Estimating the dynamical dimension of hybrid neurorobotic systems

Based On


Prashant Joshi (joshi@igi.tugraz.at)
Key Questions:

- How can neural tissue be used in a closed loop with external dynamical systems in an effective manner?
- How can we measure the critical features of this neural dynamics in the closed loop setup?
- What are the means by which we can establish the dynamical dimension of the neural circuitry in these hybrid systems?
Outline

- Overview
- Details of the neurorobotic system
- Previous Research
- Experimental Protocol
- Method for establishing the dynamical dimension of the system
- Results
- Discussion
Under normal circumstances, the selected tissue receives vestibular and other sensory signals and issues motor commands.

Velocity commands proportional to the population spike rate.

Stimulus proportional to Light Intensity Signals measured by robot sensors.

Single Point Mass
Double Point Mass
Khepera

Lamprey
An eel-like fish, whose nervous system has been extensively studied, particularly for its ability to generate and modulate locomotor behavior.
Neural Tissue

- Brainstem of sea-lamprey
- Extracellular recording from reticular region
- Two recording electrodes among axons of right and left PRRN
- Two stimulation electrodes among axons of nOMI and nOMP
- Placement of stimulation electrodes induces excitatory response in downstream neurons
The external dynamical systems

The simulated systems

- One dimensional movement
- System work under a potential force field
- Single point mass system has 2 dimensions and double point mass system has 4 dimensions

Robot

- The base Khepera module.
- 8 sensors located at 10, 45, 85 and 165 degrees from the front direction
- Circular workspace with 2 feet diameter
- 8 lights mounted at 45 degree intervals at the workspace boundary
Slice – ‘Dynamical System’ Interface

- Acts as an interpreter between the neural signals and external dynamical system
- Responsible for transformation of dynamical system output to vestibular input signals and for real-time transformation of population activity in the slice to input commands for the external dynamical system
- For example, the rate of pulses emitted by the stimulating electrodes is proportional to the light intensity measured by Khepera sensors
Previous Work

- Establishment of stable phototaxis
- The two wheels of robots receive velocity commands proportional to population spike rates
- The neural stabilizing behavior – in which the lamprey tracks the vertical axis is translated into the robot tracking the source of light
- Positive or negative phototaxis can be changed by swapping the right and left commands of the wheels
Experimental Protocol

For simulated point mass systems
- Closed loop system operated for 20 sec
- 2D and 4D systems were used alternatively
- Initial configuration of the system was drawn at random
- Rest intervals between simulation varied from 40 to 100 seconds

For Khepera
- Movement of robot restricted to single degree of freedom (only rotation about its center)
- The two robot wheels always rotate in opposite directions with equal speeds
- Speed is proportional to difference between spike rates from left and right electrodes
- Values of interest - $\theta$ and $\theta_l$
Mathematical Background

For the external dynamical system
\[ x_{t+1} = h(x_t, u_t) \]
\[ y_{t+1} = p(x_{t+1}) \]

Slice – ‘dynamical system’ Interface
\[ i_t = \alpha(y_t) \]
\[ u_t = \beta(o_t) \]

For the neural slice
\[ s_{t+1} = f(s_t, i_t) \]
\[ r_{t+1} = w(s_{t+1}) \]

The entire hybrid system
\[ q_{t+1} = m(q_t) \] , where
\[ q = [x \ s]^T \]

So it follows that:
\[ \dim(q) = \dim(x) + \dim(s) \]
Establishing the dynamical dimension – Part I

- Trajectories exhibit multiple intersections as they are projection from higher dimension to 1D space
- To measure the dimension of the hybrid system trajectories were increasingly unfolded into higher dimensions till no intersections were found in them
- Unfolding trajectories into higher dimension was done with surrogate state vector representation
- The surrogate state vector of dimension $d$ consists of $d$ consecutive values of the original trajectory
  \[ s_i = [x_1(t), x_1(t+\Delta t. \tau), \ldots, x_1(t+(d-1).\Delta t. \tau)] \], where,
  \[ \Delta t = \text{time-step of experiment} \]
  \[ \tau = \text{lag-parameter used in dimension reconstruction analysis} \]
- $\tau$ is defined as the first (smallest) local minimum of mutual information
Intersection of trajectories was determined by ‘delta-epsilon’ method.

For trajectory dimension $d$, pairs of consecutive points along the trajectories are analyzed.

For 2 pairs, $(s_i, s_{i+1})$ and $(s_j, s_{j+1})$, $\delta$ and $\varepsilon$ are defined as:

$$\delta = |s_i - s_j| \text{ and } \varepsilon = |s_{i+1} - s_{j+1}|$$

If $\delta \to 0$ causes $\varepsilon \to 0$, it means there is no intersection.

If $\delta \to 0$ causes $\varepsilon$ to grow to large values, it means the trajectories are intersecting.

The lowest dimension $d$, where the trajectories don’t intersect, is the dynamical dimension of the hybrid system.
Results – Khepera

• Results were collected using four preparations
• Observed trajectories and deduced dynamical dimension are similar for different preparations
• $\Delta t = 200$ msec, time delay between consecutive samples

Fig. 4. (a) Sample trajectories produced during the experiment. (b) One of the trajectories. Notice that in this experiment the trajectories are represented in terms of $\Delta \theta$ versus $t$, which is different from trajectories in phototactic behavior experiments, like those shown in Fig. 2.
False Nearest Neighbors Analysis

- Used to determine if a given dimension $d$ is adequate dimension
- Form a surrogate state vector of $d$ consecutive points
- For each sample of the surrogate state vector find the nearest neighbor in the $d$ dimensional space
- Each surrogate vector is then analyzed in the $(d+1)$ dimensional space
- If the nearest neighbor remains close to the state in question in $(d+1)$ dimensional space, it is a true nearest neighbor

Fig. 5. False nearest-neighbors analysis reveals a high-order system.
Conclusions

- Independent dynamical components can be utilized to achieve a richer behavior in brain-machine systems.
- Dynamical dimension provides lower bound on the number of tunable parameters.
- Dynamical dimension relates to various structural properties of the neural system, e.g. connectivity patterns.
- Dimension assessment can be used as a basic tool for estimating the temporal capacity of the neural slice as a memory element.
And so...

It’s Over, Thank You 😊