Neural Networks 72 (2015) 48–61

Contents lists available at ScienceDirect

Neural Networks

journal homepage: www.elsevier.com/locate/neunet

2015 Special Issue

Bio-inspired homogeneous multi-scale place recognition

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ARTICLE INFO

Article history:
Available online 29 October 2015

Keywords:
Bio-inspired
Multi-scale place recognition
Robot localization
Metric learning

ABSTRACT

Robotic mapping and localization systems typically operate at either one fixed spatial scale, or over two, combining a local metric map and a global topological map. In contrast, recent high profile discoveries in neuroscience have indicated that animals such as rodents navigate the world using multiple parallel maps, with each map encoding the world at a specific spatial scale. While a number of theoretical-only investigations have hypothesized several possible benefits of such a multi-scale mapping system, no one has comprehensively investigated the potential mapping and place recognition performance benefits for navigating robots in large real world environments, especially using more than two homogeneous map scales. In this paper we present a biologically-inspired multi-scale mapping system mimicking the rodent multi-scale map. Unlike hybrid metric-topological multi-scale robot mapping systems, this new system is homogeneous, distinguishable only by scale, like rodent neural maps. We present methods for training each network to learn and recognize places at a specific spatial scale, and techniques for combining the output from each of these parallel networks. This approach differs from traditional probabilistic robotic methods, where place recognition spatial specificity is passively driven by models of sensor uncertainty. Instead we intentionally create parallel learning systems that learn associations between sensory input and the environment at different spatial scales. We also conduct a systematic series of experiments and parameter studies that determine the effect on performance of using different neural map scaling ratios and different numbers of discrete map scales. The results demonstrate that a multi-scale approach universally improves place recognition performance and is capable of producing better than state of the art performance compared to existing robotic navigation algorithms. We analyze the results and discuss the implications with respect to several recent discoveries and theories regarding how multi-scale neural maps are learnt and used in the mammalian brain.

1. Introduction

The vast majority of robotic mapping and navigation systems perform mapping at either one fixed spatial scale or across two, typically comprising a local metric map and a topological global map. A range of recent high profile discoveries in neuroscience have demonstrated that animals such as rodents, and likely many other mammals including humans, encode the world using multiple parallel mapping systems, each of which encode the world at a different scale (Hafting, Fyhn, Molden, Moser, & Moser, 2005a, 2005b). In rodents, the mapping system scales from neurons that encode an area of a few square centimeters to neurons that encode an area of several square meters, with many intermediate scales represented in-between. Unlike hybrid metric-topological multi-scale robot mapping systems, rodent maps are homogeneous, distinguishable only by scale. While a number of theoretical-only investigations have hypothesized possible benefits of such a multi-scale mapping system (Burak & Fiete, 2009; Welinder, Burak, & Fiete, 2008), no one has comprehensively investigated the potential benefits of multi-scale mapping on place recognition in challenging real world environments.

In this paper, we present a biologically-inspired multi-scale mapping system mimicking the broad properties of the rodent multi-scale map. The first key innovation is to consider the place recognition problem as a hierarchical process—utilizing wider environmental context for more robust, coarser localization in

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http://dx.doi.org/10.1016/j.neunet.2015.10.002

parallel with finer localization on a smaller scale to improve localization accuracy. In this context, place recognition is framed not as the challenge of finding the single database image that best matches the current frame, but rather as one of finding all the database images within local spatial neighborhoods that are the best match for the sequence centered around the current frame. Our approach utilizes arrays of distance metrics, with each one trained to perform place recognition at a specific spatial scale, and a process for combining place recognition hypotheses from these different spatial scales. Unlike traditional probabilistic robotics methods, where spatial specificity is passively determined by sensor observation models, our approach intentionally creates parallel training systems to map the sensor input to the environment at different spatial scales.

This research extends on our previous work presented in Chen, Jacobson, Erdem, Hasselmo, and Milford (2013, 2014) in which we demonstrate that mapping over multiple scales uniformly improves place recognition performance over a single scale without sacrificing localization accuracy. We make three novel research contributions. Firstly, we introduce a metric learning-based algorithm to model the grid cells' discrete firing patterns. Secondly we propose an improved hierarchical framework to recognize places at multiple spatial scales. Lastly, for the first time our approach surpasses the performance of state of the art robotics algorithms, demonstrating the practical performance benefits of a homogeneous multi-scale mapping framework.

We conduct experiments on two robotics benchmark dataset and compare single- and multi-scale place recognition performance and demonstrate that multi-scale recognition leads to significantly improved recognition performance. We also conduct a systematic series of experiments and parameter studies that determine the effect on performance of using different neural map scaling ratios and different numbers of discrete map scales.

The paper is organized as follows. Section 2 discusses related place recognition and mapping techniques. In Section 3, we describe the components of the multi-scale place learning system. The experiments are detailed in Section 4, with results shown in Section 5. Finally we conclude the paper in Section 6 by discussing ongoing and future work.

2. Related work

Place recognition and mapping has been the subject of wide-ranging study both in the robotics and neuroscience community. This article is motivated by both fields, drawing inspiration from discoveries in neuroscience to develop novel multi-scale mapping algorithms for robots. To this end, we review the current state-of-the-art in place recognition algorithms for robots, including the existing use of multi-scale mapping within robotics. We briefly review evidence for multi-scale maps in the mammalian brain and note other bio-inspired mapping and navigation systems.

2.1. Place recognition methods

A fundamental challenge in mobile robotics is to develop robust navigation techniques. Place recognition – the ability to recognize places that the robot has already visited, and thereby correctly localize itself within the environment – is a key element of any navigation system. A great number of different sensors have been utilized for place recognition. Among them, visual sensors are the predominant sensor modality in many robot platforms with extensive research on vision-based place recognition (Angeli, Filliat, Doncieux, & Meyer, 2008; Cummins & Newman, 2008; Newman, Cole, & Ho, 2006; Ulrich & Nourbakhsh, 2000). The field of visual place recognition is well advanced, with place recognition systems being tested over paths measuring dozens (Schindler, Brown, & Szeliski, 2007) or even hundreds of kilometers (Cummins & Newman, 2009). Most appearance-based approaches start with image pre-processing (such as histogram normalization or noise removal), to improve image quality for future processing. Features are then extracted from the image, and a place matching process determines the most likely current position of the robot.

If multiple streams of data are available (such as multiple color channels) then a *voting* scheme (Ulrich & Nourbakhsh, 2000) can decide the robot location. Alternatively, a probabilistic calculation such as FAB-MAP (Cummins & Newman, 2008) can be used, where a likelihood model associating perception and location is learned on the extracted image features. FAB-MAP also compensates for *perceptual aliasing*; multiple locations may appear very similar and so observations must also be distinctive before FAB-MAP will match with high confidence. In RatSLAM (Milford, Wyeth, & Prasser, 2004), a biologically-inspired place recognition system based on a rat brain, localization is performed using a continuous attractor network (CAN) model combined with local view cells that excite and inhibit the elements in the neural network. Although RatSLAM is widely regarded as one of the state of the art biologically inspired robotic navigation systems, it is important to note that all of its benchmark achievements have come about due to a *single-scale* mapping system.

2.2. Multi-scale place recognition

In robotic navigation, multi-scale mapping often takes the form of a *hybrid metric-topological* or *topometric* map (Bosse et al., 2003; Konolige, Marder-Eppstein, & Marthi, 2011; Kuipers & Byun, 1991; Kuipers, Modayil, Beeson, MacMahon, & Savelli, 2004; Segvic, Remazeilles, Diosi, & Chaumette, 2009). Metric mapping develops geometrically accurate representations of the world, and allow centimeter-level accuracy in robot localization (Rowekamper et al., 2012), but is computationally infeasible over large areas, and struggles to close large loops (Bazeille & David, 2011). A compromise is to maintain small local metric submaps linked together in a topological map.

These mapping frameworks are *heterogeneous*, in that different types of maps (metric and topological) are used at different scales, and limited to two distinct scales. In contrast, in this research we consider *homogeneous* multi-scale mapping for robotics. This concept has been proposed (Kuipers, 1978, 2000) with topological *places* contained within a structure of topological *regions*. A similar concept to multi-scale topological mapping is the notion of summarizing an environment online, where the robot's observations are grouped into *topics* to allow for efficient summarization. This summarization can be performed using topic modeling (Paul, Rus, & Newman, 2012), coresets (Paul et al., 2012), Bayesian surprise (Girdhar & Dudek, 2012) or extremum summaries (Girdhar & Dudek, 2012). However, these environmental summarization techniques have not explicitly been used to perform place recognition (Theocharous, Murphy, & Kaelbling, 2004) investigate the concept of multi-scale robot localization and demonstrate that multiple scale representation helps to scale the H-POMDPs's algorithm to much larger models. However, up to now, there is still no quantitative evaluation on the benefits of multi-scale mapping in place recognition.

2.3. A multi-scale neuronal map

Over the past 30 years, there have been extensive studies on mapping and navigation mechanisms in rodents. Early studies focused on the part of the rodent brain known as the hippocampus, which was thought to be responsible for navigation tasks, and led to the discovery of *place cells* (O'Keefe & Dostrovsky, 1971) within the rat hippocampus which are only active when the animal is in