Research article

A novel neurophysiological based navigation system

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ABSTRACT

This paper introduces a novel neurophysiologically based mobile robot navigation system, which emulates the dynamics of a rodent's navigation and spatial awareness cells found in the hippocampus and entorhinal cortex. The model presented here replicates the functionality of these neurons in their hardware and software counterparts. By using data structures and computational logic that best utilizes currently available processing architectures, a cognitive map is created using a unique multimodal source model for place cell activation. Path planning is performed by using a combination of Euclidean distance path checking, goal memory, and the A* algorithm. Localization is accomplished using simple, low power sensors, such as a camera, ultrasonic sensors, motor encoders and a gyroscope. The place code data structures are initialized as the mobile robot finds goal locations and other unique locations, and are then linked as paths between goal locations, as goals are found during exploration. The place code creates a hybrid cognitive map of metric and topological data. In doing so, much less memory is needed to represent the robot's roaming environment, as compared to traditional mapping methods, such as occupancy grids. A comparison of the memory and processing savings are presented, as well as to the functional similarities of our design to the rodent's specialized navigation cells.

Introduction

Autonomous mobile robotics have many diverse applications and domains (i.e., indoor, outdoor, underwater, and airborne). For instance, indoor applications include: security, rescue, and service mobile robots, while outdoor applications include driverless automobiles. Underwater and airborne robot systems include ocean and space exploration robots, respectively. The success of any autonomous mobile robot is based on its ability to reliably navigate in its environment. This is especially true for animals and other living creatures, whose survivability is dependent on their ability to navigate effectively in their environment. They would perish if they were unable to relocate food and cache locations, their home, as well as shelter spots from predators. Navigation, for both biological creatures and machines, can be defined as the ability to maintain a course when going from one location to another (Franz & Mallot, 2000; Trullier, Wiener, Berthoz, & Meyer, 1997).

The basic tasks and capabilities required for accomplishing navigation are localization and mapping. In robotics, the combination of these two tasks is referred to as the simultaneous localization and mapping (SLAM) problem (Bailey & Durrant-Whyte, 2006; Durrant-Whyte & Bailey, 2006; Wallgrün, 2010, chap. 2). Mobile robots using a SLAM algorithm to both map its environment and localize itself within that map, do so at a level of adequacy that is based on the fidelity of their sensory input data. Because autonomous mobile robots have

sensors, actuators and navigation algorithms that cater to their application and working environment (Gonzalez-Arjona, Sanchez, López-Colino, de Castro, & Garrido, 2013; Sariff & Buniyamin, 2006), these robots can still be very rigid and short coming in their navigation capabilities. The problem areas that arise in navigation include dealing with dynamic environments, as well as the need for high precision localization data for mapping and path planning.

Animals, on the other hand, are masters at navigating in their environments. For central to biological based navigation is the ability to travel from one place to another without getting lost (Tolman, 1948). It was suggested by Tolman in 1948 that for rats and humans to be able to accomplish various navigation tasks, they must have a cognitive map of their environment in their head (Redish, 1999; Tolman, 1948). In 1971, O'Keefe and Dostrovsky (1971) discovered a special type of neuron in the rodent's hippocampus that fired only when the rodent was in a specific location and was aptly named the place cell. It became evident that place cells were part of the suspected cognitive map and it has been heavily researched from that point on. Since the discovery of the place cell, the head direction cell, and the boundary cell were discovered in the rodent's hippocampus and its surrounding area, and the grid cell in the neighboring entorhinal cortex. These specialized brain cells are believed to play a vital role in the navigation abilities of the rodent. The hippocampus is also believed to be involved in the storage of new episodic memory (Burgess, Maguire, & O'Keefe, 2002; Fyhn, Molden, Witter, Moser, & Moser, 2004).

In addition to cognitive maps used by rodents, many species, such as spiders, crustaceans, insects, birds, and many mammals are capable of homing. That is, they continually update an internal vector trajectory with respect to their previous location to be able to return directly home (Müller & Wehner, 1988; Redish, 1999). These creatures can do so even after wandering in its environment for some time. Homing can also be accomplished in the dark and through unknown areas, and despite having traveled a circuitous route. This is accomplished through dead reckoning, which is also known as path integration (PI), as originally proposed by Darwin (1873). For the rodent, the neural circuitry involved is speculated to take place in or around the hippocampus and its surrounding area.

The remainder of this paper outlines the navigation system designed around the functional concepts of these specialized rodent's navigation and spatial awareness cells. First, the firing and functional characteristics of these cells are reviewed.

Rodent's specialized navigation cells

The rodent brain has been studied greatly, particularly the hippocampus and its surrounding area for its navigation related cells (Bush, Barry, & Burgess, 2014; Redish, 1999). These cells include: place cells, boundary cells, head direction cells (in the subiculum), and grid cells (in the neighboring entorhinal cortex). The rodent is not the only mammal with these special brain cells. Mice, rats, and bats have been found to also have place cells and grid cells (Burgess, Recce, & O'Keefe, 1994; Moser et al., 2014). However, this list is most likely broader. A brief description of the firing characteristics of these navigation related brain cells follow and can also be found in (Zeno, 2015; Zeno, Patel, & Sobh, 2016). Fig. 1a illustrates the location and size of the rodent hippocampus (left and right), while Fig. 1b illustrates the major components of the hippocampus, via a cross section horizontal slice of the ventral portion of the hippocampus. The locations of the specialized navigation cells with respect to the areas shown in Fig. 1b, as well as their basic behavior are covered next.

Place cells

A place cell (PC) fires maximally when the rodent is in a particular location of its environment (Bush et al., 2014). A place cell is usually limited to a single firing field (FF), unless the environment is large. Thus, many PCs are utilized to map a rodent's environment. Additionally, the firing of a PC is only dependent on location and not direction (in rodents), unless the place field is in a constrained location, such as a maze corridor. PCs are found mainly in CA3 and CA1 of the hippocampus (pyramidal cells), and to a lesser degree in the dentate gyrus (DG) with smaller place fields (Redish, 1999). As described in the introduction, PCs play an important role in the mapping of the rodent's environment, which is typically identified by the term place code. A PC's FF size is dependent on its type and location in the hippocampus. As presented in (Kjelstrup et al., 2008), a place field can be defined as the area between the points in an environment where the theta phase precession begins and terminates.

Head direction cells

The head direction (HD) cell fires at a preferred direction (± a few degrees) of the rodent's head direction in the horizontal plane, and has no relation to the rodent's body position. HD cells are aligned to the rodent's allocentric cues found in its environment, but are informed of motion through vestibular signals. HD cells are found primarily in the rodent's postsubiculum (PoS), the anterior thalamic nuclei (ATN) and the lateral mammillary nuclei (LMN) (Redish, 1999; Taube, 2007).

Boundary cells

The boundary cell (BC) is direction invariant and location specific in its firing. The BC typically has a single FF, which is dedicated to a particular boundary or border in the rodent's roaming environment. BCs can be found in the medial entorhinal cortex (MEC), parasubiculum (PaS) and subiculum (Bush et al., 2014). Additionally, it is believed that there are boundary vector cells (BVCs) in the subiculum which fire according to a fixed distance and direction to a boundary (Derdikman, 2009; Lever, Burton, Jeewajee, O'Keefe, & Burgess, 2009). From here on, we will use BVCs in our system description and will simply designate them as BCs.

Grid cells

The grid cell (GC) is a unique spatial awareness brain cell found in the entorhinal cortex (EC) of a rodent. GCs are predominantly found in layer II of the medial entorhinal cortex (mEC), which is located one synapse upstream of the PCs in the hippocampus (Fyhn, Hafting, Treves, Moser, & Moser, 2007; Hafting, Fyhn, Molden, Moser, & Moser, 2005). The GC differs from the PC and BC such that it has many spatial FFs. Each GC's FF maps over the rodent's entire roaming environment in a hexagonal lattice formation. At the node of each equilateral triangle in the lattice is the location of a single FF of a GC. The FFs of a GC,
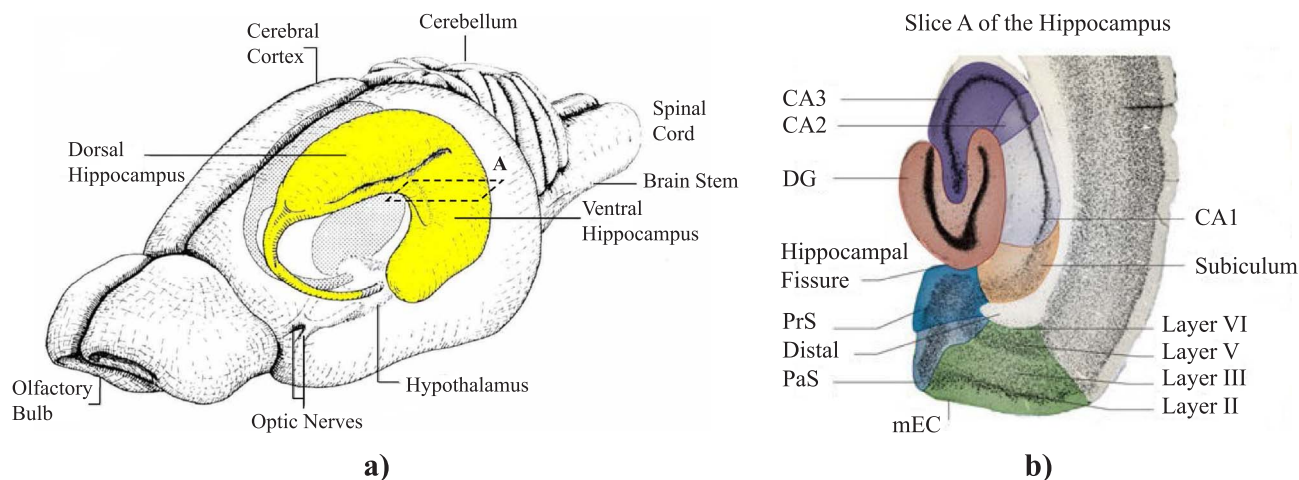

Fig. 1. The rodent brain. (a) In yellow is the left hemisphere hippocampus. (b) Anatomy of hippocampal formation and parahippocampal region (horizontal slice A in part a). Abbreviations: Carnu amonis (CA), dentate gyrus (DG), lateral entorhinal cortex (lEC), medial entorhinal cortex (mEC), parasubiculum (PaS), and presubiculum (PrS). Picture adaptions: Figure (a) from (Little, 2007), and (b) from (Moser et al., 2014).