Evolvable Hardware, a Fundamental Technology for Homeostasis

Andy M. Tyrrell*, Jon Timmis*†, Andrew J. Greensted* and Nick D. Owens*
*Department of Electronics, University of York, Heslington, York, UK
Email: {amt, jt512, ajg112, ndlo100}@ohm.york.ac.uk
†Department of Computer Science, University of York, Heslington, York, UK

***Abstract*— Maintaining electronic systems in a steady (homeostatic) state of operation so that they perform their tasks when under stress is non-trivial. In order to achieve this we propose an extensible architecture, inspired by the natural immune system. We believe that evolvable and adaptive hardware is a critical underlying technology for homeostasis, and maintenance of homeostasis in electronic systems will be one of the application where evolvable hardware could make a significant impact.**

I. Introduction

Evolvable electronic hardware (EEHW) has been with us now for approximately ten years [1]. During this time a number of forms of evolvable hardware have been developed. A rather successful example of this being antennae design [2]–[4]. Within EEHW the usual bifurcation made between systems is related to implementation: intrinsic (approximating to on-line evolution) and extrinsic (approximating to off-line evolution) [5]. Within both of these implementations the applications used are generally simple digital circuit design, we will not give a particular reference here, a quick search on evolvable hardware will furnish the reader with many and varied examples.

While these basic applications are useful for illustrating a particular point or method, in most cases they are not on their own of any inherent use, nor, in our opinion, will they ever be. A quick search through the literature should be enough to convince the reader. Being generous, the most complex digital designs produced by evolvable hardware (whether intrinsic or extrinsic) is of the order to 10,000 transistors. The significance of this number can be highlighted by Figure 1 which illustrates the progress of Intel processors over the last 30 years. This particular graph demonstrates Moore's Law [6], [7], however it is also very useful for our purposes. Consider where 10,000 transistors are on this graph, 1975. Given this, it is clear how more advanced conventionally designed circuits are, it is also difficult to imagine how evolvable hardware will ever catch up. EEHW may of course be useful within as part of a standard design process, but that is not the topic of this paper.

Despite this rather pessimistic view, all is not lost for evolvable hardware. What are the characteristics that one might expect to find in an evolvable hardware system? It is difficult to generalise because the answer depends on a number of factors decided at the beginning of the process. However, a core set of characteristic are listed below [9].

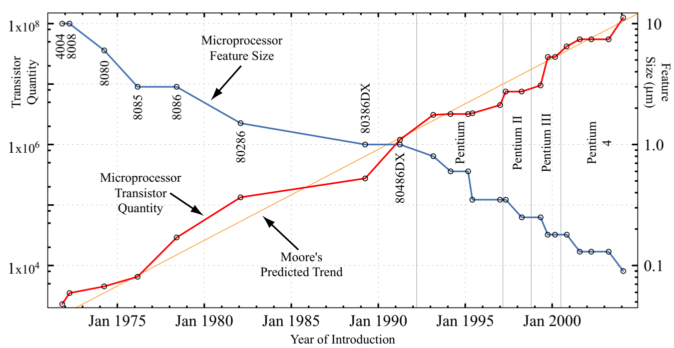

Fig. 1. A illustration of Moore's Law related to Intel® microprocessors. The graph shows the trend in microprocessor feature size and transistor quantity from 4004 (1971) to Pentium 4 (2002) [8].

1) The system will be evolved not designed (an obvious one, but worth pointing out)
2) A final solution may not be an optimal design, but will be fit for the purpose (typical of biological systems in general-due to the evolutionary process)
3) Evolved systems show levels of fault tolerance not seen in designed systems (again typical of biological systems)
4) The system should be adaptable to environmental changes (this is dependent upon when the evolutionary cycle stops. This is not necessarily true for evolved systems that stop once the goal has been reached. Again this is a characteristic of all biological systems)
5) Unverifiable systems are produced. Indeed in many cases it is difficult to analyse the final system to see how it actually performs the task.

For the purpose of this paper, the third and fourth points are of particular interest to us here: fault tolerance and adaptability. Electronic devices can suffer from perturbations of normal operational performance. Such perturbations may be caused by environmental conditions, ageing effects, design flaws or poor manufacturing. In order to maintain service, mechanisms are required to restore the operation of the device to within these normal operating parameters. In this paper we take evolvability and another bio-inspired method, artificial immune systems, and propose a new area where the use of evolvable hardware could make major strides: Homeostasis.

It is the capacity for adaptability of evolution that is of interest. Take a system that includes domain knowledge in structure and design and allow evolution to adapt the system to environmental change. In other words, rather than using evolution to design complete systems, utilise evolution's intrinsic adaptivity.

The biological immune system performs an integral part in maintaining host homeostasis; the maintenance of a steady operational state [10]. This process is similar to many tasks that are performed by Electronic systems, such as condition monitoring and fault circumvention. We propose that when realised in an artificial case, homeostasis will be maintained via the system's ability to predict, detect and react to system faults, something that is at present unobtainable by traditional methods.

In this position paper we explore the role of the immune system in maintaining the hosts body, and how this can give rise to a homeostatic system. We then map these ideas into an immune inspired extensible architecture that we propose can be used as a blueprint for the development of homeostatic electronic systems. We outline a simple case study of a mobile robot, where the architecture can be realised and explain what one might expect to observe from such a system. We make the argument, that in order to realise this *homeostatic* architecture, the use of an EEHW platform is necessary. This will break new ground for the application of EEHW away from the traditional application of an evolutionary algorithm in hardware, to the use of the adaptability of the EEHW platform itself to assist in maintaining host homeostasis.

II. Immune System Homeostasis and Maintenance

In order to maintain homeostasis, there exist many systems within an organism that, through their interactions, give rise to stability. These interactions are widely acknowledged as operating between the immune, neural and endocrine systems [10]. However, homeostasis also occurs individually within each one of these systems. In order to develop an extensible architecture, we have decided to concentrate on a single system, the immune system, and the property of immune homeostasis [11].

The most popularly held purpose for the immune system is defence against pathogens, requiring the discrimination between self and non-self. In physiological terms, the output of the immune system is simple inflammation. The effect of inflammation is to perform maintenance on the body keeping it fit for living, not the discrimination of self from non-self antigen. Cohen [12] believes that the result of inflammation, and hence the role of the immune system, is to repair and maintain the body. As the removal of pathogen is beneficial to the health of the body, defence against pathogen can be seen as just a special case of body maintenance.

In order to achieve body maintenance, the immune system must select and regulate the inflammatory response according to the current condition of the body. This condition is assessed by both the adaptive and innate immune agents, which are required to recognise both the presence of pathogen (non-self antigen) and the state of the body's own tissues (self antigen) [13]. The specificity of the immune response, therefore, is not just the discrimination of danger [14], or the distinction of self/non-self, but the diagnosis of varied situations, and the evocation of a suitable response.

In summary, Cohen's maintenance role of the immune system requires it to provide three properties: *Recognition:* to determine what is right and wrong, *Cognition:* to interpret the input signals, evaluate them, and make decisions. *Action:* to carry out the decisions. We propose that these roles are analogous to those performed by any artificial monitoring system. Our proposed architecture exploits these roles in an artificial context. Exploitation of the ideas from Cohen in Artificial Immune Systems has already begun in the context of the evolution of degenerate pattern recognition systems [15].

III. Overview of the Proposed System

As we have stated, we propose to develop an architecture that enables the creation of homeostatic electronic systems. Our overall vision is a system capable of performing all its primary functions even when subjected to harsh environmental influences and disruptive internal factors.

Maintaining homeostatic stability may be defined as the requirement to satisfy a set of stability measures through actions that adjust the host's internal state and external environment. Therefore, by selecting an appropriate set of metrics, providing the sensors to quantify them and the necessary corrective actuators, the system will continue to undertake its mission, despite adversity, in an effort to achieve homeostatic stability. However, it should be obvious that for this to occur a major component of such a system will require an underlying adaptable hardware system - a system capable of evolving.

Using the proposed architecture, system operation is driven by the need to satisfy the list of metrics. Metrics are classified as either stability metrics, those that provide a measure of the system's stable state, or task metrics, those that measure the progress of the system's tasks. An example stability metric might be system temperature (you can think of your own example here - it is applicable to many scenarios). Satisfying this metric requires controlling system temperature within safe bounds, which consequently contributes to overall system homeostasis by helping maintain system stability. A task metric, such as robot progressing along a path, would be satisfied by moving towards the path's target, thus driving the operational progress of the system.

Satisfying metrics, of either class, requires the ability to sense and act upon the internal system state and the external environment. To fulfil this requirement, any architecture will be required to utilise a rich sensory input to inform the level of metric satisfaction. In turn, actuators provide the capabilities to change metric satisfaction levels. A powerful feature of our proposed architecture is the extensibility of the sensor and actuation field. Increasing, or even decreasing, the sensory and actuation range is an intrinsic property of the architecture. This feature may be harnessed statically at designed time, or more interestingly, dynamically during system operation.

To be more concrete, we will now present an example of a mobile robot system. This example will demonstrate; how

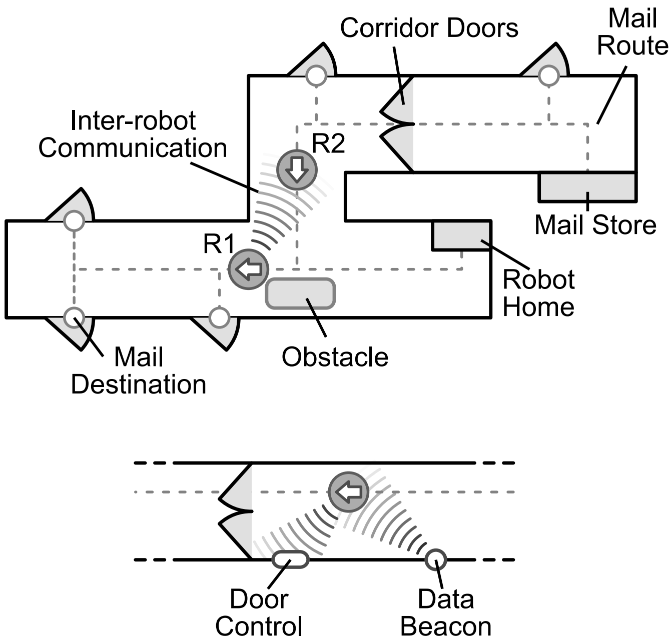

Fig. 2. An example system, a robotic mail handling system. The robots must operate in a dynamic environment making use of information from fellow robots and the environment in order to maintain stability.

a single, general homeostasis architecture may be used to both coordinate system operations as well as maintain internal system integrity; how the extensibility of the architecture may be utilised; and how the architecture design may be inspired by the immune system. From this it is clear that an underlying evolvable platform is required to implement these ideas.

IV. An Example System: Robotic Mail Handling System

Many possible non-trivial applications for the homeostasis architecture can be found in the field of robotics. Robots operating in anything but the most constrained environments will be subjected to many disruptive external influences. Not only do these influences hinder the completion of tasks, but they can also affect the reliability of a robot's constituent components.

Figure 2 depicts two robots performing the task of distributing mail in a populated office environment. Each robot collects mail from the mail store, then, via a preset route, delivers its payload to the correct mail destination.

During the process of delivery, each robot will encounter obstacles to its delivery objective due to the dynamic nature of the environment. These obstacles are both external, such as physical objects blocking movement, and internal, such as component failure. Using the proposed architecture and a suitable set of metrics, each mail delivery robot can be driven to perform its task even with the occurrence of perturbing obstacles. A basic set of metrics for a single mail delivery robot is shown in Table I.

A brief analysis of Table I shows that in the effort to satisfy every metric, each mail delivery robot will attempt to deliver mail from the store to their destinations. Furthermore, the same metric set will drive the maintenance of system stability by feeding into a control system to regulate temperature, and speed.

The robots have access to a diverse range of sensors in order to quantify the level of satisfaction for each metric. These sensors are both internal, those that measure system state, and external, those measuring environmental state. For example to guide a robot along the mail delivery path, input data can be received from wireless transmitters along the route, on board ultrasound measurements indicating distance from obstacles, and signals from other robots.

Actuators provide a mechanism to control the robots operation, internal state, and external environment. For example, to keep driving circuitry within an acceptable temperature range, actuation in the form of fans keeps temperature stability.

In order that the architecture can interact with a dynamic environment, it must be able to tolerate changes in the availability of sensor data and actuator controls. This is made possible due to the extensible and adaptive nature of the architecture. The architecture's extensibility lies in its intrinsic ability to evolve and dynamically fuse new data sources and make use of new actuation outputs. Furthermore, evolution provides a method of adapting how sensory information is interpreted, providing different approaches to detection of instability. Similarly, using evolution to adapt methods of responding to instability provides the system with a method of maintaining stability when a form of actuation becomes unfeasible.

In the example application, one robot is able to receive information from another, adapt its architecture and incorporate the remote robot's data stream into its own homeostasis system. This would, for example, allow one robot to inform others of a new obstacle. Furthermore, the ability to dynamically increase the range of actuation allows a robot to take control of new environment actuators. In the case of the example application, this would allow a robot to control a door, gate or lift once within the obstacle's proximity.

V. The Homeostatic Architecture

We will now outline how the homeostatic evolvable architecture will be built. Consider Figure 3, using the immune system as our inspiration, we propose an innate like layer, comprised of Dendritic cells (DCs), and an adaptive like layer, comprised of T-cells (TCs).

A. Innate Layer

The innate biological immune system is believed to classify unusual entities (antigens) encountered in the body and to elicit higher-level immune responses only when necessary. This occurs by presenting the antigen to the adaptive immune system in the presence of signals that indicate danger [14]. The presentation of antigen is performed in the biological immune system by antigen presenting cells (APCs). The presence of 'danger-signals' is one of the biological theories that are used to explain the way in which the immune system deals with

TABLE I

A SET OF EXAMPLE TASK AND STABILITY METRICS FOR THE EXAMPLE ROBOTIC MAIL DELIVERY SYSTEM.

Task Metric	**Metric Variable**	**Desired value**	**Action**
Delivery of Mail Payload	Letters left to deliver (L_D)	$L_D = 0$	Deliver Letters to Mail Destinations
Collectable Mail	Letters Awaiting collection (L_C)	$L_C = 0$	Collect letters from Mail Store

Stability Metric	**Metric Variable**	**Desired value**	**Action**
Circuit Temperature	Temperature (T)	$T < 45^oC$	Enable cooling fans
Drive Speed	Speed (S)	$S < 1m/s$	Reduce speed
Proximity to Mail Route	Distance from route (D_R)	$D_R = 0$	Steer towards route
Proximity to Obstacle	Distance from obstacle (D_O)	$D_O > 1m$	Steer away from obstacle

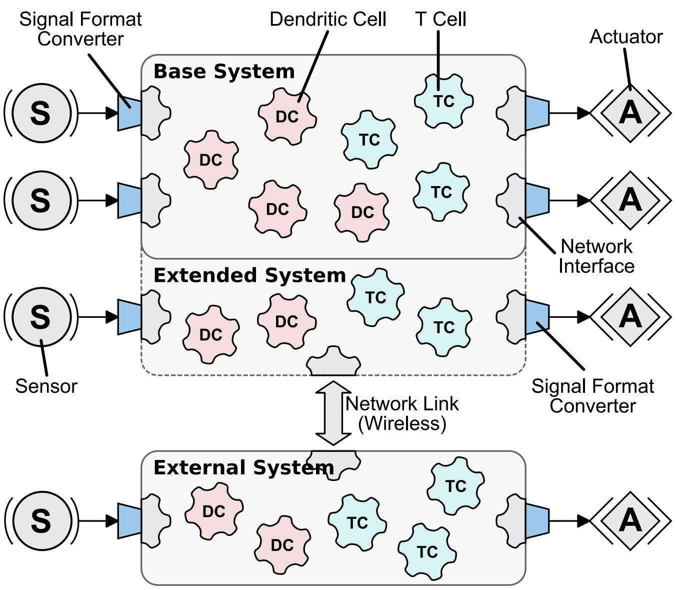

Fig. 3. The immunology inspired homeostatic architecture. An innate layer provides a detection stage, signalling potential deviations from stability. An adaptive layer acts upon the signals by invoking actions to restore stability.

various threats and is ripe for exploitation within a system such as that proposed here. But to implement this successfully the hardware architecture needs to be adaptable, hence the requirement for an EEHW platform.

The use of the innate immune system APC analogy will allow this mechanism to be tested in a closely analogous environment. The innate artificial layer of the prototype is the monitor and will be analogous to that of dendritic cells. This layer will allow an effective ’filtering’ of the data for detecting potential anomalies in the data stream. For example, our robot will contain a number of sensing devices such as ultrasound, bump sensors, internal sensors to monitor components of the robot, identified in Figure 3 as S. The detection of unusual patterns will be based upon the mechanisms used in DCs that break down antigens into chunks that capture the essential identifying features of the antigen. These features distinguish between different antigens and may require different types of remedial action. When an unusual pattern is detected, a signal will be transmitted from the innate layer, to the adaptive layer of the artificial immune system. Recent work by [16], [17], has developed a simple immune inspired approach based on the notion of dendritic cells, for the identification of possible danger signals that a system may create. Their approach created a system that could identify data items that deviated a certain amount from danger signals, or signals that indicate some form of deviation from normal behaviour.

B. Adaptive Layer

The adaptive biological immune system’s role is to attack pathogenic material that the innate system has identified as dangerous. The adaptive immune system is capable of inter-relating and coordinating the response to such threats.

The ultimate objective being removal of pathogenic material and retention of the ability to deal with similar threats in the future. This is achieved through a complex process of pattern matching, cloning of cells, mutation and selection of B and T-cells (basic components of the immune system), and the creation of a memory set of cells that are capable of identifying and reacting to potential danger.

In our architecture, as shown in Figure 3, we have simplified the picture with the adoption of only T-cells. The adaptive artificial layer will be analogues to the production of memory T-cells through the process of cloning, mutation and selection.

This layer of the system will continuously monitor incoming danger signals from the innate layer, and update the repertoire of potential dangers that it can recognise. The simplicity of the danger signals generated by the innate layer means that (as in the biological immune system) a large number of data will be presented to the adaptive immune system. Ultimately, when a sufficient level of activity is present in the adaptive layer of the immune response, an alarm will be raised to indicate a high probability of deviation from our desired homeostatic state. Figure 3 shows that actuation, labelled A, can be performed to take any corrective action required. This will be controlled

Fig. 4. Cohen's [12] view of immunology. Detection of instability, instigation of a solution, followed by action to restore stability.

by specialist T-cells that will adapt to the role of initiating actuation.

C. Architecture Layer

It seems clear to us that if we are to achieve real-time system performance, with characteristics that in someway mimic anything like the processes described above we need a new hardware vision for future systems design - for us this is an evolvable hardware platform. An architecture that can adapt continually to the changes in its environment, to its own condition (is in someway self-aware) and can prioritise its actions (should the mission be continued or start other procedures that will mean preventing disaster?).

This is a new field of research both in evolvable hardware and in system reliability, but one with much scope and promise. As a starting point to this work, we have hypothesised a new architecture that incorporates the novel ideas mentioned above. The architecture is based on Cohen's view of immunology as illustrated in Figure 4. Homeostasis is maintained in 3 stages. A recognition stage uses information sensed from the environment to detect a threat to, or a deviation from, stability. A cognition stage provides a solution to restoring stability. Finally, the action stage drives the system to adjust the environment (both internal and external) and thus restore stability.

A more detailed implementation of this approach is depicted in Figure 5. A variety of sensors provide the main input to the system that feeds the **initial recognition stage**. Recognition is itself subdivided into two sections. The first takes the sensory inputs and applies a set of assorted transforms to the data. The result is a diverse set of 'views' of the environment. Using a temperature measurement as an example, data from a single thermometer sensor can be transformed into different 'view' such as; rates of change, fuzzified classification and maxima and minima. This stage provides a richer view of the environment to the detection part of the recognition stage.

Detection of actual or expected deviation from stability is performed by monitoring the various environmental data. This particular part of the process is an example of where the architecture utilises evolvability to adapt to environmental change and is explained separately below.

The signals output from the recognition stage inform the **cognition stage** how stable the system is in terms of the defined metrics. The signals analogous to immunological danger and safe signals determine whether an action is required to restore homeostasis. Dependant on the magnitude and crucially the combination of signals the cognition stage will determine a restorative solution. At this level we envisage a form of data fusion across a number of inputs to help

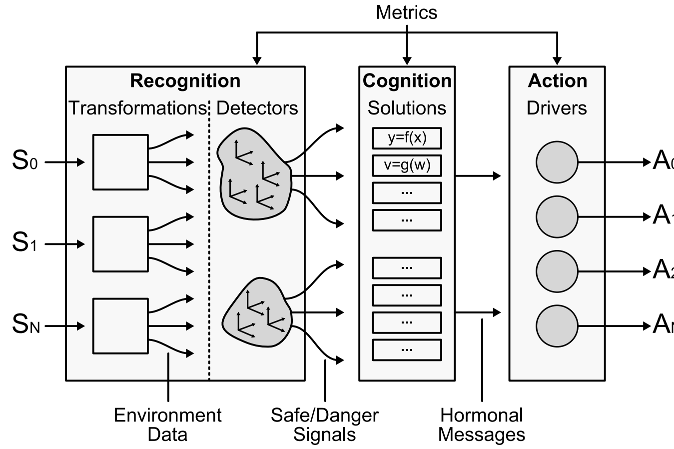

Fig. 5. An initial architecture for homeostasis.

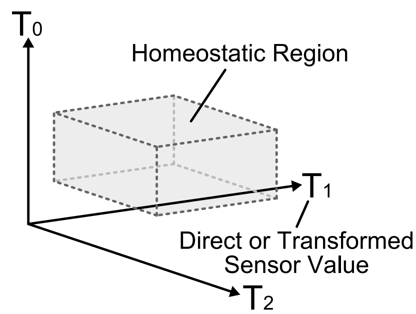

Fig. 6. A detector subspace is a partial image of the system's state in terms of the space's sensory axes. Detectors subspaces are comprised of transformed or direct sensory inputs.

guide this decision making process. If a response is required an **action** is requested. The last stage is used to arbitrate between different requested actions. As it is likely that a number of stability controls will vie for the same actuation resources, a decision based upon metric priority is made to determine which response is more important. A *hormonal messaging space* between the cognition and action stages uses the concentrations and interference between hormonal signals to help determine which action will be undertaken.

Detecting threats and deviations to stability needs to be an adaptive process in order to accommodate changes in environment. Without adaption it would not be possible to recognise new threats, therefore the detection stage is a clear candidate for implementation on an evolvable platform.

The detection of instability is performed using a set of detector units. Each metric that defines stability has a set of associated units. These individual units monitor a subset of sensory information, whether directly from a sensor or transformed, and determine if within its view of system state the metric is satisfied (stable) or unsatisfied (unstable). The system metrics infer a region within the detector subspace that delineates a homeostatic region, an example detector subspace is shown in Figure 6. This detector uses three sensory inputs to determine if a metric is satisfied by detecting if the system state falls within the homeostatic region.

The detecting process is adaptable in a number of ways. Initially, a set of detectors are created that provide the system with innate knowledge of how to detect instability. However, the detector spaces are not fixed, and neither is the detector population. In order to adapt to environmental change, detectors can adjust their subspace view of the system, changing the axes they use to judge stability. Furthermore, new detectors can form that allow discovery of different ways in which to detect instability. Clearly implementing such a scheme will require an adaptable and evolvable platform.

VI. Conclusions

Imagine an autonomous system with unreliable components with vast numbers of heterogeneous sensors and actuators, having to make decisions across multiple timescales, in an unpredictable, and potentially hostile, dynamic environment. Despite having the technology to engineer such systems today, they are still unable to achieve acceptable levels of performance. Although techniques within engineering go some way to tackling this problem, there still exists a considerable gap between what is desired and what we can achieve. An entirely novel approach to engineering is required to bridge this gap. We propose to look to biological systems, in particular the human immune system, to develop a new discipline that will allow for the construction of engineered artifacts that are fit for purpose in the same way as their biological counterparts.

What becomes quickly apparent when following the argument above is that if we are to realise such a 'utopian' ideal, current 'traditional' hardware architectures are simply not sufficient. What is required are architectures that are more adaptable, more aware of the environment they are operating in, more responsive to both internal and external conditions - that are evolvable.

What we have proposed in this paper is the beginnings of a new architecture that will allow immune system ideas and more fully, homeostasis characteristics, to be integrated into our engineered systems. But to do this we need evolvable hardware. This promises to be a fruitful and unique area where evolvable hardware can really make a difference.

Acknowledgements

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