The morphofunctional approach to emotion modelling in robotics

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Abstract

In this conceptual paper, we discuss two areas of research in robotics, robotic models of emotion and morphofunctional machines, and we explore the scope for potential cross-fertilization between them. We shift the focus in robot models of emotion from information-theoretic aspects of appraisal to the interactive significance of bodily dispositions. Typical emotional phenomena such as arousal and action readiness can be interpreted as morphofunctional processes, and their functionality may be replicated in robotic systems with morphologies that can be modulated for real-time adaptation. We investigate the control requirements for such systems, and present a possible bio-inspired architecture, based on the division of control between neural and endocrine systems in humans and animals. We suggest that emotional episodes can be understood as emergent from the coordination of action control and action-readiness, respectively. This stress on morphology complements existing research on the information-theoretic aspects of emotion.

Keywords

Embodiment, emotion, reconfiguration, morphology, dynamical systems

1 Introduction

The classical approach in cognitive science has been characterized as disembodied, for its commitment to the idea of intelligence as fundamentally a brain-based information-theoretic process. As a consequence, intrinsically embodied phenomena, i.e., phenomena that emerge from the interplay between brain, body and environment, remained at the periphery of cognitive science and the AI project. This was the case for emotion, a 'prototype whole-organismic event, for it mobilizes and coordinates virtually every aspect of the organism' (Thomson, 2007, p. 363). In the last decade though, the restoration of embodiment has been accompanied by an increasing interest in emotion in all areas of cognitive science.

Two lines of emotion research are present in robotics: first, attempts to give robots emotional appearance, in order to facilitate or improve interaction with humans; second, attempts to endow robots with adaptive characteristics of emotion. Arguably, the latter may be a precondition for the former (Arbib & Fellous, 2004), as emotional appearance can only be meaningful (beyond shallow entertainment) if it expresses some significance for the robot. Emotional expression is more a form of adaptive interactive behaviour than a tool for communication. This paper is concerned with the task of increasing the adaptability of robots through emotion-based organizational processes.

The main challenge that researchers face is to identify what aspects of emotion are relevant for robotics. Physiological, cognitive and behavioural aspects can be clearly identified as constituent of human emotion (e.g., Frijda, 1986, among many others). Nevertheless, researchers in robotics have consistently argued that the importance of emotion comes in the role it plays within a cognitive architecture of control. The question 'What is it that makes emotion relevant for robotics?' is often answered as: the way information is processed, decisions made and actions selected, or learning and memory organized. 'There is a consensus that emotions are an evolved adaptivity mechanism related to situation assessment and decision making' (Sanz, Hernández, Gómez, & Hernando, 2008).

Emphasis on information-theoretic aspects of emotion can be compatible with the embodied approach. For many researchers, the role of emotions as forms of control has to be grounded, in one way or another, in the internal organization of the body (Ziemke, 2008). There is the intuition that there is a link between the internal metabolic mechanisms that ensure the stability of the system, such as homeostasis, and the logic of emotion in adaptation. This underlies the idea of internal robotics (Parisi, 2004), the study of 'the interactions of the robot's control system with what is inside the body', or the study of the role of internal variables (such as those modelling hormone levels) in the organization of cognitive control (Avila-García & Cañamero, 2005).

This paper challenges the idea that this stance captures the whole importance of embodiment in emotion. The preparation for action underlying emotion and how bodily disposition may safeguard the agent's concerns has been a recurrent theme in emotion theory: Frijda (1986) argue that emotions are characterized by distinct modes of (embodied) readiness; James and Lange's classic definitions of emotion as the felt experience of the organism's physiological preparation for behaviour; Plutchik's (1980) categorizing of primary emotions by behaviour modes serving biological functions; Ekman's (1994) description of basic emotions as preparations for specific patterns of functional motor activity; in Oatley and Jenkins' (1996) definition of emotions as ready repertoires of action serving as resource-saving shortcuts to adaptive behaviour (Oatley & Jenkins, 1996, p. 285).

Under this perspective, emotions are purposeful changes in bodily disposition:

> … emotion is outward movement. It is the 'stretching forth' of intentionality … The key characteristic is that action wells up from within the organisms. It is not a reflex. It is directed toward some future state, which is being determined by the organism in conjunction with its perceptions of its evolving condition and its history. (Freeman, 2000, p. 214)

Robot models of emotion have favoured a version of emotional behaviour that considers the outcome of emotion as a more or less fixed behavioural program triggered by some evaluation of the situation which can be modelled in information processing terms (whether based on typical cognitive processing or involving internal dynamics). Scherer attributes this version to basic emotion theories, which assume

> … a specific type of event triggers a specific affect programme corresponding to one of the basic emotions and producing characteristic expression patterns and physiological response configurations. (Scherer, 2009)

The other version, defended for instance in appraisal theories, claims that emotions are complex phenomena that emerge from the inherent intentionality of the body – thus posing greater challenges to robotic design. The emergent nature of emotion, the unity and specificity of the notion of emotion, the distinction between attitudes, motivations, sentiments, emotional episodes, moods, etc. have created perennial problems in the conceptualization of emotion (cf. Frijda, 2008). For this reason, the aim of this paper is not to answer the question of what emotions are. Rather, our first and foremost question is: What sort of bodies may allow for the emergence of emotion? Why may such bodies present advantages that other sort of bodies would not? What are the control requirements for such type of bodies? The answer we propose comes from a recent area of research that emphasizes the role of morphology in robotics.

Embodied approaches to robotics argue for a central role of morphological design (Pfeifer & Scheier, 1999). The potential of morphological design goes beyond investigating how different bodies can simplify the requirements for cognitive control. The question that has not been fully explored yet is how a single body (with a plastic morphology) can be subject to organized morphological modulation to fulfil different functional roles. In this context, the notion of morphofunctional machines has been proposed as those 'devices that can change their functionality not only by a change in (neural) control but by modifying their morphology' (Pfeifer, Lungarella, & Iida, 2007).

Studying the potential plasticity of morphology relates directly, we argue, to the physiological changes that occur in emotion. In this line, we envision robots that can modify the functionality of their sensors and motors, and other morphological parameters, to better adapt in real-time to situations. Degrees of alertness and readiness may be facilitated through this process that leads to the emergence of adaptive flexible behaviour.

This paper thus aims to bridge the gap between two important areas of research in current robotics: *morphofunctional systems* and *robotic models of emotion*. We do this in the conviction that neither of them can prosper unless their relationship is sufficiently clarified. In order to achieve this, we review the notion of morphofunctional machine and the development of robotic models of emotion.

We give a central role to morphological modulation and emergent action readiness, but this is not to say that other aspects of emotion should be ignored. Quite to the contrary, what is interesting about morphofunctionality is how it may transform the research questions on emotion action-selection, decision-making, appraisal or cognition generally. The morphofunctional approach to emotion modelling thus is not a particular robot model of emotion, but instead a framework under which questions about the role of emotion in robotics may be approached.

2 Current approaches to emotion in robotics

There have been considerable efforts in developing robot controllers that model emotional processes. It is believed that emotions provide a kind of functionality that helps the agent respond adaptively to environmental pressures (Cañamero, 1997). In this section, we review how researchers have presented the case for emotion in robotic design, and how it has driven research towards a search for models of emotion as purely information theoretic process – in which neural and other metabolic systems may participate in equal terms.

For emotions to be of interest in robotics, they need to present some functionality.

> In the case of autonomous robots having to interact and make decisions in dynamic, unpredictable, and potentially 'dangerous' environments, mechanisms functionally equivalent to (some) emotions present in biological systems facing the same types of problems can greatly improve their performance and adaptation to the environment. (Cañamero, 2005)

The sense of urgency in emotional situations and the need to make decisions under pressure are considered fundamental to understand the adaptive value of emotion. This thesis is related to the notion of *bounded rationality*, a concept that originates in classical AI. Agents have limited information, limited cognitive capacities and a finite amount of time to make decisions. An agent can only sustain its interaction in an unpredictable environment if it has the capacity to generate good-enough real-time responses that may be suboptimal. Emotions would thus be seen as a sub-optimal decision-making system to kick in when demanded by the situation.

This was the stance of 'Why robots will have emotions', one of the first papers in the field (Sloman & Croucher, 1981). Under this perspective, emotions appeared essential for control, and therefore part of the cognitive machinery. 'So the belief that emotions and intellect are somehow quite separate is mistaken'. Emotions are thus best understood within a 'computational architecture of a mind', essentially as 'processing motives' (Sloman & Croucher, 1981).

Damasio's theory of emotion, very influential in research on robotics and emotion provided the key for a role of the body in this process. For Damasio, information processing is not an exclusive task for the brain, but hormonal and other physiological variables (as well as their simulation carried out in neural structures in the brain) play important information-processing roles. The central argument is the role of physiological variables, called somatic markers, in decision-making (Damasio, 1994). Much of current research follows this approach, assigning different roles to emotion in relation to decision-making and action-selection.

For instance, Cañamero proposes a cognitive architecture that includes a value-system. The cognitive architecture processes a number of variables, including simulated physiological variables, controlled homeostatically, simulated 'hormones' that control the variables; a set of motivations activated by deficit or excess in the levels of the controlled variables; a repertoire of behaviours the execution of which also carries a modification in the levels of specific variables; and a set of 'basic' emotions (anger, boredom, fear, happiness, interest, and sadness) that can be activated as a results of the interactions of the robot with the world – the presence of external objects or the occurrence of internal events caused by these interactions – and release 'hormones' when active (cf. Cañamero, 2005). Internal variables are thus allowed a role in behaviour control as triggers of pre-determined behavioural response.

Similarly, emotions can be used as an attention mechanism in a reinforcement-learning task (Gadanho & Hallam, 2001). Gadanho's model prescribes a number of 'emotional states', defined as the state of a specialized emotional module in the controller, which modulates the reinforcement function and is influenced by a system of simulated hormones. In both Cañamero's and Gadanho's models, emotional states are defined by the discrete internal state.

A different approach would be to consider emotional behaviour as emergent (Cañamero, 2005; Pfeifer, 1994). For instance, Pezzulo considers that emotions can be viewed within a motivational system, which has a crucial role in determining (1) what task to fulfil and when; (2) which information to attend in order to resolve the task. The elements of the motivational system are drives, feelings and emotions. The motivational system has the capacity to drive behaviour, but not solely through a selection process (Pezzulo & Calvi, 2007). On the distinction between action selection and motivation see Parisi and Petrosino (2010). Following a dynamical systems perspective, the claim is that the motivational system 'modulates behaviour in a very broad, often unselective way, although it can indirectly produce qualitative effects' (Pezzulo & Calvi, 2007).

An example of this is found in Montebelli, Herrera, and Ziemke (2008). In a simulated experiment in evolutionary robotics (ER), robots are allowed to modulate their behaviour in real time through neural activations depending on energy level. The experiments show that behaviour can be dynamically modulated, from which emerges a dynamic, non-deterministic, and highly self-organized action selection mechanism, and a repertoire of behavioural attractors that give rise to motivation and preference (Herrera, Montebelli, & Ziemke, 2009).

The rigidity in sensory and motor systems is nevertheless common to all these approaches. The choice of an experimental set-up (which may respond to a practical choice rather than a question of principle), in which morphology is considered static, means that emotions are modelled exclusively as patterns of neural control. All models present adaptive responses that, either chosen among a pre-defined repertoire of actions or dynamically generated, respond to patterns of neural activation, and model information-theoretic aspects of emotion, overlooking the role of physiological activation in the modulation of sensory, motor and neural systems.

Biological emotions, on the other hand, present a strong physiological component. In short, the function of different subsystems is modulated to provide different modes of action readiness to the agent. In the following section, we review a well-studied phenomenon of embodied modulation for adaptive purposes: the fight/flight response (Cannon, 1929). This will allow us to determine the nature of the modulatory role of physiological arousal.

3 The role of arousal in biological systems

As we have seen, robotic models of emotion underestimate the embodied relevance of physiology. They at most recognize that certain metabolic processes play an information-processing role. Physiological changes, nevertheless, do have a very noticeable effect on the functioning of the body, with clear consequences for adaptation. As we shall see, functional reconfiguration through physiology is a powerful strategy for the generation of adaptive behaviours.

A simple example of this is found in the clione, a sea slug with a limited repertoire of behaviours. The clione has a sensor, the statocyst, which is used for orientation, coordination of movement and to perceive vibration (Zaitseva, 2001). What is interesting is that a modulation of the statocyst can be sufficient to produce distinct behaviours. Concretely, the hunting search motor program could be generated by changes to the statocyst receptor network, all due to its intrinsic dynamics (cf. Levi, Varona, Arshavsky, Rabinovich, & Selverston, 2004). Thus, in order to generate two distinct behaviours, the clione resorts to a change in the function of the sensor, rather than on a change in neural patterns of activation (which thereby follow).

The full relevance of physiological changes for adaptation comes within emotional processes. Their effect on sensorimotor dynamics and the control of behaviour in emotional episodes can be exemplified by the fight-or-flight response. This response refers to the way animals respond to acute stress. It can be used to illustrate the role of physiological arousal for two reasons. First, fear is often considered a paradigmatic example of emotion, and many robotic models of emotion focus on the recognition of danger in the environment, and how to safeguard the safety of the system. Yet most robotic models have investigated neural aspects of fear processing, and have ignored the modulation of physiological systems to prepare the body for action.

Second, the intensity of physiological states (the response is often referred to as hyperarousal) allows us to identify modulatory roles more clearly. The functional role of physiological states is nevertheless not restricted to fear, or even to emotional episodes generally. Regulating the physiology is a constant demand on any system where its embodiment can change its functionality dynamically, but it is in emotion where changes in physiology have an more clear adaptive purpose.

The fight/flight response is triggered by events that relate to the potential threats to the animal. It fundamentally involves a discharge of the sympathetic nervous system that primes the organism for either fighting or fleeing. Although pain signals can trigger the response through a direct connection between sensors and sensory-cortex to the periaqueductal grey, the recognition of threat events normally involves the activation of the amygdala (Arbib & Fellous, 2004)

Following the recognition of threat, there is a cascade of distributed modulation of physiological systems (Fogel, 2009). There are four major pathways from the amygdala for such a modulation, two neural and two hormonal. The amygdala directly affects the autonomic nervous system, through an activation of the sympathetic nervous system. Heart rate, digestion, respiration rate, salivation, perspiration, diameter of the pupils, urination and sexual arousal are affected by the activation of the sympathetic nervous system. It also affects the periaqueductal grey, which in turn affects the autonomic nervous system.

The two hormonal routes result in the production of cortisol and norepinephrine. Input from the amygdala to the hypothalamus produces a cascade of hormonal secretions through the hypothalamus–pituitary–adrenal axis that leads to the secretion of cortisol. These affect blood pressure, glucose and activity of the immune system. The other hormonal route goes through the locus cereleus to produce norepinephrine, which along with epinephrine affects heart rate and blood flow to the muscles.

There are feedback connections between all four routes, therefore the organization of the fight or flight response is homeostatic and resorts on the balance between the different modulatory roles involved. The final result is a distributed modulation of sensory, motor and nervous systems, through distribution of energy and neuromodulation. These effects are summarized in Table 1.

Coordinated modulatory effects result in a disposition that determines the range of perception-action loops the animal may engage in. For instance, there is an acceleration of instantaneous reflexes, therefore a disposition to react automatically to certain stimuli

Table 1. Modulatory effects mediated by arousal

Modulation type	Effect	Examples in human physiology
Mobilization of energy	Making energy available and directing it from some subsystems to others	Acceleration in respiration and heart rate, slowing down of digestive system, constriction of blood vessels
Modulation of sensory systems	Increasing–decreasing sensitivity, modulating particular sensor	Dilation of pupils (midrise), auditory exclusion (loss of hearing) and tunnel vision (loss of peripheral vision)
Modulation of motor systems	Changing the way they respond to neural activation	Liberation of nutrients to muscular system and the dilation of blood vessels for muscles
Neuromodulation	Changing cognitive readiness through the plasticity of the neural system	The serotonergic (5-HT) system sets the threat level for risk aversion, the cholinergic (ACh) system sets the level of attentional effort, the dopaminergic (DA) system drives reward anticipation and motivation, and the noradrenergic (NE) system sets the level of response to novel and salient objects (cf. Krichmar, 2008)
Other effects		E.g. the release of opiates has an analgesic effect that makes the system less sensitive to pain

(Fogel, 2009). While certain responses may be reflex-like 'locally', the nervous system retains the flexibility to adopt different emergent behavioural strategies, such as flight or fight. In other words, although some parts of the emotional response may be stereotyped patterns of behaviour, the overall response emerges in the negotiation between the agent and the environment. Arousal predisposes the body, but does not prescribe what the actual behaviour is going to be.

Emotion theorists speak of action tendencies, 'present prior to execution and independently of execution' in order to capture this feature (Frijda, 1986, p. 70). 'Action tendencies are hypothesised … for theoretical reasons: to account for latent readiness and to account for behaviour flexibility' (Frijda, 1986, p. 71). Emotions are thus embodied in the sense that they comprise body changes that project different readiness for embodied interaction. 'State of action readiness is defined as the individual's readiness or unreadiness to engage in interaction with the environment … Autonomic arousal can be considered the logistic support of certain variants of action readiness' (Frijda, Kuipers, & ter Schure, 1989).[1]

The adaptive value of physiological changes underlying emotion thus cannot be overlooked. The capacity to change its body so to favour certain types of interaction, through autonomic arousal, which allow flexible yet purposeful behaviour, is what marks emotion as an adaptive response. As we see in the next section, an emotional system can be considered an instance of a morphofunctional machine.

4 Morphofunctional machines and artificial physiology

While physiological changes play a decisive functional role in the generation of adaptive behaviour, finding a robotic counterpart to physiology is far from straightforward. Attempting to replicate some of the metabolic processes found in biological agents in machines is not only extremely intricate, but can easily overlook the radical differences between biological and artificial embodiment (Ziemke, 2001). We are thus interested in the function of modulatory effects, abstracted from biological details. This is a concept that, as we shall see, has already been considered in the field of embodied robotics.

One of the implications of taking into consideration embodiment in robotics is to acknowledge the role of morphology for the dynamics of control. Morphology allows for forms of interaction that induce regularities in sensory input, whilst materials may provide self-stabilizing properties (cf. Pfeifer et al., 2007). These factors can therefore be exploited in robotic systems: morphological arrangement of sensors can simplify problems and facilitate adaptation; increase robustness and exploit physical properties of materials in locomotion. For example through passive dynamics, in which movement is partially determined by morphological properties (as demonstrated in passive walkers, McGeer, 1990).

Rolf Pfeifer is one of the main defendants of the importance of morphology:

> Clearly, the neural processing required for a particular task depends on embodiment since the latter delivers, so to speak, the raw material, the signals for the neural system to process. Similarly, the motor system has a particular dynamics that depends on the morphology and materials and this dynamics needs to be controlled or modulated by the neural system. And last but not least, through the interaction with the real world, the agent actively generates sensory stimulation which is why we often talk about sensory-motor coupling. (Pfeifer, 2002)

This implies that self-organizing methods such as evolution needs to take into account morphology, as '… separating morphology from control is […] difficult to justify from an evolutionary perspective and potentially misleading' (Cliff, Husbands & Harvey, 1992,

p. 3). Bongard and Paul (2001) show that introducing morphological parameters can improve the evolution of biped locomotion. In this framework, the morphology of each individual is considered static, but the evolutionary process is allowed to modify the morphology across generations. This can be applied to adjusting parameters for sensor or motor information (e.g., Lund, Hallam & Lee, 1997), as well as to evolve anatomical characteristics of the morphology (Funes & Pollack, 1998).

The areas of morphological design and morphological computation have an ample scope. A first distinction can be made between morphologies depending on their plasticity (cf. Bentley and Clack, 2005). A dynamic morphology would be one in which 'the sub-component connectivity can continually change in relation to the environment', whilst a static morphology does not change during lifetime. Systems with dynamical morphologies have been defined as *morphofunctional machines* (Hara & Pfeifer, 2000; Kawai & Hara, 1998): 'devices that can change their functionality not only by a change in (neural) control but by modifying their morphology' (Pfeifer et al., 2007).

A further distinction can be made depending on what sort of morphological change can be effected. One approach, undertaken for example by research on self-configuring modular robots, considers that morphological modulation is best effected through a rearrangement of the connectivity of the parts, without any modification in the local function of each of the parts. Such robots can 'morph', for example, from a snakelike structure into a quadruped walker or vice versa (Murata et al., 2007; Yim et al., 2007), maximizing the utility of morphology for a given task.

The other, less explored approach to morphological modulation would be one that applies change not just through the re-arrangement of the components, but also through the re-configuration of the functionality of the components. This distinction between two forms of modulation can be analogue to the distinction in biology between 'anatomical' characteristics, as the form and structure of a body, and 'physiological' characteristics, i.e., the function that each part plays in the overall organization. Whereas the word morphology normally relates to form and structure, in contrast to physiology, which relates to function, we understand the concept of morphofunctionality as covering both.

The question is thus whether real-time morphofunctionality needs a structural change, or we may explore other ways to modulate functionality without altering the overall structure. Movement and preparation for movement in most vertebrates involve changes in weight distribution and the role different parts of the skeleton and the associated muscles play in the overall anatomical structure, so to a certain extent there is this type of anatomical adaptation. Nevertheless, major anatomical changes normally occur within an evolutionary process (as exploited in the ER examples above). In biological systems, real-time adaptation is mostly effected through physiological modulation of sensory and motor systems.

Although there is a tendency to consider the notions of organism and physiology as referring exclusively to biological agents, the question is whether we can interpret the notion of physiology in relation to morphofunctional machines. Do robots (by definition) lack physiology? Here we argue that they may be applicable also to robotic systems, as any modulation of the parameters governing the functioning of motors and sensors.

The word *organism*, which refers primarily to living systems, describes a form of organization in which there is a number of mutually interdependent parts that play a functional role within the totality. A living organism and a social organization can both be defined as organisms. In this context, physiology is defined as the study of the functionality of the constituent parts in an organism and their integration into a functional whole. Therefore a robot, insofar it is composed of parts that play a functional role and that can be modulated, are subject to physiological modulation too.

We understand *robotic physiology* to denote the set of parameters that determine the function of its components, such as motors and sensors. Physiological modulation, as a provision for robot adaptation, falls within the area of morphofunctional machines. The challenge is of course to coordinate such modulation so that the emergent response is adaptive, since an uncontrolled change in the functionality of morphological parameters would disrupt sensory-motor coordination.

This complex form of organization may be approached from the perspective of emotion. As Scherer argues,

> … most of the subsystems of the organism must contribute to response preparation. The resulting massive mobilization of resources must be coordinated, a process which can be described as response synchronization. I believe that this is in fact one of the most important design features of emotion, one that in principle can be operationalized and measured empirically. (Scherer, 2005, p. 701)

Emotions are thus viewed as a network of processes that self-organize around morphological modulation, giving rise to an orchestrated adaptive response preparing the body with readiness for a certain type of interaction. Attending to the responses that we call emotions in biological systems can enlighten how to approach such a coordination challenge in robotics. Emotional responses include the activation of physiological systems, the mobilization of energy and the modulation of sensory and motor systems.

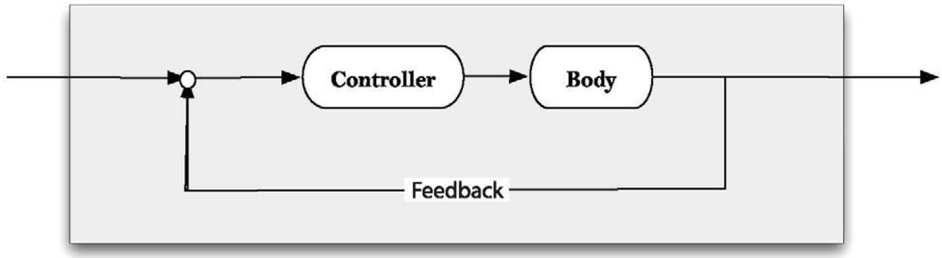

Figure 1. Standard control system.

5 Principles of a morphofunctional architecture

In this section, we tackle the question of a morphofunctional architecture from two parallel perspectives. From the first one, we consider the problem of controlling a morphofunctional body from a control systems perspective. In the second, we take inspiration from the organization of behaviour in humans and animals, in particular through the division of control between endocrine and nervous system.

5.1 A control systems morphofunctional architecture

The morphofunctional approach to emotion in robotics is fundamentally a study on what sort of embodiment is (minimally) required for modelling emotion – a morphofunctional body. Our main aim is not to present a model of emotion in particular (of emotion generally or a single emotional episode), but to lay down the control requirements implicit in the reconfiguration of morphological parameters to generate adaptive readiness. Different control strategies and design methodologies may be used to control a morphofunctional robot, but some features should be considered by all:

- Robots are composed of different components, such as mechanical structures, sensors and motors (i.e., they are 'artificial organisms'). The *arrangement* of these components and their *integrated functionality* is the morphofunctional configuration of the robot.
- In *dynamic morphologies*, the sub-component connectivity/functionality can continually change in relation to the environment, providing states of action readiness.
- Dynamic morphologies can change two interdependent features: *anatomical features* (re-arrangement of components) and *physiological features* (functionality of the components). This is in addition to *meta-control*, i.e., changes to the control system, which integrates the function of all systems.

From a control systems perspective, a basic robot system is composed of two essential components: plant (sensors, actuators and structural parts) and controller. The control system describes the regulatory process that allows the system to operate adequately – the relationship between inputs and outputs of the system. A particular device that is put in place to bring some reference variables towards a desired range of values is called a controller. This basic control system representation is shown in Figure 1.

In a morphofunctional system, some of the plant components support internally driven modulation. This is the case of any existing robotic sensors, motors or processors. These are actual devices in which local functioning is governed by parameters that can in principle be modified online. Progress in the morphofunctional approach can also lead to new sensors and motors designed so that they allow for more comprehensive forms of modulation. Such devices already exist. For instance, physical motors could also be enhanced to support modulation. For example, electromagnetic clutches are used in locomotion. These include mechanism (e.g., magnetic powder technology), which modulates the relationship between the motor and the wheel rotation, and can be used for acceleration or for engine braking.

A morphofunctional system needs therefore to control two types of values: actuator variables and morphological parameters. Controlling actuator variables correspond to a classic control system. In addition to this, real-time modulation of morphological parameters changes the functional operability of motors and sensors, changing the dynamics of the overall system. This includes parameters that affect the arrangement of the components of the morphology. Coordinated modulatory effects on sensors, motors and structural parts serve a global purpose of redirecting resources to facilitate certain action readiness. From a dynamical systems perspective, it does so by changing the dynamic structure of the agent/environment interaction.

A dynamical system is characterized by a state space that comprises potential trajectories of the system over time, which can be described by a set of differential equations. A variable structure system is one that can be characterized by different state spaces at different times: or more precisely, one with a compound state

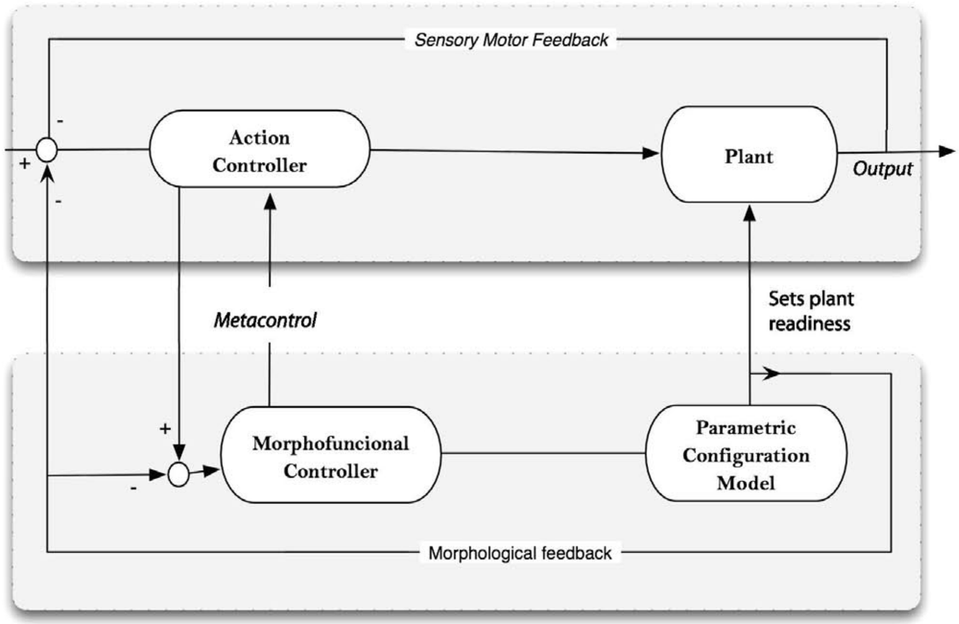

Figure 2. Dual controller. The action controller is in charge of sensory-motor activation and activating bodily changes, whilst the morphofunctional controller prepares the body through morphological reconfiguration and metacontrol.

space. Reconfigurable robots are an example of variable structure systems. Control methods such as sliding mode can be put in technical systems so that the system autonomously reconfigures itself to stable dynamics (Zinober, 1994).

Figure 2 shows a dual control architecture with control over morphological parameters. Rather than having a centralized controller in charge of all parameters, we add a morphofunctional controller that, alike sliding mode controllers, is decentralized. Its role is to provide the system with a dynamics background (through action readiness), that is amenable to control. The morphofunctional controller thus controls the disposition of the body through the reconfiguration of morphofunctional parameters. It is activated by the action controller, and its output is what we have named as the intentional (or predisposed) body.

The task for the action controller is to generate sensory-motor coordination, given the current underlying body dynamics. Its plant is not the body in its full range of possibilities, but an intentional body that shows readiness to behave in particular ways. Changes to body configuration demand that the action controller to re-organize, adapt and change some of its internal functions accordingly in order to operate under these new configurations. Thus, morphofunctionality requires some degree of metacontrol, i.e., changes to the controller itself (Sanz, Lopez, Rodriguez, & Hernandez, 2007; Sanz, Sanchez-Escribano, & Herrera, 2011). The stability of a action-morphofunctional dual control system thus relies on the coordination of existing reciprocal connections between both.

The control system described thus emerges from the cooperation of two partially independent control systems. The actual implementation of this dual morphofunctional control will obviously depend on what sort of control mechanisms are in use, which are not prescribed here. In the next subsection, we propose a biologically inspired architecture that would support the requirements for morphofunctional reconfiguration, although this is by no means the only architecture that could exploit morphofunctionality.

5.2 A bio-inspired architecture

Morphofunctional control is effected in biological agents through the neuro-endocrine regulatory network,[2] from which we take inspiration to provide an instance of a morphofunctional architecture. Besides biological plausibility, the division of control between neural and endocrine systems addresses the requirements of morphofunctional control. It also relates to more or less established areas of current research in bio-inspired systems from which it can benefit, such as artificial neural networks (ANNs), models of neuromodulation and artificial endocrine systems (AESs).[3]

Much of cognitive science research attributes the bulk of control to the nervous system, and in particular the brain. Nevertheless, any medical book defines the function of the endocrine system as primarily of control, similar to the nervous system but with certain differences, in relation to the flows of information and their function (Table 2). The neural system is characterized by fast and localized signals – it processes sensory

Table 2. Information-theoretic differences between nervous and endocrine systems

	Communication type	Duration of the signal	Strength
Nervous system	'Telephone system': fixed channels, precise destinations.	Faster communication and shorter duration (ms)	All-or-none action potentials (but different frequencies)
Endocrine system	'TV broadcast system': signals spread throughout body and are picked up by scattered receptor cells	Slower communication (sec, min) – longer lasting	Graded in strength

information and controls the activation of motor systems. The endocrine system is based on slower signal transmission and longer-lasting effects. It controls most metabolic processes, but its effects go beyond homeostatic control: it also affects moods, emotions, attention, motivations, etc.

Hormones produce coordinated effects on all receptive organs and systems. For example, consider how in the fight/flight response an increased activation of the muscles is accompanied by a loss of refinement in the senses, as well as different forms of (de-)activation in different physiological systems. This serves the purpose of preparing for action. One of the main roles of the endocrine system is thus to coordinate the modulation of different morphological subsystems, so that together they create action readiness.

Hormonal concentration is subject to regulatory homeostatic loops, which maintain a balance between the different hormones and their function. Processes of hormone production, their decay rate and the relationship between concentration of different hormones are some of the essential components of an AES (e.g., Timmis, Neal, & Thorniley, 2009; Xu & Wang, 2011).

The bio-inspired architecture presented thus has two main components: an ANN and an AES. These should be tightly integrated systems, with bidirectional causal links between them. Glands secrete in response to neural activation – in humans this role is played by the hypothalamus, which largely controls endocrine activation and maintains homeostasis. The states of the AES can also be inputs to the ANN. This hypothesis is entertained for instance by Damasio, with the assumed role of somatic markers, afferent feedback from the internal milieu that is required for the ANN to appraise situations of relevance (Damasio, 1994).

Last but not least, we have neuromodulation. This is the process through which neurotransmitters, such as dopamine or serotonin, regulate the function of populations of neurons in the nervous system. Hormones and neurotransmitters are closely related, and sometimes the same substance plays both roles, such as norepinephrine. Neurotransmitters affect the central and autonomic nervous systems, as well as a hormone affecting parts of the brain and causing the physiological modulation present in the fight/flight response. The last causal link is thus the potential of endocrine states to reorganize neural dynamics, inducing states of cognitive readiness (Krichmar, 2008, see table 1 for detailed effects of neuromodulation in humans).

Figure 3 describes in more detail the functional relationship between the components of the system. There are three sources of sensory feedback: exteroceptive (acquired through senses in interaction with the environment), proprioceptive (coming from motor activation) and interoceptive (stimuli from within the body, highly dependent on endocrine system states). Interoceptive stimuli can play a role as somatic markers in different processes – for instance, they can lead the ANN towards certain attractor points that correspond to decision-making tasks.

The ANN is the primary source of sensory-motor coordination, whatever the functional configuration of morphology may be. In particular, it is also in charge of appraisal, i.e., deciding when morphofunctional reconfiguration should occur. Through appraisal, the ANN can activate glands, which in turn secrete hormones that modulate morphological parameters. What the neural/embodied antecedents of an appraisal process are would depend on the nature of the relevant events for the agent.

The AES thus has distributed effects on all systems. Centrally, the artificial endocrine network (AEN) is also responsible for modulating the function of sensors and motors, creating a state of action readiness. Then, it plays a neuromodulatory role, influencing neural dynamics. This can be the essential mechanism for motivation and control precedence (Table 1).

The AEN thus controls the cognitive and behaviour disposition of the body, while the ANN generates sensory motor coordination. This results in a dual control, which we call *somato-sensory-motor coordination*, that emerges from the interaction of ANN, the AEN, the body and the environment.

6 Three scenarios

In this section, we provide three scenarios in robotics research where the morphofunctional approach could be exploited. Exploring a variety of scenarios, robot morphologies and design approaches allows us to get an idea of the potential application of morphofunctional approaches across intelligent systems generally.

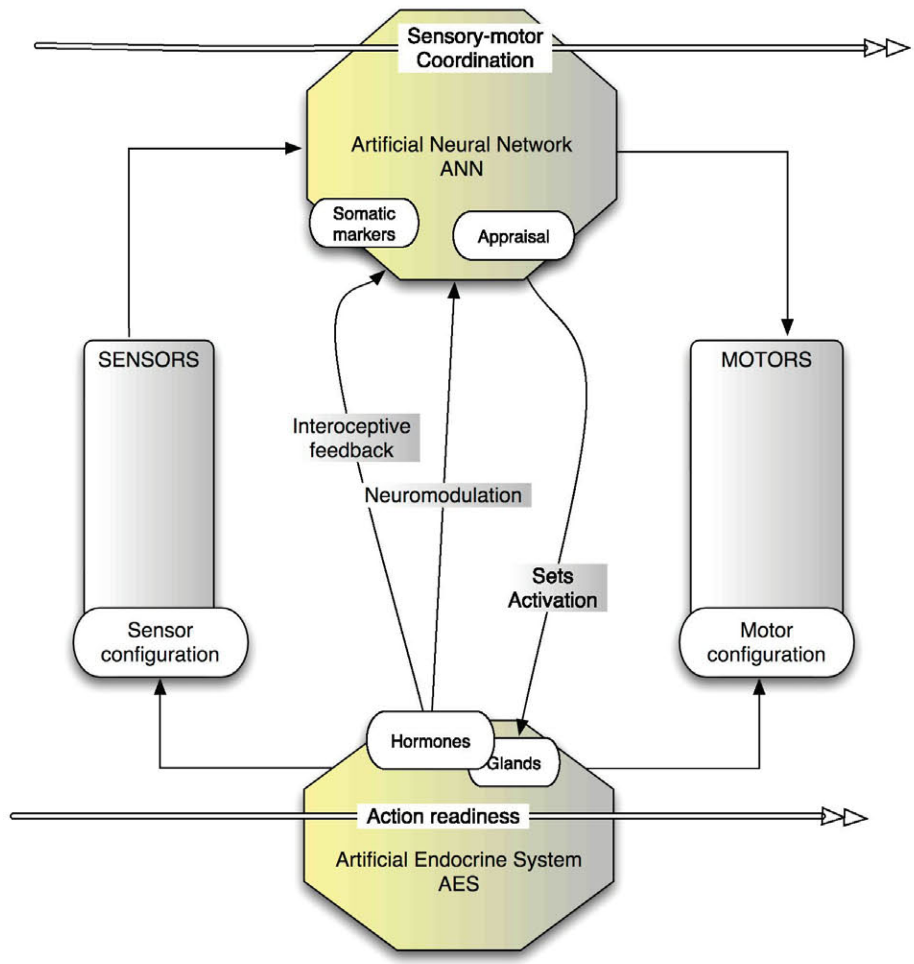

Figure 3. Bio-inspired architecture with functional and emergent roles. The artificial neural network (ANN) for sensory-motor coordination and activation of arousal through appraisal, artificial endocrine system (AES) modulates systems, neuromodulates ANN and provides somatic markers.

The three case examples are thus of very different nature. The first will relate to standard robotic platforms, such as the Khepera, controlled by neural networks designed by artificial evolution. The second case will be a non-standard robotic platform, such as an anthropomimetic robot. The third case will be the operation of industrial systems, which illustrates how the principles of emotion as reconfiguration can be applied to a wide scope of embodied systems beyond robotics.

6.1 Evolutionary robotics with simple embodiment

ER is a promising methodology for the design of autonomous robots. An evolutionary process is a heuristic search (usually performed by a genetic algorithm) of potential configurations within a solution space, given a measurement of performance (fitness). The genotype encodes the solutions within an evolutionary process – while the phenotype is the actual expression of the genotype. Defining an ER experiment requires that we define the robot morphology; the genotype/phenotype structure and the robot control architecture; and the task and environment.

One simple way to use ER is to evolve an ANN controller for a fixed morphology robot. Simple robots, such as the Khepera robot, are particularly suited for ER, as they can be faithfully simulated, which allows to speed up the evolutionary process (see Nolfi & Floreano, 2000, for a plethora of examples). Genotypes encode some of the parameters that define the ANN (e.g., weights, learning rules, etc.), while other parameters will remain fixed (often the network structure). As we have seen, structural morphological parameters may be also be evolved in conjunction with the controller – but remain fixed through the lifetime.

To exploit morphofunctionality, we must first identify parameters that could be modulated in a simple robot platform like Khepera. Parameters that affect the functionality of subsystems, but that can be changed in real-time for adaptation. Some of these parameters may have a real effect on the robot components – others could simulate such effects.

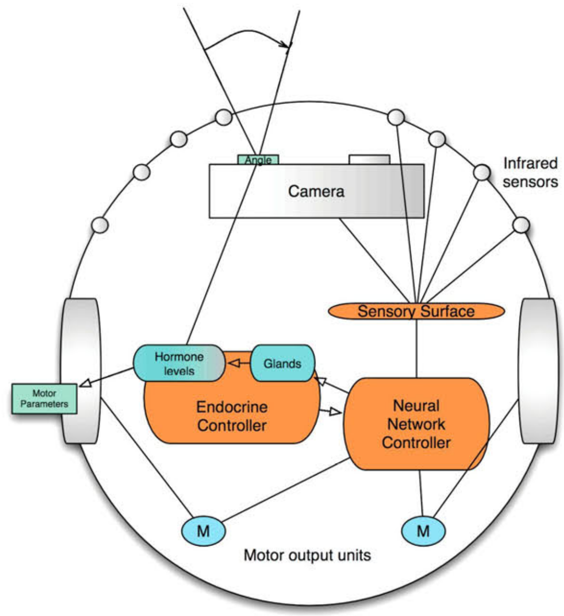

Figure 4. A dual control architecture for a Khepera robot. The artificial neural network (ANN) connects sensory inputs and produces motor outputs. It also activates glands that produce hormone levels. Hormones affect the function of sensors and motors.

For example, if the robot has a camera, parameters such as camera view angle and view range affect camera functionality, and thus can be evolved (as done by Buason, Bergfeldt & Ziemke, 2005). Other parameters affecting infrared or sonar sensors could be modulated to bring about different functionality. Motor parameters, such as maximum speed, have also been used in ER to affect morphology without changing the underlying machinery (cf. Nolfi & Floreano, 2000; Parisi & Petrosino, 2010). Although Khepera motors do not include this functionality, its effects could be simulated.

ER experiments require a task and a correlated fitness function to be defined. In order to exploit morphofunctionality, the task should be varied. Consider a robot that faces two situations in its lifetime. In the first situation, the robot has to carry out a simple task such as approaching a light, or finding an object and lifting it. In the second part of its lifetime, the robot is in the same scenario but a predator is present. Both are different situations for which different morphological configurations might be best. The question is whether an evolutionary process would find such configurations.

This will ultimately depend on the controller structure. A large ANN taking care of both movement generation and morphological configuration may not find such solutions, and effectively leave morphology fixed. This is because scattered moment-by-moment changes to morphology may not be of any evolutionary advantage. Using a control structure such as the neuro-endocrine architecture presented above may produce different results.

The control architecture is depicted in Figure 4. It is composed of a neural network, alike those normally used in ER (feed-forward, recursive, etc.). It mediates between sensor readings and motor outputs. Nevertheless, it has extra outputs that activate the endocrine system. The endocrine system is composed of a number of glands (outputs of the ANN), which secrete different hormones. The hormones control parameters that affect motors and sensors, as well as neuromodulating the ANN. A simple way to achieve neuromodulation may be through providing a number of extra inputs to the ANN (as in Montebelli et al., 2008).

Neural weights, number of glands/hormones, absorption rates, effect on motors and sensors, could be some of the characteristics encoded in the genotype. Experiments could address whether the ANN would successfully implement an appraisal process, through which it can categorize the different situations, and generate distinct action tendencies. To what extent would interoceptive feedback be essential for such a process?

6.2 The anthropomimetic robot

The use of the approach presented is particularly interesting if we consider new generation of robotic bodies that aim to avoid the typical rigidity of mechanical devices (for instance in the area of soft robotics). Here we consider the case of a robot designed to resemble not only the human body shape, but also its skeletal and muscular structure, such as the Eccerobot (Eccerobot.org). Its control appears in the first instance much more complex and difficult than standard robotics systems, as the use of inverse kinematics to generate predictable movement is made almost impossible by the highly non-linear dynamics implied.

Artificial muscles are simpler than their biological counterparts,[4] yet they share some characteristics and generating reliable movement patterns remains a complex problem. The actuator system in Eccerobot is composed of a network of small motors that, through a winding mechanisms, 'innervate' or 'relax' artificial muscles, creating movement around the joints. The muscles have an elastic component (shock cord), which provides elasticity through its tension. This needs to be always above a minimal value to prevent damage to the cord, called the reference tension force. Position and reference tension force are thus the two reference variables for controlled movement, which can be changed in real time (cf. Potkonjak, Svetozarevic, Jovanovic & Holland, 2010).

Like in the human body, skeletal muscles work in pairs, playing an either agonistic (for extension) or antagonistic (for flexion) role. Even though linear models may be applied to single joints, multi-joint robots are non-linear systems, which control needs to take into account joint inertia, gravity load and dynamic coupling between joints (cf. Potkonjak et al., 2010). When a group of muscles are activated, the movement produced on the robot as a whole will depend too on muscles that are passive, i.e., not currently activated. Passive dynamics is the study of the interaction between active and passive components in a physical system.

How passive muscles adapt to the initiating movement will depend on their physical properties, one of which is the tension that the muscle holds at rest. Changing this underlying tension is thus a potential way to alter the performance of the system as a whole. Attending to the case of the human body, arousal (e.g., in the fight/flight response) affect the elasticity of muscles and affects the body passive dynamics. Higher muscle tone gives the body strength and speed, while reducing flexibility and controllability.

We can thus relate muscle tone in humans and the reference tension force in Eccerobot, as morphological parameters that can be modulated for adaptation. In order to control such a body we not only need to move the appropriate muscles, but also maintain the system in a state of readiness that depends on such parameters.

Another potential parameter is the current fed to the motors. In humans arousal modifies the provision of oxygen and nutrients through blood flow, changing muscle performance, and so the speed and force of the movements. The same modulatory effect can be achieved by changing the current. If the robot reaches for an object, it loses precision for manipulation but gains force of impact if required. On the contrary, if the amount of energy committed to the motors is low, the contraction of muscles will be slower and there will be less strength in the whole structure.

We have thus identified two global parameters that can affect the behaviour of an anthropomorphic robot. In principle, those parameters could be fixed by the designer in order to predict movement patterns better and thus design a control system that generates desired behaviours. Arguably, changing those parameters can be very useful if the robot can do tasks that require different movement patterns. For example, the robot may be capable of things such as making tea or digging a hole, which require different strength and controllability. A morphofunctional approach that models the effect of arousal on muscle performance can be effected through setting general muscle tension and voltage provision.

Although these may be updated at every time step, they may also be adjusted according to the situation as a whole. This is so if different behaviours are favoured by different configurations of such parameters. In other words, rather than letting the controller set these parameters individually for each muscle and each time-step, the morphofunctional approach would target a global configuration. This could be used for control of action readiness.

Now consider the case that the control system cannot predict entirely what the course of interaction is going to be like, what concrete task it is going to face and thus the optimal action readiness. In this case, the control system has to take its chances and produce a state of action readiness that may be functional, or maybe present some dysfunctional characteristics. For instance, think of a search and rescue operation – what is the best underlying state of readiness? Providing a state of action readiness that is mostly adequate will depend on evaluation mechanisms that perform appraisals of the situation. Organizing readiness would thus be linked to emotion.

6.3 Case scenario: the immobile robot

Another application domain of high relevance is the case of large industrial systems, where morphofunctional control render alternative systems able to attain their objectives in changing circumstances. Examples abound: refineries, nuclear power plants or complex utilities like electrical distribution grids or telecommunication networks.

The embodiment of these systems is radically different to that of mobile robots, and they do not attempt to replicate animaloid capacities such as navigation, search for sources of energy or mating. They however do implement other kinds of functions that are quite close to biological operation: continuous variable chemical physiologies, strong – mass and energy – coupling with their environments, protection and safety measures, etc. Despite the obvious different nature of complex technical systems, they can be regarded as much closer to some of the aspects and nuances of biological bodies operation and adaptation, such as:

- Emergent – systemic – behaviour: the function of the system is attained at the whole system level.
- High complexity: some of these systems may have tens of thousands of elements in continuous dynamic interaction.
- Continuous 24/7 operation: some of these systems cannot stop in the provision of the service they are giving.
- Hierarchical organization: complexity is handled by hierarchical organization into subsystems – also including heterarchical subsystems that address transverse, system-wide needs.
- Fault tolerance: these systems can overcome faults thanks to redundancies and adaptation mechanisms.

Complex industrial systems are composed of collections of hierarchically organized subsystems operating concurrently in pursue of a global, holistic set of objectives. Industrial plant units – reactors, distillers, tanks, generators, substations, etc. – constitute semi-autonomous organs that organize into functional subsystems. For example, a chemical process – the process carried out in a chemical plant – is made up of elementary steps called unit operations, which occur in the different individual units – reactors, distillers, pumps, etc. – that provide elementary functions. The global function is emergent in relation to unit and subsystem functions.

A high level of availability – the degree of being able to perform its mission when required – is an usual requirement of industrial systems. This implies improved robustness and/or adaptivity to cope with expected and unexpected changes. Components at all scales – units, subsystems and whole plants – are dynamically adapting to provide some specific function that contributes to the global functionality of the plant. For example, redundant chemical reactors can resiliently provide a unit operation in a chemical process to improve plant-level robustness. The change from a unit to another, redundant element happens dynamically as the developing problem is appraised and handled.

The conditions that trigger the functional reorganization of the system are associated to three basic classes of circumstances. The plant must change its organization to 1) overcome some developing problem – a unit fault, an emergent dynamical interaction, a sudden change in workload, etc.; 2) optimize system or subsystem operation; and 3) keep functionality while suffering maintenance or re-engineering activities.

These complex systems are socio-technical in nature, with humans playing important roles inside them. Most morphofunctional changes in the plant are usually driven by human decisions. However, in some cases they are fully automated because they are too fast to be handled by humans or because they follow pre-defined reorganizational schemas. Open-ended autonomous reorganization is still not in use in industrial systems for safety reasons.

A possible way to increase autonomy in such type of plants may be to exploit the idea of patterned metacontrol and its relation to emotion in biological systems (Sanz et al., 2011). The re-organization of the plant can affect several classes of parameters; from parameters of the control model and the control model itself (i.e., changes in the way the plant is controlled) to changes in the functional organization of the physical plant or the concrete components realizing the diverse functions needed. The complexity of such a space of potential configurations is enormous and the problem of finding the right configuration – i.e., the right plant design – is an NP-complete problem.

The only viable alternative so far is the reduction of the dimensionality of the configuration space by reduction of the number of alternatives to decide about. This reduction is achieved both by interface minimization – simplifying the connections between components – and by patterning, i.e., by selection among a reduced collection of pre-established morphic configurations. The specification of these plant or subsystem configurations is tailored to concrete classes of operational situations.

The parallelism with biological and robotic emotion can be established but, obviously, with major differences regarding embodiment, typical cognitive processes, social interactions, etc. Morphofunctional changes are driven by the perception – the appraisal – of the ongoing events, both internal and external to the plant, and the evaluation in terms of consequences over plant objectives, whilst the patterned re-organization of the plant is equivalent to a morphofunctional reconfiguration. In summary, the morphofunctional approach to emotion opens up the possibility to applications in non-animaloid industrial systems with requirements for increased autonomy.

7 Challenges in modelling emotion

We have motivated the morphofunctional framework as the proper background for modelling emotion. We have not explicitly attempted to answer the question of what emotions are or to what extent they are adaptive, but to provide a framework in which these questions may be tackled. From a synthetic perspective, this would involve creating models of emotion. Here we briefly discuss the modelling challenges that emerge from this framework.

In its most simple version, emotion is a twofold process. Appraisal is the cognitive process by which an agent becomes aware of potential relevance of some aspect of the environment for its concerns. Response is the way the agent tries to deal with the situation, i.e., emotional behaviour. This division does not imply, as many classic theories defended, that both constitute independent processes: there may be shared underlying processes that are essential for the emergence of both. In particular, we argue that morphofunctionality can be understood as such a shared process.

7.1 Appraisal

One of the central questions regarding emotion is: when and how are emotional episodes triggered? There is little agreement on what perceptions are characteristic of determined emotional episodes. To a certain extent, perceptual antecedents will depend on the situation. If, for example, we are concerned about a predator that is always marked by a singular stimulus (a cat's smell for rats), sensation of that single stimulus will be sufficient to trigger an emotional response. In other cases, dangers might be more difficult to appraise and may require complex cognitive processes. The cognitive content of triggering appraisals is thus determined largely by the ecological niche, and cannot be answered *a priori.* Consequently, the question of appraisal in robotic systems has to be approached pragmatically.

In any case, morphofunctionality can have a major impact on the question of appraisal when we consider embodiment. *Embodied appraisal* is the thesis that information coming from bodily states plays a central role in the cognitive processes that determine appraisal. Damasio's somatic marker hypothesis is an example of such an approach (Damasio, 1994). Instead of evaluating a situation solely through the information that has been obtained about the external object/situation, internal information is taken into account. The question for a robotic model is when and how such internal information can be relevant for assessing the situation.

For Prinz (2004), the condition for perceptions of bodily states to be relevant is that they are 'changes in the body … reliably caused by the instantiation of core relational themes', i.e., organism/environment relations that bear on well-being. Under this perspective, there is a dynamical quasi-representational relationship between what happens within the organism and its relationship with the environment at large. By virtue of what can there be such a relationship between organismic/environment relations and internal states? Is it sufficient that internal states play a function in the homeostatic control of the body (as discussed in Di Paolo, 2003)? Or should there be another intentional link to the external world? (Ashby & Conant, 1970).

Morphofunctionality can help establishing such a causal relationship. States of action readiness ultimately constitute a functional relationship with the environment. As they are caused by configurations of morphology, these can be considered such embodied 're-presentations'. Morphofunctionality could be then considered as the grounding of embodied appraisals, a hypothesis that nevertheless requires further experimental work and dynamical analysis to be verified.

Considering morphofunctionality also allows us to distinguish between primary and secondary appraisal, an important distinction in emotion theory. Primary appraisal would be the awareness that there is certain relevance in the situation regarding the agent's concerns, and it is marked by morphofunctional activation and change in action readiness, without necessarily having any explicit awareness of factors involved. Secondary appraisal follows primary appraisal, and evaluates the agent's own action readiness and the situation, resources and affordances, coping potential, etc This approach thus gives grounds to model aspects of constructivist emotion theories (cf. Scherer, 2009), which claim that 'continuous core affect – constituted by valence and arousal – is interpreted and categorized in the light of situational cues' (Russell, 2003).

7.2 Response

Most models in robotics, in line with basic emotion theories (cf. Scherer, 2009) have considered the issue of behaviour secondary. They postulate affect programmes, with relatively rigid execution – which make response stereotyped action patterns, brought about by specialized modules. Morphofunctionality nevertheless allows us to understand the adaptive properties of emotional behaviour as an emergent pattern that involves cognitive, morphofunctional and interactive processes.

As we have seen, taking into account morphofunctionality gives emotional response a dual nature: the modulation of underlying embodied systems, which creates a state of action-readiness, and cognitive and motor commands, which constitute behaviour proper. Emotional behaviour thus is about the balance between both. In emotion, successful action selection and performance depends not only on the goals of the agent, but also on whether the underlying action readiness supports that type of action chosen. This allows us to explain not only the desirable functional roles of emotion, but also the situations under which the emotion process may be considered disruptive.

8 Conclusion

In this paper, we have introduced an approach to organized morphofunctional modulation towards real-time adaptation from the perspective of emotion modelling. Whilst most robotic models of emotion have overlooked the morphological aspects of emotional responses, there is a strong tradition in emotion theory and phenomenology that consider the body to project intentionality through its sensory-motor capacities and embodied disposition.

Under this perspective, some functional aspects of emotion may be investigated as a result of a change of bodily disposition. The explanation of emotion considers not only the information-theoretic effects of physiological activation, but also how the modulation of morphology transforms the intentionality of the body, and how cognitive and physiological processes are coordinated into an global pattern we call emotion. The notion of action readiness and the dynamical systems approach to cognition may help conceptualizing the dynamics of emotional episodes.

We have not attempted to provide a definition of emotion, and we have hinted that there may not be a universal process called emotion. The concept *emotion* refers to processes and phenomena that are often diverse and that dynamically emerge from the interrelation of virtually every subsystem of an autonomous agent. Whether emotion form a natural class should continue to be a topic of debate in not only the philosophy of psychology (e.g., Charland, 2002; Frijda, 2008) but also in robotics and artificial systems, where the discussion has revolved around the notion of emotion as emergent and its relationship with the machinery of emotion (Cañamero, 2005; Pfeifer, 1994; Scherer, 2009). Meanwhile, it is also open to debate whether robotic models of emotion should aim to construct a universal model of emotion, to reproduce a number of human emotions, or simply demonstrate that new *ad hoc* robotic emotions can be synthesized for adaptive purposes.

We have presented arguments in favour of the morphofunctional approach as the adequate framework for the development of models of emotion in robotics. It will provide robotics with a framework for the flexibilization of robotic embodiment required for the development of more autonomous machines. Morphologies subject to modulation will allow robots to cope with a wider range of situations, as well as making possible for refined tuning to the situation. This may prove essential to advance our understanding of what emotions are, why evolution has favoured them and how they may become an adaptive resource for building autonomous robots.

Notes

1. The same state of alertness and energy mobilization towards strong and fast muscular movement that serves the purpose of fleeing is also functional for fighting. The decision-making process nevertheless does not occur in isolation from the actual pattern of sensory-motor coordination. Rather than a detached process of evaluation of the probability of success of escape, it is the perception of affordances in actual interaction with the source of threat. The purpose of the coordinated modulation of all systems is therefore not to determine what the response is going to be, but to facilitate certain families of behaviours that are functional for such type of situations (Sanz et al., 2011).
2. Arguably, the third essential component of this regulatory network may be the immune system (De Castro & Timmis, 2002).
3. The word 'endocrine' derives from the Greek 'endo' (internal) and 'crine' (secretion), and it was coined at the end of the 19th century to denote the functions of organs that play an internal regulatory role. It is therefore plausible to use the same word to denote subsystems in an artificial architecture that play a similar role.
4. Biological muscles are composed of motor units (bundles of cells), each controlled by a single neuron. Motor units are divided between low and high threshold, depending on how much force they exert to contract a muscle and how quickly they fire (cf. Fogel, 2009). Feedback comes from muscle spindles, intrafusal muscle fibres that contain proprioceptors and can be stretched or contracted for modulating their feedback. Skeletal muscles are associated in pairs of agonist/antagonist muscles – while agonist muscles create movement, antagonist are responsible to returning to a resting position. Tendons too play a role in the overall generation of movement by modulating forces through their elasticity.

Funding

This work has been funded by FP7-PEOPLE-COFUND-2008, through the grant agreement UNITE 246565 between the Technical University of Madrid (UPM, Universidad Politécnica de Madrid) and the European Commission.

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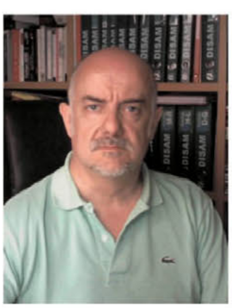

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