Improving Robustness to Environmental Fluctuations – Dynamical Hierarchies Included

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***Abstract*—Dynamic environments present an everlasting challenge for any system, be it the one emerging in nature or the one designed by humans. Biological solutions – living systems, successfully tackle the challenge by adapting to their varying environment. Human designers, when faced with a similar challenge, may turn to biology to seek inspiration for possible solutions. Therefore, our previous work has considered strategies and mechanisms for achieving adaptation in living systems. In particular, the focus was on the achievement of adaptation through preservation of homeostasis and the role of hormones within such processes. This paper builds upon those findings. Further, it investigates one possible way to increase the robustness of an adaptive process performed by a man–made system where the system architecture is assumed to be of a grid–of–cells style. We suggest that some of the principles underlying dynamical hierarchies be used to enhance the previously developed model of an adaptive system in order to improve system robustness. This idea is supported with simulations which show that such model exhibits an increased robustness to environmental variations.**

***Keywords*-**

adaptation; environment; dynamical hierarchies; homeostasis; hormones

I. Introduction

When man–made systems are exposed to dynamical environments, their functionality is endangered. If the system is to preserve its functionality, it needs to adapt. Often, the possibility of human intervention is excluded so besides adaptivity, autonomous fashion of the system operation is desirable, if not required. Also, the robust operation is of particular interest because of the often unpredictable and sometimes harsh nature of environmental variations.

Living systems exhibit these qualities – they preserve their viability in dynamic environments by adapting to environmental variations. Therefore, our investigation has considered adaptive mechanisms and principles in living systems. Previous simulation results have shown how principles of preservation of homeostasis can be used for the achievement of adaptation in a modular man–made system whose modules (cells) are placed in a grid formation [1], [2]. This paper goes a step further and investigates one particular way in which a system can increase the probability of successfully reaching adaptation to environmental variations. It looks into the organisation of living systems and addresses its hierarchical nature examining the effect which the inclusion of principles of dynamical hierarchies into the adaptation process may have on the system robustness to environmental fluctuations.

Engineering applications of the principles of dynamical hierarchies have been recognised as one of the challenges for the topic of *dynamical hierarchies* within the field of Artificial Life [3]. It is our belief that this paper represents a significant contribution to further establishment of this topic by suggesting that the robustness to environmental fluctuations in a man–made system may be increased if the adaptation process performed by the system is enhanced with the principles of dynamical hierarchies.

The paper is organised as follows. Section II gives an introduction on biological principles which were used in our investigation providing the reference to the work of other researchers inspired by similar biological solutions. In particular, the notion of hierarchies within the context of organisation of biological systems is introduced in subsection II-A. Section III briefly presents our previous work. It is included here because the results presented in this paper build up on it. Section IV presents the model of the system under investigation which includes dynamical hierarchies. Further, Section V explains experimental setup, while Section VI provides simulation results. Finally, the conclusion of the presented work as well as some directions for future work may be found in Section VII.

II. Adaptivity of Living Systems

Adaptivity of living systems is the result of a number of processes which may be viewed as long term and short term processes dependent on the process duration relative to an individual's lifetime. The long term processes refer to the evolution of living systems realised through coevolution with environment. Their effects can be monitored at the population level. Such processes have resulted in individuals possessing inherent adaptive mechanisms. Once the environmental variation is detected, these mechanisms are employed in order to achieve adaptation to new environmental

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conditions. Processes performed by these inherent mechanisms upon sensing environmental fluctuation are short term processes. In general, these processes may be said to aim at the preservation of homeostasis i.e., the steady state of the organism's internal environment despite environmental fluctuations, be it of internal or external origin. A plethora of homeostatic processes is performed by different systems within the body, mutually intertwined and interdependent in their operation [4]. The prominent role belongs to endocrine system which is responsible for control and communication within homeostatic processes.

In some cases, however, environmental variations are such that organisms are unable to adapt despite possessing inherent adaptive mechanisms. Examples may be found at the population level e.g., the extinction of whole species due to abrupt, unpredictable or extreme change, or at the level of one individual when exposed to extreme or harsh senvironmental conditions e.g., too high temperature. Therefore, it can be said that living systems exhibit certain *normativity* in withstanding environmental variations. The higher the probability of withstanding environmental variation, the more robust the living system is to this variation. Further, if the environmental effect on living systems is described by a set of parameters e.g., temperature, pressure, salinity, acidity, then environmental variations are represented by variations in the values of these parameters.

The preservation of homeostasis for adaptive processes as well as the tasks performed by hormones have been addressed by a number of researchers, be it as a general framework for adaptive processes [5]–[7] or for a specific task like control and self–organisation within evolutionary robotics field [8]–[11] or fault tolerance in a multiprocessor system [12]. Our approach aims at establishing a model of an adaptive man–made system inspired by these biological principles which could find its application in adaptive hardware and electronics systems.

A. Hierarchies

Ever since its creation, the living matter has been faced with a difficult task of preserving the viability despite ever–changing environment. Clever strategies emerged providing optimal solutions not only for the present environmental conditions but also for maintaining the possibility of further evolution. Living systems as we see them today, are the result of such processes. As can be observed, the design strategy which has proven most successful through the evolutionary mechanism of natural selection is a step–wise creation of more and more complex living systems. Their complexity refers to both the complexity of organisation and the complexity of the behaviour they are able to perform, the latter being the result of the former. Different solutions would be created competing with each other and *the winner* would be a stable solution for the present conditions [13].

Further evolutionary processes would include these stable units and create future solutions with these units included as subunits together with some novelty brought about with the resulting, hierarchically higher organisation, as a rule more complex in its organisation and behaviour. Organisms built up of cells, which form tissues, tissues which form organs, organs entwined into systems which make up an organism, represent a well–known example of such organisation. Hierarchical organisation can be noticed even further, towards eco–systems all the way up to the living planet [6]. Such organisation which exhibits hierarchies in structure, where higher level units contain lower level units, also need to account for the dynamics between these entities (units), be it the entities on the same level or entities pertaining to different levels. For the example given in [14], just a mere aggregate of amino acids would not make an enzyme. It takes a certain order of amino acids when forming the enzymatic protein and in addition a certain folding of the protein to yield enzymatic properties. Novel properties of the amino acid sequence which form the enzymatic protein emerge as a result of interactions between amino acids but would be impossible to exist if the hierarchically higher level – the protein, did not possess the novel property i.e., the ability to fold. Observed from the protein level, properties of the pertaining amino acids can be described in a novel way. In general, we speak of levels of description so that a higher description level requires certain amount of information from the lower level to be discarded [13] i.e., some of the dynamics from the lower level need be abstracted – the higher the level in hierarchical organisation, the lower the level of detail with which the pertaining dynamics is described.

Further, organisation into dynamical hierarchies leads to a 'hierarchical control arising from a collection of elements' [15]. In this way, higher levels impose certain control on the lower level dynamics. The novelty brough about by the dynamics at a higher level plays a significant role in generating hierarchical control for the lower level entities. However, dynamical hierarchies still represent a challenge to address which is partly due to the lack of the established theoretical framework for this topic. Although a significant amount of work has been done with the aim of establishing such framework [16]–[19], a number of issues still remain open. Primarily, the criteria for the definition of novelty generated by the system intra- and inter-level dynamics need be established. In [20], the necessary condition for the existence of a new level is given from the information theoretic approach. There, this condition is based on the relation between entropies of the higher and lower hierarchical level.

In this paper, we make a contribution to the establishment of dynamical hierarchies by proposing a design principle for man–made systems which exhibit robust adaptation to environmental variation. In our investigation, the distinction is made between environmental variations whose effects can

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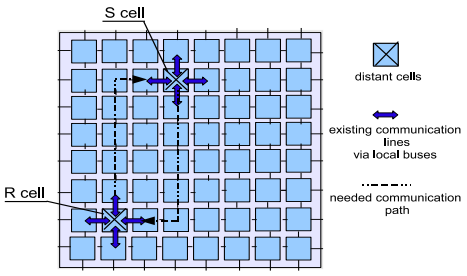

Figure 1: Schematic view of the system architecture

be seen on whole populations and those with effects on particular individuals. The former we term environmental changes and they are assumed to be tackled by the long term, (co)evolutionary processes; the latter we further refer to as environmental fluctuations and presume them tackled by the short term adaptive processes. Our work, as further described, considers the short term adaptive processes which take place in response to environmental fluctuations.

III. Modelling Adaptive Processes for the Preservation of Homeostasis

Our approach has a starting point in the framework presented in [5]. It is explained in greater detail in [1], [2]. At this place, the main characteristics of the introduced model are repeated for the ease of understanding the work presented further in the paper. The system architecture under investigation is schematically represented in Figure 1. Such architecture can be related to cellular automata (CA) formalism [21] where each cell communicates only with the nearest neighbours in its Von Neumann neighbourhood. Its behaviour is performed and monitored over the discrete time steps (ticks). The system is assumed to perform some functionality which is the result of the functionality performed by each of its cells. Therefore, if the functionality of one of the system cells deviates from the desired, the functionality of the system as a whole is also affected.

Further, each cell is assumed to possess a sensor through which it can sense fluctuations in its local environment. Two types of identifiers are used for the cell identification: one referring to the physical position of the cell within the system, *physical ID*, and another to its functional relatedness to other cells, *encoding ID*. Functional relatedness defines from which cell the functional input is received and to which cell the functional output is sent. More precisely, the cell with the *encoding ID* n is functionally related to the cells with the *encoding IDs* $n-1$ and $n+1$. Finally, the system configuration is given as a sequence of numbers where the position within the sequence corresponds to the cell's *physical ID* and the actual value represents its *encoding ID*.

The cell behaviour is defined by the finite state machine,

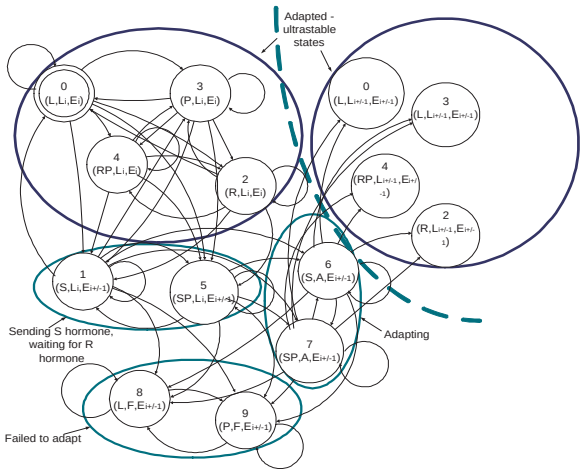

Figure 2: The finite state machine diagram describing the cell behaviour [22]

see Figure 2. The cell state is represented by a 3-tuple (H,A,E): H referring to hormonal flows; A to the cell functionality and E to the value of some environmental parameter which describes the effect of the fluctuation in the cell's environment on the system. Possible values for each member of a 3-tuple are as follows:

- H: L - no hormone present, S - sending *S hormone*, R - sending *R hormone*, P - passing hormone not functionally related to the cell, SP - sending *S hormone* and passing functionally unrelated hormone, PR - sending *R hormone* and passing functionally unrelated hormone;
- A: L0, L1, L2, L3 or L4 - functionality adapted to E0, E1, E2, E3 and E4 respectively, A - adapting or F - failed to adapt;
- E: E0, E1, E2, E3 and E4 - five different values of environmental parameter under consideration.

Control variables for the state transitions are as follows: 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), incoming S hormone recognised (RR), incoming R hormone recognised (FB), hormone(s) from functionally unrelated cell(s) present at inputs (HI). They are omitted from Figure 2 for the sake of clarity.

According to the state diagram in Figure 2, the cell adapted to its environment will be in one of the ultrastable states (states 0,2,3,4), while upon detecting environmental fluctuation, it will start sending the message on possible deviation in its functionality (states 1 and 5) and perform adaptation process (states 6 and 7) after it receives information on its functional deviation. This information is provided by its functionally related cell, see Figure 1. If it fails to adapt, it will remain in one of the states 8 and 9. However, if it successfully achieves adaptation, it will move to one of the ultrastable states of another set pertaining to the new

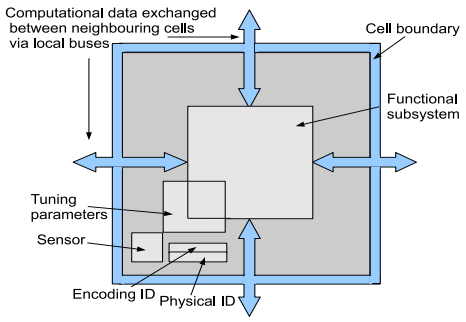

Figure 3: Schematic view of the cell architecture corresponding to the model of chemoton [23]; equivalent subsystems in chemoton model are given in parentheses

value of the environmental parameter. These states are shown to the right from the dashed line in Figure 2. Such behaviour is in accordance with [5].

We have further addressed the organisation of living systems for its autonomous and self-referring character. The cell architecture is related to the model of minimal living system provided by the chemoton theory [23]. Therefore, it is assumed that the cell consists of three subsystems, see Figure 3. The subsystem of tuning parameters is sensitive to environmental variations. It steers the operation and determines the performance of the cell's functional subsystem. The third subsystem - membrane, is rather straightforward to explain when the cell boundaries are considered. Additionally, the flow of nutrients and metabolic waste through the chemoton membrane corresponds to the flow of computational and control (hormonal) data via local communication lines.

The behaviour of the system can be described by the finite state machine diagram shown in Figure 4. The system can be in one of the three possible states:

- state 0: the system is adapted to its environment - none of the system cells detects environmental fluctuation, neither exhibits functional deviation
- state 1: the system performs adaptation process - at least one of the system cells detects variation in its environment and undergoes adaptation process
- state 2: the system fails to adapt - either $1/3$ of the system cells failed to achieve adaptation to the detected environmental fluctuation or $2/3$ of the cells detect environmental fluctuation

Such view of the system states can be related to the *levels of living* and *life criteria* as given in [24]. There, the state 0 would correspond to *the state of living*, the state 1 to *the state of being capable of living* and the state 2 to *the state of being dead*. As in Figure 4, once the system reaches this state, it remains in it i.e., it can not recover its functionality any more. On the other hand, state 1 still allows the system to achieve adaptation and eliminate functional deviation.

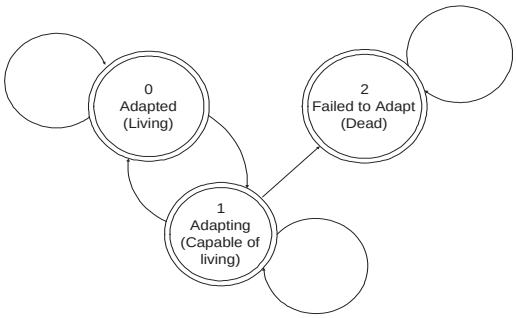

Figure 4: The finite state machine diagram describing the system behaviour

Based on such system behaviour, *we define system robustness to environmental fluctuations as its ability to avoid the state of failure* (the state 2 in Figure 4). Further, we introduce the degree of robustness as the probability to avoid the state of failure: *the greater the probability the system escapes from reaching the state 2, the greater the level of robustness it exhibits towards environmental fluctuations.*

A. Adaptation Process and the Role of Hormonal Loops

Adaptation process performed by the cell was described and demonstrated in simulation in [1]. In [2] it was reconsidered from the perspective of hormonal flows where hormonal loops were recognised to initiate and sustain adaptation process until adaptation is achieved. Hormonal loops are formed between functionally related cells through the following sequence of events:

1) the cell (*S cell*) senses environmental fluctuation
2) *S cell* begins secreting *S hormone* as a response to the sensed fluctuation, see Figure 5a
3) *S hormone* reaches the functionally related cell (*R cell*)
4) *R cell* recognises *S hormone*, see Figure 5b
5) *R cell* begins secreting *R hormone* which carries the information on the functional deviation exhibited by the related *S cell*, see Figure 5c
6) *R hormone* reaches *S cell*, see Figure 5d

Once the hormonal loop is closed, *S cell* begins adaptation process. This process can be performed provided two hormones are present in the cell: its *S hormone* and the *R hormone* from its functionally related cell. If any of these hormones is cleared from the system before adaptation is achieved, the cell fails to adapt. However, if both hormones are present during adaptation process until no functional deviation is detected by the related *R cell*, S cell achieves adaptation to environmental fluctuation which triggered the whole process.

Figure 6 shows the loops for the configuration used in simulations in [2]. There, the value of the environmental parameter was changed for the cells with *encoding IDs* 52, 23 and 32. The loops which were formed between these cells and their corresponding functionally related cells can

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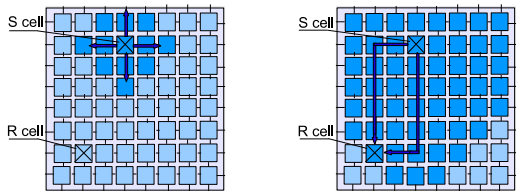
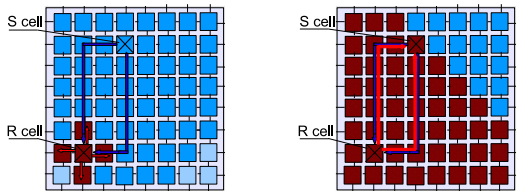


(a) S cell senses environmental fluctuation and begins secreting S hormone

(b) R cell recognises S hormone as coming from the functionally related cell



(c) R cell begins secreting R hormone

(d) R hormone reaches functionally related S cell - hormonal loop is closed

Figure 5: A loop formation: the flows of hormones which form the loop

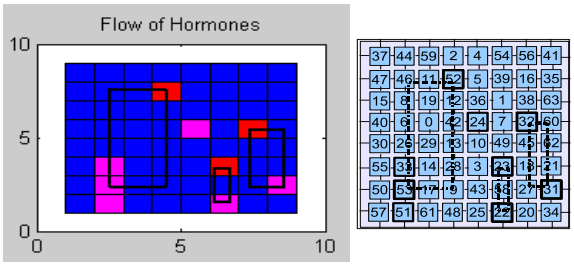
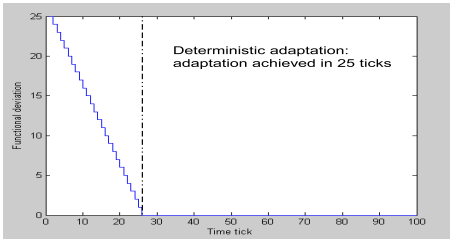


Figure 6: Hormonal loops as observed during one of the simulation runs for the system configuration to the right

be seen on the plot on the left side in Figure 6. This figure represents a plot of the system state pertaining to the *flow of hormones*, H, part of the state 3–tuple (H,A,E) during simulations. The amount of hormones flowing around the architecture during adaptation process is determined by the exponential decay rate parameter. This value can be made adaptive so that the presence of the hormone is ensured until adaptation is successfully achieved [1].

We denote a hormonal loop as $(S_i(n), R_i(n+1))$ if it is formed between *S cell* with the *encoding ID* n and *R cell* with the *encoding ID* $n+1$. Index i serves for the loop identification and corresponds to the order in which the loop was formed relative to other loops during simulation.

The progress of the adaptation process performed by the cell is modelled by a counter which is stochastically



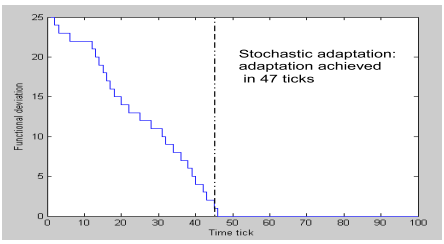


Figure 7: Model of the stochastic decrease in functional deviation during adaptation process

decremented each time tick during this process. The counter value reflects the functional deviation exhibited by the cell: upon the change in the environmental parameter value, this counter is assigned some value which represents maximum functional deviation exhibited by the cell; decrementing this value corresponds to the decrease in functional deviation as a result of the ongoing adaptation process. Figure 7 shows how this is performed for the case of maximum counter value 25 which was used in our simulations.

IV. Enhancing the System Model – Dynamical Hierarchies Included

We pose the question if the adaptation process performed by the model introduced in Section III can be improved with respect to the exhibited robustness if the principles of hierarchical organisation are included. To investigate such possibility, the existing model need be enhanced so as to account for hierarchical organisation. However, for such an endeavour there are no straightforward solutions. In [25], preliminary considerations were presented concerning different ways in which hierarchies could be included. There, a number of arguments is provided in favour of dynamical against structural hierarchies. Primarily, for the environmental *dynamics* (fluctuation) we seek *dynamic* response of the system. Therefore, we look into the system dynamics initiated by environmental dynamics.

Several issues need be addressed. Firstly, higher level entities need be recognised: what entities arise as a result of the cell dynamics in response to environmental fluctuation? Secondly, the behaviour of these entities must be addressed: how do these entities behave, how do they interact? Does such behaviour bring in some novelty? If so, how can this

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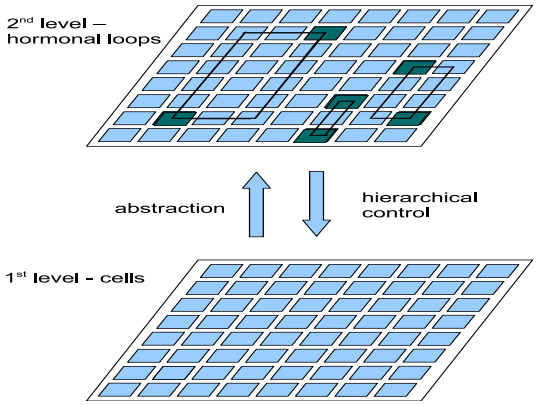

Figure 8: Schematic view of the hormonal loops observed as entities at the second hierarchical level

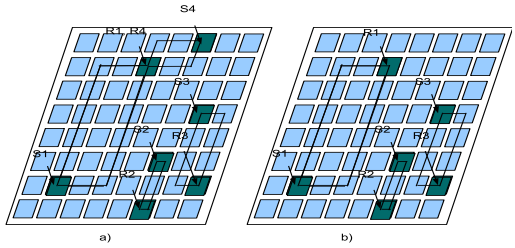

Figure 9: Hormonal loops: a) four loops out of which 2 are related i.e., loops $(S1, R1/R4)$ and $(S4, R1/R4)$ where $R1/R4$ stands for the cell which recognises incoming *S hormones* from both cells $S1$ and $S4$; b) three unrelated loops. The cells *encoding IDs* are omitted for the sake of clarity

novelty be used for the increase in the robustness of the performed adaptation process?

Further, when the description of such system is considered, different levels of description need be provided. This requires the granularity of each description level be chosen. A careful choice has to be made on what information from the lower level is to be discarded when describing the higher level dynamics. Finally, as our particular interest lies in adaptive processes, we address the issue of hierarchical control for such a process: what kind of hierarchical control could be imposed from a higher hierarchical level on the adapting cell at the lower level so that it accounts for the dynamics of higher level entities and improves robustness of the performed adaptation process? Figure 8 shows schematically relations between the two levels within the proposed model. Subsections IV-A and IV-B further explain the abstraction and the hierarchical control denoted by the upward and downward pointed arrows in this figure.

A. Describing Behaviour from a Higher Level

The system responses to environmental dynamics through a sequence of hormonal secretions as described in section III-A. Therefore, we seek the candidates for the higher level entities among these hormonal flows. Hormonal flows which arise in the system upon the cell sensing the fluctuation in its environment are given in Figure 5 and introduced in section III-A. At first, one cell which secretes *S hormone* does not possess enough information to perform any meaningful action within adaptive process (Figure 5a). The information on the functional deviation exhibited by the *S cell* is available only after its functionally related *R cell* has recognised the incoming *S hormone* and began secreting *R hormone* (Figures 5b and 5c). This information can be provided by the related *R cell* due to the functional relatedness between the cells. However, although available within the system, it has no effect as long as it does not reach the cell affected by environmental variation. It is only at this point that the cell can begin its adaptive process. Hormonal loop is closed between the two functionally related cells (Figure 5d) one of which exhibits deviation in its functionality due to the environmental fluctuation, while the other provides information on this deviation which is necessary for the adaptive process to be performed. Hormonal loops can not be observed at the cell level but it takes a view from a higher level to observe them.

Next issue to address is the hormonal loop dynamics. The new level of description is needed which describes the behaviour related to the level of hormonal loops. This description level concerns the dynamics of the higher level entities – hormonal loops. Relevant information for the hormonal loop behaviour is contained in hormonal flows which make this loop as well as the status of the adaptation process. Hormonal flows define the loop existence: dependent on the flows of hormones, the loop will come into existence but also disappear. Moreover, the achievement of adaptation and failing to do so will affect the loop existence and behaviour.

When hormonal flows form the loop, the information on functional deviation is provided and the adaptation process may be performed. Further question may be posed if it is possible to enhance this information so that the adaptation process is improved. The information on the functional deviation is provided by the functionally related *R cell*. Can situations occur when this cell possesses more information on functional deviation performed by the related *S cell* than it otherwise would when based only on the functional relatedness between these two cells?

In a broader picture, because of the way in which the system configuration is implemented, one cell is functionally related to two other cells. Therefore, the *R cell* within the loop will be functionally related to one more cell beside the *S cell* within the loop. Dependent on the environmental dynamics, this other functionally related cell may also be affected by environmental fluctuation causing it to start

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secreting *S hormone* upon which its related *R cell* would secrete hormone with the information on its functional deviation as well. In that way, one *R cell* will be part of two hormonal loops, as schematically shown in figure 9. Because the cell functionality is dependent on the functionality of its predecessors as well as its successors in the configuration string, the *R cell shared* between two loops may provide each of the related *S cells* with more information on their functional deviation. Therefore, we introduce interaction between the loops based on the functional relatedness of their pertaining cells: *two hormonal loops will interact if their S cells share the information provided by the R cell which is part of each of the two loops simultaneously*. Such loops are said to be related. Figure 9 schematically shows the case where related hormonal loops are identified (a) and when no related loops exist (b).

The finite state machine diagram which describes the loop behaviour is shown in Figure 10. When no environmental fluctuation is detected, no hormonal flows are present and the loop is in the state 0. Such case corresponds to the cases when the cell which may initiate creation of hormonal loop, i.e., the *S cell* of the loop, is in the state 0, see Figure 2. The loop remains in the state 0 also when this cell is passing a hormone from another functionally unrelated cell (state 3 in Figure 2), when secreting *S hormone* without having recognised *R hormone* (state 1), when recognising the incoming *S hormone* (state 2) or corresponding to both first and either of the two mentioned cases (states 5 and 4 respectively). The loop comes into existence when the cell which is already secreting *S hormone* detects and recognises the incoming *R hormone*. Then, the loop moves to either of the states 1 or 2. This transition corresponds to the cell state transitions to states 6 and 7 in Figure 2, the exact transition being dependent on the presence of some hormone from a functionally unrelated cell: when such hormone is present, it corresponds to the cell state 7 and when not, to the state 6. As said, the loop also moves to one of the two states but which one in particular is determined by somewhat different criteria from the presence of the hormone from a functionally unrelated cell. If the *R cell* pertaining to the loop is already part of another loop, the loop will move to the state 2. Otherwise, it moves to state 1. In this state, the *S cell* is the only cell to which the *R cell* provides the information on functional deviation. If any of the hormones forming the loop is cleared from the system before adaptation is achieved, the pertaining *S cell* fails to adapt so the whole loop fails as well and it moves to the state 3 in Figure 10. This state corresponds to the cell states 8 and 9 in Figure 2. Again, which of the two in particular is dependent on the presence of the hormone from the functionally unrelated cell: it moves to the state 8 when no such hormone is present and to the state 9 when it is present. The loop may also move to the state 3 from the state 0. Such situation corresponds to the case when the cell begins secreting *S hormone* upon

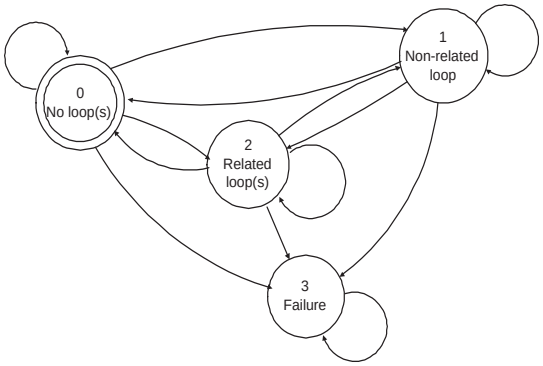

Figure 10: The finite state machine diagram describing the hormonal loop behaviour

the detection of environmental fluctuation but it does not begin to adapt because one of the two hormones needed to sustain adaptation process is cleared from the system before the loop is closed. It can be noticed that the behaviour at the loop level can not be fully described without the knowledge on the existence of the related hormonal loops. This concerns transitions between states 1 and 2. As the existence of the related hormonal loops can be observed only at the hormonal loops level, it may be said that the hormonal loops relatedness arises at this higher hierarchical level.

Comparing Figures 2 and 10, it can be noticed that the description of the behaviour at the higher, hormonal loop level (Figure 10), contains much less detail than the description of the behaviour at the lower, cell level (Figure 2). This is in accordance with [15] where the loss of detail at different description levels is explained from the physical point of view and related to the loss of information at different description levels respectively [20]. Such behaviour brings in new means of communication within the layer, realised through the interaction between hormonal loops, but, as explained further, also between the layers through the hierarchical control of adaptation process which accounts for the hormonal loops dynamics.

B. Hierarchical Control of Adaptation Process

In [15], the role of hierarchical control within hierarchically organised systems is discussed. Here, the possibility of using the information generated by the higher level dynamics is examined with the aim of improving the adaptation process within the system. As mentioned, adaptation process performed by the cell is dependent on the existence of the hormonal loop to which the cell belongs as its *S cell*. Moreover, it was explained how the existence of related loops can provide more information on the functional deviation exhibited by the cell. Therefore, in cases when related loops exist for the loop to which the adapting cell belongs, this cell stands better chances to adapt due to the availability of

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a larger amount of information on its functional deviation. So, we suggest the following scheme for performing the adaptation process which accounts for the hormonal loops dynamics:

- If adaptation process is performed within the loop which does not detect related loop, the counter modelling this process is stochastically decremented by 1. Such scheme is depicted in Figure 7.
- If adaptation process is performed within the loop for which a related loop exists, the counter is decremented by 3 thereby modelling the case when more information is available for the achievement of adaptation.

In short, the more information available from the higher hierarchical level, the larger the adaptation increments are i.e., the larger the decrements in functionality deviation. For the example given in Figure 9 a), this means that the cells $S1$ and $S4$ would have the functional deviation value decremented by 3 during adaptation process while the cells $S2$ and $S3$ would have this value decremented by 1. This is because the cells $S1$ and $S4$ are part of the loops which share the *R cell* $R1/R4$. The novel feature brought into the system model would then be the hierarchical control determined by the second level dynamics which accounts for the interaction and relatedness between the second level entities – hormonal loops.

V. Experimental Setup

The system is exposed to environmental fluctuations and its behaviour observed until its failure. To investigate how useful the information on the higher level dynamics can be for the hierarchical control of adaptation process as well as its effect on the system robustness, two types of simulation runs are performed:

- type 1: hierarchical control of adaptation process does not account for the interactions between the higher level entities – hormonal loops
- type 2: hierarchical control takes into account interactions between hormonal loops

The time ticks of the system failure are compared for the two types of run. If the information on the interactions between the higher level entities helps the system improve its robustness towards environmental fluctuations, the system will fail at a later point in time i.e., a later time tick when this information is accounted for than when it is not.

Exponential decay rate parameter is kept constant thereby allowing the cells to fail to adapt in some cases due to the insufficient amount of hormones. The value of this parameter was set to 0.9 based on the consideration of optimal values, see [1].

We define that the system fails to adapt if either of the following two conditions is fulfilled:

- one third of the system cells fails to adapt; for our system of 64 cells (a grid of $8X8$ cells), this value equals approximately 21
- two thirds of the system cells are sensing the fluctuation in the environmental parameter; for the system under investigation this value equals approximately 43

The numbers of the system cells which failed to adapt i.e., which are affected by the environmental fluctuation are chosen arbitrarily.

The effect of environmental fluctuations on the system is modelled by a change in the value of the parameter E, see section III. So, the system is being driven to *the state of being dead*, see Figure 4, by imposing more and more changes in the value of this parameter. The rate of change of the parameter value reflects the harshness of the environmental dynamics. It is expressed as a parameter R_C which stands for the percentage of occurrences of environmental variations and is set to 5% for the pertaining simulations. At each time tick, according to the R_C value, the environmental parameter E is changed with some probability $p(n)$. This probability models the stochastic nature of the environment. In the beginning, it is as low as 0.001. As the time proceeds, it is increased also with certain probability p_{st} by a small amount i.e., 0.0005. Therefore, for each cell i, the probability of having the local environment changed may be expressed as:

$$p_i(n) = p_i(n-1) + incr_i(p_{st}), p_i(0) = 1e-3 \quad (1)$$

where $incr_i$ represents the increments added to the preceding time tick probability with some probability p_{st}:

$$\begin{aligned} incr_i(p_{st}) &= 5e-4, p_{st} \geq th \\ &= 0, p_{st} < th \end{aligned}$$

where th is a threshold value. In this fashion, the total number of cells affected by the fluctuation in their local environment increases with time. In a real case, where the system tissue is rather of a continuous nature, it would be more realistic to speak of the gradient of environmental parameter over the system architecture. So, to account for this, we assign a greater probability of having the environmental parameter changed to those cells which are in the neighbourhood of the cells already affected by some environmental fluctuation. For these cells we set the threshold value to be higher than otherwise: 0.8 and 0.5 respectively.

In order to achieve statistically relevant results, this procedure is repeated for 10000 configurations. The value of 10000 was chosen based on the findings for the experiments with the same architecture within our previous work [1].

VI. Results

The simulation results are summarised in table I. It shows averaged values of the time ticks when the system failed. The first row refers to the cases when the hierarchical control did not account for the interactions between second level entities during adaptation process, while the second row shows the result for the cases when it did. It can be noticed

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Table I: Numeric data on the system failure for two types of simulation runs averaged over 10000 configurations, $R_C = 5\%$

Type of the run	Average time tick when the system failed	Avrg # of related loops for equal ticks of fail.	Avrg # of related loops for different ticks of fail.
No loops interactions included in control	**6.13e2**	–	–
Loops interactions included in control	**6.46e2**	2.13e-1	1.58

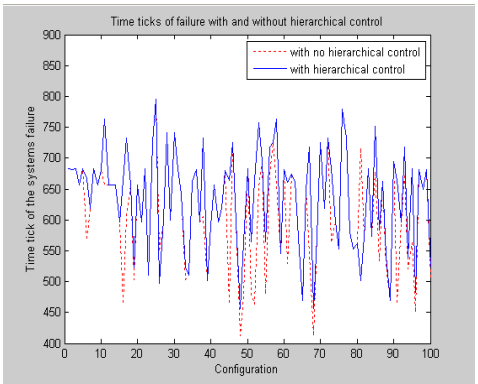

Figure 11: Time ticks of system failures for configurations used in simulations

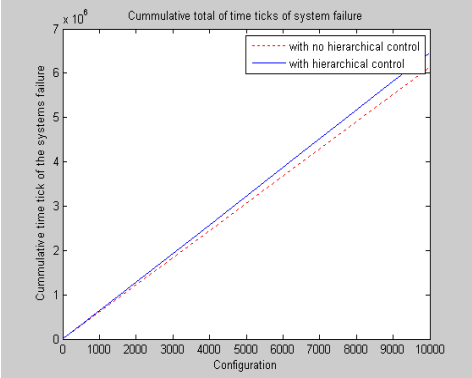

Figure 12: The cummulative time ticks of the system failure for configurations used in simulations

that the system fails at a later point in time i.e., a higher time tick when the hierarchical control is enhanced with the information generated by the interactions between the higher level entities. The results show that the time tick of the system failure is equal or higher when the interactions between the higher level entities are accounted for than when they are not. *This finding stands in support to the claim that hierarchies i.e., dynamical hierarchies can improve robustness in the assumed man–made system based on a grid-of-cells architecture.*

Figure 11 shows the values of the time ticks of failure

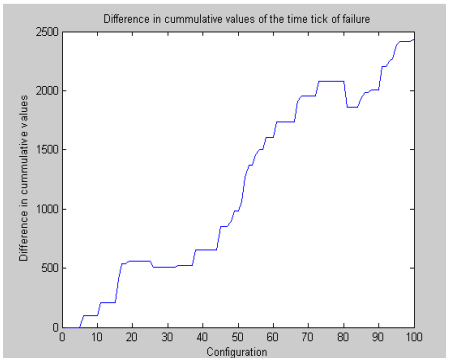

Figure 13: The difference in the cummulative time ticks of failure for the two types of adaptation processes - detail

for the first 100 configurations examined under simulations. It can be noticed that the tick of failure is equal or higher when the interactions between the higher level entities are accounted for than when not. Only 100 values are shown for the sake of clarity. However, the same trend holds for all configurations used in simulations. To visually support such observation, we present the accumulated value of the tick of failure for the two types of runs, see Figure 12. There, the graph corresponding to the case when the dynamical hierarchical control accounts for the interactions between the hormonal loops has a steeper slope throughout. In more detail, Figure 13 shows the difference between these cummulative values for the first 100 configurations.

VII. Conclusion and Future Work

We have addressed the challenge of increasing robustness of a man–made system to environmental fluctuations. The assumed system was modular, its architecture based on CA. One possible way in which this could be achieved has been presented on previous pages. Moreover, the simulation results have shown that application of the principles of dynamical hierarchies can improve system robustness to environmental fluctuations. The improvement is due to the hierarchical control of adaptation process which accounts for the higher level dynamics while adaptation process is performed by entities at the lower level. At the same time, suggested solution has opened a number of questions which remain for further work to answer. One of the questions is related to the dynamics of environmental fluctuations. The results presented in the paper accounted for only one value of R_C. It would be interesting to look into the system behaviour under different environmental dynamics modelled by varying parameter R_C. Further challenge would be also to extend the investigation to even higher levels seeking general recommendations for building up a higher level dynamics.

On the other hand, this work has addressed the topic of dynamical hierarchies which has raised a great interest and inspiring discussions within the ALife research community

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over the recent years. We believe that the model presented in this paper might be the way towards bringing closer the theoretical research into dynamical hierarchies and engineering applications for man–made systems when needed to operate in dynamic environments. In particular, we have in mind applications where hardware and electronics systems need to operate not only in dynamic but also extreme, harsh environments.

Before we engage into addressing open challenges, the system model needs to be put within a firmer theoretical framework with dynamical hierarchies included. However, debates are still being held on this topic so such an endeavour is not a straightforward thing to do. Rather, to begin with, we have chosen one of the proposed approaches which is based on information theory [20]. Our deep belief is that in succeeding to do so, a firm theoretical basis for our research would be established opening new possibilities for further development of ideas.

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