LIVING SYSTEMS' ORGANISATION AND PROCESSES FOR ACHIEVING ADAPTATION

Principles to Borrow from Biology

Dragana Laketic and Gunnar Tufte
Department of Computer and Information Science, Norwegian University of Science and Technology
Sem Saelands vei 7-9, NO-7491 Trondheim, Norway

Keywords: Adaptation, Homeostasis, Endocrine system, Hormones, Cybernetics, Living systems organisation.

Abstract: Man–made systems, just like their biological counterparts, need to operate in a fluctuating environment. Living systems survive despite these fluctuations. Their viability is made possible due to the ability to adapt to environmental fluctuations. Such ability the living systems possess is due to the organisation of these systems and processes performed in response to fluctuation. Therefore, deeper understanding of those aspects of the living systems which make them adaptable may be beneficial for human designers when faced with the demands for the design of adaptive systems. This paper presents current state of our investigation and some interesting postulations about how adaptation process may be sustained until adaptation is achieved in the system under consideration. Further, we discuss some aspects of the living systems' organisation which may offer useful guidelines for adaptive systems design.

1 INTRODUCTION

No environment is static and all systems which are to survive or maintain functionality, must adapt to the changes and fluctuations imposed. From the first autocatalytic cycles which exhibited basic characteristics of life onwards, the living systems have been co-evolving with their environment into more and more complex systems characterised by particular organisation. This organisation has enabled them to survive and further procreate despite incessant environmental changes and fluctuations. The viability of the living systems is therefore due to their organisation which makes it possible for the systems to perform some structural or functional change as a response to environmental fluctuation so as to survive despite this fluctuation.

It is recognised that adaptations result from more than one kind of adaptive processes which take place at different levels. On a larger time–scale, co–evolution of whole populations with their environments has produced living systems which are endowed with inherent mechanisms for performing adaptive processes. At individual level these mechanisms are activated once the fluctuation in environment is detected so that the actual process of adaptation is performed at a much smaller time–scale. This coarse distinction related to the time scale at which the adaptive processes occur, can serve as a basis for further investigations into adaptability.

Adaptations are results of processes happening at different hierarchical levels of the living systems, as has been widely recognised and investigated (Belew and Mitchell, 1996). At the level of the individual genotype, adaptations take place during evolutionary processes or, to be more precise, during co-evolutionary processes with the environment. According to natural selection laws, those individuals which possess such genotypes which develop into the fittest phenotypes within the population environment, will pass their genetic heritage to their offspring with greatest probability. At the phenotypic level, different forms of plasticity are exhibited by various systems, such as learning in neural system or certain behaviours, and they are all made possible thanks to the organism's organisation and accordingly inherent adaptive mechanisms it possesses.

Out of the many facets of inherent mechanisms in the living systems, processes which help organism preserve its internal environment within the state of equilibrium are prominent. This preservation, termed *homeostasis* (Walter, 1967), is vital as it makes physiological processes, the essence of life, to occur at the right point in time and in the right order so that the life

Laketic D. and Tufte G. (2009).
LIVING SYSTEMS' ORGANISATION AND PROCESSES FOR ACHIEVING ADAPTATION - Principles to Borrow from Biology.
In *Proceedings of the International Joint Conference on Computational Intelligence*, pages 254-259
DOI: 10.5220/0002335702540259

is preserved. In keeping internal environment within certain limits, a whole plethora of different processes occur performed by a number of different systems in a human body (Guyton and Hall, 2005). Such processes exhibit remarkable characteristics with respect to the usage of various mechanisms employed at different organisational levels. Not only are these mechanisms intertwined so as to achieve common goal – adaptation, they also do so with the efficient use of resources.

The question naturally posed for a human designer when faced with the task of designing a system to operate in a fluctuating environment, is: what can be learned from living systems and what principles of adaptiveness can be adopted in a man–made system? This question has been asked by many researchers and some of the results of such investigations are genetic algorithms (Koza, 1992; Mitchell, 1999; de Jong, 2006), cybernetics (Wiener, 1948; Ashby, 1957) and, if 'the first notions of adaptation come from biology' (Holland, 1992), then it can be said that any adaptation in any man–made system is biologically inspired.

In this paper, we present the state of the ongoing investigation into adaptation process inspired by preservation of homeostasis and, in particular, endocrine system within homeostatic processes. Some results regarding the adaptation process in a modular system are commented in section 2. Further, directions for possible continuation of the work in this area are discussed and some ideas for experiments are introduced in sections 3 and 4. Finally, section 5 draws a conclusion on the presented material.

2 HOMEOSTATIC PROCESSES AND CONTROL AND COMMUNICATION WITHIN THEM

Preservation of homeostasis occurs thanks to the interplay of several systems within the human body. Within homeostatic processes, the role of communication and control is performed by endocrine system and it can be said that homeostasis, as we know it today, would be impossible without this system. Endocrine system is responsible for secretion of hormones, special substances which play the role of messengers. Hormones transmit information about the change which has occurred in the body's internal or external environment. Hormones are secreted into the bloodstream by special glands and tissues as a response to some stimulus – a signal carrying information about the change. They reach all the cells via bloodstream and yet affect only the cells which possess the matching receptor. The amounts of secreted hormones vary during their lifetime. In general, these amounts are regulated through mechanisms of positive and negative feedback. One of the remarkable characteristics exhibited by hormones, is that the small amounts of these substances can cause reactions, or avalanche of reactions, which can have a huge impact on the organism's physiology and behaviour. In that sense, the hormones exhibit very efficient use of the resources available within the body.

The principles enabling the preservation of homeostasis have been studied by many researchers from a more technical standpoint. In (Ashby, 1960), the achievement of adaptation based on homeostatic principles is related to the achievement of stability. There, the environment is described through a set of parameters and the environmental fluctuations are represented by the change in some of these parameters. The state of the system is described by variables out of which the set of *essential variables* is identified whose preservation within certain limits is equivalent to the preservation of homeostasis. The homeostatic equilibrium within the system is, therefore, characterised by the system finding itself in one of the ultrastable states.

Further, in (Neal and Timmis, 2003) artificial homeostatic system is considered. Within such framework, special attention has been paid to immune and endocrine systems (Vargas et al., 2005; Moioli et al., 2008), their mutual interaction and interaction(s) with nervous system. Endocrine system has been further studied for its many characteristics which are also desirable in man–made systems. Examples come mostly from the field of evolutionary robotics (Paolo, 2003; Suzuki and Ikegami, 2008; Asada et al., 2008; Moioli et al., 2009), but can be found also in self–reconfigurable and swarm robotics (Shen et al., 2002) and multiprocessor systems (Greensted and Tyrrell, 2005).

2.1 System under Investigation – Architecture

In order to examine system adaptation to an environmental fluctuation, a model has been designed to meet the simulation needs of such processes. Here we provide only its basic characteristics to enable easier understanding of the presented results for further discussion while details may be found in (Laketic et al., 2009).

Figure 1 shows a schematic view of the model's architecture. It is modular where the modules – cells are placed in a grid formation. Each cell is assumed

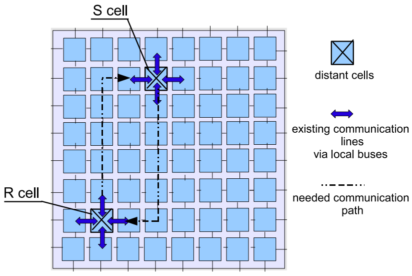

Figure 1: Schematic view of the system's architecture.

to possess a sensor which provides information about the fluctuation in some environmental parameter. In this way, the measure of the fluctuations in the cell's local environment is provided. It is further assumed that each cell communicates via direct lines to its four immediate neighbours to the north, east, south and west. Such assumptions lend the model to the study by the formalism of cellular automata (CA) (Sipper, 1997). Also, each cell possesses a set of tuning parameters which determine its functionality.

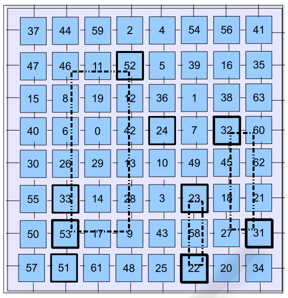

Figure 2: System configuration under simulation and hormone flow loops between functionally related cells

The cell is identified by two kinds of identifiers, similar to (Macias and Durbeck, 2004), one corresponding to its physical placement in the grid and another to its functional relatedness. Figure 2 shows one example of such cell identification. This configuration was used in the experiments for which the results are further presented. The cell marked with i is assumed to receive functional input from the cell $i-1$ and produce functional output for the cell $i+1$.

2.2 System Behaviour and Hormone Flows Sustaining Adaptation

Hormone secretion is initiated dependent on the sensed fluctuation in the environmental parameter under consideration. By the term *hormone* we assume some kind of message which is transmitted around the system architecture because of the sensed environmental fluctuation. The hormone secreted by the cell which senses the fluctuation is further transmitted around the architecture in the manner the signals are transmitted around CA. The cells are changing their state according to the state diagram given in figure 3, details being omitted for the sake of clarity. In this way a hormone can reach all the cells within architecture, as it does so via bloodstream in a living organism. In this case, it is only functionally related cells which will recognise the incoming hormone, functional relatedness, therefore, being analogous to the receptors in their biological counterparts. It is further assumed that adaptation process is conditioned by the presence of the cell's hormone and the hormone coming from its functionally related cell.

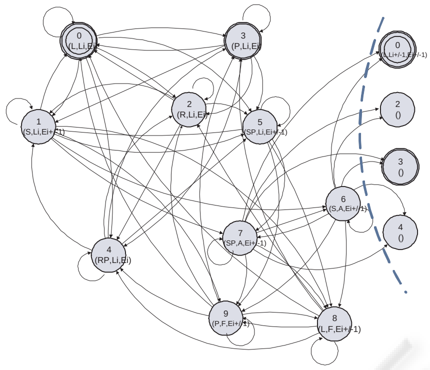

Figure 3: Finite state machine diagram which determines the cell's behaviour.

The state of the system is monitored with respect to the hormone flow, functionality and environmental parameter under consideration. In (Laketic et al., 2009) we have described how hormone secretion is realised in the assumed architecture and investigated the values for the parameters which determine the hormone lifetime so that the presence of hormones is ensured until adaptation is achieved.

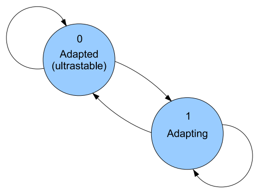

Figure 4: System state machine diagram.

If the states of the system are considered in which it can be while the cells are behaving according to the state diagram presented in figure 3, it can be noticed that the system may find itself in one of the two states – it is either adapting to new environmental conditions or it is adapted to these conditions. The case when the system fails to adapt is disregarded for the reason that parameters which determine amounts of secreted hormones are chosen so that the presence of hormones is secured until adaptation is achieved, as presented in (Laketic et al., 2009). Therefore, the system behaviour can be described by a state diagram as given in figure 4.

When the system is in state 0, i.e. adapted to its environment, all its cells are in either of the two states marked with thicker borders in figure 3. These states correspond to the cell being adapted to its local environment. There, the values of the tuning parameters are such that the cell performs desired functionality under the local environmental condition.

Such view on the system's behaviour draws analogy with the somewhat mechanistic approach to the achievement of adaptation presented in (Ashby, 1960). When the system is in state 0, it is in one of its ultrastable states, while the system state 1 refers to the states through which the cells are passing while performing adaptation process i.e. while rearranging its tunable parameters so as to reach corresponding ultrastable state thereby achieving adaptation.

Further, in (Laketic and Tufte, 2009) it has been shown how formation of hormone flow loops may sustain adaptation processes until system adaptation is achieved. There, the sensed fluctuation in some environmental parameter initiates secretion of hormones whose recognition by functionally related cells further initiates secretion of different types of hormones thereby leading to the formation of the hormone flow loops. Such loops are closed between functionally related cells and, upon it, the adaptation process is initiated. It is sustained by the existing hormone flow loops until adaptation is achieved at the system level.

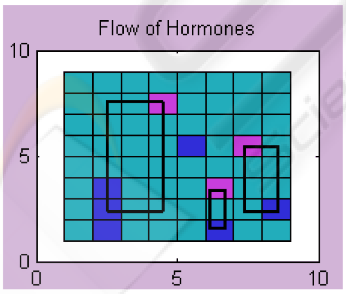

Figure 5: Hormone flow loops which sustained adaptation process until adaptation was achieved

Figure 5 shows the loops of hormone flows which are formed between functionally related cells. The cells which sensed the fluctuation in their local environments were 52, 32, 23 – see figure 2, and the loops were formed between them and their functionally related cells 53, 31, 22 respectively as shown in figure 5. These loops sustained adaptation process until adaptation was achieved.

3 AN AUTONOMOUS AND SELF–REFERRING UNIT OF A LIVING SYSTEM

As said, the adaptiveness of living systems to environmental fluctuations is due to the inherent mechanisms they possess as a result of the co–evolution with the environment. However, a more general question of the organisation of living systems might provide a more general answer so as to offer more useful principles for adaptive systems organisation. Organisation of living systems has become the focus of the study of many researchers. Among the existing theories, those which underline its autonomous and self–referring nature are of particular interest when it comes to addressing properties of adaptable system.

Investigation into the living systems organisation is presented by the theories of the minimal system which can be said to be alive. The model presented in chemoton theory (Ganti et al., 2003) provides the basic principles which define life. Within it, the cyclic nature of the chemical reactions is recognised and quantitatively studied so that the transition to the emergence of life within such system can be distinguished. There, three different subsystems are recognised according to the role they perform within the system model. Similar ideas are presented in the theory of hypercycles (Eigen and Schuster, 1979). Again, the cyclic nature of reactions is prominent and recognised at different hierarchical levels.

The theory presented in the seminal work on *autopoiesis* (Maturana and Varela, 1973) distinguishes itself. The ensuing work pertaining to such *Chilean school of thought* has resulted in the view on the living systems' organisation as an autonomous and self–referring in its self–creation (therefore the term *autopoiesis* – 'self–creating', coined by F. Varela to denote such organisation). These theories offer a framework for studying dynamics of adaptive behaviour and many models have been created to represent autonomous and self–referring nature of the processes taking place within such systems (McMullin, 1997; Hutton, 2002).

It can be further investigated how systems of such organisation adapt to environmental fluctuations. In order to do so, a suitable model for simulations would be advantageous. The field of artificial chemistries, AChem, (Dittrich et al., 2008) offers the tools flexible enough to accommodate for this purpose, particularly when AChem models are applied for the information processing task.

4 DISCUSSION

The results of our investigation into the aspects of the organisation of living systems which provide their adaptiveness to fluctuating environment, have demonstrated how a simplified control and communication principles borrowed from endocrine system in the human body can be used to initiate and sustain adaptation process until adaptation is achieved. The simulations show the adaptation which is in agreement with the theory of preservation of homeostasis as presented in (Ashby, 1960). Moreover, we have postulated that the loops formed by the hormone flows can make up the control part for adaptive mechanisms, as well as realise communication within the assumed system architecture. However, further investigation into the organisation at different hierarchical levels is expected to provides solutions with the improved efficiency of the adaptation process.

4.1 Adding Functionality

Present simulations do not consider which functionality is performed by a single cell or by a system. It has only been assumed that some functionality is performed and that it needs to be maintained despite environmental fluctuations. Enhancement of the present model with some functionality is advantageous for the proof of principle of the existing findings. In this respect, several AChem models have been examined and the current investigation revolves around such simulations.

We begin with enhancing the cell model within the assumed architecture with some kind of metabolism. The metabolism is affected by environmental fluctuations and so is the functionality within the cell. The *healthy metabolism* is defined and the goal of the adaptation process is to keep the metabolism *healthy* despite environmental fluctuations. For the problem at hand, such adaptive system can ensure the achievement of adaptation when the cell metabolism is replaced with the actual cell functionality.

4.2 Hierarchical Organisation

Presently considered model refers only to one hierarchical level i.e. an architecture resembling tissue formed of cells which follow the same rules of behaviour. It is our belief that further examination of the presented control and communication principles for adaptive processes at different hierarchical levels of organisation, may result in findings which can improve efficiency of achieving adaptation. The efficiency may be measured in time needed for the system to achieve adaptation, the resources used to achieve it or the complexity of the stages through which the system achieves adaptation, if such stages can be identified during adaptation process.

In the first place, the formation of the tissue out of the cells of the same type should be considered. Introduction of different sets of rules which guide the cell's behaviour may determine different types of cells and therefore different types of tissues. Further, organs as units with some functionality may be assigned. Secretion of control messengers can then be initiated at a higher hierarchical level. Such models would further allow for the implementation of some of the endocrine system characteristics which present model does not support. Primarily, it refers to a whole avalanche of reactions initiated by small amounts of hormones once they reach the matching receptor.

5 CONCLUSIONS

This paper has presented some considerations regarding the adaptiveness in biological systems and how the underlying principles of this property of living systems could be used for the design of adaptive man–made systems. Our investigation has tackled the principles of homeostatic processes for the achievement of adaptation within the assumed modular architecture. In particular, endocrine system control and communication role has been used to guide and sustain the simulated adaptation process.

In the discussion section, some ideas have been presented on what directions our future investigation may take. On one side, further development of the model for simulations is considered with respect to adding the functionality to the simulated system. Such enhanced model is planned to serve for proving the principle of the proposed adaptive technique. On the other hand, hierarchical organisation of the living systems need be further investigated for increasing the efficiency of adaptation process.

Lastly, let us mention the challenge which remains for the time beyond the completion of the investigation – to design a unit in some technology which would exhibit properties of the cell considered in our simulations and with it lend itself to the construction of an adaptive system based on the investigated adaptive principles borrowed from living systems. Silicon? Microfluids? Or, ...?

REFERENCES

Asada, M., Hallam, J. C. T., Meyer, J.-A., and Tani, J., editors (2008). *Extended Homeostatic Adaptation: Improving the Link between Internal and Behavioural Stability*, Lecture Notes in Computer Science. Springer.

Ashby, W. R. (1957). *An Introduction to Cybernetics*. Chapman & Hall Ltd.

Ashby, W. R. (1960). *Design for a Brain, the origin of adaptive behaviour*. Chapman & Hall Ltd.

Belew, R. K. and Mitchell, M. (1996). *Adaptive Individuals in Evolving Populations: Models and Algorithms*. Addison-Wesley Publishing Company, Inc.

de Jong, K. (2006). *Evolutionary Computation, a Unified Approach*. The MIT Press.

Dittrich, P., Ziegler, J., and Banzhaf, W. (2008). Artificial chemistries – a review. In *Artificial Life*, pages 225–275. Massachusetts Institute of Technology.

Eigen, M. and Schuster, P. (1979). *The Hypercycle, a Principle of Natural Self-Organisation*. Springer-Verlag.

Ganti, T., (contributor), J. G., and (contributor), E. S. (2003). *The Principles of Life*. Oxford University Press.

Greensted, A. J. and Tyrrell, A. M. (2005). Implementation results for a fault-tolerant multicellular architecture inspired by endocrine communication. In *NASA/DoD Conference on Evolvable Hardware, Proceedings*.

Guyton, A. and Hall, J. (2005). *Textbook of Medical Physiology*. Elsevier Saunders.

Holland, J. H. (1992). *Adaptation in Natural and Artificial Systems*. The MIT Press.

Hutton, T. (2002). Evolvable self–replicating molecules in an artificial chemistry. In *Artificial Life*, pages 341–356.

Koza, J. R. (1992). *Genetic Programming: On the Programming of Computers by Means of Natural Selection*. MIT Press.

Laketic, D. and Tufte, G. (2009). Adaptation in tissue sustained by hormonal loops. In *10th European Conference on Artificial Life*. submitted.

Laketic, D., Tufte, G., and Haddow, P. (2009). Stochastic adaptation to environmental changes supported by endocrine system principles. In *NASA/ESA Adaptive Hardware and Systems, AHS 2009, accepted*.

Macias, N. and Durbeck, L. (2004). Adaptive methods for growing electronic circuits on an imperfect synthetic matrix. In *Bio Systems*, pages 173–204. Elsevier.

Maturana, H. and Varela, F. (1973). *Autopoiesis and Cognition: the Realization of the Living*. Dordecht: D. Reidel Publishing Co.

McMullin, B. (1997). Computational autopoiesis: The original algorithm. In *Working Paper Number:97-01-001*.

Mitchell, M. (1999). *An Introduction to Genetic Algorithms*. The MIT Press.

Moioli, R., Vargas, P., Von Zuben, F., and Husbands, P. (2008). Towards the evolution of an artificial homeostatic system. In *IEEE Congress on Evolutionary Computation 2008, Proceedings*, pages 4023–4030.

Moioli, R. C., Vargas, P. A., and Husbands, P. (2009). A multiple hormone approach to the homeostatic control of conflicting behaviours in an autonomous mobile robot. In *2009 IEEE Congress on Evolutionary Computation, Proceedings*, pages 47–54.

Neal, M. and Timmis, J. (2003). Timidity: A useful emotional mechanism for robot control? In *Informatica – special issue on perception and emotion based control*, pages 197–204. The Slovene Society Informatika, Ljubljana, Slovenia.

Paolo, E. A. D. (2003). Organismically-inspired robotics: Homeostatic adaptation and natural teleology beyond the closed sensorimotor loop. In *Dynamical systems approach to embodiment and sociality. Adelaide, Australia: Advanced Knowledge International 2003*, pages 19–42.

Shen, W. M., Salemi, B., and Will, P. (2002). Hormone-inspired adaptive communication and distributed control for conro self-reconfigurable robots. In *IEEE Transactions on Robotics and Automation*, pages 700–712.

Sipper, M. (1997). *Evolution of Parallel Cellular Machines, The Cellular Programming Approach*. Springer.

Suzuki, K. and Ikegami, T. (2008). Homeodynamics in the game of life. In *Artificial Life XI: Proceedings of the Eleventh International Conference on the Simulation and Synthesis of Living Systems*, pages 600–607. MIT Press, Cambridge, MA.

Vargas, P., Moioli, R., Castro, L. N., Timmis, J., Neal, M., and Zuben, F. J. V. (2005). Artificial homeostatic system: A novel approach. In *European Conference in Artificial Life, Lecture Notes in Artificial Intelligence*, pages 754–764. Springer-Verlag Berlin Heidelberg.

Walter, C. B. (1967). *Wisdom of The Body*. W.W.Norton and Company, Inc, Copyright 1932.

Wiener, N. (1948). *Cybernetics or Control and Communication in the Animal and the Machine*. The Technology Press, Cambridge, Mass., John Wiley and Sons Inc.