# Extreme—Temperature Electronics Adaptability Based on Hormonal System Regulation

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**Abstract**

To survive, the internal temperature of the human body must be maintained irrespective of the temperature changes which occur in the surrounding environment. Thermoregulatory mechanisms, which involve various systems in the body e.g. hormonal systems, are responsible for ensuring that adaptation to such external temperature variations is sufficient so as to maintain the internal temperature.

A similar challenge is faced in the field of extreme temperature electronics (ETE). Electronic systems are exposed to temperatures far beyond the operational temperatures for such devices. Lack of mechanism enabling absorption or adaptation to temperature changes results in, at best, erroneous operation and, at worst, device failure. Thus internal temperature must be maintained despite extreme external temperatures. Further, accessibility to such devices is often limited or non existent. Some solutions exist but at present they may be said to only partially solve the problem. This paper outlines ways in which thermoregulatory mechanisms may provide a bio-inspired solution to ETE. In particular, attention is given to the hormonal systems involved and the two phase adaptation inherent in this hormonal response: the immediate, resource-heavy response and the slower adaptation to new conditions.

*Key words:* extreme temperature electronics, adaptation, bio-inspired systems, thermoregulation, hormonal systems

## 1 Introduction

The automotive and aerospace industries, space exploration and deep sea drilling are all examples of application areas where extreme temperature conditions exist and affect the electronic circuits in their systems. Extreme temperature electronics (ETE) is a field of electronics which addresses the extreme temperature challenge. However, although some success stories exist [1–8], many challenges remain. These challenges refer to the temperature challenge itself as well as to challenges such as application inaccessibility and the lack of advance knowledge about the possible temperature changes. Further, the electronics in question might be included in a safety–critical part of the system so that any adaptation to temperature changes, beside being automated, must be safe in that the original functionality is maintained throughout the operation.

Although many advances in ETE have been achieved in recent years, existing solutions are not satisfactory in many respects. Additional cooling and isolation equipment employed are rather cumbersome and in many ETE applications the size and weight of such solutions provide further challenges. New ETE design techniques and new materials e.g. wide band-gap semiconductors, are advantageous but are only partially addressing the challenges. Adaptive techniques exist which enable circuits to adapt to new temperatures. However, most current adaptive techniques require that the temperature changes are known in advance and, as such, are limited to those applications where sufficient knowledge is available. An advantage of such pre-defined adaptive solutions is that swapping between solutions may be achieved in real-time, thus ensuring maintenance of functionality.

If the case of ETE is considered where the application is neither easily accessible nor the temperature change easily identified in advance, a more flexible adaptive system is needed i.e. a system where the design is adapted by reacting to the changing temperature environment. Such an adaptation strategy, as is the goal of this project, must tackle the problem of ensuring that functionality is maintained whilst the adapted solution is created. Further, no matter which adaptive algorithm is employed, some way of ensuring that the adapted solution is safe, has to be employed.

Adaptation to temperature variations has already been solved in living organisms. Systems within the organism ensure that the internal temperature is retained within a certain range even in the presence of extreme temperatures. The maintenance of an optimum temperature range is termed thermoregulation and is performed by various regulatory mechanisms which are mutually interwoven. One of the systems which is involved in the regulation of the activities of the cells, tissues and organs within the body is the endocrine system [9] which also reacts to the changes in the environment contributing to the preservation of the organism's homeostasis. In particular, being one of the systems employed by thermoregulatory mechanisms, it reacts to temperature changes as well. The study of thermoregulation principles and the control mechanisms, as well as the subtle hormonal activity, provide much biological inspiration for addressing the challenge of ETE.

Inspiration for technical solutions related to the hormonal system is not new. Hormonal-inspired solutions have been applied to the distributed control of metamorphic robots and robotic swarms [10] and for self-organisation of the latter [10,11] where Adaptive Communication (AC) and Adaptive Distributed Control (ADC) protocols have been applied to robot communication and control [12]. Further, hormonal-inspiration has been applied as a tool for fault-tolerance [13,14].

This paper provides a very brief overview of the extreme temperature electronics field in section 2. An introduction to the hormonal systems involved in temperature regulation in human beings is presented in section 3. The concepts regarding the bio-inspired adaptive system and the process of adaptation are presented in section 4. The paper finishes with conclusion remarks and some directions for the future work.

## 2 Extreme Temperature Electronics

Temperature is an important issue for electronics operation. Conventional electronics is characterised by the temperature range in which it is guaranteed to operate according to manufacturer's specification. As stated, for some applications, electronics is expected to operate even under extreme temperature conditions. The term Extreme Temperature Electronics (ETE) refers to the electronics which operates in the temperature ranges lower than $-65\,^{\circ}\mathrm{C}$ and higher than $+125\,^{\circ}\mathrm{C}$ [15].

There are a number of traditional solutions for ETE. The simplest, but at the same time the most cumbersome solution, is the employment of additional isolation shields around the electronics or the use of heating or cooling equipment. However, in some applications this is unacceptable due to the increased size and weight.

Another approach addresses the cause of the problem. Why does the functionality of the electronics deviate from the desired functionality when it is exposed to extreme temperatures? The answer is in the materials themselves and the technology employed in their manufacture. The extent of functional deviation depends on material characteristics. A solution is thus to use materials which are less temperature-dependent. Today's electronics is based on semiconductors and every semiconductor is characterised by its intrinsic properties. Much of the current research efforts focuses on the production of synthetic wide band-gap semiconducting materials. SiC and diamond electronics [6,16] are terms for some of these new-age semiconductors. However, to date this area of research, although very promising, is far from maturity.

Further approaches are oriented towards the system/circuit design i.e. compensation circuitry [17] or modifications at the technology level [18]. Compensation circuitry is additional circuitry which compensates for temperature effects on the original circuit thereby preserving the desired functionality. Technological modifications include adjustments to transistor structures during manufacture which lessen undesirable temperature effects.

In recent years, much attention has been given to the use of reconfigurable technology as a technology for ETE due to the possibility to reconfigure the design. A design implemented in reconfigurable technology consists of a description in the form of a string of bits which is loaded onto the chip causing switches to either be open or closed thus programming the chip for a given design. The design may be changed by downloading a new string of bits i.e. a new configuration onto the chip. Thus a new design which is more suitable for a given temperature may, in principle, be downloaded onto the chip. However, the new design needs to be created and the question is how and when?

There are two ways in which the new design may be created and applied. The first builds on the assumption that the temperature variation is known in advance. For each temperature range a new design solution is created and stored. Either traditional or bio-inspired design techniques may be applied to find such solutions. When the device is exposed to a particular temperature, the corresponding design for that temperature range is retrieved and applied. A particular drawback of such an approach is that the extreme temperature(s) to which the device will be exposed must be known in advance. Further, each solution will have to be stored off-chip and loaded onto the chip. In many cases loading an external design onto the chip is very expensive. Not only does it require additional resources for the configuration storage, it takes time for the new configuration download to complete, which might be unacceptably long for the safety—critical applications. In the case of some applications e.g. space exploration, reconfiguring devices from earth is relatively slow with fairly inaccessible and expensive communication links.

The second approach assumes that the design is adapted without any predefined solutions i.e. a new solution is created which meets the requirements of the current temperature conditions. The most significant contribution to this area of research has been conducted by the members of NASA's Jet Propulsion Laboratory (JPL) on reconfigurable analogue arrays [19].

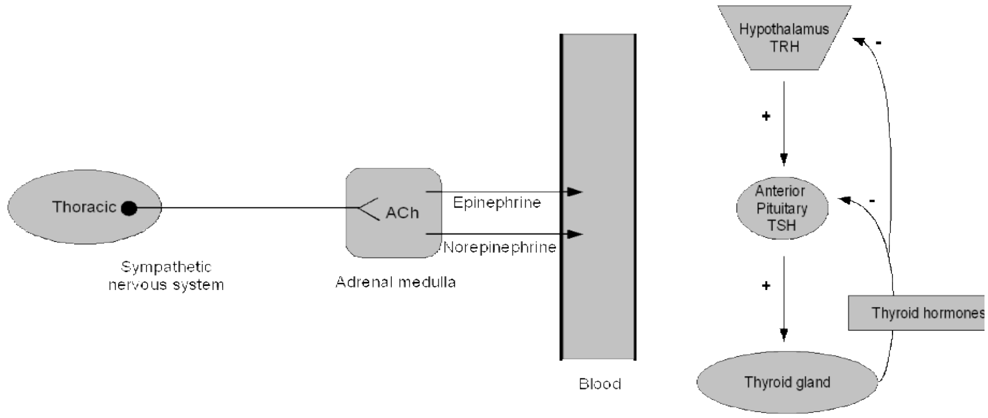


Fig. 1. Schematic view of hormonal systems involved in the thermoregulatory mechanisms: adrenal medulla hormones (left) and thyroid hormones (right)

A further approach proposed, but not implemented, interestingly considered approaching temperature regulation by changing the temperature of the chip itself by triggering logic that would heat up the chip [20] in the case of a drop in temperature beyond the range of acceptable temperatures for the chip. As such, no adaptation of the design itself would be necessary. Such a solution may be said to have a similar effect to protecting the chip from temperature effects but without the size and weight disadvantages.

## 3 Turning to Biology for Inspiration

The human body is a biological system highly adapted to the ever-changing environment. In order to survive, its internal environment must be maintained irrespective of the changes which occur in its surrounding environment. This maintenance of the internal environment is termed homeostasis [9]. Almost constant conditions are required for the correct operation of the physiological processes which life itself is based on. The physiology of the human body consists of chemical reactions and these reactions are temperature dependent. If the temperature is not appropriate for these reactions, some may not take place and some may take another sequence of reactions. In the worst case, vital functions may be inhibited leading to death. Therefore, maintenance of the internal body temperature is vital for the living organism.

The internal body temperature is maintained nearly constant thanks to thermoregulatory mechanisms. Thermoregulation is performed by different systems of the human body e.g. muscular, respiratory, cardiovascular and hormonal. The control and coordination among the systems employed is achieved by the nervous system. Thermoreceptors, which are the neural endings of specific type, react to the temperature change in the surrounding environment or within the body. These receptors are located in the skin and in internal organs, providing information about the peripheral and core body temperature respectively. Information which they gather is forwarded to the temperature control centres in the hypothalamus — the central control place for many regulatory mechanisms within the human body. Upon receiving information about temperature variation, thermoregulatory mechanisms are triggered. These mechanisms involve and affect different systems in the organism so as to react in appropriate ways with respect to the size and direction of the temperature change.

One of the initiated reactions to a temperature decrease is *chemical thermogenesis*. The term stands for the heat production in organisms achieved through an increase in the cell metabolic rate. Metabolic rate increase is stimulated by the raised level of specific hormones. In particular, it is the epinephrine and norepinephrine secreted in the adrenal medulla and thyroid hormones secreted by the thyroid gland.

Hormonal systems employed may be classified as those providing a quick resource-heavy response and those that provide a slow resource-light response to temperature changes. The two systems exist to complement each other and ensure an effective system response, see figure 1. Adrenal medulla hormones are characterised by their quick response whilst thyroid hormones take longer time to be secreted.

Adrenal medulla is part of the central nervous system and its hormones secretion is also regulated by the nervous system. Hormones secreted within it, epinephrine and norepinephrine, may have the role as hormones as well as neurotransmitters in some other parts of the body. Their effect is an immediate rise in the cell metabolism. This immediate response ensures that the body temperature is maintained. However, as these hormones affect various systems and organs as well by causing the increase in the heart rate, the increased alertness, mobilisation of glucose from the liver and muscles, to name a few, such an operation exerts a significant strain on other systems in the body. Such response cannot be maintained over longer time. Thus their purpose is to achieve a fast reaction, providing time for a less resource–demanding process to take over. The hormone secretion of the adrenal medulla is then decreased under the control of the nervous system i.e. the process is reversed.

Initiation of secretion of the thyroid hormones and their effect on metabolism is much slower but may be maintained as long as needed. As a response to a temperature decrease, a neuroendocrine hormone *thyrotropin-releasing hor-*

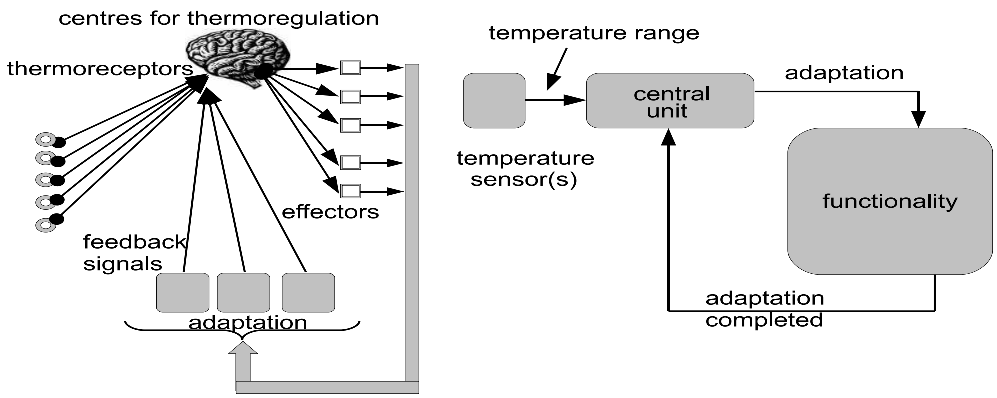


Fig. 2. Global view of the biological system of thermoregulation, left, and the proposed adaptive system, right

*mone*, TRH, is released in the hypothalamus. TRH stimulates secretion of the *thyroid-stimulating hormone*, TSH, in the anterior pituitary gland. TSH further causes the production of the thyroid gland hormones, in the first place thyroxine, which leads to an increase in the metabolic rate. However, when the thyroxine level in the blood reaches a certain value above the normal, it inhibits secretion of the TSH in the pituitary gland, closing the negative feedback loop. Although such endocrine hormones are released into the bloodstream through which they reach all the cells in the body, it is only the cells which possess the matching receptor which are affected by these hormones. Therefore, the cell metabolism will be affected only in those cells which possess receptor molecules for the hormones secreted in response to the temperature change.

## 4 Conceptual Framework for the Bio-inspired System for ET

With many ET applications being safety—critical, maintenance of system functionality throughout their operation, irrespective of changes in the environment, is the principal challenge. To ensure maintenance of functionality, real-time adaptation is required. However, this kind of adaptation is, in general, characterised by high-costs. These costs may be due to extra logic/memory area allocation to reserve solutions or the high cost of transferring these solutions, as stated. Bio-inspired solutions are interesting in this context as they provide the possibility to tune the solution to the current temperature. However, can this be achieved in real—time? In general, one can assume that all but the simplest adjustment will not be achievable in real—time. It would be, therefore, of great advantage to find a solution which provides the advantage of a fast real–time solution but at a lower cost.

As stated, the hormonal response to temperature change achieves an interesting solution. In terms of resources used when the system is active, the system is quite effective. The quick response occurs at a considerable cost for the system — drawing on system resources; but it is reversed and replaced by a slower low-cost solution. As such, it maintains functionality. However, the existence of the system itself in the body is also a cost in terms of the resources it occupies. It is proposed herein to exploit this two stage approach to adaptation whilst considering ways in which such a complicated system might be simplified so as to minimise the total resources required.

*Temperature—sensitive elements*

One of the first issues which needs to be addressed in designing an adaptive system, is the identification of the environmental component to which the system is to adapt [21]. In this case it is, of course, temperature changes in the environment. More precisely, it is the temperature change within the system caused by the extreme temperature in its environment. The system must thus possess temperature sensitive elements providing temperature relevant information which can act as stimulus for the initiation of temperature adaptation, where and when necessary. In biology, these elements are the thermoreceptors whose signals are sent to the centres in the hypothalamus.

It should be noted, however, that these biological sensors can be found in internal organs as well as on the peripherals of the body i.e. monitoring internal and external temperatures respectively. Even though the temperature of the environment changes, it may not necessarily lead to a change in the internal temperature. It is, therefore, important to include temperature sensors which will be responsive to temperature changes within the system or, for the case of a single chip, to the temperature changes on the chip itself as well as external temperature sensors.

A further issue is the fact that temperature effects vary across the chip which may be described by temperature gradients. Together with external temperature variations, temperature gradients could be studied to provide predictive models as to the direction and rate of the expected temperature change. Such models may be applied to support triggering the adaptive process or perhaps even short-cutting to the slow response in cases where a fast response is not necessary.

*Temperature control centres*

Thermoregulation in the human body is realised on the basis of the information flow following the sequence: *thermoreceptors — centres in the hypothalamus — effectors — adaptation — feedback signal*. Accordingly, the adaptive system for extreme temperatures, as viewed from the global level, includes the following elements: *temperature-sensitive elements — central unit(s) — adaptation signal — functionality adaptation — adaptation completed signal* as shown in figure 2.

The temperature-sensitive elements send signals to the central unit(s). In response to the received sensory signal, the central unit generates signals which initiate adaptation process in the functional part of the system. In order to perform the designated role within the control loop, the *central unit* must possess such characteristics that provide it with the ability to:

- receive the sensor signals
- process the signals so as to detect critical temperature regions
- generate the neural-like signals which initiate and stimulate the adaptation process
- send these signals around the system architecture so that they reach every part of it
- receive the feedback signal about the adaptation completion

In terms of achieving an artificial representation of such a system one notable issue is that of the central controller. In a biological system this controller is within the brain itself. The brain is a highly complex processing system which may be regarded as a fault tolerant system due to its dynamic and highly redundant structure. Thus the brain avoids many of the problems attached to centralised control in artificial systems.

Any form of solution sought will not, of course, include anything as complicated as a brain and thus centralised control is a problem. As such, possible solutions will include back up controllers or some form of distributed control.

*Quick response to the detected temperature change*

When a non–desired temperature change is detected, preservation of the system functionality is the first stage, particularly ensuring that the requirements of safety—critical applications are met. The first response of the system is to exploit available resources, possibly at the expense of area, speed, additional power consumption etc. so as to maintain functionality. The key point here being that the system should be reversible in a sense that when a more efficient adaptation system is ready to take over, these resources should be freed. As typical time constants for temperature changes are of the order of milliseconds [22], the quick response should provide for functionality preservation within this time limit.

Taking inspiration from the quick response in the biological system, the key is to find some resource that might be exploited in the short term. One such resource is that of power dissipation. Power dissipation may be managed so as to provide chip cooling or heating as required. Power dissipation comes from static and dynamic components. The static component is determined by parameters which are not adjustable during operation time. Dynamic components, on the other hand, may be controlled during operation. For CMOS technology, which is dominant in today's electronics, the dynamic component accounts for 80% of the total dissipation. It has been reported that each component exhibits specific change with temperature variations [23].

A major contributor to the dynamic component is the charging and discharging of capacitances where power dissipation is directly proportional to the value of the capacitor and the operating frequency while reducing or raising power supply voltage has a quadratic effect on dynamic power dissipation. However, changing the supply voltage may cause clocking instability.

In most high-speed digital processors, the majority of the power is dissipated in the clock network [22]. Therefore, using clock gating i.e. the ability to shut down parts of the clock network, may be a way to decrease dynamic power dissipation and, therefore, decrease temperature or to raise temperature by turning on parts of the clock networks. However, in either case this also might lead to additional clock uncertainty.

No matter what approach is taken, it is decided by the central unit, or units distributed around the architecture, based on the sensory information or the prediction derived from these data.

*Adaptation to extreme temperatures*

The second stage is, similar to the biological system, the creation of an adapted solution to the new temperature conditions. Here the triggering mechanism and adaptation algorithm may be slow but the key is that resource use should be efficient. Once the adapted solution is created, the first stage may be cancelled and the relevant resources released.

Adaptation to ET conditions can be realised through various adaptation algorithms, bio-inspired evolutionary algorithms being one class of such algorithms which have already been shown to yield a suitable temperature adaptation solution [19]. However, an important issue must be born in mind. When the fast-response has changed the temperature on the chip, the original response on the chip will no longer be available for the slow-response to adapt to. Some measure of storing such information as the basis of the slow-response process is needed.

The triggering process of the slow-response, as illustrated in Figure 1, is quite a complicated process. Again, similar to the central controller issue, consideration has to be given to whether such a complicated series of triggering is essential or not. Further, what about the negative feedback? In biology this feedback causes cancellation of the adaptive effects i.e. reversal to normal functioning behaviour. It may be the case that it is less resource–demanding to treat a return to normal external temperatures as another change in temperature rather than reversal. Thus negative feedback might not be necessary. On the other hand, when considering safe adaptation, the possibility to revert might be important.

If one assumes that the system is implemented in a modular fashion, then the complete design does not necessarily have to be adapted, only the modules affected by the change in temperature. Further, partial and dynamic reconfiguration possibilities in today's reconfigurable technology may be exploited so that the non–affected modules continue to operate whilst the designs in the affected modules are adapted. Some sort of communication amongst the functional modules may be necessary to identify which modules to adapt and which modules will remain operational during adaptation. Such communication may be inspired by the hormonal system. Functional modules might communicate the information about their states e.g.'no adaptation needed', 'adaptation in progress', 'adaptation completed'; amongst themselves with only those modules with appropriate 'receptors' being susceptible to this information within the network of functional modules.

## 5 Conclusion and Future Work

This paper has addressed the issue of achieving real-time adaptivity to temperature changes in extreme temperature electronics. The paper presents the concept of bio-inspiration for ETE solutions from the process of thermoregulation in human beings. The systems employed in such a process and their appropriateness for a solution to ETE are discussed. In particular, how a quick resource—heavy solution together with a slow resource—light solution could be achieved and what issues such solutions would raise. Future work will address different elements of the conceptual framework described.

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