$
- Game 2: $S_0 = 100$, $S_1 = 25\% - S_2 = 75\%$

Example Stimuli Game 1
Larva Playing the Game

HeadCast

Game 1

Game 2
Exploring to make good decision vs ε-greedy

Game 1
(5500 games)

Game 2
(3000 games)

HeadCast Number

Evolution of Score with Number of HeadCast

Evolution of Cumulative Score with Number of HeadCast

Score vs Average number of HeadCast per Larva

Individual Larva
Larva playing the Bandit Game

- The Bandit Game as a probe of exploration/exploitation dynamics
- Larva modulates the number of HeadCasts
- Explorers outperforms exploiters
- Strategy Switch between games
- Neural substrate for the strategy
- Strategies depend on the nature of the stimuli: Nociceptive, Olfactory, Thermal.

Turbulence

mean wind $U \approx 0.5 \text{ m/s}$

Source size $d = 0.8 \text{ mm}$

Velocity fluctuations $u \approx 0.1 \text{ m/s}$

E. Villermaux, IRPHE Marseille


Consequences

- No Global Gradients
- Intermittent Signal
- Local Gradients don’t point towards the source
- Local detections give very limited information on the source (Position, Emission Rate, Multiple Sources)

Information Theory

- R.E. Bellman, Princeton University Press (1957)
Deciphering the Noisy Message sent by the source

- Detections (and no detections) are messages sent by the source
- \( R(r \mid r_0) \)  hit rate at the position \( r \) when the source is at \( r_0 \)
- After H detections

\[
P_t(r_0) = \frac{\int_0^H R(r(s) \mid r_0) \prod_{h=1}^H R(r(t_h) \mid r_0)}{\int dze e^{-\int_0^H R(r(s) \mid z) \prod_{h=1}^H R(r(t_h) \mid z)}}
\]

- Maximizing Likelihood : Lost Searchers
- Information Based Decisions: Infotaxis

\[
\langle \Delta S \rangle(r \rightarrow r_j) = P_t(r_j)[0 - S] + \left(1 - P_t(r_j)\right)[\rho_0 \Delta S_0 + \rho_1 \Delta S_1 + ...]
\]


Insect Space Perception

- Probability Map building requires space perception and odometry error corrections.
- How to integrate external cues?
- Definition of cognitive maps and space perception?
- Various Orientation/navigation Strategies depending on insects
- Integrating space perception in search strategies

R. Wehner, Birkhauser, Basel (1987)

Free Energy Based Search Strategy

• Limited Space Perception

\[ P_t^M (\vec{r}_0 | \Theta_t) = \frac{e^{-\frac{||\vec{r}_0 - \vec{r}_G||^2}{\lambda_G^2}}}{Z_t} \left( 1 - \frac{1}{N_M} \sum_{j=N_t-N_M+1}^{N_t} e^{-\frac{||\vec{r}_0 - \vec{r}_j||^2}{\lambda_j^2}} \right) \]

Detections term  No Detections term

• Decision process

\[ F_t (\Theta_t) = W_t (\Theta_t) + TS_t (\Theta_t) = \int_0^T d\vec{r}_0 P_t^M (\vec{r}_0 | \Theta_t) - T \int_0^T d\vec{r}_0 P_t^M (\vec{r}_0 | \Theta_t) \log P_t^M (\vec{r}_0 | \Theta_t) \]

Work  Entropy  Max Likelihood  Exploration/exploitation

\[ \Delta F_t (\vec{r}_t \rightarrow \vec{r}_{t+dt} | \Theta_t) = P_t^M (\vec{r}_{t+dt}) [1 - F_t] + (1 - P_t^M (\vec{r}_{t+dt})) \sum_{i=0}^{1} \rho_i (\vec{r}_{t+dt}) \Delta F_t^i \]

Discovery  Nothing

• Tradeoff between exploration and exploitation: Control with T


Experimental Searches

- Windless
\[ \Delta F_t^s (\vec{r}_t^s \rightarrow r_{t+dt}^s | \Theta_t) = P_t^M (\vec{r}_{t+dt}^s | \Theta_t) [1 - F_t] \\
+ (1 - P_t^M (\vec{r}_{t+dt}^s | \Theta_t)) [\rho_0 \Delta F_t^{s,0} + \rho_1 \Delta F_t^{s,1}] \]

\[ \Theta_t = \{ \Theta_1^s, \Theta_2^s, \ldots, \Theta_s^s, \ldots \} \]
Searching in the Turbulent Realm

- Space Perception not required
- Error accumulation
- Short memory
- Greedy Decision
- Sharing incomplete and noisy Information
Rhyncophorus Ferrugineus (Rhynco)

• **Advantage**
  - Complex Behaviour
  - Large and small scale searches
  - Flying (5m.s\(^{-1}\)) Walking (1-5cm.s\(^{-1}\)) search strategies
  - No predators (in some ways)
  - Eat Palm Trees (No more Palm Trees)

• **Disadvantage**
  - Very Limited knowledge
  - Realistic environments (light, sky, landscape)
  - Small pieces of knowledge on neuro-biology
  - No Dictionary of Behaviour
Experimental Searches

- Infer detections from behaviour is too difficult

- 2 Elements
  - Insect trajectories
  - Olfactory signal along the decision path
Antenna as “Sensors”

- Insects’ Antenna highly efficient detectors
- Simple ElectroAntennoGram measures $\text{cis}-7$-dodecenyl acetate

Vivkers

Exploiting Turbulence properties and Antenna Selectivity

- Few Scaling and order of magnitudes

\[ p(t) \propto \frac{1}{\tau} \left( \frac{\tau}{t} \right)^{\frac{3}{2}} f(\tau) \]  
Whiffs/Blank duration

\[ \kappa \propto 10^{-7} - 10^{-8} m^2.s^{-1} \]  
Whiff Clumps

\[ P e = \frac{U L}{\kappa} \]

\[ N(T_w) \propto \sqrt{T_w/\tau} \]

- Turbulence maintains blends in the plumes

- Pheromones are specific to insect species

- Add Pheromone detected by another antenna to the odor mix.

Mixture Plume Detection

- PID not sensitive enough
- Measure with double EAGs:
  - One *Agrotis* (Black)
  - One *Spodoptera* (Red)
Quantitative elements

- \( U = 0.3 - 2 \text{m.s} \)
- \( \delta v / U \approx 0.05 - 0.3 \)
- \( \text{Re} \approx 10^3 - 10^4 \)
- \( \text{Pe} \approx 10^6 \)
- \((Z)-7\text{-dodecenyl acetate (Agrotis Pheromon)}\)
  1-10\( \mu \text{g} \) in 10\( \mu \text{l} \) Hexane
  \( \text{EAG(10m)} \approx 300 \mu \text{V} \)
- 4-\text{méthyl-5-nonanol (ferrugineol)}
  1\( \mu \text{g} \) in 10\( \mu \text{l} \) Hexane
Trajectory and Pheromone Detection

- Complex temporal dynamics
- Multi-scale peaks, Multi-duration peaks and peaks in peaks
- Peak detection using Random Forest
- Ground-Truthing on double EAG experiments (Manual correction)
- Out of Bag Error = 5.10^{-3}

Image Analysis Using Robust PCA
Trajectory/Detections

The surprising, **disappointing** and inefficient strategy of the Rhynco: Key elements

- **Correlated Two Mode Poisson motion:** Run-Stop (0.08s\(^{-1}\), 0.1s\(^{-1}\))
- **Decorrelation of characteristic scales**
  - \(\tau_{\text{turbulence}} \sim 100\ \text{ms-1s}\)
  - \(\tau_{\text{rhynco}} \sim 10\ \text{s}\)

**Velocity-Rate correlation:** non-adapted chemotaxis (Bacteria)
\[v_{\text{chemotaxis}} \sim 0.7 \pm 0.2\ \text{cm.s}^{-1}\]
- **Stop-Rate correlation:** Exploiting rather than exploring
Conclusion and Perspective

• Neural substrate to play the Bandit Game (Mushroom body?)

• Q-Learning for olfactory search

• Disentangling cue statistics and other cues
  – Pheromone detection statistics and wind dynamics
  – The Bandit Game for thermal (chiral thermal Gradient)

• *Agrotis Ipsilon* turbulent searches
  – Challenge: adding the extra antenna setup without modifying flight pattern
  – Clear Patterns during flight

M. Renou, INRA Versailles

Embedded olfactory circuits: Patent EP-B140164
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