A *C. elegans* inspired robotic model for pothole detection

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Abstract

Animals navigate complex and variable environments, but often use only limited sensory information. Here we present a simulated robot system using a *C. elegans* inspired sensory model and navigation strategy and demonstrate its ability to successfully identify specific, discretely located cues. We show a range of conditions under which this approach has performance benefits over other search strategies.

1 Introduction

The development of truly autonomous systems is a major driver of Artificial Intelligence. Despite remarkable progress, today's systems tend to be highly task-oriented and struggle to operate appropriately in the presences of variation [8, 9]. Recently, more open-ended embodied approaches to AI have been shown to be highly adaptive and possess behavioral flexibility in a range of conditions [9, 10]. Such approaches are often inspired by living systems, that are inherently embodied and situated. Indeed, evolutionary pressures have led to the emergence of adaptive solutions that are often relatively "simple". The unassuming nematode worm *C. elegans* is a perfect example of this. Using just 302 neurons (including sensory neurons) it exhibits highly streamlined yet rich and effective adaptive behavior [1, 4, 5, 6].

In this paper we consider a potential application for *C. elegans* inspired algorithms, in particular its impressive chemotaxis ability. *C. elegans* chemotaxis inspired robot models have previously been shown to allow robust phototaxis in real world environments [11]. Here we consider the potential of finding discrete objects, using a real world case study of finding road surface damage such as cracks and potholes. While searching for road damage and following chemical gradients are vastly different problems and might therefore appear to require vastly different solutions, we find that an approach inspired by the sensory system of *C. elegans* provides an effective, elegant and robust search algorithm.

The motivation for the choice of road surface damage is due to the major challenge they present for transportation. In the UK alone, deteriorating road conditions are exasperating an existing multi-billion pound backlog of repairs [3]. Autonomous systems which can find surface damage, and potentially even repair them would go a long way in furthering the possibility of self-maintaining cities.

2 Robot model

The *C. elegans*-inspired model was designed to operate in a simple differential wheeled robot with limited sensory capacity. In this case a two-wheeled robot was created and simulated in various 3D environments. The robot possessed a front facing camera that samples every second. The camera detected surface damage with a simple object detection algorithm using contours and color. IR
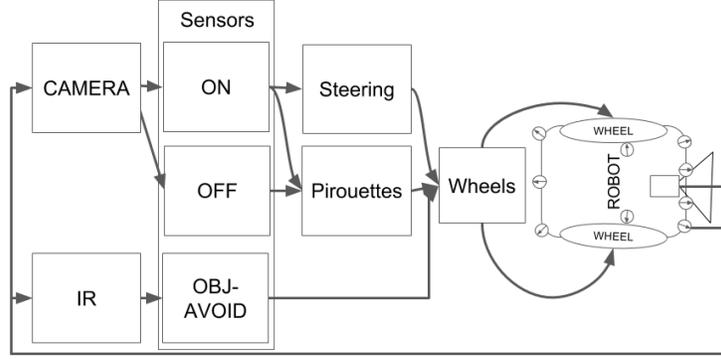
Figure 1: The robot model showing the input and output for one action loop (0.125 seconds). Rather than having handcrafted behaviors, the model leads to emergent motor behaviors.

sensors surrounding the body exclusively controlled object avoidance. The robot had a top speed of 1m/s; however, this was controlled by the sensory neurons and was usually between 0.2-0.4 m/s. All computation takes place in an action loop of 0.125 seconds. A schematic of the complete model can be seen in Figure 1.

2.1 Sensory neurons

In *C. elegans*, the ASE sensory neuron pair [6] plays a key role as a regulator of salt chemotaxis. *C. elegans* follows salt (and other) gradients in search for food [6]. Here, we asked whether ASE-like sensors could be adapted to detect road surface damage such as potholes, and whether the chemotaxis strategy that so excels at gradient navigation could mediate a search for discretely dispersed landmarks. In *C. elegans*, many sensory neurons (including ASE) respond to changes in the intensity of the cue, rather than to its absolute value. Unlike other sensory neuron pairs, the ASE pair responds asymmetrically to sensory cues. The left neuron is an ON-cell which is stimulated by up-steps in salt concentration. In contrast, the right neuron is an OFF-cell which responds to down-steps in salt concentration [15]. The sensory neurons' responses to stimuli $C(t)$ have been modeled here using two components; a fast component F and slow delayed rectifier S

$$\frac{dF}{dt} = -\alpha F + \beta \log C \,,$$

$$\frac{dS}{dt} = \gamma(F - S) \,, \tag{1}$$

yielding a differential signal of $F - S$ [5, 14]. ON and OFF sensor responses are shown in Figure 2.
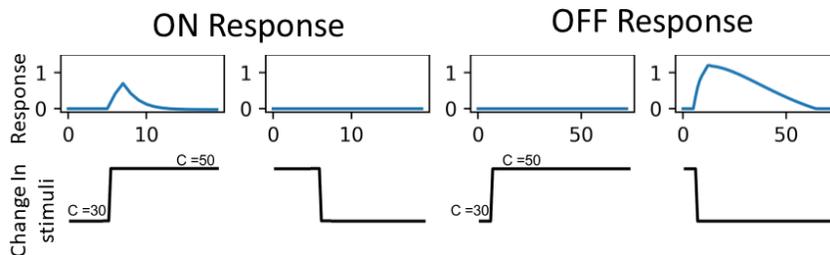
Figure 2: Sensor responses to an up- and down-step of stimulus intensity. Activation rates α, β, γ are $(0.6, 0.8, 0.1\text{Hz})$ for the ON sensor and $(0.3, 0.2, 0.011\text{Hz})$ for the OFF one, respectively. We found that a slow re-polarization of the OFF neuron (as compared to the ON neuron), as reported in *C. elegans* [15] resulted in a significant performance increase.

2.2 Sensor adaptation

Surprisingly, neuronal recordings have shown the depolarization rate of left and right neurons are experience dependent ([7, 12, 14] and personal communication with Gert Jansen). Here we model

this neuronal plasticity as sensitization and desensitization of the OFF and ON polarization rates, respectively

$$\beta_{\text{ON}} = \frac{0.8}{1 + \delta_{\text{ON}}C_{\text{avg}}}, \quad \beta_{\text{OFF}} = 0.2(1 + \delta_{\text{ON}}C_{\text{avg}}),$$

where C_{avg} is the exponential moving average of stimuli exposure [14].

2.3 Motor control

Motor control was achieved by direct modulation of actuators through a minimal set of modulations. For simplicity only the ON neuron modulated the steering strategy (implemented as direct inputs to the two wheels, with opposites signs). Sharp turns mimicked so called pirouettes [13] (or Omega turns) in *C. elegans* controlled by the ON and OFF neurons. As in the biological worm, the stronger the ON activation, the lower the probability of a sharp turn, and the higher the OFF activation, the higher the probability of a sharp turn. Finally object avoidance stimulates movement away from solid objects and sharp drops, reminiscent of object avoidance in *C. elegans*.

Additional strategies emerge as combination of the camera ans IR sensors. For instance when exposed to a sheer pothole, the ON neuron will steer the robot towards it while object avoidance stimulates aversion, leading to an emergent strategy in which the robot circles around the pothole. All observable behaviors are therefore a result of the activity of the three sensory neurons, the body and environmental conditions.

3 Experiments

To test whether the *C. elegans* inspired robot model is capable of detecting discrete cues, we used the webots simulator and tested robot performance on various forms of road surface damage. Firstly in Section 3.1 we compare a number of models in simplified environments of various sizes and various gradient distributions. Secondly in Section 3.2 we undertake an investigation in a more realistic setting, using satellite images to recreate environments containing potholes.
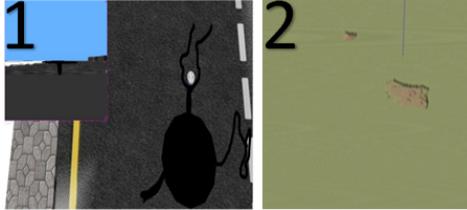
Figure 3: Example of the Webot environments and pothole appearances as well as the robot's vision used in simple simulation in Section 3.1 (panel 1) and realistic simulation 3.2 (panel 2).

3.1 Preliminary experiments in a simple environment

In the first experiment we tested six different models using the same robot in a simple simulated environment shown in Figure 3. These models included our *C. elegans*-inspired model with and without sensory adaptation (Section 2.2), a Braitenberg vehicle (2b [2]) and three random walks, all using IR for object avoidance and the camera to detect potholes.

Nine environments of three sizes and pothole densities were tested. Initially, potholes were represented as black circles (Figure 3). Simulations were run 10 times per environment with a maximum duration of 20 minutes. Here, if a robot finds a pothole it is instantly "repaired" and removed from the environment. The results are summarized in Table 1, showing either the time taken to find all potholes, or the mean % found after 20 minutes, if a robot failed to find all potholes over the 10 runs.

Overall, the adaptive bio-inspired model proved the more effective and in particular performed better than the non-adaptive robot in environments with lower numbers of potholes. In contrast, sensor adaptation seemed to hinder the robot in cases of constant exposure, which led to almost complete

Table 1: Simulation results for six robot types in simple simulated arenas, showing time in (s)econds, (m)inutes for clearing all potholes, or the % found (in grey) if time expires. The three random walk models differed in turn probabilities - uniform with $P_{turn} = 0.5$ per step, or P_{turn} sampled from either Cauchy or Gaussian distributions.

Area	$5m \times 5m$			$10m \times 10m$			$20m \times 20m$		
# Potholes	1	5	25	1	20	100	1	80	400
Braitenberg	4.5m	68%	24%	9.3m	41%	12%	20m	28%	21%
Non-adaptive	42s	1.8m	8.5m	5.5m	88%	79%	12m	34%	25%
Adaptive	33s	48s	6.4m	4.5m	13.3m	74%	10.1m	28%	20%
Cauchy	17.0m	25%	16%	0%	20%	17%	0%	18%	8%
Gaussian	17.3m	16.5m	58%	34%	28%	25%	19.2m	22%	18%
Random walk	14.3m	52%	47%	15.1m	29%	38%	17.4m	23%	28%
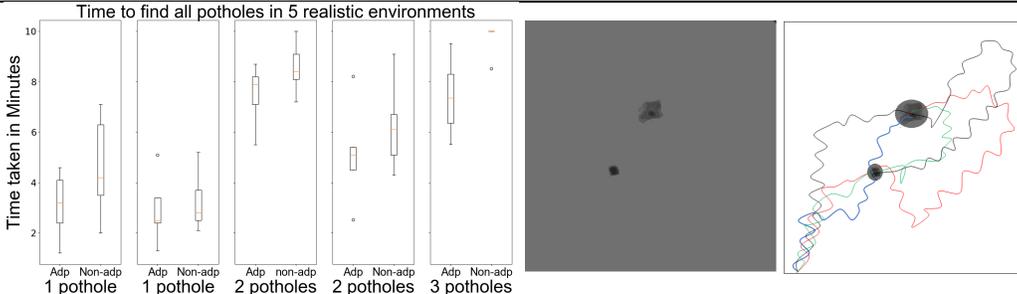
Figure 4: Robots' performance in five different satellite image generated environments. Left: Adaptive and nonadaptive results. Middle: Sample height-map used to generate a 3D environment. Right: sample trajectories of the adaptive *C. elegans* robot in this environment.

desensitization of the ON neuron, drastically suppressing forward locomotion (speed). Secondly oversensitivity of the OFF neuron resulted in larger pirouettes, and pothole avoidance, reminiscent of the emergence of repulsive behavior described in [12].

3.2 Simulation experiments in realistic arenas

Given the strong performance of the adaptive *C. elegans*-inspired model our next step was to investigate it in a more realistic simulation. Here we used satellite images of a major UK city to model and generate virtual pothole formation found in roads (Figure 3). In total we investigated the robots' performance in 5 different environments of 10x10m with between 1-3 potholes in each. Each experiment was conducted 100 times, and lasted until all potholes had been found or 10 minutes had passed. Once again, upon successful detection of a pothole it was instantly "repaired". As shown in Figure 4 the adaptive *C. elegans*-inspired robot demonstrated the best performance. In all cases it was able to find all potholes within the 10 minute limit. The non-adaptive *C. elegans* model also showed good performance in one to two pothole environments, but had limited success with three. The Braitenberg and random walk variations rarely completed the search in time for any environment.

4 Conclusions

In this paper we have briefly outlined our initial investigation into a potential *C. elegans* inspired adaptive sensory computational model. In particular we focused on the application of finding road damage such as potholes. Over two sets of experiments we demonstrated how our approach leads to a highly robust and efficient search algorithm that is achieved with limited sensory capabilities and no prior knowledge of the environments.

4

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