Fault Tolerance via Endocrinologic Based Communication for Multiprocessor Systems

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Abstract. The communication mechanism used by the biological cells of higher animals is an integral part of an organisms ability to tolerate cell deficiency or loss. The massive redundancy found at the cellular level is fully taken advantage of by the biological endocrinologic processes. Endocrinology, the study of intercellular communication, involves the mediation of chemical messengers called hormones to stimulate or inhibit intracellular processes.
This paper presents a software model of a multiprocessor system design that uses an interprocessor communication system similar to the endocrine system. The feedback mechanisms that govern the concentration of hormones are mimicked to control data and control packets between processors. The system is able to perform arbitrary dataflow processing. Each processing stage within the system is undertaken by a separate group of microprocessors. The flow of data, and the activation of the next stage within the process is undertaken using the bio-inspired communication technique. The desired result is a system capable of maintained operation despite processor loss. The feasibility of the multiprocessor system is demonstrated by using the model to perform a simple mathematical calculation on a stream of input data.

1 Introduction

Biology provides a diverse source of inspiration that reaches across many fields from both artistic and scientific disciplines. Electronic Engineering is no exception.

One of the strongest impetuses for Bio-Inspired Engineering is the assistance it lends to the development of engineering design, especially where solutions via traditional techniques fall short. Such biological based solutions have led to the creation of artificial learning and pattern matching systems based on neural networks [1, 2], as well as self re-configuring systems [3] based on biology's ability to evolve and adapt.

Of more interest to the area of Reliability Engineering is biology's ability to maintain operation in the face of adverse conditions. Biology is able to employ

automated fault tolerance, detection and recovery characteristics that enable organisms to remain functional despite injury. It is the desire for electronics to also exhibit these three characteristics that has led to an interest in Bio-Inspired Reliability Engineering.

Both Embryonics [4] and Artificial Immune Systems [5, 6] mimic aspects of biological reliability systems. The Embryonic Architecture is capable of removing faulty circuit areas. Reconfiguration via the shifting of functionality to healthy circuitry in redundant areas returns the system to full functionality. Whereas Artificial Immune Systems provide a fault detection and removal mechanism based on the biological self, non-self principle [7].

The ability of biological systems to tolerate and recover from a subsystems death is reliant upon the use of redundancy. This is a common feature present on a number of levels within biology's structural hierarchy. Society maintains activity through redundancy in individual organisms, similarly organisms can function without certain organs. However, it is the cellular level that utilizes redundancy to the greatest effect.

Cellular biology of higher animals provides the inspiration for the multiprocessor system presented in this paper. A software model of an inter-processor communication system based on biology's endocrine system is presented, including results that demonstrate the system's fault tolerant characteristics.

The subject of biological cell signalling is discussed in Section 2. How such signalling can be translated into a useful electronic system is presented in Section 3. The model of the resulting multiprocessor system and operation results are described in Sections 4 and 5 respectively. The paper is concluded in Section 6 with suggestion for further work in Section 7.

2 Cell Signalling

Cells are heavily dependant on signalling mechanisms for survival. The ability for cells to influence each other enables a multicellular organism to maintain a level of homeostasis [1]. Even some unicellular organisms utilise signalling to influence proliferation of other like cells [8].

A variety of different communication systems are employed in higher animals. Each system varies in a number of ways, but especially with regard to range and speed. However, in each case communication is achieved via signalling molecules. Each messenger molecule exhibits a biological signature that determines its recognition by other cells. Target cells recognize messenger signatures through receptors. A receptor-messenger match allows molecules to bind to their target and complete the communication process.

The synaptic signalling process shown in Figure 1 is the most directed messenger based communication system. Nerve cells directly steer their messengers via their connected axons. As the neurotransmitter messengers are released so close to their target, affinity between receptor and messenger can be low. In

[1] Homeostasis is the process by which organisms or cells maintain a stable internal equilibrium via physiological changes.

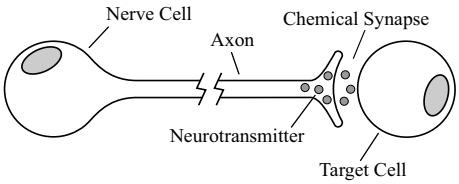

Fig. 1. Synaptic signalling via neurotransmitters.

contrast, messengers used in endocrine and paracrine signalling are not directed straight to their target. Endocrine signalling, as shown in Figure 2a, transport their messengers (called hormones) through the blood stream. Paracrine signalling, Figure 2b, is similar, however the message chemicals are limited to a localized area of tissue.

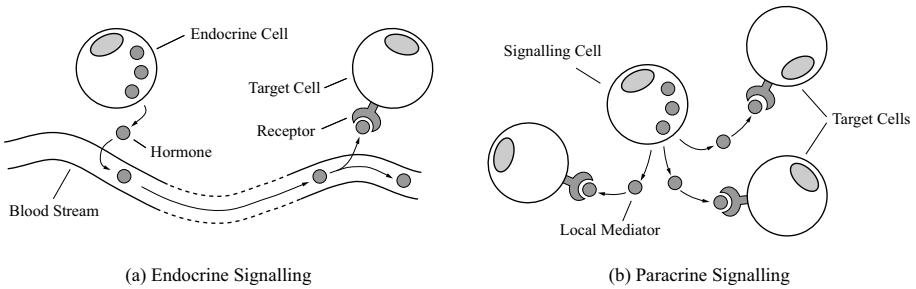

Fig. 2. Two types of cell signalling. (a) Endocrine communication, hormones are transported via the blood stream between source and target cells. (b) Paracrine communication, local mediator messengers are restricted to local tissue diffusion to travel from source to target cells.

2.1 Endocrinologic Control

Homeostasis of higher animals is achieved by the body's nervous and endocrine systems [9]. Mediated by their respective communication systems, changes in an organism's internal or external environment invoke responses that stimulate the appropriate physiological changes required for organism adaption.

In the case of the endocrine system, hormones released from special glands are able to stimulate cells, activating a variety of reactions. These reactions may involve the production of other hormones that in turn activate other cells.

It is possible for cells with hormone receptors with different specificities to bind to the same hormone signature. Therefore, the release of a single hormone type is able to initiate a response in more than one type of target tissue. Also,

hormones are not limited to stimulatory effects. They may also produce an inhibitory effect on their target. These combined abilities of hormones provide the foundation for hormone based control. Figure 3 depicts two possible scenarios for endocrine control.

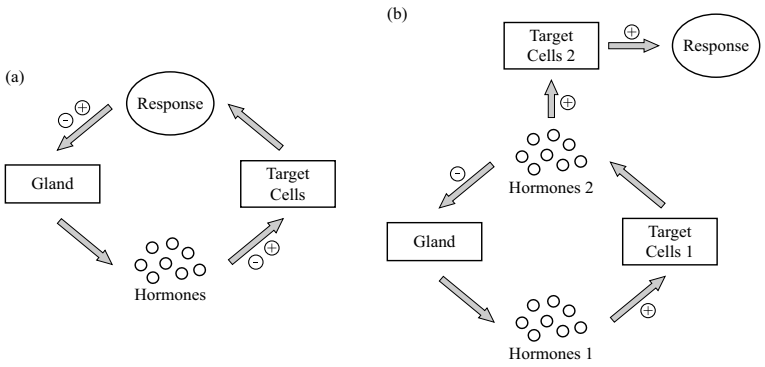

Fig. 3. Two possible scenarios for endocrine based control.

In Figure 3a, the release of hormones by the gland initiates a response by the target cells. The response itself then stimulates or inhibits the original gland to increase or decrease the production and secretion of hormones. The second system, shown in Figure 3b, contains a second stage. The initiating gland produces an initial set of hormones that activate the first group of target cells. The resulting action is the production of a second set of hormones that target both the original gland and a second group of target cells. The gland is inhibited by these hormones to stop its own hormone production, whereas the second cell group is stimulated producing the desired overall response.

3 An Electronic System from Biology

The biological endocrine system provides higher animals with a robust control mechanism. Unfortunately, this is all it is, it does not directly lend itself to use as an information processing or calculation system. However, if the hormone messengers contained data, and target cells performed operations on the data, the endocrinologic paradigm could be used to create such a system.

Figure 4a depicts a system adapted from the biological model shown in Figure 3b. In this case, the system has been extended to contain a number of target groups. Each group, on stimulation, releases messengers that stimulate the next target group and inhibit the previous. The result is a cascade of data processing stages. The equivalent system, in block diagram form is shown in Figure 4b.

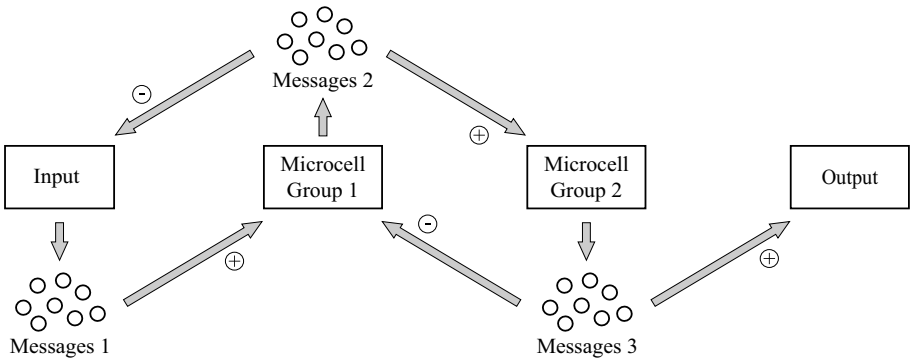

Fig. 4. Adapting the endocrine system to a data processing platform. (a) A succession of messenger activated microcell groups forming a chain of data operations, (b) An equivalent block diagram view of the system.

3.1 Microcells: Microprocessor Cells

All biological cells develop from a common ancestor type, the stem cell [10]. When new cells are required, they can be developed and put to use. Unfortunately, *physical growth* of electronic hardware to replace malfunctioning circuitry is not feasible at the moment. Instead, resources have to be made available which can be brought into use, mimicking regrowth.

In the case of the cells in the new system, a hardware unit is required that can assume a variety of functions. Then, in the situation that a cells needs to be replaced, a new generic cell can take its role, configuring itself to perform the required task.

A microprocessor based cell, or microcell, is able to fulfil such a task. Each unit stores all the required cell procedures within memory, and on activation, programs itself with the appropriate section of software. This is an established bio-inspired technique used especially in Embryonics [11, 12], and in this case forms a neat parallel with the ability of biological cells to to develop into any number of roles [8].

3.2 Communication Space

Biology exists in a non-rigid framework that allows the movement of matter and the constant reorganization of its constituent parts. In electronics this is simply impossible. The structure of the silicon within a device determines exactly where a component is located, and where it shall stay. This static nature of electronic features make replicating the endocrine communication mechanism difficult. Endocrine hormones must be free to move and co-exist if they are to reach their target effectively.

As it is not possible to create a medium where data packets are able to freely *roam* between microcells, a more restricted solution is taken in this paper. A fully-connected mesh topology [13, 14] would allow free communication between any

two microcells, but would result in an unrealistic number of connecting links for any reasonable size system. Instead, a 'closest-neighbour' system is used, where each microcell is connected to a number of its closest neighbouring microcells. Messenger data packets are able to diffuse across the network by passing from one microcell to the next. If the target is reached, the message data is consumed as its travel is complete, if not the message is moved on.

3.3 Topology

In a system so dependant on communication, the network topology is an important consideration. To give each microcell an equal communication standing, each cell's view of its IO connections must appear the same. To achieve this, a boundary free topology with an equal quantity of neighbour connections per microcell is used. This takes the form of a toroidal mesh. However, this is an area for further work (see Section 7.1).

3.4 Data Processing

The system resulting from the conversion of the endocrine control system to electronic system is a simple dataflow processor. The system has a single input, the Stimulator and a single output, the Drain as shown in Figure 4b. The microcells that lie in between are grouped depending on the stage they represent in the system. Redundant microcells that do not perform operations on the data are also included in the system. Their role is to simply traffic data without alteration, and when required, assume a data operating function to replace the loss of a faulty microcell.

4 Multiprocessor System Model

The multiprocessor system was simulated using a multi-threaded Java Model [15–17]. To demonstrate the operation of the model a simulation of the simple data processing system, shown in Figure 5, has been performed. The results are presented in Section 5.

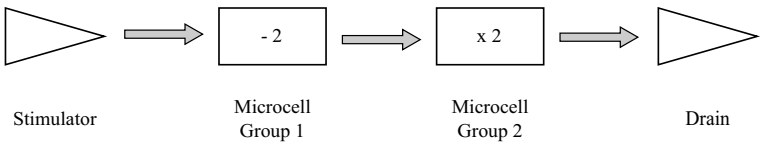

Fig. 5. A block diagram of the configuration used to test the multiprocessor system.

The network produced by the model is shown in Figure 6. Each sphere represents a single microcell. The connections between the spheres show the connectivity of the network. In this particular network all connections are full-duplex,

however half-duplex connections are possible. The system Stimulator and Drain can also be seen.

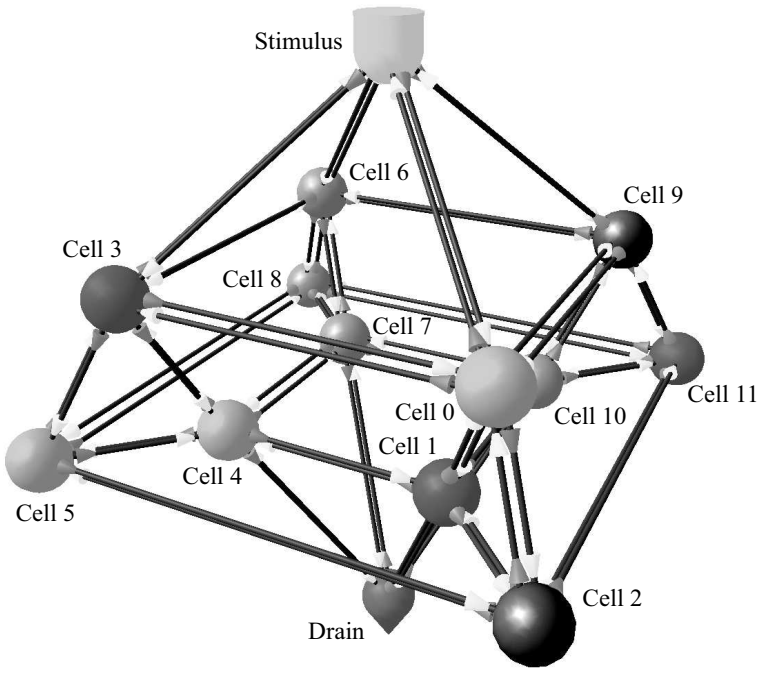

Fig. 6. A representation of the multiprocessor system. Cells 0, 4 & 5 and Cells 1, 3 & 11 perform different processing tasks. Cells 2 and 9 have been killed off to demonstrate fault tolerance. The remaining cells are redundant. The main system input (Stimulator) and output (Drain) are also shown.

5 Simulation Results

The key points of the systems operation are shown in the following three Figures 7, 8 & 9 (The data for each graph were taken from the same simulation run). The messaging activity of the system is complex due to the random nature in which microcells pass data. However, a pattern in cell activity levels, with similarities to biorhythms [9], can be observed. Figure 7 shows the activity levels of cell 4 (see Figure 6). The stimulation and inhibition components that define the cells activity can be seen.

Each rise and fall in activity is regulated by the initial stimulus of input data. Comparison of this graph and that in Figure 8 show a correlation in the introduction of new data, and subsequent cell activation.

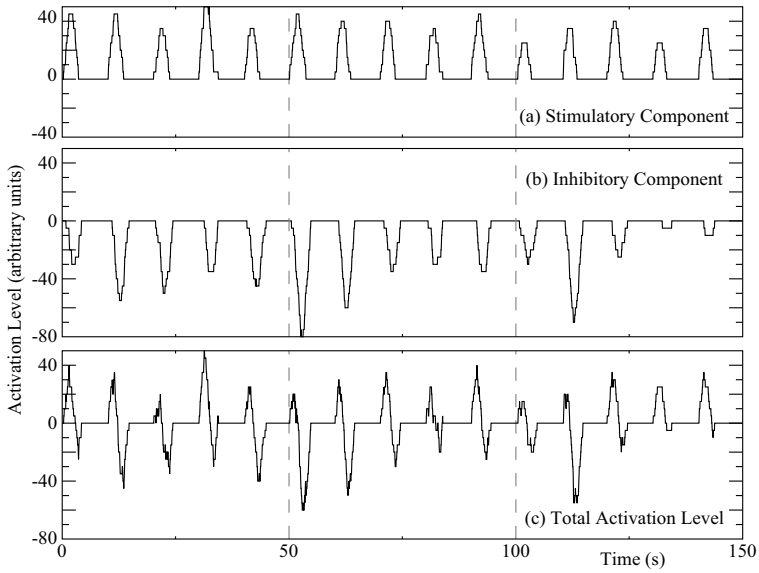

Fig. 7. Graph of the activation levels of microcell 4 (See Figure 6). The total activation level (c) can be seen as the addition of the stimulatory (a) and inhibitory (b) components.

Figure 8 shows the overall system input and output. Each spike of Figure 8a represents the activation of the system Stimulator. It can be seen that these spikes lead to a number of output spikes, Figure 8b. These represent the arrival of final stage messengers at the system Drain. Further study of the graph shows that the correct mathematical operations (see Figure 5) are being performed on the data.

The final graph shown in Figure 9 shows the effects of microcell loss. At two points during the simulation a microcell is killed off, and then replaced by a redundant cell. As Figure 8 proves, operation is maintained despite the loss.

6 Conclusion

So far, the simulation results have been encouraging. Even though the system is in its very early stages of development it is able to perform simple processing on a flow of data. Microcell loss is also tolerable and the ability to return the system to a full complement of processing units is possible.

Biological Endocrinology has been presented as another source of inspiration for engineering. Furthermore, this paper has made a start to show it is possible to glean some of its reliability properties via its replication as an electronic communication system.

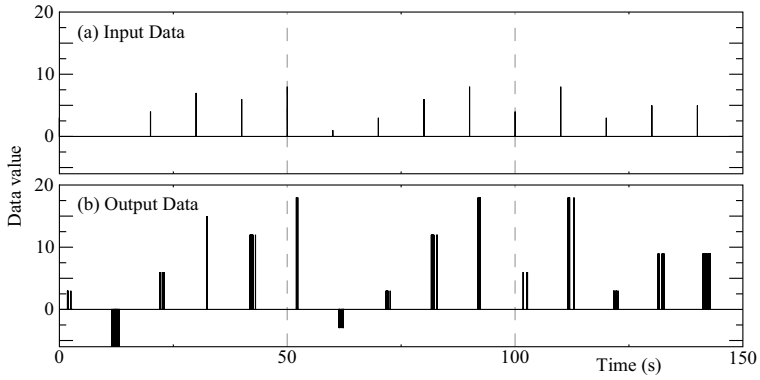

Fig. 8. Graph showing the overall system input (a) and output (b) data streams.

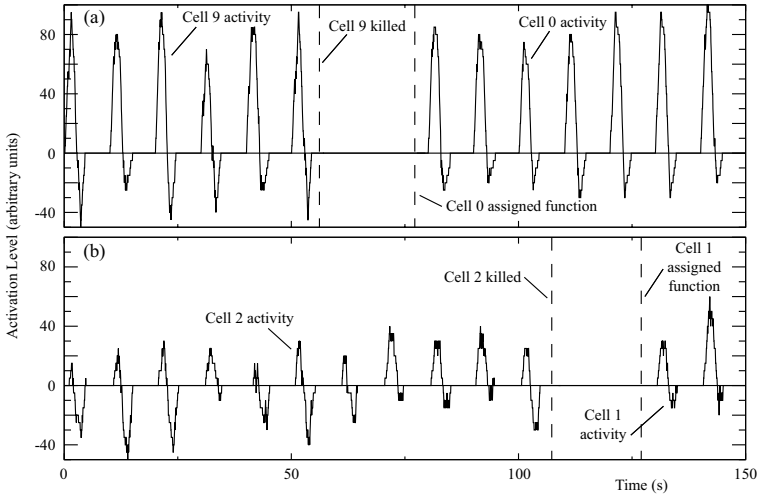

Fig. 9. Graph of activity levels in four different cells as they become activated and deactivated, demonstrating the systems ability to deal with microcell loss.

7 Further Work

The development of the presented system model is currently still within its early stages. Consequently, there remain many features to be included and issues to be dealt with. The rest of this section introduces some of these.

7.1 Different Topologies

At present each microcell is linked to only four other neighbours. This is supported in a toroid topology that enables the removal of boundaries from a standard square grid.

Other network topologies that have more intermicrocell links need to be tested. Extra connections should provide greater freedom of movement for messages. Although this would bring the communication space representation closer to that of biology, there is a cost in extra hardware.

7.2 Pipelining

The system developed so far has a very limited throughput. The activation level of each microcell must always settle to zero between stimulations. This is required to avoid data from different time frames mixing and consequently invalidating the output data stream. Ideally, the system should perform in a similar manner to a pipeline [18, 19] with each microcell group performing concurrently on consecutive data samples.

7.3 Message Redirection

The level of activity in each microcell is dependant on its location in the network. This is an undesirable consequence of the random nature in which the choice of next cell is made when passing messages. The flow of blood in a biological organism provides a broad transport medium for hormones. Blood carries hormones past all the cells in the organism, thus averaging the likelihood of cells receiving hormones.

The introduction of a biasing in the redirection algorithm for message transmission would make it possible to create a general direction of message flow within the network. This would lower the likelihood of activity localization within the network.

7.4 Fault Detection and Recovery

Ultimately, a system that has automated fault detection and recovery is desired. Following the design based on endocrine communication has led to a very suitable architecture for implementing such features.

7.5 Real World Application

The need for Reliability Engineering is a consequence of the use of electronics in Real World applications. A feasibility study of the presented system in use within a 'real world' context would be an interesting area for further work. Due to the data flow processing nature of the system, a possible application could be found in the area of Automated Control Systems.

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