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Burrow-centric distance-estimation methods inspired by surveillance behavior of fiddler crabs

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Abstract
There are several ways to estimate the distance to an object based on visual information. Many robotic systems compute object distances based on disparity values or motion information. In addition to a disparity cue or image motion, research has shown that animals can possibly estimate the distance using the image size as well as the azimuth and elevation angles in their visual field. In this paper, inspired by the vigilance behavior of fiddler crabs, we suggest distance-estimation methods with several visual cues for engineering applications. A foraging fiddler crab can estimate the distance of an intruder from the burrow entrance. If the intruder is close to the burrow, the crab rushes back home to maintain possession of the burrow. In this study, we investigated burrow-centered distance-estimation methods based on visual information such as the retinal position, that is, the azimuth and elevation angles in an omnidirectional view as well as the image size and retinal speed of a target object. The methods show potential for engineering applications to the surveillance problem.

Keywords
Distance estimation, exocentric distance, vision, fiddler crabs, bio-inspired application

1 Introduction

Many animals show well-organized skills in their navigation, prey or predator detection, or vigilance behaviors. Desert ants have excellent homing navigation abilities, utilizing path integration and landmark navigation (Cartwright & Collett, 1983). Sand scorpions detect prey at night with tactile sensors rather than visual or auditory senses (Brownell, 1984; Kim, 2006). In addition, the vigilance behavior in fiddler crabs can be easily observed when a predator approaches their burrows (Hemmi & Zeil, 2003a). Since many invertebrates perform tasks with a comparatively small number of neurons, researchers have been interested in analyzing their behaviors and applying them to agent behaviors or artificial systems translated into the engineering point of view. Vigilance, an important behavior for the survival of animals, requires several information-processing procedures. In order to successfully protect their home from intruders, the agent should continuously monitor the environment to check if an intruder approaches too closely to their home. In addition, the agent should monitor the distance and the moving direction of the intruder. Recently it has been reported that fiddler crabs use landmarks, and the visual cue plays an important role in their homing navigation (Kim, Kim, & Choe, 2010). In this paper, inspired by the vigilance behavior of animals (fiddler crabs in particular), we suggest distance-estimation methods using several different cues in the visual sense, such as image size, azimuth and elevation angles in the visual field, and their rates of change over time.

The apparent size of an object is one of simplest and intuitive cues to estimate the distance to an object. A closer object appears larger and an object with a small retinal view can be considered to be distant. Crabs are also known to perceive the apparent size of an object since they are only interested in objects belonging to the class of small-sized objects (Land & Layne, 1995). Experiments conducted using fiddler crabs and approaching objects (intruders) with varying sizes showed that crabs perform vigilance behavior and respond at the same intruder–burrow distance, regardless of the actual size of the object (Hemmi & Zeil,

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2003b). The results indicate that the apparent size alone may not be used as a cue in the distance estimation.

Another possible cue is retinal elevation. Closer objects lie lower in the visual field, while farther objects appear at higher elevations. The elevation difference depending on distance is clearly shown in the mudflat environment, which is the habitat of fiddler crabs. The contact point of an object with the ground is uniquely determined by the distance between the observer and the object (Zeil, 1998). Research on the burrow surveillance of fiddler crabs (Hemmi & Zeil, 2003b) also showed that they use retinal elevation information to estimate the distance of an intruder from the burrow in order to protect their burrows. However, the predictive effect of elevation can be applied only to target objects that move on the ground. It is still unknown, however, how crabs encode the intruder–burrow geometry for surveillance.

The predator-avoidance system of fiddler crabs has different characteristics from the burrow surveillance system. Hemmi (2005) investigated the predator-response system of fiddler crabs and found the response depends on the speed and the approach direction of the predator (in this case, a flying bird). It has also been reported that objects at low retinal elevations with a flickering or fast-moving signal will be an indicator of a real predator (Smolka, Zeil, & Hemmi, 2011). A flicker signal as a response criterion can be evaluated from the input of a single ommatidium, while the retinal speed involves the photoreceptors of at least two ommatidia.

So far there is no detailed evidence of what neural processes are involved in the sensory mechanism and the response system for burrow surveillance or predator avoidance. The fiddler crab's surveillance behavior is an interesting topic for engineering applications as well. The judgments of the exocentric (inter-object) distance can be used to detect an intrusion into a secured area in the visual field. There are several engineering approaches to estimate the distance to target objects in the visual field. In robotic experiments, multiple vision sensors form stereovision to distinguish objects with different distances based on disparity values or motion information of the objects, or the observer induces optical flow information with ego-motion to estimate the distance to the objects. A number of robotic systems applying stereovision have been suggested. Two identical vision sensors separated by a certain distance offer two simultaneous images of the environment and by matching features in the image, they are able to determine the distance to the recognized objects (Huber & Kortenkamp, 2002). Stereo vision is applied to obtain distance information of an object with respect to the observer. There have been previous works estimating the position of a person relative to a robot for tracking purposes (Méndez-Polanco, Muñoz Meléndez, & Morales, 2009), and to compute distance information in order to build a map for navigation (Murray & Little, 2000). In both cases, distance estimation based on stereovision focuses on the distance between the target object and the observer. Instead of using two vision sensors, multiple images obtained from one moving camera also provide the same type of disparity information (Yu & Kim, 2011a; Yu & Kim, 2011b). The disparity is greater for objects located closer to the camera (observer) than objects located farther from the camera. Therefore, the distance to the object can be computed as disparity information based on an appropriate camera calibration. However, the distance estimation by optical flow information applied in robotic systems also focuses on the distance between the observer and the target, which is an ego-centric point of view.

As far as we know, not many approaches consider the distance of a target and its direction to a specific zone in the visual field. A visual map of an intruder in the visual field as a matched filter allows estimation of the distance and direction of the intruder from the burrow (Hemmi & Zeil, 2003b). From an engineering point of view, the viewing angle of the two objects can be simply measured and the distance to each object can be obtained with the disparity map or optical flow. Then, the inter-object distance can be found by applying simple trigonometric functions. However, a more direct expression of the inter-object distance or relative direction would be helpful to address the surveillance problem and to understand the fiddler crab's behavior.

In addition to disparity cues and image motion, animals can possibly estimate distance using the image size, elevation in the visual field, and their rates of change over time. These visual cues would provide distance information with respect to their home, as an important marker. We investigate possible visual cues for the surveillance problem in this paper. The sensory cues include the retinal position, the apparent image size, and the retinal speed to encode the intruder location relative to the burrow. In our model, these are all relevant parameters to influence the surveillance behavior. We demonstrate an analytical method to estimate the burrow–intruder distance and the approach direction.

2 Methods

Inspired by the behavior of animals (fiddler crabs in particular), we suggest surveillance methods which utilize the retinal position, image size, and retinal speed information obtained from an omnidirectional view. We considered the environment shown in Figure 1. The figure shows a graphical representation of the geometrical relationship between the burrow, the observer, and a target object (intruder). The home location is shown as a square. The distance between the home and the

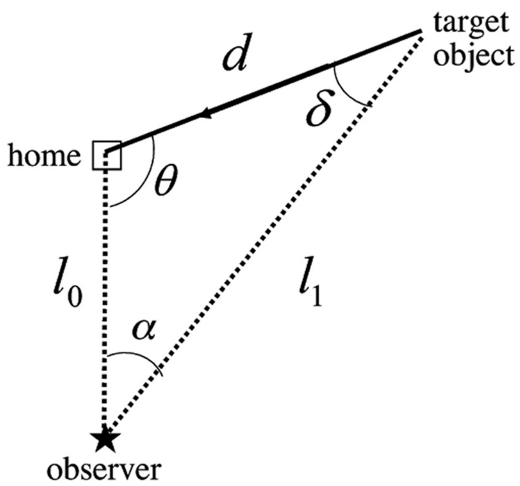


Figure 1. Graphical representation of the distances l_0, l_1 and d and angles α, θ and δ between the home, observer, and target object locations.

observer indicated as a black star is l_0 and the observer is assumed to be moving towards home. Therefore, the angle between the home and target object location in terms of the observer's view is equal to the azimuth angle α in the visual field. From fiddler crab observations, they are also able to maintain their longitudinal body axis direction toward home using path integration (Zeil & Hemmi, 2006). This indicates that crabs can estimate the distance to the burrow, l_0. The distance between the target object (intruder) and the observer is l_1, and the approach direction of the intruder and distance to the home are θ and d, respectively. These parameters represent the burrow-centered coordinate value, that is, the angular position and the distance of an intruder relative to the burrow. Based on the estimation results, the observer is able to determine the responding point where the object (intruder) is at a certain distance from home, which can be given by the threshold distance, d_t. Throughout the method description given in this section, we assume that the position of the target object (intruder) is (x, y) while the home location is considered to be the origin $(0, 0)$. Here, we investigate three possible visual cues to estimate the burrow–intruder distance and the approach direction, the retinal position, image size and retinal speed.

2.1 Method 1: retinal position

The retinal position of an object is represented as the horizontal position, α, and the vertical position, β, in the visual field. The azimuth α is the angle between the burrow entrance and the target object (intruder) along the horizontal axis parallel to the ground plane and β is the elevation angle from the horizontal axis towards a target object.

Equation (1) shows a target position (x, y) in the environment based on its retinal position.

$$x = h\frac{\cos(\alpha)}{\tan(-\beta)} - l_0 \quad y = h\frac{\sin(\alpha)}{\tan(-\beta)} \tag{1}$$

where l_0 is the distance between the burrow and the observer, and h indicates the height of the view, which is usually the height of the observer's eye from the ground.

As shown in equation (1), the relative position of an intruder (target) to the burrow can be computed from the retinal position (α, β) along with the height, h, and the distance to the burrow, l_0. The parameters of interest are the distance between the burrow and a target object, d, and the angle of approach, θ. The distance between the burrow and the intruder, d, is represented in equation (2) with the approaching angle θ

$$\begin{gathered} d = \sqrt{x^2 + y^2} = \sqrt{\frac{h^2}{\tan^2(-\beta)} - 2hl_0\frac{\cos(\alpha)}{\tan^2(-\beta)} + l_0^2} \\ \theta = \operatorname{atan2}(y, x) = \operatorname{atan2}(h\cos(\alpha) - l_0\tan(-\beta), h\sin(\alpha)) \end{gathered} \tag{2}$$

where θ is measured counterclockwise from the observer–burrow line.

The retinal position (α, β) can be used to obtain the distance and approaching angle using the equation shown above. Based on the positions shown in Figure 1, the observer obtains the omnidirectional view of the environment. An example of the view is shown in Figure 2. Figures 2(a) and (b) show the visual field of the observer, which reflects the environment in an omnidirectional view. The middle of each visual field with an azimuth of 0° is the heading direction of the observer and the range from -180° to 180° shows the surrounding environment. Each point in the visual field represents a specific point in the environment by one-to-one mapping (some regions are densely mapped). In Figure 2(a), each line represents the contour line at the same distance from the home location. In the figure, the lines are at distances of $R = 10, 20, 30, 40$ and 50 cm from home, while the observer is at a distance of $l_0 = 25$ cm from home. The lines in the visual field are comparatively continuous since they are shown in a high-resolution view. On the other hand, the same points are shown as discrete points in Figure 2(c) in a low-resolution view (1°); distances of 40 mm and 50 mm are indistinguishable at that resolution. As in the figure, the more distant points from the observer are densely positioned in the retinal map, which makes it harder to discriminate the distances using the retinal map alone. On the other hand, the points close to the observer are rather sparsely distributed and would provide more accurate information of the actual distance of the intruder. The lines in Figure 2(b) show the approaching path

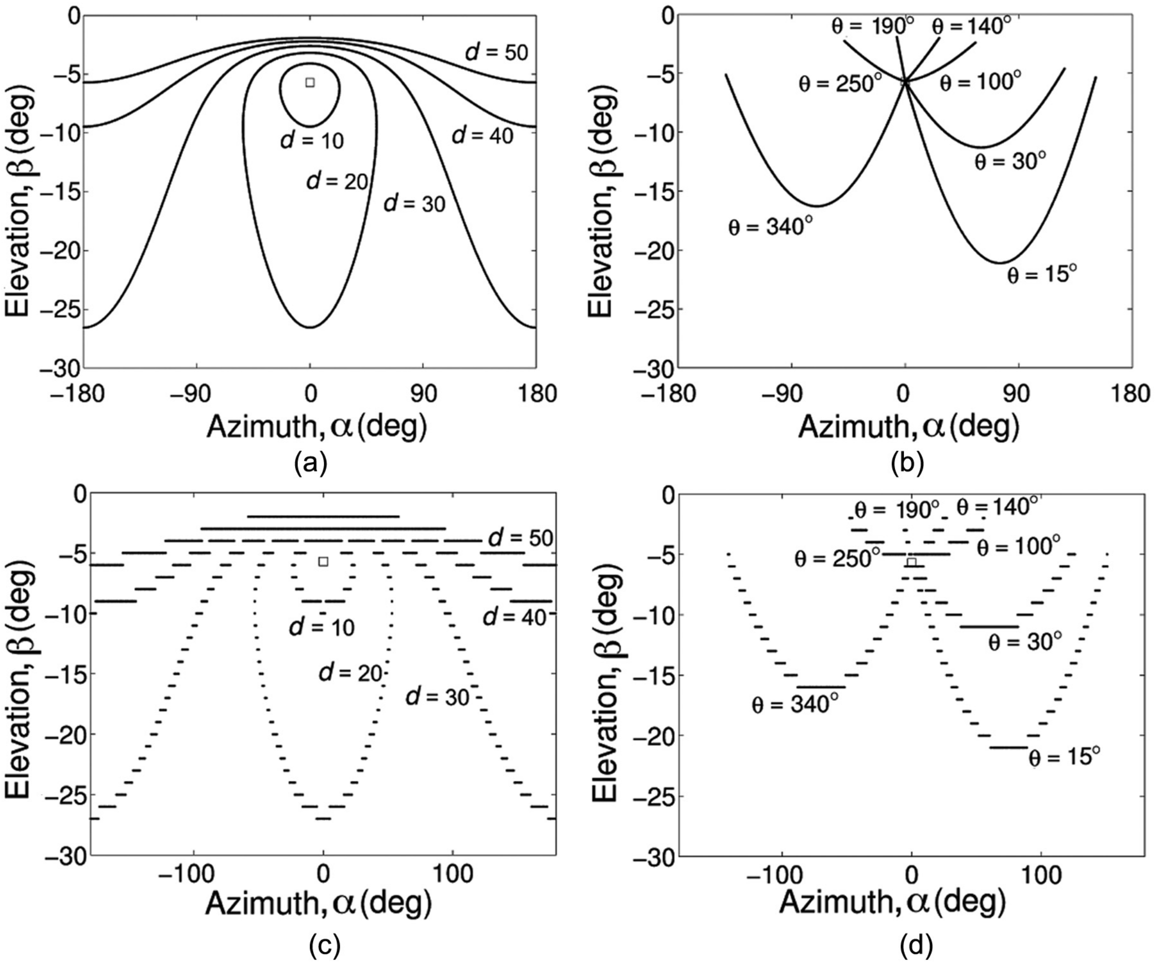


Figure 2. Retinal position of specific points in the omnidirectional view where in (a) and (c) each line indicates points with the same distance from home and in (b) and (d) the points indicate the moving path of an intruder with a given approach direction. The results are shown in (a) and (b) at high resolution and in (c) and (d) at low resolution. We assume that the observer estimates the burrow–intruder distance with its approach direction only by visual cues.

of an intruder while maintaining the same direction towards the burrow, which is often observed in the crab's behavior. The corresponding directions, θ, for the lines in the figure are $15°, 30°, 100°, 140°, 190°, 250°$ and $340°$. In the same manner, Figure 2(d) shows the approaching path of an intruder in the same directions in a low-resolution view.

As shown in Figure 2, the retinal position information obtained with a low-resolution view would not represent the target location accurately in the environment, leading to some errors in the estimation results. The resolution problem affects the position estimation significantly, especially when the object is located far from the observer, where the corresponding point in the visual field experiences very small displacement. For intruders approaching the burrow from the opposite side of the observer, which is farther from the observer's location, the approaching path appears only in a small region in the visual field and would have a larger location estimation error in a low-resolution visual field.

Crabs have high visual acuity at elevations close to the horizon and the acuity declines as the elevation of an object decreases (Smolka & Hemmi, 2009). With this property, they can discriminate the positions of intruders at the far side. However, for a visual camera with the same acuity in the entire region, the resolution affects the performance of the target location estimation. Although the above method is effective in most cases, using only the retinal position in a low-resolution image may not be able to provide accurate information of the distance between the target object and home. An omnidirectional camera with shaped mirrors to mimic the visual structure of fiddler crabs might be helpful to adjust the acuity at high elevations.

2.2 Method 2: image size

In the surveillance problem, the image size of an intruder, that is, the apparent size in the visual field is strongly related to its distance from the observer.

A distant object would be smaller in the visual field and a closer object would appear larger. If the actual size of an intruder is given, the apparent size of an intruder can determine the distance of the intruder from the observer. Thus, the distance to the intruder, l_1 can be computed using equation (3), where w represents the size of the intruder. We are interested in the distance between the burrow and an intruder, d, which can also be estimated using equation (3) based on the second cosine law applied to the geometrical relationship shown in Figure 1.

$$l_1 = \frac{w/2}{\tan(s/2)}, \quad d = \sqrt{l_0^2 + l_1^2 - 2l_0 l_1 \cos(\alpha)} \tag{3}$$

where the distance from the observer to the burrow is l_0, which is obtained from the path integration result (Hemmi & Zeil, 2003b), α is the azimuth location of the target in the visual field, and s is the apparent size of a target object (intruder) measured in terms of the view angle.

The distance can be simply estimated from the apparent size, but a critical assumption is that the observer possesses information about the size of the object, w. In an environment where only objects with a size within a certain range are considered, the distance measured based on the image size is reasonable and effective. However, the estimated distance from the image size would have large errors depending on the variance of the target object size and thus, the apparent size cue may not be appropriate to accurately determine the distance. Also, small view angles of the target in the far distance may lead to large errors in the distance estimation. In addition, the image size would only provide the distance between the observer and the intruder, without any information on the approach direction of the intruder. The direction estimation should be obtained using equation (4)

$$x = l_1 \cos(\alpha) - l_0, \quad y = l_1 \sin(\alpha) \tag{4}$$

where the sign of y can be determined from the azimuth angle, α.

The approach direction, θ, can be easily computed as $\theta = \mathrm{atan2}(y, x)$ if the relative position of the object to the burrow is obtained as in Method 1. In equation (4), the relative position, x, can be obtained by using the distance from the target, l_1, the distance to home, l_0, and the azimuth position of the object, α. In addition, since the distance d was already obtained using equation (3), the relative position, y, can be computed using the relation $d = \sqrt{x^2 + y^2}$.

As shown in the previous equations, the approach direction can be obtained using the apparent size and the azimuth angle of an intruder, but the process requires several steps. An alternative to estimate the approach direction is to use the rate of change of the apparent size over time. We will consider this issue in the following analysis.

2.3 Method 3: retinal speed

In this paper, we define the retinal speed as the speed of movement in the retinal space, more exactly, the moving speed of a target object, which is estimated from the retinal map.

For an intruder approaching the burrow, we can divide the moving speed of the intruder into two components: the tangential component, v_t, and the normal direction speed, v_n, with respect to the observer's visual field. A graphical representation of the moving speed components is shown in Figure 3. The normal component, v_n, can also be represented as dl_1/dt and thus, it can be analyzed using the size variation of an object with respect to time, that is, the rate of change of the image size, ds/dt. The change of the apparent size of the intruder, depending on the approach, is strongly related to the normal component of its speed.

The first method we suggest to estimate the distance and approach direction of an intruder is to utilize the retinal speed, v_s, which is composed of $d\alpha/dt$ and ds/dt, where α is the azimuth angle and s is the apparent size of a target object. The normal component, v_n, is related to the rate of change of the image size ds/dt, while the tangential component, v_t, is obtained based on $d\alpha/dt$. The distance to the target from the observer, l_1 is related to the size, s. Here, l_1 is the distance from the eye of the observer crab to the target in three-dimensional (3D) space. We assume that elevation change on undulated ground surface has only a small impact on the normal direction speed, $v_n = dl_1/dt$.

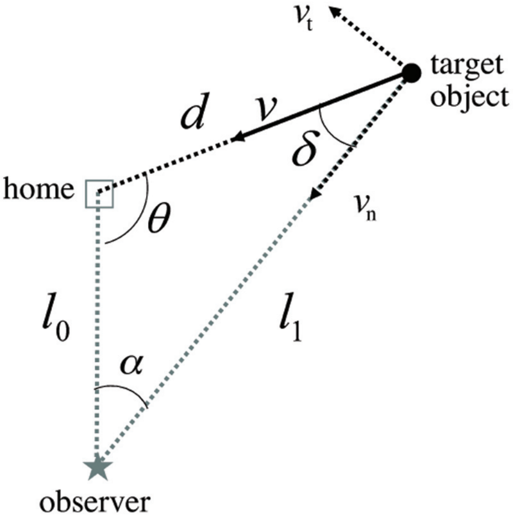


Figure 3. Graphical representation of the speed with tangential and normal components (v_t,v_n).

$$
\begin{aligned}
v_{\mathrm{n}} &= \frac{\mathrm{d}l_1}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{w/2}{\tan(s/2)}\right) = -\frac{w}{4\sin^2(s/2)}\frac{\mathrm{d}s}{\mathrm{d}t} \\
v_{\mathrm{t}} &= l_1\frac{\mathrm{d}\alpha}{\mathrm{d}t} = \frac{w}{2\tan(s/2)}\frac{\mathrm{d}\alpha}{\mathrm{d}t}
\end{aligned}
\tag{5}
$$

Using the normal and tangential components in equation (5), we can define the retinal speed, v_s, (more strictly, target speed) as in equation (6), where v_s combines the target speed in azimuth direction and the looming speed of the target. The looming speed increases as the intruder comes closer to the observer.

$$
\begin{aligned}
v_s &= \sqrt{\left(\frac{\mathrm{d}\alpha}{\mathrm{d}t}\right)^2 + \left(\frac{\mathrm{d}s}{\mathrm{d}t}\right)^2} \\
\delta &= \operatorname{atan2}(v_{\mathrm{t}}, v_{\mathrm{n}}) = \operatorname{atan2}\left(\frac{1}{\tan(s/2)}\frac{\mathrm{d}\alpha}{\mathrm{d}t}, -\frac{1}{2\sin^2(s/2)}\frac{\mathrm{d}s}{\mathrm{d}t}\right)
\end{aligned}
\tag{6}
$$

Since the normal and tangential speed components are related to the actual speed of the object, the angle δ can be obtained based on their ratio. Through the relationship of the approach direction θ, $\alpha + \theta + \delta = 180^\circ$ from the triangle of the burrow for an intruder and the observer (see Figure 3), the speed components allow estimation of the approach direction. In addition, it is assumed the square root of v_{n} and v_{t}, that is, $\sqrt{v_{\mathrm{n}}^2 + v_{\mathrm{t}}^2}$ does not change much throughout the approach. Therefore, we define the retinal speed, v_s, which only depends on the change rate of the azimuth and the size, and can be used as the criterion for the responding point. As the intruder moves, the observer can estimate the angle, δ, of its movement in the visual field using equation (6) and then determine the possible approach direction, θ. Monitoring the movement of the object over time, the observer could determine the responding point efficiently.

In summary, the retinal speed, v_s can be used to determine the responding point for the surveillance. A lookup table of the appropriate retinal speed values (v_s) for each approach angle is prepared for the surveillance behavior and the retinal speed of an intruder is compared with the threshold speed to check if the intruder reaches a distance too close to the burrow.

3 Experimental results

We applied three different parameters in the visual space to estimate the burrow–intruder distance: the retinal position, image size, and retinal speed. Then, these parameters were evaluated considering three criteria: the approaching path, distance errors, and approach direction. A path map was used to show the tracks of target objects approaching the home from various directions. The target objects are continuously monitored in terms of their distance to the home. When the estimated distance is equal to or smaller than a given threshold, the observer should respond by rushing home to protect its home, similar to the crab's behavior. This responding point is marked on the map. Using the response distance, we measured the difference between the response distance and the threshold distance. It was assumed the desired response should follow circular boundary points around the burrow and the observer agent should respond at the same intruder–burrow distance for any approach direction. In the last criterion, the approach direction to the burrow is also measured by the observer. We evaluated how accurately the approach angle of an intruder in the burrow-centric coordinate is measured. The error was calculated using the difference between the measured approach angle and the actual angle. To test the robustness of the methods, the crab's world had an undulated surface, instead of a flat surface, and the crab's size ranged from a maximum of 50% smaller to maximum of 50% larger than the normal size (assumed size). The movement speed also experienced a maximum of ±10% or ±20% change relative to the normal speed. Each approach test had 25 runs to estimate the intruder–burrow distance error as well as the angular error of the approach direction. The averaged errors were calculated by assuming that the angular errors follow *t*-distributions. In the path map, the standard deviation of distance errors are displayed for each approach direction.

For all experiments, we simulated an intruder (target object) to approach a fixed burrow and each method was used to determine the burrow-centric distance and angle. We then compared the advantages and shortcomings of each method.

3.1 Results of method 1 (retinal position)

First, we applied the retinal position in the visual field to localize a target object. This idea was suggested by Hemmi and Zeil (2003b) to explain the surveillance behavior of fiddler crabs. Figures 4 and 5 show the results of distance estimation using the retinal position with only the azimuth and elevation in the visual field. The circle with a solid line in the map indicates the threshold distance, the square at (0,0) in the center of the figure is the home location, and the star at (0,–25) indicates the observer. Approaching lines show the path of an intruder with the responding points marked as black dots.

The results are shown for two cases: a very high-resolution retinal view (Figure 4) and a low-resolution view (Figure 5). We simulate an intruder's moving on a new undulated ground surface for each experiment. The intruder moves with a time course of varying speeds for each run. With the high-resolution retinal

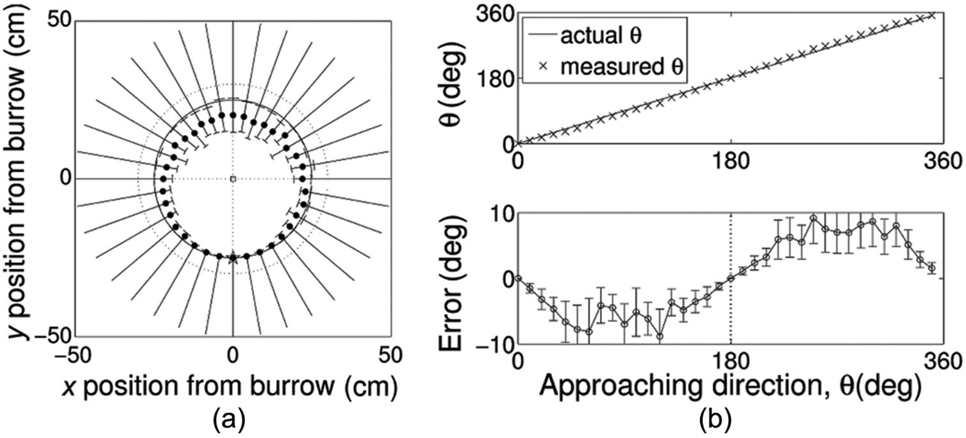


Figure 4. Distance and direction estimation results with the retinal position alone in a high-resolution view: (a) approaching path of the target object along with the responding point and (b) direction estimation results.

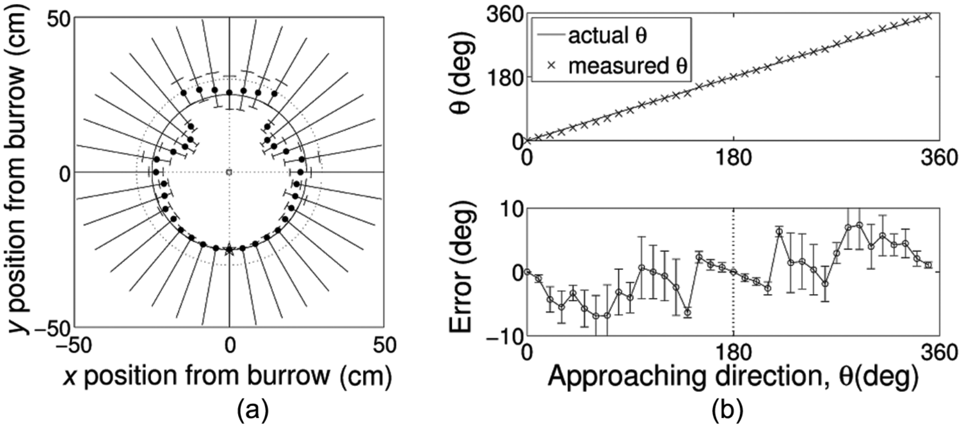


Figure 5. Distance and direction estimation results using the retinal position alone in a low-resolution view: (a) the path of target objects approaching the home at the center (0,0) and the responding point considered to be located at the threshold distance from the home, and (b) the results of the estimation of the approach direction.

view, the observer is able to discriminate objects differing by 0.1° in the view, while in the low-resolution view, the observer is able to discriminate objects only in 1° increments. As expected, Figure 4 shows better estimation of distance and direction. However, the agent may experience some restrictions in the resolution of the visual information. As explained with Figure 2, due to the visual resolution problem, it is difficult for the observer to estimate the distance of intruders approaching from farther points. In Figure 5(a), the graph show the error bars for the distance estimation for each approach direction. While the approaching object path shows the results of distance estimation, the graph in Figure 5(b) shows the performance of the approach direction estimation. When intruders (targets) approach from the upper region, there are distance errors at the responding points, while the distance of targets approaching home from the lower region can be estimated more accurately. The errors in the figure are much larger in the upper region compared to the lower region. Figure 5(b) shows the performance of the direction estimation with a low-resolution retinal image where the direction θ was estimated with relatively small errors in the range of $[-10°, 10°]$.

3.2 Results of method 2 (image size)

Method 2 uses the apparent size of a target object (intruder) to determine the target–burrow distance. The results are shown in Figures 6 and 7 after applying equation (3), and the responding points are displayed. As shown in the results with the retinal position, the responding points also have larger errors in the upper region, but the errors are much smaller than those resulting from Method 1, as can be seen by comparing the error levels in Figures 5(a) and 7(a). It seems that the method using the image size is more effective in a low-resolution visual field than that using the retinal position. Figure 7(b) shows the corresponding direction estimation results, which have different error patterns.

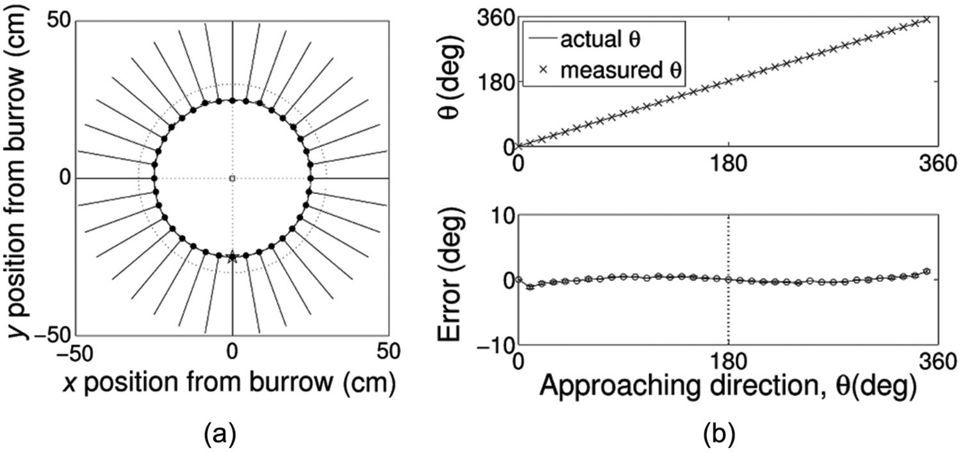


Figure 6. Distance and direction estimation results using the image size alone in a high-resolution view: (a) approaching path with responding points and (b) direction estimation results and the associated error.

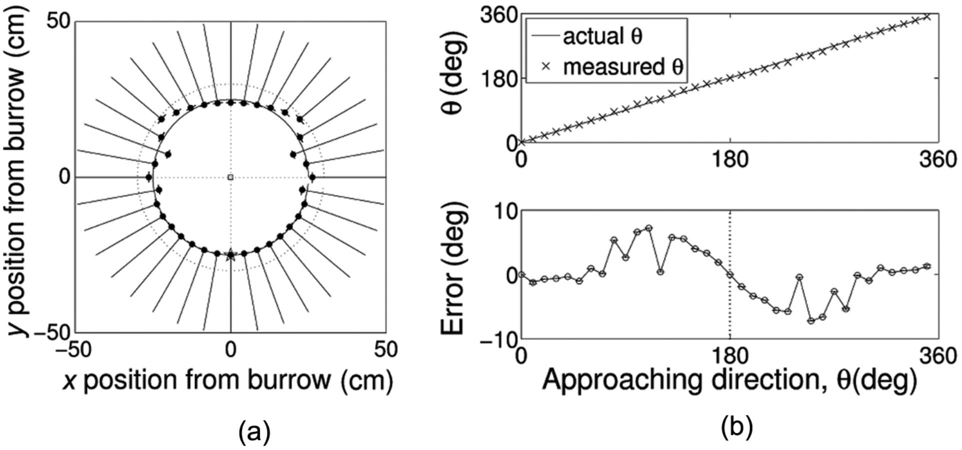


Figure 7. Distance and direction estimation results using the image size in a low-resolution view: (a) the path of target objects approaching home in the center (0,0) and the responding point considered to be located at the threshold distance from the home, and (b) the estimation results of the approach direction.

The approach direction was estimated based on the size information and azimuth position of an object using equations (3) and (4). The experiments with the image size show very low variance of errors. The measure of distance or approach direction with the image size of a target is not influenced by the undulated surface or the movement speed of an intruder.

The size criterion can be severely affected by the difference between the actual size and the estimated (assumed) size of an intruder. The following results show that the difference between the actual and the assumed size influences the approach path map and the error. Figure 8 shows the results of applying the image size method to estimate the distance when there is a gap, ϵ, between the actual size and the assumed size used in the computation of the distance; here, we tested ϵ with 10% difference from the assumed size. Figures 8(a) and (b) show the results where the crab size was $(w + \epsilon)$ and Figures 8(c) and (d) display the results when the crab size was $(w - \epsilon)$, where w is the assumed size of the intruder or object. Both the smaller and larger size tests have the same amount of difference, ϵ, from the assumed size, w. Comparing these results with those shown in Figure 7, the errors increased due to the discrepancy. When the smaller sized target is tested at the same distance, it looks farther away than expected, resulting in closer responding points to the home. On the other hand, the distance was underestimated when the target size was larger than the predicted size and the observer responds to a target at points farther than a given threshold distance, as shown in Figure 8(c). In this case, the approach direction has large errors, and it is affected by the difference between the actual and assumed sizes. The

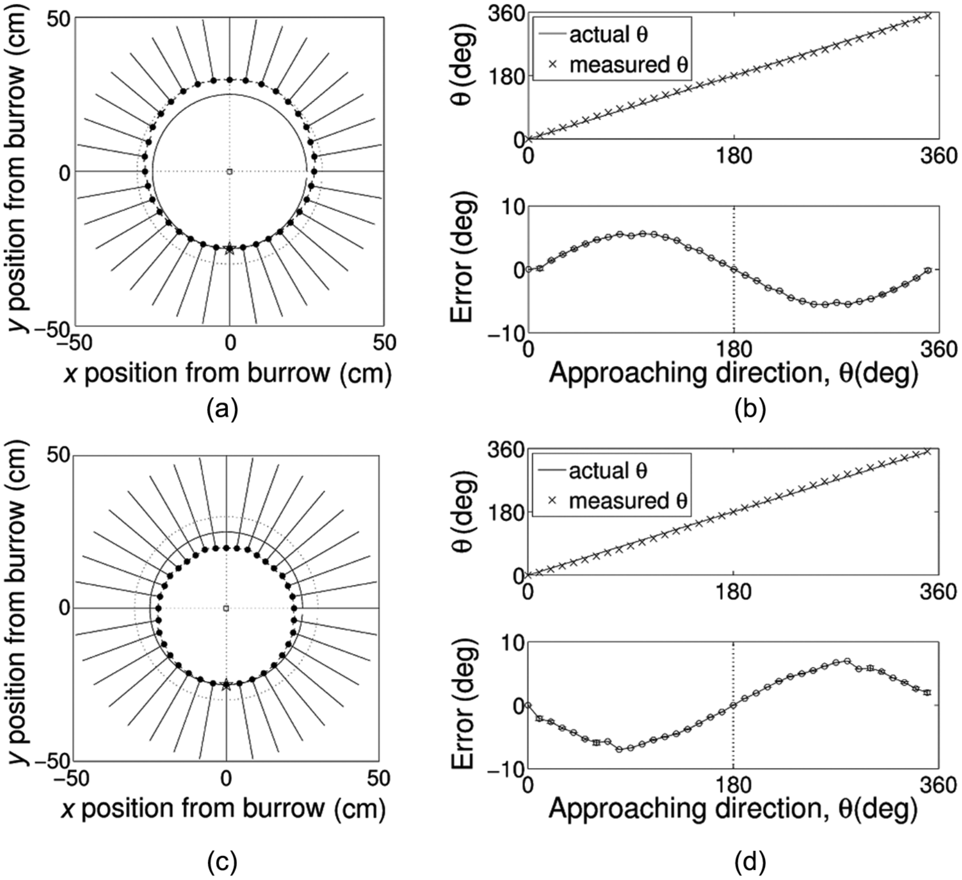


Figure 8. Distance and direction estimation results using the image size with the difference between the actual and assumed size of an object where the actual size of the object was larger, (a) and (b), or smaller, (c) and (d), than the assumed size. For these cases, the (a) and (c) path maps, and (b) and (d) direction estimation results are shown.

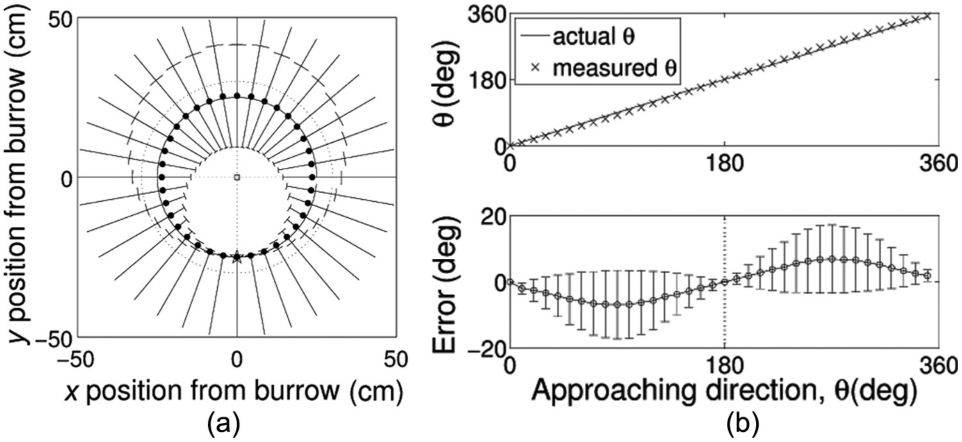
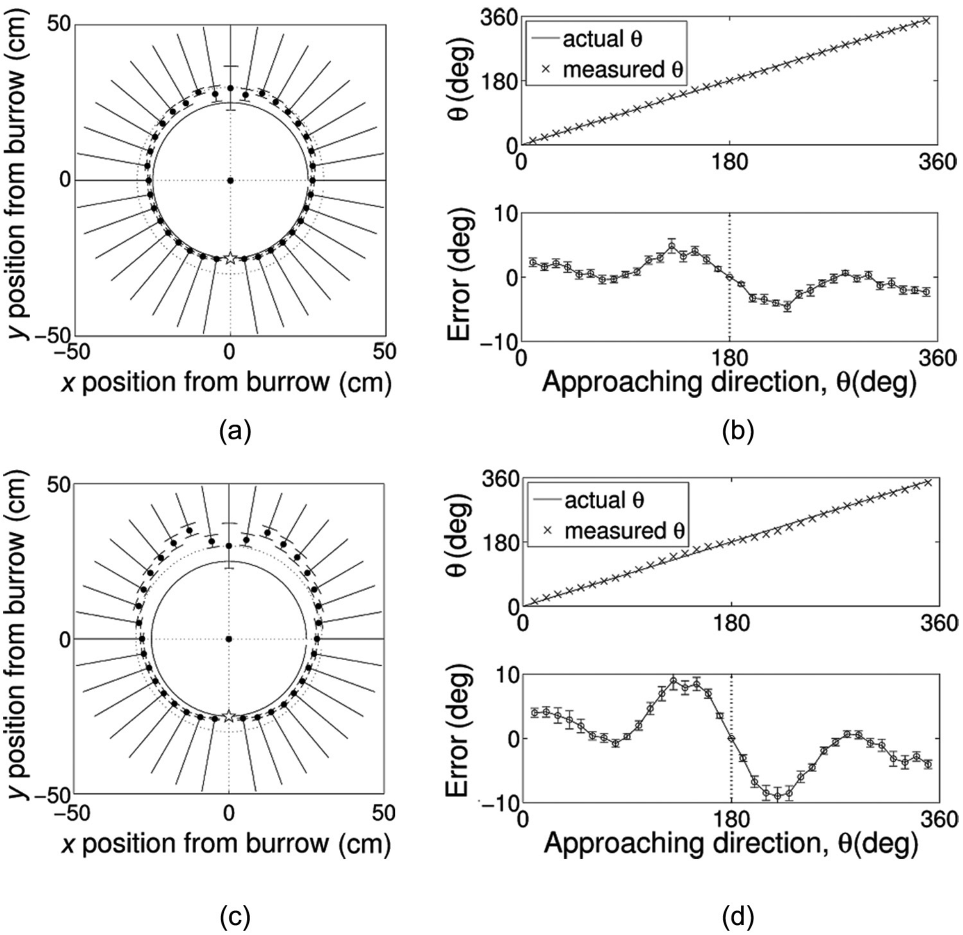


Figure 9. Distance and direction estimation results using the image size variation from −50% to 50%: (a) average approaching path of a target object, and (b) average direction estimation results.

moving direction is often estimated to be close to the actual θ but in some directions, the estimation shows large errors. The above experiments assume only 10% change of crab size, but if the actual size is 50% smaller or 50% larger than the assumed size, the performance becomes significantly worse.

We tested the random variation of crab sizes ranging from −50% to 50% for each approach (see Figure 9). We can observe much variation on the estimation of intruder–burrow distance and approach direction. In the crab's world, the crab size varies in a large range and so the image size may not be a good estimator for



(a) (b)

(c) (d)

Figure 10. Distance and direction estimation results using the retinal speed, v_s with $\pm$ 10% random movement speed of an intruder, (a) and (b), and with $\pm$ 20% random movement speed of an intruder, (c) and (d): (a) average approaching path of a target object, and (b) direction estimation results, (c) average approaching path of a target object, and (d) direction estimation results.

the distance and direction of intruders. Method 1 based on the retinal position had larger errors in detecting objects approaching from farther points to the burrow, while it showed good performance for the other areas. Also its performance is sensitive to the undulated ground surface. Exploiting the size information is an effective method, if the actual size is correctly estimated, which results in high accuracy in terms of both distance and direction estimation but the performance degrades if the actual size of the approaching object is incorrectly estimated. The retinal position method and the image size method experience good or poor performance depending on the approach direction.

3.3 Results of method 3 (retinal speed)

We applied the retinal speed to estimate the distance as described in Method 3. The method using the retinal speed is relatively simple compared to the other methods discussed previously. Earlier, in the method description, we defined a retinal speed: v_s. For the retinal speed, v_s, the estimation is related to the tangential and normal component of the target movement in 3D space. The results are shown in Figure 10. The observer uses the retinal speed and if the speed is greater than a threshold, then the observer rushes back to the burrow. The movement speed of an intruder varies from -20% to 20% in an approach path. It often happens that the retinal speed of the intruder exceeds the threshold even at a far distance, and the underestimated result on the distance can be found in Figure 10. In addition, the retinal speed method is not affected by the error in the assumed size at all. The size component, $w + \epsilon$, is a factor which influences the components v_{n} and v_{t}, but it is eliminated in the equation used to calculate δ and thus it does not affect the result of estimating the approach angle, θ. Since it only considers the rate of change of the size rather than the actual size, as in equation (6), it is not influenced by the difference between the actual and assumed sizes. If the intruder has more variation in the movement speed, for example, larger than 20%, the approach direction as well as the intruder–burrow distance have larger errors in their estimation, and they will follow similar trends to those observed in Figure 10.

In contrast, the retinal position method and the image size method are not affected by the movement speed. Regardless of higher variance of the movement speed, their path maps remain almost unchanged.

We can consider another type of retinal speed, the horizontal (azimuth) and vertical (elevation) position differences. However, for an undulated ground surface, changes of the elevation angle produce very noisy signals, which makes it hard to estimate the distance and direction accurately, unless a filtering process is applied to the signal data.

It seems unlikely that the above retinal speed method would work as a burrow surveillance cue for fiddler crabs, because other crabs do not walk with constant speed and intruder crabs could fool a system using the retinal speed, by slowing down as they approach another crabs' burrow. Instead of using the retinal speed, v_s to check the intrusion of other crabs, another type of measure should be introduced to solve the problem.

We used an undulated ground surface for test environments of the burrow surveillance system, and also tested the variation of intruder sizes and variation of moving speed of intruders. An undulated ground surface influences the elevation angle significantly, and the angular size of an intruder by a small amount. As a result, the performance of the retinal position approach is affected by undulated terrain. In contrast, the image size approach depends on a prior knowledge of the assumed size of intruders. If there is much discrepancy between the actual size and the assumed size of the crabs, it degrades the performance. The target speed v_s greatly depends on the actual speed of movement of intruders, although there is a minor impact from the terrain style or the intruder size, while the retinal position or image size is not affected by the actual speed of intruders.

4 Discussion

A number of distance-estimation methods have been applied in robotic systems but they usually focus on the distance between the target object and the agent itself, rather than considering an important point such as the home. Therefore, the burrow-centric distance and approach direction estimation method at a third location would lead to useful applications in robotic systems. The distance-estimation methods with the burrow-centric view can be useful in such applications as service mobile robots which observe users and respond when the users need help near a specific location like a burrow. The methods were initially inspired by the burrow protecting behavior of fiddler crabs observed in previous research but was approached from an engineering point of view.

In addition, an approach of developing methods in biologically plausible ways could contribute to the modeling of methods applied by animals used to exploit visual information. Based on the results in this paper, animals may use retinal position, speed, or apparent size to estimate the position of a target. Especially in fiddler crabs, an investigation of their viewing range and the sampling resolution across the visual field (Smolka & Hemmi, 2009) shows the possibility of using a retinal position map to estimate the position of a target object. In order to observe the target object in the flat world efficiently and accurately using the retinal position, the visual neurons along the regions of interest play an important role, as demonstrated by the performance results as a function of the resolution of the visual field. In previous research, it was found that the number of receptors varies depending on the region. In particular, the visual space around the horizon possesses a larger number of visual sense receptors than others and the resolving power is large near the horizon (Zeil & Hemmi, 2006). Therefore, based on the high level of performance in object detection demonstrated in these results, the retinal position is the most likely used by fiddler crabs for object detection.

In addition, as mentioned earlier in this paper, the image size is the simplest cue to determine the distance of an object and can easily be used not only by crabs but also by other animals. The retinal speed of the object may be difficult to use for animals living in a complex terrain environment, but it is useful for animals living in a flat environment such as fiddler crabs. Calculating the retinal speed requires more computation than the other methods but if animals have templates stored in the neural network for several cases of target approaches, it could allow successful estimation of the distance of an object.

Further investigations on the behavior of fiddler crabs responding to a target object would help to determine the applicability of the suggested methods. Based on previous work on the behavior of fiddler crabs (Hemmi & Zeil, 2003a), they maintain a closer distance to their burrow than potential intruders. However, the probability of response is lower when the dummy approaches from the opposite side of the burrow. We have shown in this paper that if the observer uses the retinal position information, the accuracy of the estimated position of objects on the opposite side of the burrow becomes lower since the objects are located closer to the horizon in the retinal view.

Experiments on dummy intruders for the surveillance behavior have been performed with varying approaching speeds, and it seems that the speed does not affect the crab's probability of response or its timing (Hemmi & Zeil, 2003a; Hemmi & Zeil, 2003b). If we were to observe the responses of fiddler crabs when the approaching speed of the dummy varies, we could investigate the effect of the actual or retinal speed of the object. Since the speed of the object projected in the retinal view of the crabs would differ with respect to the approach direction of the intruder, experiments on objects from various directions would be needed to yield an appropriate conclusion.

The effect of the size of the dummy intruder on the response distance of burrow surveillance was also investigated in a previous work (Hemmi & Zeil, 2003b). Based on the observations, the researchers concluded that the apparent size of the dummy does not influence the crab's decision for burrow surveillance in terms of when to respond. In fact, fiddler crabs have two different styles of responses for burrow surveillance and predator avoidance. The detection and efficient avoidance strategies of fiddler crabs against predators have been investigated (Hemmi, 2005). In the results, fiddler crabs responded earlier to predators which approached faster. It seems that the angular size and looming affects the timing of predator avoidance responses (Hemmi, 2005). Many birds change apparent size and shape through wingbear or orientation change. It is unlikely that crabs use retinal size or looming at an early stage to detect their predators, but the signals might be helpful to detect walking birds at close vicinity (Smolka et al., 2011). For engineering application, the image size or looming could be an alternative visual cue to estimate the distance of an intruder, if the interested size of the intruder is known in advance.

We assumed that path integration provides high quality distance estimation between the observer and its burrow. However, still there is an error in burrow distance estimation using leg odometry as pointed out by Kim et al. (2010). Possibly fiddler crabs could use landmarks near the burrow to estimate the burrow distance when they move away from the burrow. In that case, the image size of a landmark or looming can effectively determine the burrow distance.

In our experiments, an intruder walks towards the burrow for each angular configuration. We have not tested an arbitrary approach direction of the intruder. We expect the observer to rush back home only when an intruder is within the circular boundary (the same distance) from the burrow. We believe that the methods involving retinal position or image size will be effective for any arbitrary approach movement, since the methods estimate the distance and angular position of the intruder. However, the method with retinal speed might result in a false alarm, when the intruder moves near the observer or it displays a speedy movement even in the wrong direction. For future work, we will test rigorous experiments with varying approach directions and distances to validate the methods mentioned in this paper.

Since there are no conclusive results of how animals determine the location of a target object with respect to their home, the three different cues investigated in this paper may offer additional possibilities for the analysis of fiddler crab behavior. As a result, further work could also focus on implementing the methods in biological perspectives, especially in applying the suggested methods in neural networks efficiently, in order to understand the underlying neural mechanism.

This paper handles surveillance behavior against a single intruder. There has been no report about the surveillance behavior of fiddler crabs against multiple intruders. That style of surveillance would be an interesting issue in engineering problems. Possibly, a visual attention model could be applied to that kind of situation (Santana & Correia, 2010), however, further study is needed in this area.

5 Conclusion

In this paper, we examined methods to estimate the distance from three different perspectives: retinal position, image size, and retinal speed. For each method we showed its characteristics for distance and direction estimation in the burrow-centric coordinates.

The retinal position provides sufficient information to estimate both the distance and direction of a target object to the burrow. However, in a low-resolution visual field, it has difficulties in accurately estimating the objects approaching from farther locations. The image size is less affected by the resolution problem than the retinal position method. However, in order to exploit the image size information effectively, the observer needs to know the actual size of the object. If the actual size and the assumed size of the target object differ, the estimation of the object's position will contain errors. The retinal speed can also be used to predict the distance and direction of an intruder. It is estimated by the target movement speed by considering the azimuth direction and normal direction (rate of change of the size). For this method, storing templates of each approach direction of a target object may be needed to process the estimations. Therefore, if the observer has previously stored information on the approach of the object, the method shows good performance in estimating the position of the object. The templates of approaching objects may require a large amount of memory in order to be applied over a wide range of environments. However, defining the appropriate neural network architecture for the method or suggesting a simple model representing the respective information would reduce the required memory and still maintain the performance level.

In this paper, we tested various methods to estimate an object's position based on the burrow. Each method could be complementarily enhanced by being combined with other methods. The performance of methods combining two visual cues, retinal position and image size, was also investigated (not shown here) in addition to each individual evaluation. The results were improved since the two different methods complemented each other. Combining the position and size information, the observer obtains better results for objects approaching from the other side of the burrow. The method using position with the retinal speed information, v_s, actually exploits the position and size information in the retinal field. As a result, the method can greatly improve the estimation of distance and approach direction. We need to note that the predator avoidance response system of fiddler crabs is affected by elevations, flickering signal and retinal speed (Smolka et al., 2011). Looming speed also influence the predator response (Hemmi, 2005). Possibly crabs could use retinal speed to estimate the distance of predators like terns flying often at an altitude over the ground. Or they might have an alarm signal depending on the target speed, consisting of looming speed and retinal speed. In particular, the visual cue of retinal speed seems be more suitable for the predator response system rather than for the burrow surveillance system.

The above methods could be applied to estimate the exo-centric (inter-object) distance in engineering applications. The surveillance problem of monitoring the intrusion of agents is a common problem. We can tackle the problem with the aid of visual cues such as the retinal position, the image size or the retinal speed.

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References

Brownell, P. (1984). Prey detection by the sand scorpion. *Scientific American*, *251*(6), 86–97.

Cartwright, B., & Collett, T. (1983). Landmark learning in bees. *Journal of Comparative Physiology, A, 151*(4), 521–543.

Hemmi, J. (2005). Predator avoidance in fiddler crabs: 2. The visual cues. *Animal Behaviour, 69*(3), 615–625.

Hemmi, J., & Zeil, J. (2003a). Burrow surveillance in fiddler crabs. I. Description of behaviour. *Journal of Experimental Biology, 206*(22), 3935–3950.

Hemmi, J., & Zeil, J. (2003b). Burrow surveillance in fiddler crabs. II. The sensory cues. *Journal of Experimental Biology, 206*(22), 3951–3961.

Huber, E., & Kortenkamp, D. (2002). Using stereo vision to pursue moving agents with a mobile robot. In: *IEEE international conference on robotics and automation*, vol. 3, pp. 2340–2346. Piscataway, NJ: IEEE Press.

Kim, D. (2006). Neural network mechanism for the orientation behavior of sand scorpions towards prey. *IEEE Transactions on Neural Networks, 17*(4), 1070–1076.

Kim, T., Kim, T., & Choe, J. (2010). Compensation for homing errors by using courtship structures as visual landmarks. *Behavioral Ecology, 21*(4), 836–842.

Land, M., & Layne, J. (1995). The visual control of behaviour in fiddler crabs. *Journal of Comparative Physiology, A, 177*(1), 91–103.

Méndez-Polanco, J., Muñoz Meléndez, A., & Morales, E. (2009). People detection by a mobile robot using stereo vision in dynamic indoor environments. In *MICAI 2009: advances in artificial intelligence*, pp. 349–359. Guanajuato: Springer.

Murray, D., & Little, J. (2000). Using real-time stereo vision for mobile robot navigation. *Autonomous Robots, 8*(2), 161–171.

Santana, P., & Correia, L. (2010). A swarm cognition realization of attention, action selection, and spatial memory. *Adaptive Behavior, 18*(5), 428–447.

Smolka, J., & Hemmi, J. (2009). Topography of vision and behaviour. *Journal of Experimental Biology, 212*, 3522–3532.

Smolka, J., Zeil, J., & Hemmi, J. (2011). Natural visual cues eliciting predator avoidance in fiddler crabs. *Proceedings of the Royal Society of London, Series B, 278*(1724), 3584–3592.

Yu, S.-E., & Kim, D. (2011a). Image-based homing navigation with landmark arrangement matching. *Information Sciences, 181*(16), 3427–3442.

Yu, S.-E., & Kim, D. (2011b). Landmark vectors with quantized distance information for homing navigation. *Adaptive Behavior, 19*(2), 121–141.

Zeil, J. (1998). Homing in fiddler crabs (Uca lactea annulipes and Uca vomeris: Ocypodidae). *Journal of Comparative Physiology, A, 183*(3), 367–377.

Zeil, J., & Hemmi, J. (2006). The visual ecology of fiddler crabs. *Journal of Comparative Physiology, A, 192*(1), 1–25.

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