

A Neural Model of Landmark Navigation in the Fiddler Crab *Uca lactea*

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Abstract. The fiddler crabs, *Uca lactea*, which live on intertidal mud-flats, exhibit a remarkable ability to return to its burrow. It has been reported that the species usually use path integration, an ideothetic mechanism for short-range homing. During the mating season, however, the accumulation error of the process increases due to vigorous courtship movement. To compensate for this, most courting males construct the vertical mud structures, called semidomes, at the entrance of their burrows and use them as landmarks. Here, we suggest a possible neural model that demonstrates how visual landmark navigation could be implemented in the fiddler crab's central nervous system. The model consisting of two levels of population of neurons, is based on the snapshot hypothesis and a simplified version of Franz's algorithm is used for the computation of home vector.

1 Introduction

Animals make use of various mechanisms to find their home after foraging far away or searching for mating partners. For example, fiddler crabs *Uca lactea* (Fig.1) highly depend on path integration, an ideothetic mechanism in their short-range homing. The expression short-range means excursions of up to 30 cm from their burrows [1]. They achieve this by calculating an egocentric home vector by maintaining their transverse body axis pointing to burrows [6], and using leg odometry [7]. During courting, however, the direction of males transverse body axis deviates from that of their home vectors when they intensively court females. Thus, it has been suggested that male-building structures (in the form of semidomes) might be used as landmarks [5].

If it is true that male fiddler crabs utilize semidomes as visual landmarks when they return to their burrows, we can consider an analogy to the landmark navigation problem found in other insect foragers such as bees and ants. The visual homing abilities of those animals may be well explained by the snapshot hypothesis. It claims that animals can decide homing movement and ultimately reach their home by continuously comparing the current retinal image with a snapshot taken at their nest. Cartwright and Collett suggested this snapshot

model [2], and later other researchers [4, 3] showed further works following the snapshot model.

The snapshot model showed its experimental reproduction of behavioural patterns found in real animals, but there has been no research what kind of neural mechanism underlies the matching procedure. Thus, in this paper, we suggest a neural model of landmark navigation for the fiddler crab *U. lactea*. The fiddler crab is an intriguing species for the landmark navigation. Many animals utilize visual landmarks available around their home nest, and it is believed that fiddler crabs are building a small semidome-style object to design a salient feature of visual landmark in their habitat of mudflat.



Fig. 1: Male *Uca lactea* with a semidome (by courtesy of T.W. Kim [5])

2 Mathematical description of the homing scheme

Following the snapshot model, Franz et al. [3] suggested a new scene-based homing algorithm which assumes that all surrounding landmarks have identical distances from the location of the snapshot. We can apply the algorithm to the landmark navigation of a fiddler crab, which requires three parameters, α, θ, ρ , in the following equation:

$$\tan \delta = \frac{(d/R) \sin(\theta - \alpha)}{1 - (d/R) \cos(\theta - \alpha)} = \frac{\rho \sin(\theta - \alpha)}{1 - \rho \cos(\theta - \alpha)} \quad (1)$$

where θ is an angle of a landmark, that is, semidome, relative to the light compass, α is a possible movement angle of a crab, δ is the displacement angle of landmark image, d is the moving distance and R is the distance between the current location and the landmark, and $\rho = d/R$ is the ratio. It is assumed that all the landmarks have equal distances away from the current location. With the estimated displacement angle, the corresponding images are generated and compared with the snapshot at nest.

Fig.2(a) shows a geometric relationship in an agent's homing navigation situation. In fact, the line of the horizon in the habitat and the pattern of polarized

skylight help them control the orientation of their eyes and their bodies [6]. The visual system of fiddler crabs has a panoramic visual field and well tuned to the geometry of vision in the flat world. Here, we assume that the agent uses the light compass, unlike Franz et al.'s approach [3]. The landmark image direction is estimated with reference to the light compass. Thus, we do not have to consider the agent's orientation for image displacements.

The homing scheme is a procedural algorithm to estimate the homing direction. It considers all possible angles for movement and evaluates all the image displacements for every angle of movement. Then it determines the angle in which the image displacement best matches the snapshot taken at the nest.

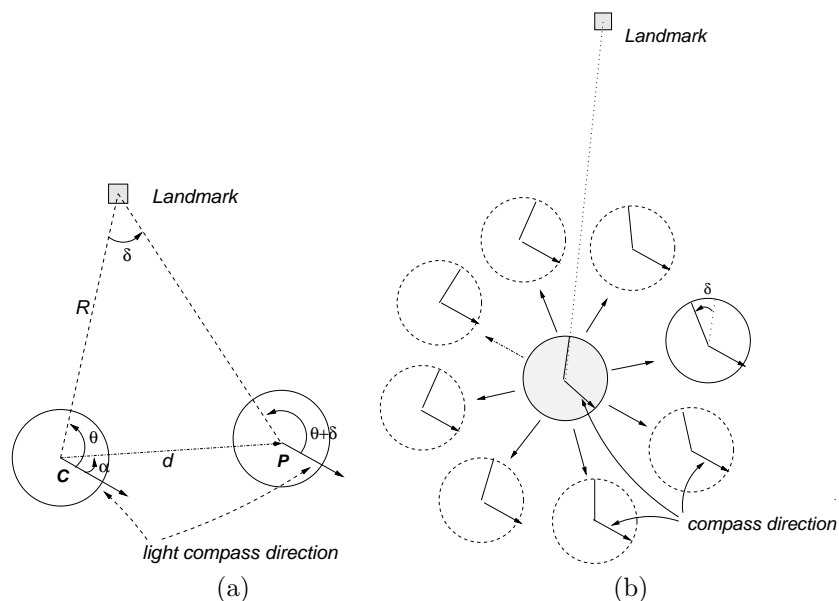


Fig. 2: Image displacements (a) geometry with landmark parameters (modified from [3]); viewing angle of a landmark is changed depending on the moving direction α with distance d (agent moved from C to P) (b) image displacement δ depending on each moving direction.

Before establishing the neural model, equation (1) is simplified in two steps. First, we assume that fiddler crabs use light compass and so the orientation angle (head angle) does not influence the image displacement, since all the landmarks can be described with respect to the compass reference. Second, if the ratio $\rho = d/R$ is lower than 0.1, then equation (1) can be approximated with

$$\delta \simeq k \cos(\gamma - \pi/2)$$

where k is a constant and $\gamma = \theta - \alpha$.

Fig.3 shows the image displacement δ depending on the changes of the parameter α (that is, the moving direction), depending on the ratio ρ . The ratio

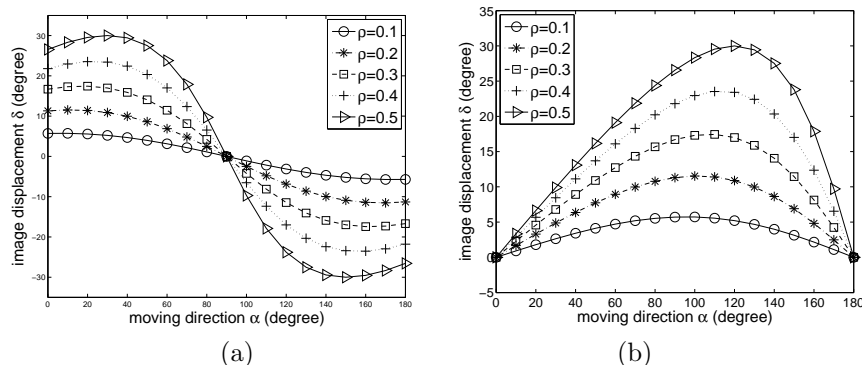


Fig. 3: Estimation of landmark (relationship between image displacement δ and moving direction α depending on ρ) (a) $\theta = 90^\circ$ (b) $\theta = 180^\circ$

$\rho = d/R$ greatly influences the curve of image displacement. Interestingly, the equation (1) follows a cosine tuning curve for small ρ , which is also derived above. Based on this result, we can build a neural model to process the image displacements in parallel for every moving direction. From the image displacements, a predictive model of image for each direction can be generated and further, this image can be compared with the snapshot near the nest.

3 Neural Snapshot Model

If we assume a population coding for image displacement for every α , the procedural algorithm for the snapshot model can be simplified to a neural implementation in parallel. A neuron may be assigned for image displacement at each angle α . A collection of the image displacement neurons has a population coding, following a cosine tuning curve. According to the population coding method, a population of neurons represent the perceptual vector or quantity. The weighted average of the neuron activations in the preferred directions can determine the perception vector. Here, a population of image displacements itself is not directly related to the homing scheme with snapshot model.

For our neural snapshot model, we can build a predictive image vector of landmarks from the image displacement for every moving direction (number of directions can be selected appropriately). If several landmarks are available, these image cells record the image displacements of multiple landmarks for a given movement angle α . Then each predictive image is compared with the snapshot image taken near the nest in parallel. The matching between the image and the snapshot at nest can be simply implemented with neurons (it has a form of sum of product operations, when the image is represented in binary form). For the homing direction, we choose the movement angle which can lead to the highest activation in the matching. Here, for several landmarks, each image for a possible movement angle is represented by a collection of neurons to

record the predictive image displacement, for example, a kind of ring structure demonstrated in Cartwright and Collet's works [2]. As a result, two levels of population of neurons should be available to handle the snapshot image matching. The lower level is a collection of predictive images and the higher level handles a comparison between the snapshot and each predictive image. This neural representation can also be applied to the landmark navigation of other animals.

With the engineering term, it corresponds to a discrete convolution of snapshot images.

$$\max_k (f * g)[k] = \sum_{m=0}^N f\left(\frac{m}{2\pi N}\right) \cdot g\left(\frac{k-m}{2\pi N}\right)$$

where $f(\cdot)$ is the snapshot image near the nest and $g(\cdot)$ is the predictive image for every possible movement. Here, we assume N images are compared with the snapshot at nest. The above function will find the best matching direction among N possible moves. At the image matching level, a population of neurons which covers the full range of directions, will determine the best direction in terms of matching criterion.

We simulated the above algorithm with landmark navigation. We used 32 neurons for directional neurons, and each image cell for both the predictive image and the snapshot at nest has a resolution of 1 degree. The higher level of neuron coding for image matching with the snapshot, will choose the best direction among a population of 32 image-matching neurons. Fig. 4(a) shows the snapshot image near the nest and Fig. 4(b) displays the best matching directions at various locations with five rounds-shaped landmarks, where (0,0) is the nest position that an agent starts to move from. After exploring in the arena, the agent should return to the nest position. As Franz et al. [3] pointed out, there is a catchment area to show reasonable homing directions, often inside a group of landmarks. Thus, the navigation should use a combinational model with egocentric information such as path integration.

4 Conclusion

In this paper, we suggest a possible neural model that demonstrates how visual landmark navigation could be implemented in the fiddler crab's central nervous system. The model follows image warping method suggested by Franz et al. [3] with the assumption of equal landmark distance. The image matching problem uses only snapshot images without any reference compass. Our neural model is based on the light compass reference and a population of neurons process all the image estimations and matchings in parallel. Thus, the complex image matching process known as a procedural task can be represented with simplified neural coding. The model consists of two levels of population of neurons, where the lower level predicts landmark images for possible movement directions, and the higher level matches the stored snapshot image near the nest and the predictive image corresponding to each possible movement angle. The above neural mech-

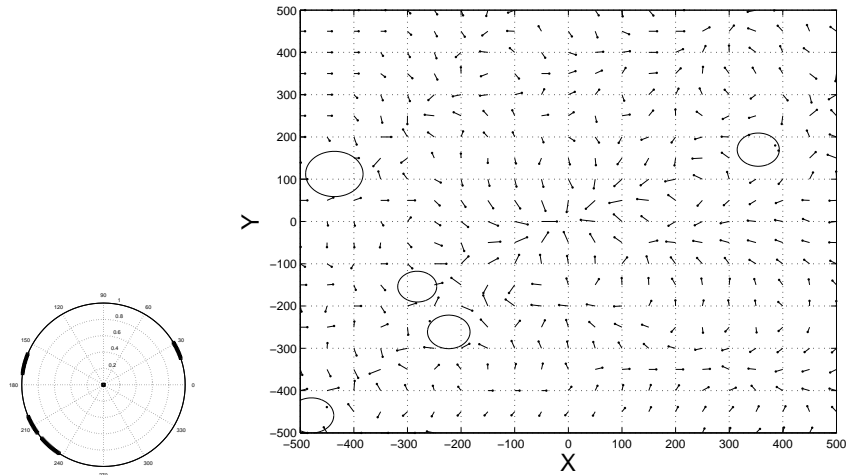


Fig. 4: Landmark navigation; (0,0) is the nest position and larger arrow indicates closer matching with the snapshot (left: snapshot image near the nest, right: best directions selected at each location)

anism can be applied to landmark navigation of other animals and also we can consider it for an image-based robotic navigation with fast response.

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