Grid cell realignment based on idiothetic head direction cues

Introduction

Autonomous robots need to incorporate a significant number of sensors to reliably plan and secure follow trajectories. The difficulty increases by 1) dynamically changing environments and 2) access to only few, i.e. embedded, computational resources. Equipped with only a limited number of sensors, rodents are however able to navigate remarkably well. Given the recent discoveries of grid cells (GCs; Hafting et al., 2005) and the prepay of future place cells (PCs; Pfeiffer, 2013), we seek to improve navigation for small autonomous robots by neuromorphic hardware and biologically inspired algorithms.

One basic mechanism that is not yet understood is grid realignment. The periodic spatial response of GCs changes when PCs undergo remapping. As GCs are one synapse upstream of PCs and thus a significant source of inputs, they may well be a cause for remapping. We asked if external cues could induce realignment signals, and to incorporate such cues into existing Continuous Attractor Network (CAN) models.

Another issue in technical systems is the setup of artificial neural networks. Especially in many CAN models, the organization of grid cells is regular (Figure 3). Setting up regular structures on neuromorphic distributed hardware is difficult and error prone. Thus we explored the capabilities of a randomized CAN model, hoping that it would yield grid responses, and to combine it with the grid realignment proposed below.

Problem description, solution and results

Most GC models impose an external coordinate system. Thus any input velocity is relative to this frame of reference. However, a rodent’s brain needs to establish a coordinate system based on, for instance, the head direction network; the head direction (encoded in a population of HD cells) implicitly encodes a local coordinate frame (Figure 1).

We assume that perceived velocities arrive in the visual system, parallel to the viewing direction. Consequently they need to be mapped to this local frame. We suggest that HD cells, anchored to external cues, can perform the mapping in a recently published but slightly modified GC model (Couey et al., 2013). The state equation for each GC is given by

$$\tau \frac{d\theta}{dt} = -\alpha_1 \theta + \sum_{i} w_{i} x_{i} + 1 + \alpha \theta \cdot \xi$$

Equation 1

$$R = \begin{bmatrix} \cos(\theta) \\ \sin(\theta) \end{bmatrix}$$

Equation 2

The rotation matrix $R$ maps the velocity $\xi$ to the local frame of reference, given by the head direction $\theta$. The model is able to adapt to single-cell grid-like network dynamics (IND) as well as single-cell grid (SCG) responses. Each neuron selected its preferred direction from a pool of possible directions $\theta$. We analyzed the network with varying $\theta \in \{\theta_1, \ldots, \theta_n\}$ and several network sizes.

Due to the uniform distribution of randomly selected directions, the response of this network should be similar to small, perfectly organized networks, as long as the number of neurons is large enough. However, we simulated that networks of plausible sizes are unable to yield SCG responses, although the IND clearly show stable, grid-like attractors (Figure 4).

In addition, we analyzed a randomized version of the model. Originally, GCs are placed on a regular lattice, each neuron selecting its preferred direction $\theta$ based on neighboring neurons (Figure 3). We assumed that a randomized network is able to exhibit grid-like instantaneous network dynamics (IND) as well as single-cell grid (SCG) responses. Each neuron selected its preferred direction $\theta$ from a pool of possible directions $\theta$. We analyzed the network with varying $\theta \in \{\theta_1, \ldots, \theta_n\}$ and several network sizes.

Discussion and future work

Our results clearly show that the model is able to realign velocity vectors into a local coordinate frame. We are currently integrating the grid realignment due to external cues into our recurrent model which is able to realign grids based on place inputs. Furthermore, we are working on a spike-based implementation that learns the association between head direction inputs and grid cells using a biologically plausible learning rule.

The results for the randomized network model are, however, more drastic. If the computations carried out in the medial Entorhinal Cortex really follow the dynamics proposed in (Burak & Fiete, 2009; Couey et al., 2013), then the connectivity needs to be either static and organized in some form of pin-wheel organization similar to the striate cortex, or very carefully tuned. Only subtle changes to the organization lead to non-isotopic displacement of the “attractor bumps”. Consequently, the SCG response will not be grid like (Figure 4). The recent discovery of a physiological grid like distribution of neurons in Medial Entorhinal Cortex (MediEntorhinal Cortex, Science, 343(6173)).

References


This work is supported by the EU FP7 FP7 GRIDMAP project.

GRIDMAP Consortium
- Molnar Lab, Norwegian University of Science and Technology (NTNU)
- Treves Lab, International School for Advanced Studies (SISSA)
- Moritz Lab, University of Edinburgh (UEDIN)

This work is supported by the EU FP7 FP7 GRIDMAP project.

GRIDMAP Consortium
- Molnar Lab, Norwegian University of Science and Technology (NTNU)
- Treves Lab, International School for Advanced Studies (SISSA)
- Moritz Lab, University of Edinburgh (UEDIN)

This work is supported by the EU FP7 FP7 GRIDMAP project.

GRIDMAP Consortium
- Molnar Lab, Norwegian University of Science and Technology (NTNU)
- Treves Lab, International School for Advanced Studies (SISSA)
- Moritz Lab, University of Edinburgh (UEDIN)