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Lifelike Systems Need Some Kind of a Skin: First Thoughts on Cyberskin Capabilities

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Abstract

Robustness is one of the primary goals of self-adaptive and self-organizing systems, including appropriate reactions to unanticipated conditions, to disturbances, and even to attacks. In this paper, we draw from biological systems to introduce a 'Cyberskin' as a concept for introducing some potentially new strategies for robustness in complex systems. We briefly summarize characteristics of the skin of animals and humans and map this into desirable computational capabilities. We then discuss some beginning ideas for implementing some of the technical functionality to support such a Cyberskin.

Introduction

Openness and adaptivity are key enablers for next-generation information and communication technology (ICT). Driven by trends such as intelligent systems (e.g., Calma et al. (2017)), cyber-physical systems (e.g., Rajkumar et al. (2010)), and Internet of Things (e.g., Atzori et al. (2010)), we face constellations of typically distributed autonomous subsystems that integrate dynamically into an overall system constellation and self-adapt their behavior. One of the goals of self-* (e.g. self-organization, self- integration, or self-healing) ICT systems is that these adaptations should not be limited to a pre-defined operational context or a fixed repertoire of behaviors at design time. In addition, we emphasize that self-* mechanisms are also critically needed to make technical systems resistant against external or internal disturbances (see Tomforde et al. (2018)). Such self-* systems may not perform better than conventional systems (although depending on the novelty of the dynamic environment they may) but they return faster to a corridor of acceptable performance in the presence of disturbances. The ultimate goal of self-* systems is to be both more creatively adaptive and resilient against disturbances and attacks from the outside. We call this property 'robustness' (Müller-Schloer and Tomforde (2017)).

In this paper, we propose a set of mechanisms which we call a "Cyberskin" that will consolidate and augment existing self-* capabilities. Inspired by biology, such a standardized enclosure will allow for even higher robustness and resilience when acting in open environments. We discuss the biological inspiration (Section 2) and map this onto a first concept for a 'Cyberskin' in ICT systems (Section 3). The paper closes with an outlook on a possible path towards the development of such a 'Cyberskin' (Section 4).

Biological Inspiration

ICT systems are approaching the complexity of biological systems in their massively large number of parallel components and subsystems, concurrent activities and goals, and very diverse hardware and software entities. One of the triumphs in computing has been message passing and the use of explicit models and knowledge in many forms. With a few basic protocols this has permitted enormous benefits in communicating among diverse systems. However, although biological systems use message passing they also make use of other different ways of being architected and integrated. These architectures are characterized by having multiple layers and multiple tightly integrated subsystems that allow a tremendous amount of implicit information to be conveyed among a widely distributed and massively parallel system. Unlike the hairs in the ear or the visual retina, sensory systems such as the skin or the architecture of joint, muscle and tendons are connected and integrated with both implicit and explicit 'signals' and actions. In addition to the continual reliance on networks, messages and explicit signals, we want to explore what qualities this implicit structuring gives to computational systems. We suggest that there may be new characteristics in terms of response speed, adaptations, robustness, and protection possible.

As background to the discussion on skin, let us look at a few of the different principles in biological systems and their implications for computational systems. Bellman and Walter (1984) suggest that a good image for biological systems may be that of a community rather than a single agent. That is, the system is composed of elements that are in themselves sophisticated living elements. As Micheva and Smith (2007) state "One synapse, by itself, is more like a micro- processor - with both memory–storage and information- processing elements – than a mere on/off switch. In fact, one synapse may contain on order of 1000 molecular scale switches". In

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our nervous system, it is estimated that there are 100 billion neurons, each with 7000 synapses. And that is only one type of cell within the human body. Hence, the scale and heterogeneity of components, subsystems and processes fits very much into the idea of today's Interwoven systems (see Bellman et al. (2014) and Tomforde et al. (2014)), which also have enormous diversity; systems with their own functions and goals connected in a variety of ways and yet also interdependent and requiring coordination.

Rather than being focused on a single goal or function, biological systems have very different 'efficiencies' and optimization criteria that include adaptability, robustness and resiliency as well as performance, see Kantert et al. (2017). Also, they have an enormous variety of subsystems and processes occurring simultaneously at different levels. For example, mammalian brains consist of different regions with distinct architectures, characteristics, and capabilities. This means at any given moment, there may be very different activities and processes and goals for those processes.

Biological systems are always multi-goaled (Bellman and Walter (1984)), and they quickly drop goals as needed, take advantage of situations to adopt new goals, merge goals, and take a long term view in optimizing their situation versus any one task. Such long term optimization includes placing oneself in a better position for later behavior and, hence, might actually result in a temporarily lower goal accomplishment for a given task. Biological systems make use of 'substitutability' (equivalent classes of actions) and compromises among activities and goals. Like computer networks that may have resource contentions, multiple users and conflicting goals among those users, biological networks have a magnitude more diverse types of processes, goals, activities and subsequently, contentions. To handle the needed coordination, biology has developed many more styles of interaction and influence that includes both explicit and implicit networks, architectures, and responses to activities. In complex systems, one needs both the speed coming from rapid communication and signaling, as well as the structure that allows the system to take advantage of implicit connections that can quickly coordinate and inform a wide variety of distributed elements. Although there are many such examples in biological systems, in this paper we focus on the properties of skin which has both explicit signaling and transmission of information and implicit and indirect methods.

One of the key stabilizing principles of biological networks is the use of active 'stabilizing' processes that include different strategies for 'buffering.' By buffering, we mean mechanisms and architectures that separate input from output and isolate the impacts of abnormal/foreign elements (including the detection of abnormal behavior as suggested in Gruhl et al. (2015)). This includes nature's version of firewalls (e.g., skin, membranes) which are permeable, controllable and, in some cases, sentient. Buffers in living systems allow the separation of immediate reaction to stimuli from response and provide time for adaptive processes and later reasoning processes. It is one of the major methods for 'buying time' for adaptive rather than fixed responses.

Skin is the largest organ in your body and compared to the other sensory systems, it does not get enough attention. Although only a subset of the skin's functions will immediately resonate with our computational goals, we are listing many of skin's diverse functions in order to convey all the processes and activities that go beyond being a barrier.

One of the major functions of skin is protection; it is an anatomical barrier from pathogens and damage between the internal and external environment. As such, it is key to heat regulation and the control of evaporation. Dilated blood vessels increase perfusion and heat loss, while constricted vessels greatly reduce cutaneous blood flow and conserve heat. In the control of evaporation, it ensures that the skin provides a relatively dry and semi-impermeable barrier to fluid loss. Skin is also a key part of the adaptive immune system (Langerhans cells) and also is one of the body's storage and synthesis sites; it acts as a storage center for lipids and water, as well as a means of synthesis of Vitamin D by action of UV on certain parts of the skin.

Given the functions above, it is not surprising to find that it plays a major role in excretion and absorption. It is good to keep these functions in mind as we consider ideas for controlling what goes into systems (desirable entities e.g., data, code, sensors etc.) and what is released from computational systems (e.g., garbage, suspicious code or data). The skin is an important site of transport in many organisms: oxygen, nutrients, or water. In humans, the cells comprising the outermost 0.25-0.40 mm of the skin are supplied by oxygen.

The role of the skin in sensation is of immediate interest for our computational systems. Skin contains a variety of nerve endings that react to heat and cold, touch, pressure, vibration, and tissue injury. The skin includes sensors and processing for touch (several types including pressure and vibration,) temperature, proprioception (body position, position of muscles, bones and joints), and nociception (pain/tissue injury). The system reacts to diverse stimuli using different receptors: thermo-receptors, nociceptors, mechano-receptors and chemo-receptors. The skin is also important in aesthetics and communication; it is used by conspecifics to assess mood, physical state and attractiveness. Both these internal state and external environmental changes are rapidly available across the system because of its intertwined and diverse architectures.

Furthermore, these numerous types of receptors are not evenly distributed across the skin. The density and variety of receptors matter. This density may relate to priorities or to coordination with other sensory systems or to the specializations of the system to its ecosystem. For example, sensing injury is an important role of skin; there are 200 pain receptors for every square centimeter of the human body. Catfish have chemo-receptors all along their body (a catfish is like a giant tongue) Atema (1980) while humans have 6-12 million olfactory receptors in the human nose alone (bloodhounds 4 billion) , see Bullock (1982). Electric eels have a sensory system (electrolocation) that combines some aspects of skins and vision; the sensing of electric fields can be used for object detection, communication, defensive and offensive behavior such as prey stunning and warding off predators Shier et al. (2004). This variety may give us new ideas for how to prioritize and fuse incoming information and how to protect key areas. One thing we would like from a Cyberskin is quick detection of the locality, the extent, and the type of attack. Skin can immediately locate site of contact (within different just 'noticeable differences'):

Some Thoughts on a 'Cyberskin'

Over the last twenty years, there has been increasing work on haptic interfaces and artificial skin. Robotics and sensors applications such as telemedicine and manufacturing have resulted in an interest in artificial touch receptors and skin-like sensor meshes (for example Lumelsky et al. (2001)). Our purpose here is different. Instead of building a skin per se, we examine the implications of skin's properties and consider how to adopt them into computational systems. There are several properties of the skin that are of particular interest to us. First, skin is inside as well as on the external interface to the world; the importance to us is that potentially the same methods and architectures may be used for different sizes of systems and for system-of-systems. Also, there are many layers and types of skin in a given biological system. The external skin has a large number of layered different sensor networks and activities. The overlapping and diverse architectures of these nets allows for simultaneous monitoring of multiple conditions of interest and layers reached have implicit information (e.g., injury or danger).

One of the most important features of skin is that it is selectively permeable, allowing for many different implementation strategies on what can pass through – both from the system and into the system. Skin is also sentient in terms of 'having sense, perception' – locality, nearness, size, damage, and so on. This is a key property in terms of having a distributed system capable of almost immediate processing where it is being interacted with and with what. The multitude of sensors noted above monitor for different things and can be used to determine size, type of interaction, and site of first responses to foreign objects. Given that, it is interesting is to imagine new relevant measurands for non-biological entities. That is, the current sensors in biological skin depend upon our animal evolution in many physical states (e.g., cold, hot) and threats (e.g., pushed, pained, pressured). These may still be of importance for cyber-physical systems as many failures are caused by temperature and dampness. However, what properties should we sense within a computational environment? Noisiness? Density of activity? In addition to the external world, skin within biological systems has a major role in self-monitoring; it informs the system of internal changes (for example, proprioception and changes such as hydration) and by nature to its external and internal interfaces, helps integrate internal and external states.

Lastly, the 'elasticity' of skin refers to the property of some solid materials that return to their original shape and size after the forces deforming them have been removed. This has been a key adaptive capability in biological systems that grow and develop, but it also allows immediate flexibility in movements. It is also clear that the deformation (stretch and bend of skins) is signaling changes of states such as a full stomach or the extent of voluntary and involuntary movements (e.g., breathing) and triggering additional actions. One of the things we would like from both rapid locality and elasticity is perhaps a measure of how long the interaction/attack has been ongoing. In biological skin, such information is conveyed by the type of sensory event and by how deeply down through skin layers the interaction has gone. Many sensed events become pain (e.g., an alert to danger) the farther down in the layers they go. Biological pain (extreme pressure, heat, cold, cuts) could have new corollaries in computational systems such as the location of a loss in connectivity or a drop in data rate.

A 'Cyberskin' for Technical Systems

In this section, we introduce a way of going beyond biology and discuss how the system would actually construct an ongoing skin due to learning and experience. Biological skin does this a little especially in terms of size (as one gets bigger), in terms of injury, and of course, the complex set of adaptive sensory mechanisms. However, the ideas here include intelligent processing and learning with some of the aspects of skin to incorporate learning.

The design process of traditional technical systems is based on analysis of anticipated and predictable events, followed by the development of countermeasures and contingent responses (Tomforde and Müller-Schloer (2014)). However, especially in dynamic and open environments, there will always be unpredictable events. This needs to be covered by a concept called "spontaneous closure" Müller-Schloer and Tomforde (2017), see Figure 1). Exception handlers and diagnosis systems are examples of implementing spontaneous closures in technical systems. In a watchdog timer, a timer is reset and restarted at regular intervals. If the timer is not reset, because the monitored system is in a malfunction, a reset is performed to a defined initial state.

Research in self-adaptive and self-organizing (SASO) systems has presented a wide variety of concepts for establishing and persisting such spontaneous closure. Most of the machine learning mechanisms used in SASO systems are dedicated to finding appropriate reactions to previously unknown or less certain conditions D'Angelo et al. (2019) – in this sense, learning means that recurring reactions of the spontaneous closure become part of the designed core.

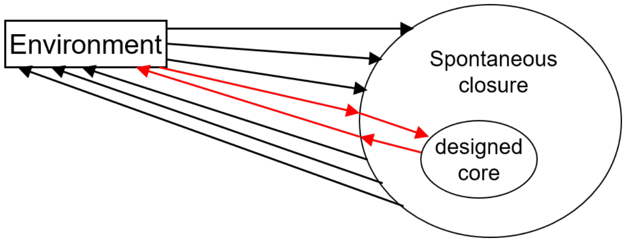

Figure 1: A 'spontaneous closure' to handle exceptions

Based on the experience of machine learning applications, we distinguish three major classes of effects that need to be handled by spontaneous closure: a) Unanticipated conditions, b) disturbances as a result of malfunctions, and c) attacks. Unanticipated conditions reflect the fact that only a fraction of environmental and internal conditions can be anticipated at design time. Disturbances as result of malfunctions include expected events such as wear and aging, as well as unanticipated effects that cause failures and malfunctions of individual components and entire systems. The system should continue to maintain its functionality despite these failures. Lastly, attacks are likely because an autonomous system operates in a shared environment where interaction with known and unknown other systems takes place. This not only opens up potentials for continuous optimization but also a multitude of heterogeneous attack vectors.

Living systems are characterized by a powerful spontaneous closure partly realized by the skin. In particular, we can observe the following technical implications as three aspects of Cyberskin. As noted above, skin can detect and classify novel conditions extremely fast. Technically, this means in Aspect 1 of Cyberskin we want to apply novelty detection mechanisms (see Pimentel et al. (2014); Gruhl et al. (2020) for details) in combination with other autonomous learning capabilities (see, e.g., Krupitzer et al. (2015); Sick et al. (2018)) to improve the reaction to these stimuli over time. Next natural skin recovers quickly from injuries (within limits determined by the system) and raises alerts through prioritized alert signals such as pain or pressure. Aspect 2 of Cyberskin technically then refers to self-healing techniques, provisioning of backup or alternative components, and alarm systems that are coupled to immediate counter measures. Aspect 3 refers to the ability of natural skin to assess contact with novel objects and operational environments and immediately map this sensory information to approximate reactions. Besides standard encryption and authentication or computational trust mechanisms (e.g., Kantert et al. (2015)), we think that skin may provide new inspiration for an interactive and context-based contact establishment protocol. This protocol would be one way to allow for some of the skin's most subtle, rapid, and widespread capabilities in technical systems. This may be part of the means to process customized security questions that need to be answered before an interaction is established.

We observe that – at least for now – all the aspects mentioned above are mostly considered in an isolated manner. The notion of a Cyberskin is especially important as a means to better integrate these efforts into a unified whole. Also the basic purpose of the Cyberskin is not restricted to the outer shell – it should also connect and protect the inner components or subsystems. Several efforts in SASO system engineering have proposed machine learning solutions to handle Aspect 1 and Aspect 2. However, Aspect 3 has mostly been considered in an attack-specific manner (i.e., trying to identify attacks based on abnormal behavior) and utilizes authentication and authorization mechanisms using standard encryption schemes. We propose to augment this (i.e., to extend the spontaneous closure) with more sophisticated and lifelike mechanisms. Especially, we would like to replace the current isolated handling by a localized, efficient and approximate computing metaphor that we call Cyberskin. There are approaches that go in this direction – such as the idea of a 'membrane' introduced in Diaconescu et al. (2016). This and related work certainly provide good starting points for developing more flexible and powerful spontaneous closures and finally a strong and efficient Cyberskin. The basis for the implementation of this Cyberskin are paradigms such as the MAPE-k cycle (Kephart and Chess (2003)) or the Observer/Controller tandem (Tomforde et al. (2011), Tomforde et al. (2016)).

Conclusion

The trends in ICT such as openness, heterogeneity of interaction partners, (hidden) mutual influences, and faster response times especially in human-machine interaction require a more 'life-like' system design. We described our vision of a 'Cyberskin' that better integrates already existing technology (e.g., self-healing techniques, learning capabilities) and contains novel safety and security means to dynamically realize a context-aware interaction protocol.

It is also important that as a community we consider new types of non-message-passing architectures and how we can imitate the other manners of interactions found in biological systems. The information conveyed by the deformation of the skin, the immediate identification of locality, and the interplay of different types of receptors are not conveyed by networks alone in biology and we need creative concepts for how we could architect and model that. Cyberskin requires new thinking about the meaning of what is monitored for and the implementation of new measurands and methods.

Future work is on implementing aspects of 'Cyberskin' and seeing how generalizable those implementations can become. Looking across the commonalities among animal skins gives us the hope that there will key principles in implementing Cyberskin, such as permeability (intelligent gating of traffic across membranes) or the criticality of having different dedicated receptors.

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