Evolving robust

evolving neural controllers which operate under these conditions, i.e. at timescales faster than that of performance, and whose elements tend to compensate for long term patterns of activation by keeping their average activation as close as possible to a middle range, thus making it difficult for action relevant information to be stored in such individual elements. In order to facilitate understanding of the results and comparative analysis and for other reasons explained below) a simple task of phototaxis is chosen. The next section further discusses the conceptual and practical motivations of this work. Section 3 describes the experimental setup and the neuron model which is a simple extension of a continuous-time network architecture. The results are presented in section 4 which shows that evolved controllers are highly robust to radical sensor perturbations such as exchange of sensor position and removal of one sensor. For every single case studied robots were able to perform the desired task as long as they had at least one sensor in the frontal half of the body. Robustness decreases as the allowed timescale of oscillation is made closer to that of performance. An analysis of the evolved strategy is also presented in this section. It is suggested that fast oscillations are not sufficient for robustness but that long-term homeostatic behaviour of neural activation is also necessary. This claim is supported by evolving a network of fast *non*-homeostatic FitzHugh-Nagumo oscillators which turn out to be much less robust. The final section discusses the implications of these results.

2. Motivations

This is an exploratory piece of work aiming at generating hypotheses. The motivations are conceptual as well as practical.

An animal nervous system is a complex network of relational patterns of electrochemical activity which is coupled with the rest of the organism and its medium through its sensorimotor surfaces. Neural

A large part of current work in understanding central pattern-generating circuits CPGs) is focused on their role in the generation of rhythmic behaviour such as locomotion and respiration ■arder and Bucher, 2001). This is also true in robotics Beer et al., 1992, Fujii et al., 2001, Ijspeert et al., 1998, Williamson, 1998). Rhythmic neural activity not necessarly associated with CPGs) may also be involved in the generation of patterns of behaviour or perception that are non-rhythmic and happen at significantly longer timescales that those of oscillations Rodriguez et al., 2001). This aspect has been less explored but it should be of considerable practical interest in robotics. If a system is synthesized to produce a large scale pattern with a typical timescale which is much longer than the timescale of its micro-components, then certain degree of robustness of performance should be expected, as, by design, no single micro-component can take a large share in the control of the overall system – the faster micro-timescale would not allow this – and so the system must make use of long range synergies that tend to be highly robust. Similar phenomena have been demonstrated in different contexts, Di Paolo, 2001, Thompson, 1996) but apparently has not been applied in robotics so far.

Whether such robustness could also happen in robots is one of the main angles of investigation of this work. For this purpose, a task that is not intrinsically rhythmic has been chosen deliberately. P19Td[delib) angle between sensors is always of 120 degrees 60 degrees each to the body central midline).

Motors can drive the robot backwards and forwards in a 2-D unlimited arena. Robots have a very small mass, so that the motor output is the tangential velocity at the point of the body where the motor is located. The translational movement of the whole robot is calculated using the velocity of its center of mass the vectorial average of the motor velocities), and the rotational movement by calculating the angular speed the difference of the tangential velocities divided by the body diameter). There is no inertial resistance to either form of movement.

Light from point sources impinges on sensors with a local intensity proportional to the source intensity and the inverse square of the distance from sensor to source. The model includes shadows on sensors produced when light is occluded by the body i.e., a sensor angle of acceptance of 180 degrees). Input current from

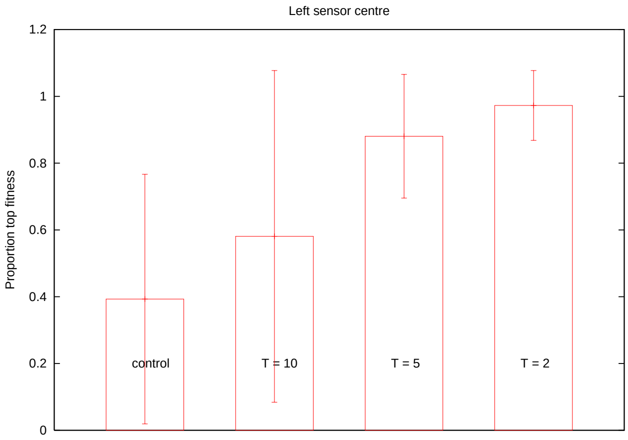
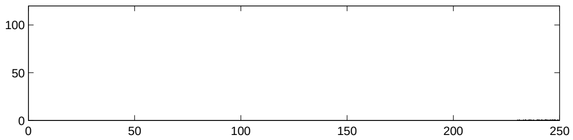


Figure 2: Average relative robustness (measured as proportion of unperturbed


100
50
0
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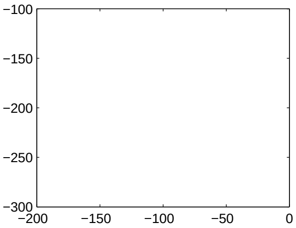
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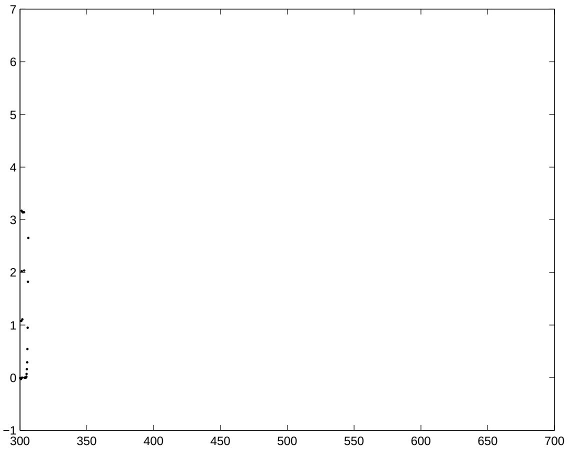
7
6
5
4
3
2
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−1
300
350
400
450
500
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600
650
700

needed to test the usefulness and limitations of this idea and explore its relation to other not-so-distant issues such as plasticity and adaptivity.

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References

Ashby, W. R. (1960). *Design for a Brain: The Origin of Adaptive Behaviour.* London: Chapman and Hall, second edition.

Beer, R. D. (1990). *Intelligence as Adaptive Behavior: An Experiment in Computational Neuroscience.* San Diego: Academic Press.

Beer, R. D. (1995). Computational and dynamical languages for autonomous agents. In Port, R. and van Gelder, T., (Eds.), *Mind as Motion: Explorations in the Dynamics of*