Embryonics + Immunotronics: A Bio-Inspired Approach to Fault Tolerance

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Abstract

Fault tolerance has always been a standard feature of electronic systems intended for long-term missions. However, the high complexity of modern systems makes the incorporation of fault tolerance a difficult task. Novel approaches to fault tolerance can be achieved by drawing inspiration from nature. Biological organisms possess characteristics such as healing and learning that can be applied to the design of fault-tolerant systems. This paper extends the work on bio-inspired fault-tolerant systems at the University of York. It is proposed that by combining embryonic arrays with an immune inspired network, it is possible to achieve systems with higher reliability.

1 Introduction

As technology moves forward, modern societies depend on it to an ever-increasing extent. However, technology is a two-sided tool. On one hand, technological advances allow the efficient production of goods, removing from humans the burden of repetitive and physically demanding jobs. However, on the other hand, the consequences of system failure are more catastrophic as technology advances and humans are left 'out-of-the-loop'. This fact becomes more critical in systems where physical human intervention is extremely difficult, if not impossible; for example, satellites, space probes or monitoring-stations situated in hostile locations around the world.

This paper follows the hypothesis that one way to design very-long-life systems, is to look to nature for inspiration. The paper is organised as follows: Section 2 presents a general comparison between biological and bio-inspired systems. The main similarities and differences between the two are portrayed. The Phylogeny-Ontogeny-Epigenesis (POE) model is the theoretical framework for the work presented in this paper and is outlined here. Section 3 presents an introduction to Embryonics and Immunotronics. These are bio-inspired disciplines that draw inspiration from the process of embryo development in multi-cellular systems and the immune system, respectively. Section 4 develops the idea of combining embryonic arrays and Immunotronics (immunological electronics) in order to obtain a highly reliable cellular system. Section 5 presents some conclusions and proposes future work on the arena of bio-inspired systems.

2 Bio-Inspired Systems

Nature has always stimulated the imagination of humans, but it is only very recently that technology is allowing the physical implementation of incipient bio-inspired systems. Bio-inspired systems are man-made systems whose architectures and emergent behaviours resemble the structure and behaviour of biological organisms [1].

2.1 Emergent behaviours and the structure of living beings

Most of what is visible in biological organisms is the result of emergent properties and behaviours. A phenomenon is called emergent when results from the interaction between a number of entities (e.g. cells) show particular behaviour, or a particular property that the individual entities cannot achieve on their own [2]. In humans, the colour of the skin, body's temperature and thinking are all emergent properties. In order to study emergent properties and behaviours in biological organisms, it is necessary to study their hierarchical organisation. The following description applies to most living multi-cellular organisms (from insects to vertebrates).

At the bottom of the pyramid are the cells. Cells are the smallest indivisible living blocks out of which all organisms are built. During embryonic development, cells differentiate into different kinds. Humans have about 350 different cell types [3]. Groups of millions of specialised

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cells form organs and tissues (e.g. liver, kidneys and nerves). Each organ has a specific function that results from the activity of its constituent cells. Several organs constitute a system (e.g. nervous system, respiratory system and lymphatic system). Systems are more complex organisations whose function is essential for the survival of the organism. An organism is a collection of systems that interact with each other. The emergent characteristics and behaviours of organisms are considered the distinctive characteristics of life. When organisms interact, the result is either a society (interacting organisms belong to the same species), or an ecosystem (interacting organisms belong to different species). Societies and ecosystems also show emergent behaviours. Table 1 shows some characteristics of each level in this hierarchy.

Level	Characteristics	Examples of emergence
Cellular	• Basic unit: the cell (neurons, skin, T-cells). • Local interaction through electro-chemical signals with nearest neighbours. • No self-diagnosis mechanisms. • Every cell has a copy of the organism's genome. • Cells generate their own energy from nutrients circulating in the blood. • Able to reproduce. (Organism reproduction is a special case of cell reproduction)	• Body temperature. • Skin colour.
Organ	• Made out of groups of specialised cells (tissues). • Emergent functions determined by the activity of constituting cells • Some organs are duplicated (e.g. kidneys, lungs). • Can live if a (not necessarily) small percentage of constituent cells die. For duplicated organs the body can survive, in most cases, with only one.	• Processing of a particular chemical. • Heart's pumping action.
System	• Made from groups of organs and specialised tissues distributed throughout the body. • All systems are essential for the organism to live. • Systems are interdependent; they fulfil each others needs. • Communications through specialised systems: blood (chemical signals) and nerves (electric signals).	• Digestion. • Breathing. • Learning. • Healing
Organism	• Single body where all the systems interact. • Multipurpose system. Specialised within narrow limits. • Able to reproduce	• Personality • Feelings • Intellect
Society or Ecosystem	• Multiple organisms interact with one another. • In some cases, the survival of one species depends on the survival of other. • Organisms in some societies organise themselves into casts, each of which performs a different task for the community. • Sexual reproduction enables the evolution of species.	• Division of work • Social hierarchy • Food chains

Table 1: Hierarchical structure of biological organisms

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Bio-inspired systems can be classified according to their level of complexity and internal organisation. Table 2 shows some examples of bio-inspired systems and their correspondence with the hierarchy presented in Table 1. Note that in a strict sense, some of the examples could fit in more than one classification. Table 2 gives an idea of the complexity and interrelation of the systems presented.

Level	Examples of research done in this level
Cellular	• Self-reproducing cellular automata [4][5][6]. • Systolic and wavefront arrays [7][8]. • Embryonics [9][10].
Organ	• Neural networks [11][12]. • Artificial brains [13][14]. • Evolvable hardware [15][16][17]. • Design of sensors and actuators [18][19]
System	• Artificial limbs [20]. • Micro-machines [21]. • Hardwired controllers [22]. • Immunotronics [23].
Organism	• Learning systems [24]. • Autonomous robots [25].
Society or Ecosystem	• Evolutionary strategies [26]. • The "Tierra" project [27]. • Ant algorithms [28].

Table 2: Classification of bio-inspired research

Table 1 and Table 2 show that, although there are a considerable number of research projects on every level of the biological hierarchy, the level of integration of man-made systems is still far from that of the source of inspiration. The implementation of very-long-life systems requires further research aiming to integrate two or more levels from Table 2. The success of future unsupervised long-term missions will depend, to a great extent, on the emergent properties shown by their systems.

2.2 The POE model

Sánchez et al. proposed the Phylogeny-Ontogeny-Epigenesis model (POE model) of Figure 1 as an alternative framework to represent the three levels of organisation that can be distinguished in living organisms, namely population level, individual level and cellular level [29]. Each one of the levels is characterised by one kind of adaptive process. The POE model can also be used to classify the bio-inspired systems on Table 2. Research on evolvable hardware is situated in the phylogenetic axis. Research on neural networks, learning systems, autonomous robots, immunotronics and artificial brains fall on the epigenetic axis. Works on self-reproducing cellular automata, and embryonics find a place in the ontogenetic axis.

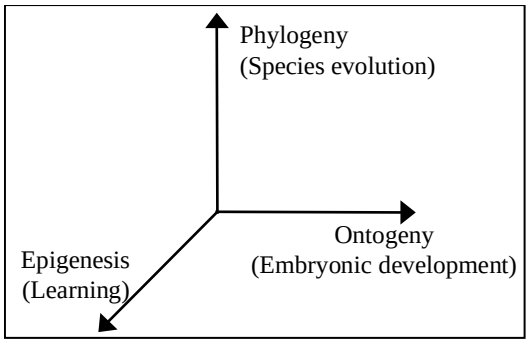

Figure 1: The POE model to classify bio-inspired systems

3 Embryonics and Immunotronics: Two Bio-Inspired systems

The Bio-Inspired Engineering Group at the Department of Electronics, University of York, investigates fault tolerance in bio-inspired systems. The aim is to investigate self-diagnosis and healing mechanisms found in biological systems and apply them to the design of fault-tolerant systems. At the present time, the research that is being undertaken covers three major topics: Embryonics, Immunotronics and Evolvable Hardware. The following sections present an architecture that integrates embryonic arrays with an immune inspired network.

3.1 Embryonics

Embryonics introduces a new family of fault-tolerant field programmable gate arrays (FPGAs) inspired by nature [9]. Its main ideas come from the mechanisms sustaining the embryonic development of multi-cellular organisms. When biological multi-cellular organisms reproduce, the new individual is formed out of a single cell (the fertilised egg). During the days that follow conception, the egg divides itself passing to every offspring a copy of the DNA that corresponds to the individual under development. Cells differentiate according to 'instructions' stored in their DNA. Different parts of the DNA are interpreted depending on the position of the cell within the embryo [3]. Before differentiation, cells are (theoretically) able to take over any function within the body because each one possesses a copy of the DNA.

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Correspondingly, every electronic cell in an embryonic array stores not only its own configuration register, but also those of its neighbours. To differentiate, every cell selects a configuration register according to its position within the array. Position is determined by a set of co-ordinates that are calculated from the co-ordinates of the nearest neighbours. Every embryonic cell performs self-checking continuously. If a failure is detected, the faulty cell issues a status signal that eliminates some cells according to the reconfiguration mechanism in use, e.g. cell elimination, row elimination. The surviving cells recalculate their co-ordinates and select a new configuration register. By doing so every cell performs a new function and, if the amount of spare cells is enough to replace all the failing cells, the overall functionality of the original array should be preserved. A detailed description of the Embryonics architecture can be found in [10].

3.2 Immunotronics

The human immune system is capable of recognising virtually any foreign cell of molecule. To do this, it must distinguish the body's own cells and molecules (*self*), that are created and circulated internally (estimated to consist of on the order of 10^5 different proteins) from foreign antigens (*non-self*). It has been estimated that the human immune system is capable of recognising on the order of 10^{16} different foreign molecules [30]. From a pattern-recognition perspective, these are staggering numbers, particularly when one considers that the human genome, which encodes the 'program' for constructing the immune system, only contains 10^5 genes, and further, that the immune system is distributed throughout the body with no central organ to control it [31].

The immune system possesses several unique features that are of particular interest in the design of fault tolerant systems [32][33]:

- It functions continuously and autonomously using its own network of lymphatic vessels independent of other systems in the body.
- The cellular defence mechanisms are distributed throughout the body to serve all the organs. The hardware equivalent suggests distributed fault detection with no centralised fault recognition and recovery.
- The immune system learns and remembers from past experiences what it should attack. The hardware analogy suggests the training of fault detection mechanisms to differentiate between faulty and fault free states.
- Detection of invaders is imperfect. Approximate matching is used to increase the range of antigens that are detected, even without previous knowledge of their structure (this is the basis of immunisation).

Immunity is a multi-layered architecture starting with physical barriers in the form of the skin, through physiological barriers in the form of temperature and acidity through to chemical and cellular interactions in the form of innate and acquired immunity [34].

Antibody mediated immunity (a part of the acquired immune system) protects the body from extra-cellular infection by performing a complex approximate matching process whereby immune cells, or *antibodies* possess 'keys' that approximately fit the 'locks' possessed by antigens. These are learnt during a centralised development stage in an organ known as the *thymus*. Self cells, or proteins circulate through the thymus and are exposed to a subset of immune cells called *helper T-cells*. If any binding occurs then the T-cell is destroyed. Only those T-cells that are self-tolerant survive to become part of the distributed immune system. The process is known as *clonal deletion* and is demonstrated in Figure 2.

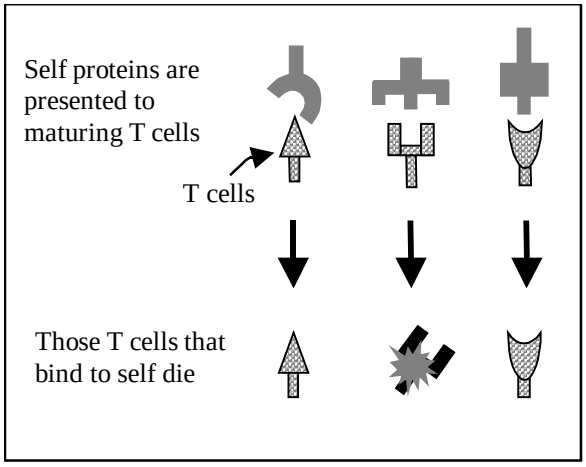

Figure 2: Centralised development of the library of immune T cells

Upon development, helper T-cells become response activators, permitting a reaction between antibodies (B-cells) and potential antigens if the corresponding T-cell exists to initiate the response. In this way only foreign antigens are attacked and the cells of the body remain intact. The process is shown in Figure 3.

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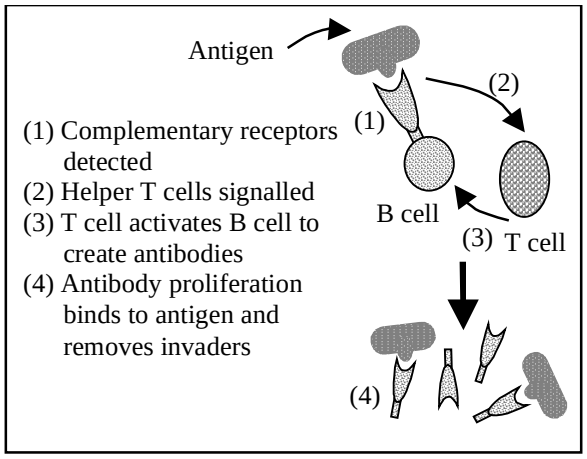

Figure 3: Antibody mediated immunity

The immune system has already been a major source of inspiration in the design of novel pattern recognition based applications including computer security [33] and virus protection [35]. The proposal of Immunotronics [36][23] is to explore the processes carried out by the human immune system to inspire new methods of fault tolerance that have already proven successful in nature. As has been provided for a software immune system [37], Table 3 demonstrates a possible mapping of features from immunology to hardware.

Immune System	**Hardware Fault Tolerance**
Self	Normal/acceptable operation
Non-self (antigen)	Faulty/unacceptable operation
Antibody (B cell)	System state/tolerance condition comparison
Memory cells	Set of stored tolerance conditions
Learning during gestation	Learning of tolerance conditions
Inactivation of antigen	Return to normal operation
Life of organism	Operation lifetime of the hardware

Table 3: Immune system to hardware fault tolerance mapping

4 Immuno-Embryonics

Reliability of an individual embryonic cell is currently implemented through duplication of the functional components (multiplexer and flip-flop) [38]. The cells currently lack a real-time method of verifying that each is performing the correct operation with respect to neighbouring cells, although off-line solutions are currently used [10]. The presence of a fault within the address generator or configuration registers has the potential to dictate incorrect logic and routing. This is very similar to a process of self/non-self discrimination.

4.1 General Architecture

It is proposed in this work to incorporate an additional layer onto our embryonic architecture that will imitate the actions of antibody cells. The cells continuously monitor and evaluate the state of each embryonic cell. Figure 4 and Figure 5 show a comparison of the natural immune system and embryonic immunity.

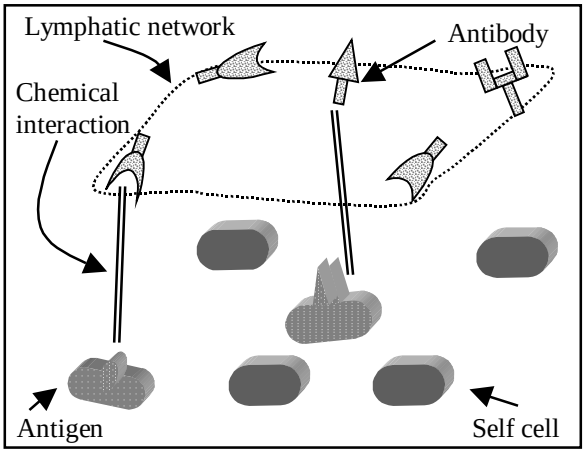

Figure 4: Lymphatic interactions with invading antigens in the body

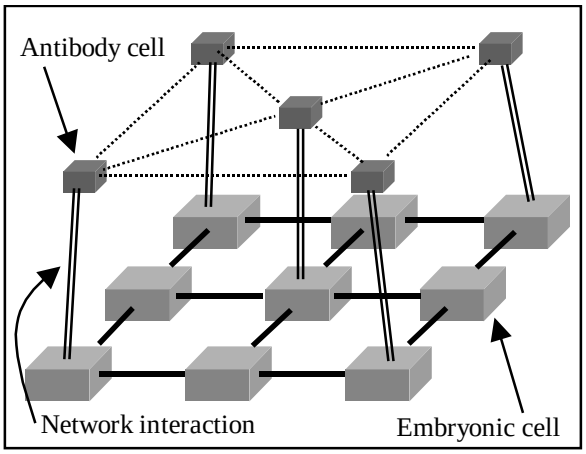

Figure 5: Immune – embryonic layer interactions

A number of potential configurations are being considered in this research. If only a single antibody cell

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monitors an embryonic cell then another single point of failure exists within the antibody cell (Figure 6). A far better solution is through the implementation of an interacting network of antibody cells. Each embryonic cell is then monitored by a number of immune cells, that in turn, monitor different embryonic cells. Figure 7 and Figure 8 present two improved configurations.

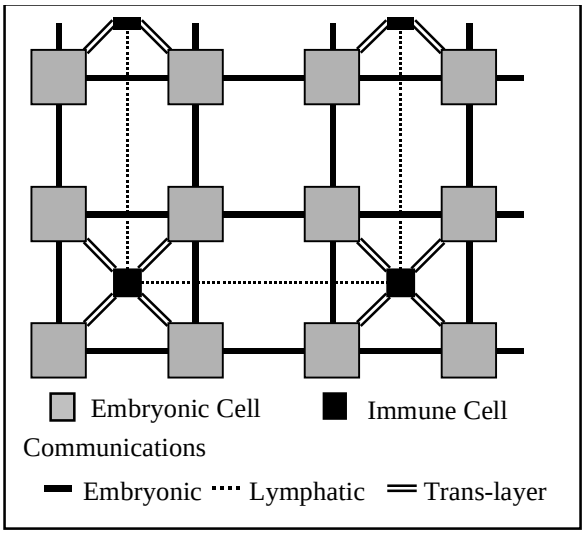

Figure 6: Antibody cell monitors the four closest neighbours. No replication of antibody cells.

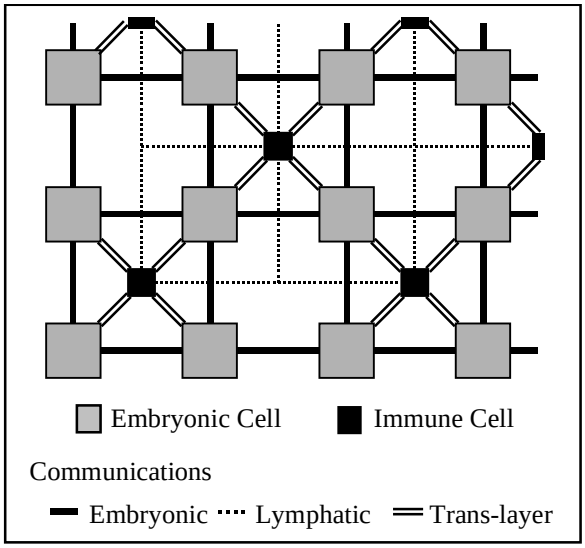

Figure 7: Antibody cell monitors the four closest neighbours. Each embryonic cell monitored by two antibody cells

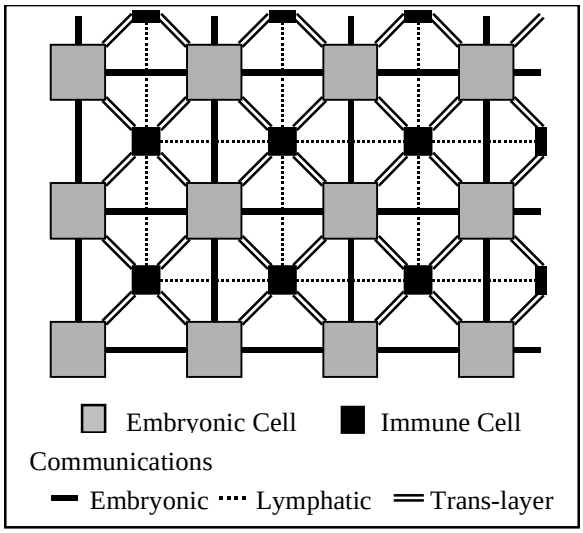

Figure 8: Antibody cell monitors four closest neighbours. Each embryonic cell monitored by four surrounding antibody cells

Each configuration uses three independent sets of communications channels: The embryonic array still maintains sole use of its data channels; the antibody cells have their own channels for data transfer, similar to a lymphatic network; the third set of channels provides trans-layer communications so antibody cells can monitor and interact with embryonic cells.

4.2 Antibody Cell Architecture

Using Figure 8 as a demonstration example, each antibody cell reads in configuration data from the neighbouring embryonic cells in turn (cell position *x,y* through to *x+1, y+1* in Figure 9), the choice of which is made through a continuously cycling counter and multiplexed set of input streams. The memory, or *tolerance condition* [23] stores the correct configuration of just the four neighbouring embryonic cells enabling a comparison of the configuration data by selecting the appropriate memory location. A data match creates an 'OK' signal, a mismatch a 'KILL' signal. The basic architecture of the antibody cell is shown in Figure 9. In contrast to the natural immune system, each antibody cell stores related self-tolerance conditions and not non-self. With only four valid tolerance conditions per antibody cell, this is a far more efficient solution.

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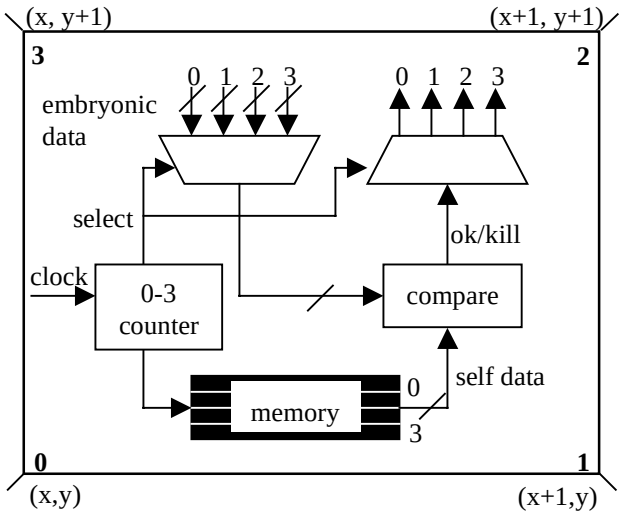

Figure 9: Architecture of the antibody cell – comparison logic

Each embryonic cell requires only a small number of modifications to support the lymphatic network of antibody cells. Configuration data needs to be output to all surrounding antibody cells (for example 4 in the case of Figure 8) either in serial or parallel. Parallel connectivity simplifies the logic in both the embryonic and antibody cells at a cost of increasing the inter-cellular communications. A neater solution is the serial transmission of data between networks and subsequent decoding within the antibody cell. To perform this each embryonic cell requires logic to shift out the configuration data bit by bit, and each antibody cell requires complementary logic to convert the data back to its original form (Figure 10).

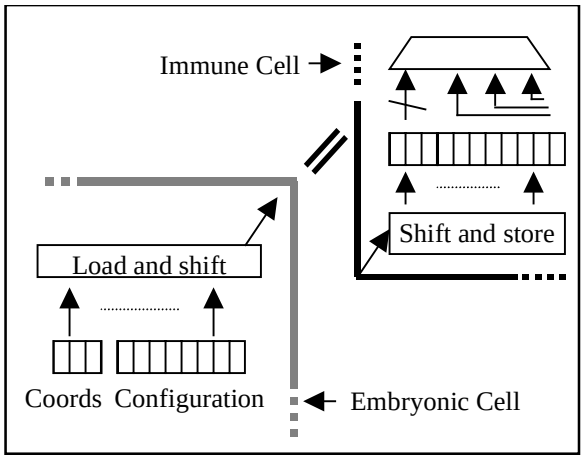

Figure 10: Additions to cells – data transfer and receive logic

Further reliability is provided through the repeated verification of embryonic cells by a number of antibody cells. Antibody cell faults can be masked if each embryonic cell requires, as in the case of Figure 8, three out of four 'ok/kill' signals to match before the appropriate action is taken.

The numbering of neighbouring embryonic cells (denoted in Figure 9 by 0 through to 3) ensures that at any one time the configuration data in every embryonic cell is being analysed, as shown in Figure 11.

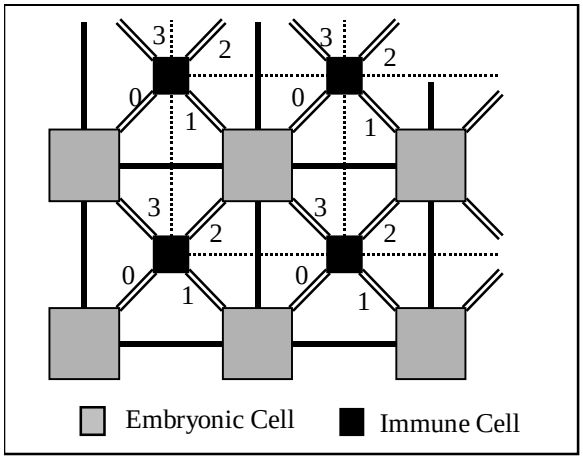

Figure 11: Cell numbering to provide continuous monitoring

In parallel to communications between the embryonic cells, the lymphatic network connects antibody cells. The network is used to load and change the tolerance conditions in each cell as the embryonic array reconfigures. This reduces the storage content of each antibody cell making each cell independent of the size of the complete array. The configuration of Figure 8 requires a maximum 23 bits for each configuration/coordinate tolerance condition for the embryonic array design of [10], giving a total requirement of 92 bits per antibody cell.

The time taken to confirm a correct configuration is dependant upon the clock used to shift data from one network to the other. Using the global clock provided to all embryonic cells is simpler, but means that cell testing is only completed at a maximum *b* clock cycles, where *b* is the number of bits per tolerance condition. A clock rate increased by a factor *b* permits complete system configuration testing every embryonic clock cycle, at the cost of additional complexity.

4.3 Antibody Learning

The antibody cells need to undergo a learning stage before the system can be used (analogous to maturation of T-cells in the thymus). Initial configurations can be read

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directly from the surrounding embryonic cells during an initialisation phase. A primary test phase can then be executed to compare the antibody and embryonic tolerance conditions to ensure the correct configurations have been stored. The antibody network therefore requires no external configuration or programming, taking the data from the embryonic network. It is assumed in doing this that the hardware is initially fully functional and fault free.

4.4 Embryonic Reconfiguration and Recovery

The act of reconfiguration prompts a new configuration register to be selected, dependent upon the new coordinates received. The process of row elimination, as shown in [38] renders numerous embryonic cells redundant for what may only be a transient error in a single cell – the best solution to prevent faulty outputs. Antibody cells can continue monitoring these rows to permit later activation of the redundant embryonic cells should the cell no longer deviate from correct functionality.

5 Conclusion

Systems intended to provide their service for long periods of time require levels of fault tolerance very difficult to achieve using conventional techniques. One possible solution to this problem is to draw inspiration from nature and incorporate biological-like characteristics to long-life systems. It is expected that by doing so, emergent mechanisms, such as healing, can be achieved.

This paper has presented a novel approach to providing increased reliability within an embryonic array. The already biologically motivated topic of embryonics is enhanced with further biological properties inspired by the human immune system. The lymphatic network of antibody cells provides fault tolerant distributed monitoring and verification of embryonic configuration and coordinate data to ensure at any point in time each embryonic cell is performing the correct operation.

Currently we are considering the integrity of configuration and coordinate data. The future of this work lies in expanding these ideas to the functionality of the embryonic cells and in the healing of cells by the antibody cells. Such mechanisms will surely be required for long-term missions whether on this planet or future off-planet missions.

Acknowledgements

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References

[1] C. Langton, Artificial Life, Santa Fe Institute Series, Vol. IV, Addison-Wesley, 1989

[2] J. Holland, Emergence: From Chaos to Order, Oxford Univ. Press, 1998

[3] L. Wolpert, The Triumph of the Embryo, Oxford University Press, 1991

[4] J. Von Neumann, Theory of Self-Reproducing Automata, edited and completed by A. Burks, Univ. of Illinois Press, 1966

[5] C. Langton, "Self-reproduction in Cellular Automata", *Physica 10D*, pp.135-144, 1984

[6] G. Tempesti, "A New Self-reproducing Cellular Automaton Capable of Construction and Computation", in F. Morán. (Ed.), *ECAL'95: 3rd European Conference on Artificial Life*, LNCS 929, Springer-Verlag, 1995

[7] J. Fortes, B. Wah, "Systolic Arrays - From Concept to Implementation", *IEEE Computer*, Vol.20-7, pp.12-17, July 1987

[8] S.Kung., S. Lo, S. Jean , "Wavefront Array Processors - Concept to Implementation", *IEEE Computer*, Vol.20-7, pp.18-33, July 1987

[9] D. Mange , M. Goeke, D. Madon, A. Stauffer, G. Tempesti, S. Durand, "Embryonics: A new family of coarse-grained FPGA with self-repair and self-reproduction properties", in E. Sanchez, M. Tomassini (Eds), *Towards Evolvable Hardware: The evolutionary engineering approach*, LNCS 1062, pp.197-220, Springer-Verlag, 1996

[10] C. Ortega, D. Mange, S. Smith, A. Tyrrell, "Embryonics: A Bio-Inspired Cellular Architecture with Fault-Tolerant Properties", *Genetic Programming and Evolvable Machines*, Vol.1-3, pp. 187-215, July 2000

[11] M. Dyer, "Toward Synthesising Artificial Neural Networks that Exhibit Cooperative Intelligent Behaviour: Some open issues in Artificial Life", in Langton C. (Ed.), Artificial Life: an Overview, pp.111-134, MIT Press, 1995

[12] T. Morishita, I. Teramoto, "Architecture of Cell Array Neuro-Processor", in [15], pp.277-288

[13] T. Ae, H. Fukumoto, S. Hiwatashi, "Special-Purpose Brainware Architecture for Data Processing", in [15], pp.289-301

0-7695-0762-X/00 $10.00 © 2000 IEEE

[14] H. de Garis, "CAM-BRAIN: The evolutionary engineering of a billion neuron artificial brain by 2001", in E. Sanchez, M. Tomassini (Eds), *Towards Evolvable Hardware: The evolutionary engineering approach*, LNCS 1062, pp.76-98, Springer-Verlag, 1996

[15] T. Higuchi, M. Iwata, W. Liu (Eds), Evolvable Systems: From Biology to Hardware, LNCS 1259, Springer-Verlag, 1997

[16] M. Sipper, D. Mange, A. Perez-Uribe (Eds), Evolvable Systems: From Biology to Hardware, Proceedings of ICES98, LNCS 1472, Lausanne, Switzerland, September, 1998

[17] A. Stoica, D. Keymeulen, J. Lohn (Eds), Proceedings of 1st NASA/DoD Workshop on Evolvable Hardware, Pasadena, CA, USA, IEEE Computer Society, July 1999

[18] J. Fraden, Handbook of Modern Sensors: Physics, Design and Applications, American Institute of Physics, 1997

[19] A. Dorey, J. Moore (Eds), Advances in Actuators, The Institute of Physics, 1995

[20] I. Kajitani, T. Hoshino, D. Nishikawa, H. Yokoi. et al., "A Gate-Level EHW Chip: Implementing GA Operations and Reconfigurable Hardware on a Single LSI", in [16], pp.1-12

[21] T. Fukuda, W. Menz (Eds), Micro Mechanical Systems: Principles and Technology, Arner Elsevier, 1998

[22] T. Naito, R. Odagiri, Y Matsunaga, M. Tanifuji, K. Murase, "Genetic Evolution of a Logic Circuit which Controls an Autonomous Mobile Robot", in [15], pp. 210-219

[23] D. Bradley, A.Tyrrell, "Immunotronics: Hardware Fault Tolerance Inspired by the Immune System", *Proceedings 3rd International Conference on Evolvable Systems*, LNCS 1801, pp. 11-20, Springer-Verlag, April 2000

[24] I. Aleksander, "Iconic Learning in Networks of Logical Neurons", in [15], pp.3-16

[25] J. Yamamoto,Y. Anzai, "Autonomous Robot with Evolving Algorithm Based on Biological Systems", in [15], pp. 220-233

[26] M. Tomassini, "Evolutionary Algorithms", in E. Sanchez, M.Tomassini (Eds), *Towards Evolvable Hardware: The evolutionary engineering approach*, LNCS 1062, pp. 19-47, Springer-Verlag, 1996

[27] T. Ray, "An Evolutionary Approach to Synthetic Biology: Zen and the Art of Creating Life", in Langton C. (Ed.), Artificial Life: An Overview, MIT Press, pp.179-209, 1997

[28] M. Dorigo, V. Maniezzo, A. Colorni, "The Ant System: Optimisation by a Colony of Cooperating Agents", *IEEE Trans. on Systems, Man and Cybernetics- Part B*, Vol. 26-1, pp. 29-41

[29] E. Sanchez, D. Mange, M. Sipper , M. Tomassini , A. Pérez-Uribe, A. Stauffer., "Phylogeny, Ontogeny and Epigenesis: Three sources of biological inspiration for softening hardware", in [15], pp.35-54

[30] J. Inman, "The Antibody Combining Region: Speculations on the hypothesis of general multispecificity", in G. Bell, A. Perelson, G. Pimbley (Eds), Theoretical Immunology, pp.243-278, New York: Marcel Dekker, 1978

[31] M. Mitchel, S. Forrest, "Genetic Algorithms and Artificial Life", in C. Langton (Ed.), Artificial Life: An Overview, pp.267-289 , MIT Press, 1997

[32] A. Avizienis, "Towards Systematic Design of Fault-Tolerant Systems", *IEEE Computer*, Vol. 30-4, pp.51-58, April 1997

[33] S. Forrest, S. Hofmeyr, A. Somayaji, "Computer Immunology", Comm. of the ACM, Vol. 40-10, pp. 88-96

[34] C.A. Janeway, P. Travers, Immunobiology, the Immune System in Health and Disease, Churchill Livingstone, 1996

[35] J.O. Kephart, "A Biologically Inspired Immune System for Computers", in R.A. Brooks, P. Maes, (Ed), Artificial Life IV, Proceedings of the Fourth International Workshop on the Synthesis and Simulation of Living Systems, pp.130-139, 1994

[36] A.M. Tyrrell, "Computer Know Thy Self!: A Biological Way to look at Fault Tolerance", 2nd Euromicro/IEEE Workshop on Dependable Computing Systems, 1999

[37] S. Xanthakis, S. Karapoulios, R. Pajot, A. Rozz, "Immune System and Fault Tolerant Computing", in Alliot, J.M. (Ed), Artificial Evolution, LNCS 1063, pp. 181-197, Springer-Verlag, 1996

[38] G. Tempesti, D. Mange, A. Stauffer, "A Robust Multiplexer-Based FPGA Inspired by Biological Systems", *Journal of Systems Architecture (The EUROMICRO Journal)*, Vol. 43-10, pp. 719-733, 1997

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