ACHIEVING ROBUSTNESS IN ADAPTIVE SYSTEMS
Can Hierarchies Help?

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Abstract: In this paper we present the latest research directions within the investigation of adaptive autonomous systems. Originally inspired by biological solutions for performing adaptive processes, we have engaged into investigating organisation of living systems with the aim of extracting useful principles for man–made systems. The work so far has demonstrated in simulation how principles of endocrine system can be used for the initiation and support of adaptive processes until the adaptation to new environmental fluctuation is achieved. Our current research considers robustness of the system and sets the stage for the investigation into hierarchical organisation of such a system. The main question we ask is if the robustness of the proposed system could be improved if hierarchies in its architecture and (or) functional operation are taken into account.

1 INTRODUCTION

The motivation behind the work presented herein lies in one of the greatest challenges today's electronic systems face when set to operate within the harsh varying environments. On one hand, the system needs to adapt to variations in the environment so that it preserves desired functionality; on the other, harsh environments impose additional requirements which, when summed up, come to the necessity for robust operation. Different techniques exist for achieving robustness in such systems (see (Laketic and Haddow, 2007) for the example of extreme temperature environments). However, achievement of the robust adaptive process presents an additional challenge when adaptive systems are considered. Moreover, operations within harsh environments as a rule exclude human intervention so that the system is to operate and adapt in autonomous fashion.

Living systems are faced with similar demands – they need to survive despite the varying environment. Therefore, our investigation into autonomous adaptive systems has lead us to taking a closer look into the mechanisms and principles through which adaptation is achieved in these systems. In particular, we have considered the processes through which a living system preserves its homeostasis. The focus has been set on endocrine system and its role within homeostatic processes for performing control and communication. Through simulations on a simple model, we have demonstrated how adaptation to a fluctuation in some environmental parameter is achieved when initiated and sustained by hormonal flows.

The aim of this paper is to present our current activities and considerations which are focused on the living systems' organisation, in particular its hierarchical organisation and the impact the hierarchies may have on the system's adaptability and robustness. In the further text, we first present some background, section 2, and introduce the reader to the previous work, section 3, through the introduction of the model of the system under investigation and brief summary of the results achieved so far. There, we also introduce novel features of such model with the aim of establishing more formal framework for tackling the robustness issue. Also, we draw a parallel between the organisation of a living system unit and the cell within our modular system. This all offers firmer grounds for the introduction of hierarchical organisation as is discussed in section 4. Finally, we conclude the paper with the discussion on the results achieved and consideration of the work that lies ahead.

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2 PRINCIPLES TO BORROW FROM LIVING SYSTEMS: SETTING THE STAGE

Living systems' viability is the result of their adaptability. This remarkable ability is the result of a long term process of evolution. More precisely, it is through a process of coevolution with the environment that living systems have been created. As no environment is static so the coevolutionary process needed to account for these environmental variations and equip the living systems with mechanisms to aid them in surviving despite varying environment. These mechanisms are activated when variation in the environment is detected or sensed, the term better suited for a living system.

But firstly, the distinction between different terms need be explained which are used throughout the text to denote environmental variations. These distinctions are primarily made based on the temporal duration of the variation. The long–term variations will be referred to as *changes*. Their effect is imposed over a longer period on a scale measured from one individual's lifetime. Therefore, effects of such variations are noticable at the population level and are tackled by evolutionary processes. The short–term variations, i.e. those whose effect happens at the time scale much shorter than individual's lifetime, will be referred to as *disturbances*.

Secondly, we need to explain the view of living systems from the framework of the general system theory (von Bertalanffy, 1973). Within such a framework, living systems are viewed as open systems which are in stable or steady state, a consequence of this being preservation of homeostasis (Ganti, 2003; Walter, 1967). Therefore, disturbance is any variation in environment which momentarily moves the system from its steady state. Further, we recognise that some disturbances will lead the system to such states from which they can re–gain the steady state after having performed some adaptive process(es) (short–term in comparison with coevolutionary processes), while some of the disturbances will take the system to the states from which they will not be able to recover their stability (steady state) i.e. where they will lose their viability and die.

The first group of disturbances we term *fluctuations* and our previous work (Laketic et al., 2009; Laketic and Tufte, 2009a; Laketic and Tufte, 2009b) has considered mainly this kind of environmental variations. Our current work considers the system's ability to escape from the states where no return to a steady state is possible. This ability is considered to be *robustness* of the system. To sum up, we say that a system is robust if it can return to its steady state after it has been moved from it by some environmental disturbance. Out of many ways in which robustness can be improved, we are, in particular, posing a question if hierarchical organisation of an adaptive system could enhance the degree of the system's robustness and, if so, how.

3 MODEL OF THE SYSTEM UNDER INVESTIGATION

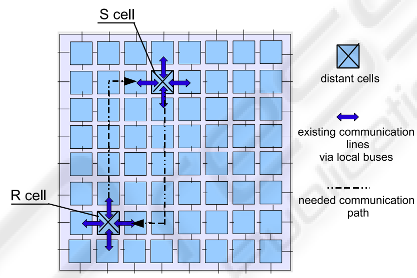

Figure 1: Schematic view of the system's architecture.

In order to examine adaptive processes in a man–made system, we have made a model of such a system as a basis for simulations. It is schematically depicted in figure 1. Detailed introduction of the model can be found in (Laketic et al., 2009), while at this place we only briefly number its fundamental properties: the system is *modular* and consists of a number of cells (modules), the cells are placed in a *grid* formation, the cells are identified by *two types of identifiers* (*physical ID* referring to the cell's position witin the grid and *encoding ID* referring to the cell's functional relatedness with other cells). The system's functionality is dependent on the functionality of its cells.

3.1 The System's Cell

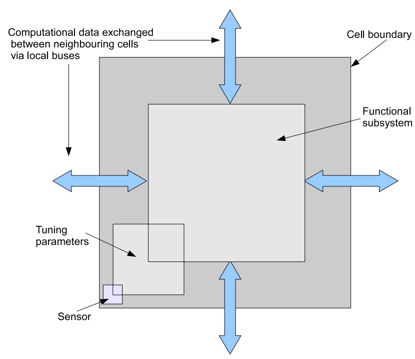

Figure 2: Schematic view of the cell's subsystems.

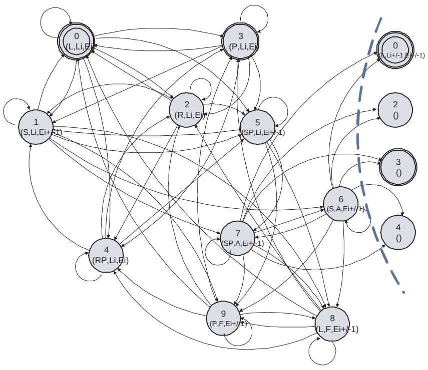

Figure 3: Finite state machine describing the cell's behaviour.

In modelling the system's cell, several theories have been considered which present the living system organisation (Ganti et al., 2003; Maturana and Varela, 1973; Eigen and Schuster, 1979). Their, perhaps greatest, commonality lies in underlying cyclic nature of this organisation and, as nicely put in (Ganti, 2003), that living is *happening* rather than *being*. Ganti's *chemoton theory* was chosen for further work (Ganti et al., 2003), in which a model of a minimal living system is presented. Such choice was motivated by the theoretical rigour with which the theory is presented as well as for its clarity.

In short, according to this theory, living system consists of three subsystems: one corresponds to metabolic network, the second carries information for template polymerisation and the third one is a membrane which divides the living system from its surroundings. Conceptually, we also recognise three subsystems within the cell of our modular system model. The functional part of the cell i.e. the subsystem within the cell which is performing some functionality, corresponds to the information carrying subsystem. The tuning parameters which determine operation of the functional part correspond to the metabolic network. These parameters' values are being adjusted during the adaptation process so that the functionality they influence is preserved.

It can be argued if the analogy is righteous because in living systems these subsystems can be altered through evolutionary variations while in our system it corresponds to the case when it is altered by some adaptive processes which occur at a smaller time scale, as distinguished in section 2. However, at this stage we leave it as simple as that and recognise that such choice leaves the room for further work to include evolutionary processes as well into the subset of processes which can alter the cell's tuning parameters.

Further, as explained in chemoton theory, these subsystems within the living system are stoichiometrically coupled. In our model this coupling is realised through the functionality being dependent on the tuning parameters value. In a real electronic system, for example, this coupling would be realised through functional interdependency of various electrical values involved.

Let us take a brief look into the cell's behaviour. The cell's state is represented as a 3-tuple (H,A,E), the first value, H, referring to the hormonal flows, the second, A, to the cell's functionality and the third, E, to the value of some environmental parameter considered for the description of fluctuation in the cell's environment. Their possible values are, respectively:

- H, presence or absence of hormones: L - no hormone present, S - sending *S hormone* (the hormone secreted in response to the sensed environmental fluctuation), R - sending *R hormone* (the hormone secreted by the cell when it recognises that the incoming S hormone comes from its functionally related cell), P - passing hormone not functionally related to the cell, SP - both S and P, PR - both P and R;
- A, functionality the cell performs: L0, L1, L2, L3 or L4 - functionality adapted to E0, E1, E2, E3 and E4 respectively, A - adapting or F - failed to adapt;
- E, the cell's local environment: E0, E1, E2, E3 and E4 - five different values of the environmental parameter under consideration.

Now, let us take a closer look into the cell's behaviour with respect to hormonal secretion. Seen through the formalism of cellular automata, our system represents a uniform cellular automata which means that all the cells are behaving according to the same finite state machine, as given in figure 3. Control variables for state transitions are following: the change in the environmental parameter (EE), the cell's *S hormone* present (SM), the cell's *R hormone* present (RM), hormones from functionally unrelated cells present (HO), the incoming S hormone recognised (RR), the incoming R hormone recognised (FB). They have been omitted from the figure for the sake of clarity. The states referring to cases when the cell's functionality is corresponding to the value of its environmental parameter are considered stable states. In figure 3, these are the states 0 and 3. When the cell is in one of these two states, it is in a stable state. When the adaptation is achieved, the cell moves to another stable state which corresponds to the new value of the environmental parameter (in figure 3 it is the states 0 and 3 in the region to the right from the dotted line, see (Laketic et al., 2009) for detailed description). Thus, our system preserves its homeostasis by achieving (ultra)stability, which is in accordance with the seminal work of W.R. Ashby (Ashby, 1960).

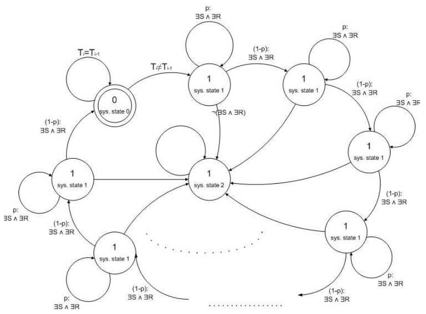

Figure 4: Cell's functional states during adaptation process.

The information sent by the cell to its neighbours, as dependent on the states, is as following, see figure 4: **'0'** when in adapted states and not sending S hormone (states 0,2,3 and 4), **'1'** when secreting S hormone (1,5,6 and 7), **-1** when failed to adapt (8,9).

Such functionality is included into the model for the sake of simplicity and clarity when analysing adaptive processes.

3.2 System's Behaviour

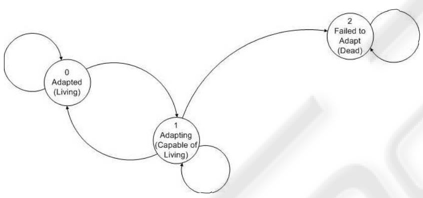

Figure 5: Finite state machine describing the system's behaviour.

The state of the system is dependent on the states of its cells. We distinguish the following three states in which the system can be:

- Stable, when all the cells are in one of the adapted, stable states
- Adapting, when at least one of the cells is performing adaptation process
- Failed to adapt, when at least one of the cells has failed to adapt to environmental fluctuation

We can relate these system states to the levels of life as distinguished by Ganti in (Ganti, 2003; Ganti et al., 2003). The stable state (state 0) would correspond to the living system in the state *living*; the state *adapting* to the state *capable of living*; finally, the state *failed* to the state *dead*. It can be noticed that while living systems are possible to move from the state *living* to the state *dead*, in our state diagram such transition is not made possible, see figure 5. This has been made so on purpose with the aim of keeping the attention only on adaptive processes and the ability of the system to adapt. In our case, such transition would, namely, correspond to the case when the system's functionality deteriorates due to some other cause, not the environmental fluctuation.

3.3 A Glimpse to Previous Findings

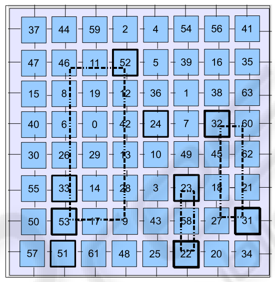

Figure 6: Encoding IDs and hormonal loops between functionally related cells.

As mentioned, our investigation so far has considered autonomous adaptation to environmental fluctuations, as introduced in section 2. We have examined the possibility for the achievement of adaptation by the assumed system and several aspects of such adaptation processes. In particular, in (Laketic et al., 2009) it has been shown how adaptation process inspired by human hormonal control and communication can initiate and sustain adaptation process until adaptation is achieved. There, we have also considered optimal amounts of hormones needed for the achievement of adaptation under stochastic adaptation process. This has been subject of particular interest because these amounts are related to the use of the system's resources, a requirement for the efficient use of resources being one of the ever–lasting challenges in man–made systems. Further, in (Laketic and Tufte, 2009a) it has been pointed that adaptation may be viewed as a result of a particular pattern formation within the system's tissue, see figures 6 and 7. These patterns which arise upon the environmental fluctuation are due to the formation of hormonal loops and are dependent on the functional interdependency between the system's cells. Also, further research directions have been addressed in (Laketic and Tufte, 2009b) for which the considerations presented at this place represent a continuation of reasoning.

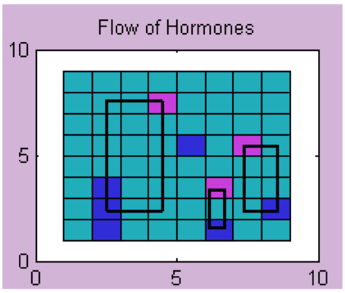

Figure 7: Hormonal loops during simulation runs.

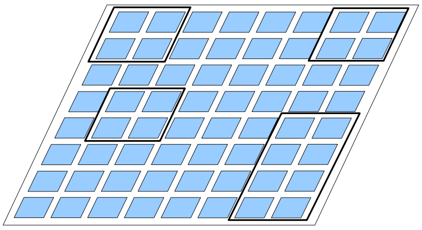

Figure 8: Schematic view of hierarchical architecture based on the underlying structure.

4 INTRODUCING HIERARCHIES

Complex adaptive systems coming from nature are characterized by hierarchical organization. Such organization gives rise to novel properties and processes to occur at a higher hierarchical level. In biology, hierarchical structure is believed to be essential for the correct and efficient functioning of natural systems. Hierarchical structure has been adopted in man–made systems as well. Therefore, we would like to further develop our model so as to incorporate different hierarchical levels. However, this does not appear to be a trivial task. Several possible hierarchical architectures have been considered based on the criteria for defining a hierarchy.

One possibility is shown in figure 8 where higher structural level is defined based on the position of the cells within the architecture. Cells close to each other form *organ* which is assumed to perform some functionality based on the functionality of the cells pertaining to it. Although such introduction of hierarchies may seem somewhat trivial, it bears with it possibilities for further improvement of adaptation process: the role of sensing the environmental fluctuation may be assigned to the organ instead of being performed by the cell; local control of adaptation process may be performed by the organ; the number of the cells pertaining to the organ may vary as the adaptation process proceeds i.e. organ can grow and shrink.

Further considerations with respect to this system's robustness may be addressed. Inclusion of the information on the current state of adaptation process into the dynamic formation of organs may increase the system's ability to avoid the *dead* state (state 2 in figure 5) i.e. increase its robustness according to our definition. Moreover, the local control within the organ may ensure that adaptation is achieved at the region which is critically affected by the environmental fluctuation before this fluctuation takes effect on the functionality of the system as a whole thereby preventing it from loosing its functionality.

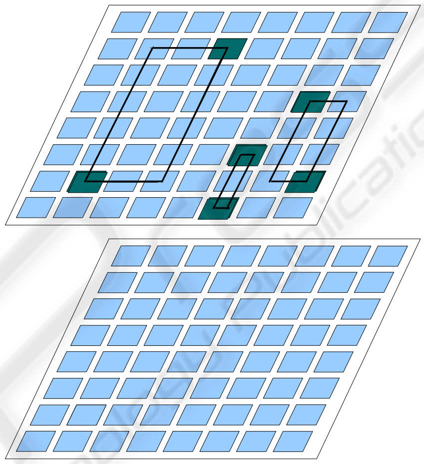

Figure 9: Schematic view of hierarchical architecture based on the hormonal loops which arise upon the detection of environmental fluctuation.

However, our results have also opened new way of thinking with respect to the introduction of hierarchies see (Laketic and Tufte, 2009a). Let us assume that higher hierarchical levels become 'visible' only after the fluctuation is detected. In figure 9, this idea is schematically represented for the hormonal loops which arise between functionally related cells. If they, or similar formations, are considered higher hierarchical level, then further question would be what novel information they would contain. How would this novel information affect system robustness?

5 DISCUSSION AND FURTHER WORK

Autonomous adaptive systems which achieve stability through processes analogous to the homeostatic processes within the human body, show certain degree of robustness to environmental fluctuations. In this paper, we have presented some initial findings into the adaptive processes within such systems. Through simulations, we have shown how the achievement of the system's stability (or *ultrastability* to put it into the words of W.R. Ashby (Ashby, 1960)) can lead to the preservation of the system's homeostasis. It can be said that the achievement of stability corresponds to the achievement of adaptation. In this way, the system exhibits robustness to the environmental fluctuations by preserving the stable state despite the variation in environmental parameter(s).

However, many additional aspects of the adaptation process may be considered so that the process efficiency and system *robustness* are enhanced. One thing would be inclusion of some long–term adaptive process(es) in analogy to evolutionary processes, as mentioned in section 3.1. Our work so far has assumed that the architecture of the system is endowed with adaptive mechanisms which are the result of the coevolution with the environment. Then, we have set to investigating these mechanisms. However, it might be worth considering how some processes of evolutionary nature could improve robustness. In this respect, we think of addressing information within individual cells and the system as a whole and choosing information content to be evolutionary unit. Further, we have addressed possibilities for the hierarchical organisation of the system under investigation. Such considerations are justified by the living systems' organisation. However, at this stage of our investigation, there is a number of issues that need be tackled. The major ones consider the 'building' of hierarchies which, in this case, is not a trivial task. we argue that in building up hierarchical organisation into the model more significance should be given to a choice of what information should be exchanged between the hierarchical levels. Useful ideas for setting the framework might be obtained from the work related to *dynamical hierarchies* (Rasmussen et al., 2001).

Moreover, if not the structure but the patterns formed are considered a higher hierarchical level, as is the case with the hormonal loops formation shown in previous work (Laketic and Tufte, 2009a), then new aspects into the very nature of the phenomena arising at the higher level may be questioned. Is it to be predicted from the operation of individual cells? Does it contain some fundamental novelty? Our speculation is that the answers may indicate emergent nature of the phenomena arising upon the occurrence of environmental fluctuation. Once the decisions on the system's hierarchical organisation are made, further investigation into robustness of such systems will be continued. Moreover, our intuition and common sense tell us that *absolute robustness* does not exist. We hope to show it and prove it within the framework set for further simulations. With the great enthusiasm we are looking forward to doing it.

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