On Bots and Bacteria: Ontology Independent Embodiment

Tom Quick[1], Kerstin Dautenhahn[2], Chrystopher L. Nehaniv[3] and Graham Roberts[1]

[1] Department of Computer Science, University College London, Gower Street, London, UK
{T.Quick, G.Roberts}@cs.ucl.ac.uk
[2] Department of Cybernetics, University of Reading, Whiteknights, Reading, UK
kd@cyber.reading.ac.uk
[3] Interactive Systems Engineering, University of Hertfordshire, Hatfield, UK
c.l.nehaniv@herts.ac.uk

Abstract. A framework for understanding and exploiting embodiment is presented which is not dependent on any specific ontological context. This framework is founded on a new definition of embodiment, based on the relational dynamics that exist between biological organisms and their environments, and inspired by the structural dynamics of the bacterium *Escherichia coli*. Full recognition is given to the role played by physically instantiated bodies, but in such a way that this can be meaningfully abstracted within the constraints implied by the term 'embodiment', and applied in a variety of operational contexts. This is illustrated by ongoing experimental work in which the relational dynamics that exist between *E. coli* and its environment are applied in a variety of software environments, using Cellular Automata (CA) with artificial 'sensory' and 'effector' surfaces, producing qualitatively similar 'chemotactic' behaviours in a variety of operational domains.

1 Introduction

This paper is concerned with the nature of embodiment — it proposes a new and precise definition of the term derived from asking 'what is it that is special about the relationship between bodies and the world?' and then suggesting how the features that are identified can be put to use independently of any specific ontological context. By focusing on the *relationship* between a system and its environment as the basis for embodiment, it is possible to analyse the significance of physical qualities without grounding the analysis *itself* in a material ontology. Material features are significant in so far as they condition the system-environment relationship, but not *just* because they are material.

The definition of embodiment presented yields practical and conceptual benefits. It provides a basis for *quantifying* embodiment, which is significant for behavioural robotics, for example with regard to understanding how to calculate and maximise embodiment, as well as understanding the problems that arise in moving between simulation and actual physical environments (cf. [1]).

The ontological neutrality of the definition also enables inter-disciplinary discussion about embodiment, for example between the behavioural robotics and intelligent software agents communities. It does this by providing a common framework for addressing embodiment — regardless of context — whilst recognising the uniqueness of different forms of embodiment.

On the same basis, it can defuse the tension between Artificial Life (ALife) and embodiment (cf. [2, 3]). From an ALife perspective, embodiment represents a theoretically well-grounded alternative to the tradition of symbol manipulation in AI. However, if *physical* embodiment is a necessary condition for the emergence of at least some life-like behaviour, this bodes ill for the synthesis of such behaviours in non-physical media — a central theme in ALife [4].

2 Embodiment and System - Environment Dynamics

Grounding embodiment in system-environment dynamics fits well with existing bodies of research. Ray's work on *Tierra* illustrates the significance of dynamics in generating the phenomena associated with living systems [5].

Striking examples of analyses of 'real world' embodiment that appeal to dynamical relationships between systems and the environments in which they are observed can be found in, for example, [6, 7], and particularly in Beer's work [8, 9].

Kushmerick [10] illustrates some of the difficulties of adherence to domain specificity in embodiment, which become apparent when trying to apply lessons learnt from the material world to that of the software agent. Without an underlying definition of embodiment, transferral of lessons learnt in the material world can only occur at the level of manifest phenomena, rather than at that of underlying or generative causes.

Franklin comes closest to the spirit of the perspective advocated here, referring to embodiment in terms of "autonomous agents structurally coupled with their environment" [11]. Etzioni [12] adopts a similar stance.

3 Embodiment as Situated Structural Coupling between System and Environment

We define what it is for a system to be embodied as follows:

> *A system **X** is embodied in an environment **E** if perturbatory channels exist between the two. That is, **X** is embodied in **E** if for every time **t** at which both **X** and **E** exist, some subset of **E**'s possible states have the capacity to perturb **X**'s state, and some subset of **X**'s possible states have the capacity to perturb **E**'s state.*

This relational definition draws on Maturana and Varela's influential notion of structural coupling [13, 14]. At once, embodiment becomes quantifiable, ontology independent and directly linked to behaviour.

Degrees of Embodiment. The definition above describes the conditions under which structural coupling is possible. The mere fact that an object is embodied in an environment is insufficient to guarantee that any interesting interaction will occur between the two. It simply affords the possibility of perturbatory interaction.

There is huge scope for variation in this common embodiment relationship across different instances of embodiment, be it as a result of design or natural development.

As the perturbatory relationship between system and environment is quantitatively measurable, embodiment itself becomes measurable — expanding our viewpoint beyond the issue of whether or not a particular system is embodied[1]. One possibility is to ground a metric in the total *complexity* (as rigorously defined in [16], or alternatively [17]) of the dynamical relationship between system and environment, over all possible interactions. Factors such as the total bandwidth of the perturbatory channels between system and environment, as well as the computational power in the dynamics of their interaction, may contribute to this complexity.

Environmentally Coupled Cellular Automata as a Generic Class of Embodiable Dynamical System. Cellular Automata (CA) designed to engage in a mutually perturbatory relationship with some environment are suitable for exploring and exploiting the embodiment relationship articulated above, in that they can participate in the interaction defining such a relationship. Precedent for such a form of CA, in contrast to the more common closed form (cf. [18, 19]) has been set by Varela's *Bittorio* [20] (see also [21] for a demonstration of CA–environment coupling in an evolutionary context).

4 Bots and Bacteria — *E. coli* on the Internet

This section provides context for the definition of embodiment outlined above, by illustrating how *E. coli*'s autonomous and adaptive chemotactic behaviour emerges, for an observer, from the embodiment *relationship* between bacterium and environment. An experimental programme is underway, designed to explore this definition of embodiment by instantiating the equivalent embodiment relationship between a CA-based software system and a variety of ontologically distinct operational environments.

Structural Dynamics in *E. coli*. Despite being far less structurally complex than some multi-cellular organisms, and equipped with only non-directionally sensitive receptors and effectively binary state effectors, *E. coli* exhibits adaptive and consistently sensitive (cf. 'dynamic range,' below) chemotactic behaviour in response to nutrient gradients over five orders of magnitude [22].

The dynamics of two structural processes play key roles in the emergence of *E. coli*'s chemotaxis — highly connected signalling pathways within the cell and spatial clustering of receptors on the surface of the bacterium [23] — operating within and in relation to its physical environment via sensory and effector surfaces (nutrient receptors and flagella, respectively).

The signalling pathway is a CA-like system, comprised of a number of interconnected elements with relatively simple interaction rules between them. Interactions are based on the transfer of phosphoryl groups, the presence of which at flagella motor sites promotes 'tumbling' (random reorientation). Internal processes produce phosphoryl groups, encouraging frequent tumbling. Encounters with chemoattractants inhibit this process, shifting the behavioural bias towards 'running' (smooth swimming). In addition, receptors are constantly methylated, which promotes tumbling, even at higher concentrations of chemoattractants (cf. [22] for more detail).

[1] As suggested in [15] with respect to robots.

Receptor clustering plays a pivotal role in *E. coli*'s dynamic range [23]. This occurs at low attractant concentrations, and has the effect of pooling the output of a group of receptors when one member is activated. At higher concentrations the receptors disperse, providing sensitivity to attractant binding that would be effectively ignored by large clusters.

***E. coli* on the Internet.** A Java program, 'Phenomorph', is under development. Its relationship to Web pages is based on *E. coli*'s relationship to its environment. The purpose is not to achieve optimal information search (cf. [24] [25]), but to investigate, in conjunction with planned future experiments[2], the validity of the concept of embodiment presented above.

At the heart of Phenomorph lies a uniform 1D binary state environmentally coupled CA which generates dynamics roughly analogous to those inherent in *E. coli*'s structure. Receptor clustering and methylation are also simulated, whilst keywords defined by the user at run-time play the part of chemoattractants. When Phenomorph visits a web page containing defined keywords, the CA is proportionately stimulated. The CA global activation level determines the likelihood that Phenomorph will 'run' rather than 'tumble,' each of which are implemented through hyperlink following. See [26] for a more detailed description of Phenomorph.

Initial Evaluation. Although not yet developed sufficiently to produce infotaxis[3], and lacking comparative studies in other operational environments, Phenomorph shows a variety of autonomously generated responses to environmental features, which arise directly from and are determined solely by the interplay between the environment and its CA-based structural dynamics. Environmental variety is constantly filtered by the (very simple) form of Phenomorph's embodiment.

5 Conclusions

The definition of embodiment presented offers immediate opportunities to bridge the interpretative gap between disciplines concerned with very different forms of embodiment, something previously hampered not least by the lack of any firm definition of the term. This understanding of embodiment has the potential to provide benefits to practitioners on both sides of the ontological divide between physical and non-physical systems and environments — from measuring the embodiment of robots to evolving distributed autonomous control systems that exploit emergent behavioural strategies across a range of operational environments. A great deal of experimental work also remains to be done investigating this concept of embodiment across operational environments, and developing possibilities for its exploitation.

[2] These will consist of embodying Phenomorph, via appropriate sensory and effector surfaces, in an abstract parameter space, and a physical environment.

[3] An informatic counterpart of chemotaxis. Phenomorph has yet to attain a level of behavioural 'fitness' that can be compared with that of the acutely honed *E. coli*.

Acknowledgements

This research is funded by an EPRSC studentship.

References

1. Brooks, R.A., Mataric, M.J.: Real robots, real learning problems. In: Connell, J.H., Mahadevan, S. (eds.): Robot Learning. Kluwer (1994) 193-213
2. Prem, E.: Epistemic autonomy in models of living systems. In: Husbands, P., Harvey, I. (eds.): 4th European Conf. Artificial Life. MIT Press, Cambridge, MA (1997) 2-9
3. Dautenhahn, K.: The art of designing socially intelligent agents: science, fiction, and the human in the loop. Applied Art. Int. 12 (1998) 573-617
4. Langton, C.G.: Artificial Life. In: Langton, C.G. (ed.): Artificial Life. SFI Studies in the Sciences of Complexity, Vol. 7. Addison-Wesley, Reading MA (1987) 1-48
5. Ray, T.S.: A network-wide biodiversity reserve for digital organisms. Imagina 96. Institut National De L'audiovisuel, Bry-sur-Marne, France (1996)
6. Pfeifer, R.: Cognition - Perspectives from autonomous agents. Rob. Auton. Sys (1995) 47-70
7. Smithers, T.: On quantitative performance measures of robot behaviour. Rob. Auton. Sys. 15 (1995) 107-134
8. Beer, R.D.: A dynamical systems perspective on agent-environment interaction. Art. Int. 72 (1995) 173-215
9. Chiel, H.J., Beer, R.D.: The brain has a body: adaptive behavior emerges from interactions of nervous system, body and environment. Trends in Neurosciences 20 (1997) 553-556
10. Kushmerick, N.: Software agents and their bodies. Minds & Machines 7 (1997) 227-247
11. Franklin, S.: Autonomous agents as embodied AI. Cybernetics & Sys. 28 (1997) 499-520
12. Etzioni, O.: Intelligence without robots: A reply to Brooks. AI Mag. 14 (1993) 7-13
13. Maturana, H.R., Varela, F.J.: Autopoiesis and Cognition. D. Reidel, Holland (1980)
14. Varela, F.J.: Principles of Biological Autonomy. North Holland, New York (1979)
15. Dautenhahn, K.: Biologically inspired robotic experiments on interaction and dynamic agent-environment couplings. In: Horst-Michael, G. (ed.): Workshop SOAVE'97, Selbstorganization von Adaptivem Verhalten. Llmenau (1997) 14-24
16. Nehaniv, C.L., Rhodes, J.L.: Krohn-Rhodes theory, hierarchies, and evolution. In: Mirkin, B. et al. (eds.): Mathematical Hierarchies and Biology. Amer. Math. Soc. (1997) 29-42
17. Crutchfield, J.P.: The calculi of emergence: Computation, dynamics, and induction. Physica D 75 (1994) 11-54
18. Wolfram, S.: Statistical mechanics of cellular automata. Rev. Mod. Phys. (1983) 601-644
19. Langton, C.: Studying Artificial Life with Cellular Automata. Physica D 22 (1986) 120-149
20. Varela, F.J., et al.: The Embodied Mind. MIT Press, Cambridge, MA (1991)
21. Sims, K.: Interactive evolution of dynamical systems. Varela, F., Bourgine, P. (eds.): 1st European Conf. Artificial Life. MIT Press (1991) 171-178
22. Levin, M.D., Morton-Firth, C.J., et al.: Origins of individual swimming behavior in bacteria. Biophys. J. 74 (1998) 175-181
23. Bray, D., Levin, M.D., Morton-Firth, C.J.: Receptor clustering as a cellular mechanism to control sensitivity. Nature 393 (1998) 85-88
24. Menczer, F. and Belew, R.K.: Adaptive information agents in distributed textual environments. 2nd Int. Conf. on Aut. Agents (1998)
25. Moukas, A.: Amalthaea: Information discovery and filtering using a multiagent evolving ecosystem. Applied Art. Int. 11 (1997) 437-457
26. Quick, T., Dautenhahn, K., Nehaniv, C., and Roberts, G.: The essence of embodiment: A framework for understanding and exploiting structural coupling between system and environment. 3rd Int. Conf. Comp. Anticipatory Syst. Liege, Belgium (1999) To appear