Emotion as Morphofunctionality

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Abstract We argue for a morphofunctional approach to emotion modeling that can also aid the design of adaptive embodied systems. By morphofunctionality we target the online change in both structure and function of a system, and relate it to the notion of physiology and emotion in animals. Apart from the biological intuition that emotions serve the function of preparing the body, we investigate the control requirements that any morphofunctional autonomous system must face. We argue that changes in morphology modify the dynamics of the system, thus forming a variable structure system (VSS). We introduce some of the techniques of control theory to deal with VSSs and derive a twofold hypothesis: first, the loose coupling between two control systems in charge of action and action readiness; second, the formation of patterned metacontrol. Emotional phenomena can be seen as emergent from this control setup.

Keywords
Emotion, action readiness, morphofunctionality, artificial physiology, variable structure systems, hybrid control

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1 Introduction

This article deals with two research areas that have gained increasing relevance over the last decade: *morphological computation* and *emotional robotics*. Both could be considered to belong to the wider paradigm of embodied robotics—yet they seem to have very few themes in common, and there has been practically no direct link between the findings or the methods of the two areas.

Embodiment has become a central issue in robotics, as it has relevance for the (cognitive) control of behavior. Morphological computation refers to the information-theoretic implications of embodiment [33]. There is evidence that morphology structures information flows, which are the basis for any cognition, and it can perform different computation roles. "As a consequence, the morphology will allow us to reduce the complex task of emulating nonlinear computation to the much simpler task to adapt some linear parameters for an additional readout" [18].

Emotion too is widely recognized to be an embodied phenomenon, but in a different sense. Much of the research in artificial emotion is concerned with the embodied expression of emotion, particularly through facial representations. Basic communication with humans is enhanced through mimicking paradigmatic expressions (ascribed to typical "basic" emotions, such as fear, disgust, interest, etc.). Although such techniques may be effective in some contexts, such as entertainment or brief human-robot interactions, they raise doubts because the robot's expressions do not reflect its concerns at any level.

Research on the adaptive role of emotion aims to understand the mechanisms that give rise to emotional phenomena in the first place. While much of this research is directed to modeling appraisal (see Section 1.1) and brain structures associated with emotion, some argue the necessity of *internal*

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robotics: "the interactions of the robot's control system with what is inside the body" [30]. In this line, there have been attempts to understand the role of internal variables in the organization of robot control, for instance, modeling hormone levels [2] or energy levels [28]. Research on artificial endocrine systems can be compared to that on artificial neural networks, as both are cases of information-theoretic functions inspired by biological systems.

This article aims to bridge the gap between morphological and emotion research, and even to claim that future progress in both areas will come hand in hand. To model emotion we need a thorough understanding of the underlying physiological processes, not only because they perform information-theoretic functions, but also because they modify morphology so as to prepare the body for action. This is therefore closely related to the issue of *morphofunctional machines* [16, 21]: "devices that can change their functionality not only by a change in (neural) control but by modifying their morphology" [34]. Morphofunctional designs may therefore be inspired by how emotion organizes adaptive responses in biological agents.

We follow here Frijda [13], one of the leading figures of emotion theory, who claims that a central characteristic of emotion is that of *action readiness* (see Section 1.1). To go through an emotion is largely to experience a change in readiness induced by patterns of physiological activation, which is one of the main functions of emotion. As Freeman argues, "The behaviors that are directed through interactions with the world toward the future state of an organism predictably require adaptations of the body to support the intentional motor activity" [12]. A morphofunctional machine thus needs to somehow "predict" future engagements with the world and control morphofunctional preparation to favor certain classes of behavior. Emotions emerge from this control setup.

Emotion research has revolved around the tension between emotion and cognition, often seen as two competing behavioral routes. Behavior may ideally be caused by rational cognitive processes, but some circumstances require less than optimal behavior generation mechanisms, identified with emotion. We challenge this view, and suggest a control challenge between bodily disposition and activity performance. Adaptive behavior is not just performing actions upon the environment—it also involves tuning the body so it is best prepared. There are two forms of concurrent control, whose integration is much of what it means to be a cognitive agent.

Our aim is thus to show that modeling emotion and building autonomous morphofunctional machines can be seen as two complementary tasks. In Section 2 we introduce the notion of morphofunctional processes and compare them with emotional responses. In Section 3 we try to clarify the scope of processes that we can count as morphofunctional and consider them from a dynamical systems approach. In Section 4 we speculate about what type of control should be adequate for such a system, and suggest the relative independence between readiness and action control. In Section 5 we discuss how the morphofunctional perspective affects the notion of emotion.

1.1 Two Concepts from Emotion Theory

Emotions are complex phenomena that involve many levels of explanation, and thus theories of emotion abound across different disciplines. Here we offer a brief overview of the approach adopted, largely inspired by appraisal theories of emotion (prominently [13]). This will allow us to introduce two key concepts: appraisal and action readiness.

The main features of emotion are [14]:

> (i) emotions are elicited when something relevant happens with direct bearing on the agent's needs, goals, values, and general well-being, (ii) they prepare the organism to deal with important events, producing states of action readiness, (iii) they engage the entire system, (iv) they are accompanied by preparatory tuning of the somatovisceral and motor systems, and (v) they bestow control precedence on those states of action readiness.

Appraisal is the process through which the agent is able to perceive the relevance of a situation and trigger an emotional response (whatever facilitates (i)). The nature of such a process has been a topic

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of intense debate. Should they be considered judgments of semantic content, or emergent from the dynamic organization of the body? The theory of embodied appraisal claims that physiological states can act as representations of organism-environment relations [35]. It thus suggests that the body can be an active component of the cognitive machinery of an agent.

Physiological responses do not merely aid cognition; they have a clear adaptive functional role: They prepare the organisms to respond adaptively, energizing the animal and motivating action [43]. Although the folk view that emotional response is just a set stereotyped patterns of behavior often influences research, what makes behavior emotional is more how you take action than what action you take.

This quality is summarized in the notion of action readiness, which refers to how a latent organizational state, among the many possible, constrains agent behavior to a specific class of potential behaviors. Action readiness is introduced for theoretical reasons to account for the flexibility of emotional behavior, and it is considered prior to action execution and independent from it [13, p. 70]. In animals, action readiness is brought about and coordinated by the activation of the autonomic nervous system and the endocrine system. Physiological activity systematically reflects appraisal in ways that prepare the agent to cope with the situation as appraised.

Emotion can be seen as "changes in readiness for action as such (…changes in activation), or changes in cognitive readiness (…attentional arousal), or changes in readiness for modifying or establishing relationships with the environment (…action tendencies), or changes in readiness for specific concern-satisfying activities (…desires and enjoyments)" [13, p. 466]. Details about the relationship between physiological activity and adaptive organization remain unclear, due to the distributed, pervasive, and dynamic nature of physiological changes.

While experimental data on physiological effects on human behavior has been explored (e.g., [43]), we lack precise systemic models of the effects of physiological activation upon adaptive behavior and cognition. Their development, we believe, could be aided by robotic modeling.

2 Morphofunctional Machines

Embodied robotics claims a central role for morphology in robot design, from low-level control to autonomous cognitive systems. It is not only the shape and organization of the body that are fundamental for determining behavioral dynamics; through the dynamics of interactuation with the environment (sensory-motor coordination) the body structures any information to be processed, changing the computational nature of cognitive tasks such as categorization [34]. Consequently, we have learned that good morphological design not only can increase robustness, efficiency, and controllability, but also offload cognitive tasks from control [38].

We can distinguish three main areas of research in morphology and robotics. The first is the design of physical structures that, through exploiting their intrinsic dynamics, improves behavior generation in different ways, from energy efficiency to robustness. We can call this area morphological design for efficient kinematics. The second area is the study of morphological computation, or more generally the information-theoretic implications of morphology. A third, less explored area is the design of systems that can change their morphology. There are two main approaches, depending on whether morphological changes occur during the design process but are fixed during operation, or whether systems can adapt their morphology in response to what is needed in the current interaction.

An example of the first case is design through the coevolution of morphology and control. For instance, [6] shows that evolving morphological parameters can improve the evolution of biped locomotion, and in general changes to the body during evolution can scaffold behavior [5]. In this framework, the morphology of each individual may be considered static, but the evolutionary process is allowed to modify the morphology across generations. This method can be applied to adjusting parameters for sensor or motor information (e.g., [27]), as well as to evolve anatomical characteristics of the morphology [15].

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A dynamic morphology is one in which “the sub-component connectivity can continually change in relation to the environment” [4]. Examples are reconfigurable robots that can *morph*, that is, they have a morphology whose structure can change into different structural configurations (e.g., [29, 47]). Simple examples of these are the industrial robots that are able to exchange tip tools to perform a varied set of tasks. The idea is also illustrated by the popular Transformers toys and their animation in films and games, where these futuristic robots are able to reorganize themselves to be competent in the performance of a variety of tasks.

A classical example of morphofunctional machines of this type is the Bell Boeing V-22 Osprey. This is a military aircraft that can tilt its rotors to operate like an airplane or a helicopter. In more precise terms, its functional change is useful during different phases of its missions. It is a tiltrotor with both a vertical takeoff and landing (VTOL) and a short takeoff and landing (STOL) capability. The morphofunctional adaptation capability provides both the functionality of a conventional hovering helicopter and the long-range, high-speed performance of a turbo-propelled airplane. For takeoff and landing, the Osprey morphs into a helicopter with horizontal rotors. Once airborne, the rotors rotate 90° forward, giving propulsion for horizontal flight, converting the V-22 to a more fuel-efficient, faster aircraft.

Another type of dynamic morphologies can be found in robots that make use of compliant materials or actuators. In contrast to a stiff actuator, which (ideally) determines its position independently of external forces, a compliant actuator allows deviations from its own equilibrium position [44]. Whereas the degree of stiffness or compliance of robot morphology can remain fixed (passive compliance), there are numerous examples of robots that can change the stiffness of actuators in real time (active compliance). An excellent review of control methods to create active compliance is found in [44], among which are antagonistic actuators with nonlinear springs, structure control, mechanical adjustment of the physical stiffness of the system or adjustment through variable transmission ratios.

In biological agents, morphological changes are essential throughout evolution and epigenetic development. During the lifetime of a biological agent, structure changes are less common, beyond a certain degree of anatomical reconfiguration in postural changes. Arguably, we can say that the differences in how biological bodies and technological artifacts are constituted may play in favor of machines in the sense of providing the possibility of new body organizations or even radically new bodies.

Animals nevertheless have powerful mechanisms, much richer than those of today’s robots, for morphological reconfiguration in order to prepare the body for adaptive interaction. It is not only muscles that use active compliance—all physiological systems are affected by patterns of activation. The function of any system, from the brain to muscles, can be attuned to the situation through hormonal and neural activation. This is apparent in the case of emotion, where an orchestrated physiological response is regarded as functional. Table 1 shows different functional effects underlying the fight-or-flight response in biological agents. Despite the gap between animals and current robotic embodiment, we believe the functional role of physiological changes in animals may be analogous to morphofunctional processes in robots.

The following section looks into different theoretical backgrounds that might help clarify what would be required in morphofunctional robots in order to come closer to the flexible physiological organization found in living creatures.

3 Robot Form and Robot Physiology

What we understand by morphology is thus crucial for the development of morphofunctionality. In biology, morphology is the study of the structure of organisms (divided between anatomy and eidonomy, referring to the inner and the outer structure, respectively). In biology, morphology takes into consideration the anatomy of the body, but generally leaves aside function, which is studied by physiology. In current robotics research too, morphology tends to be associated with structural relations and more or less permanent properties, such as the distribution of sensors or motors or properties

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Table 1. Functional effects underlying the fight-or-flight response in animals.

Physiological effect	Functional role	Biological examples	Robot analogues
Mobilization of energy	Redistribution of energy among subsystems	Acceleration in respiration and heart rate, slowing down of digestive system, constriction of blood vessels	Adaptive and autonomous energy management systems
Modulation of sensory systems	Modifying sensitivity to stimuli	Dilation of pupils (mydriasis), auditory exclusion (loss of hearing), tunnel vision (loss of peripheral vision)	Modulation of sensors (e.g., changing range of vision or laser systems); adaptive sensor fusion
Modulation of motor systems	Changing the way they respond to neural activation	Liberation of nutrients to muscular system and dilation of blood vessels for muscles	Modulation of motor operation (e.g., active compliance); adaptive body dynamics
Neuromodulation	Changing cognitive readiness through the plasticity of the neural system	The serotonergic system sets threat level for risk aversion, the cholinergic system sets attentional effort, the dopaminergic system drives reward anticipation and motivation, and the noradrenergic system sets response to novel and salient objects (cf. [24]).	Metacontrol, that is, changes to the control system (e.g., neuromodulation of ANN)
Other effects	Varied	The release of opiates has an analgesic effect that makes the system less sensitive to pain.	Any ad hoc adaptive mechanism

of materials, yet there is not a clear alternative to the notion of physiology. Researchers have nevertheless begun to develop the notion of robotic morphofunctionality, which takes into account those functional aspects of a robot's morphology that may be changed during interaction [32]. The situation is summarized in Table 2.

The close relationship between form and function has made some argue that morphology should be concerned not only with the structure and arrangement of parts of an object, but also "how these conform (i.e., fit together) to create a whole or Gestalt" [36]. In a similar vein, Laszlo and von Bertalanffy have pointed out that there are two ways at looking at order: One is spatial and is grasped as "structure,"

Table 2. Terminology regarding structure and function in biology and robotics.

	Biology	Robotics
Structure	Anatomy	Morphology
Function	Physiology	Morphofunctionality

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the other is temporal and comprehended as a sequence of events, or "function" [25]. A more generalized form of morphological research was proposed by Zwicky:

> The term morphology has long been used in many fields of science to designate research on structural interrelations… I have proposed to generalize and systematize the concept of morphological research and include not only the study of the shapes of geometrical, geological, biological, and generally material structures, but also to study the more abstract structural interrelations among phenomena, concepts, and ideas, whatever their character might be. ([48, p. 34]; cf. [36].)

Morphology and physiology can be seen as "complementary ways of studying the same integrated object… a dialectical unity of structure and function," displayed not only in a morphological hierarchy of parts but also in "a physiological hierarchy of processes" [45]. The notion of *artificial physiology* should be understood as a systemic notion referring to nested functionalities of components, instead of a flat, faithful model of the processes that underlie a particular organism. Rather than copying biological physiology, we should attend to the functional organization of the artificial system and the potential adaptive modulation of such a configuration.

Morphological analysis is a methodology suggested to capture the different ways morphology can be configured to provide different functionality. "Essentially, general morphological analysis is a method for identifying and investigating the total set of possible relationships or 'configurations' contained in a given problem complex.… The approach begins by identifying and defining the parameters (or dimensions) of the problem complex to be investigated, and assigning each parameter a range of relevant 'values' or conditions" [36].

In other words, to exploit the potential space of morphological configuration in robotics, we should attend not only to possible structural arrangements, but to the ample scope of configuration parameters that define a robot's morphology. This can be achieved, for instance, through software parameter tuning, reconfigurable hardware, different levels of energy provision, or other processes that could change the material or dynamic properties of body parts. This has to be a controlled process so that emergent sensory-motor coordination can be affected to favor adaptation.

What is required is the integration of three kinds of behaviors observed by Klir [23]: *temporary behavior* (patterns of action exhibited by the system for short intervals of time), *permanent behavior* (patterns of actions exhibited by the system that always hold), and *relatively permanent behavior* (patterns that hold for extended periods of time, but that may eventually change). These three kinds of behavior derive from three categories of properties of the system. Temporary behavior will derive from a set of properties called a *program*, whose dynamics depends on ongoing interactive processes. The most variable properties of a system form its program, and the most static ones form its structure (cf. [26]). Permanent behavior emerges from what is called *real structure*. However, morphological structure cannot always be considered static. "What are called structures are slow processes of long duration. Thus, organic structures cannot be considered as static but must be considered as dynamic" [46]. Dynamic morphologies should fall under a third category called by Klir *hypothetical structure*.

In a classical robot, we may distinguish between morphology, the real structure that defines the permanent features of behavior (navigation abilities, action repertoire, perceptual capacities, etc.); and the control program, a structure undergoing constant change that defines temporary behavior (generates actual movement patterns, goal orientation, cognitive processes). Whenever certain properties of morphology (including the morphology of the control system) can change, modifying the dynamics of sensory-motor coordination, we find relatively permanent behavior. For instance, in a robot that can switch between two morphological arrangements, the patterns associated with each configuration will be neither temporary nor permanent, but relatively permanent.

This distinction faces the problem of formally distinguishing between these three aspects of behavior and structure—a slightly different analysis may blur such distinctions, because it is impossible to test the temporal persistence of relations beyond a restricted range of activities [26]. The problem may be analyzed using the dynamical systems metaphor [3], which conceives agent-environment

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relationships through dynamical systems notions. A dynamical system is characterized by a set of state variables whose set of possible values defines the system's state space, and a dynamical law that grasps the relationship of state variables over time. The dynamical law is normally expressed through differential equations, and may be represented as a phase portrait of the trajectories of the system (see Figure 1). Such a description is successful if observable qualitative changes in the system can be explained as transitions between states in the dynamical model. Central dynamical systems notions used in cognitive science are "the concepts of attractor states with their stability properties, the loss of stability when such states go through bifurcations, and the emergence of new attractor states from instabilities" [42]. This allows researchers to formalize goal-directed behavior in terms of attractors in a state space [28].

In general, though, finding a neat dynamical analysis may be difficult or simplistic, as real systems may present nonlinear, chaotic, or metastable dynamics. It is important to note that a dynamical systems model will depend on the choice of variables that define a particular dynamical system analysis: Different dynamical descriptions may apply to the same system, although the choice of variables is generally not arbitrary and is conditioned by our understanding of the causal relationships involved [20]. The dynamical systems approach can be used as a framework to understand the dynamic relationship between morphology and behavior.

We suggest a possible distinction between the contributions of morphology and control toward the dynamics of interaction. The behavior of the system can be conceived as trajectories within a state space, generated by the sensory-motor loop through the control of relevant variables. Morphology, on the other hand, determines the structure of the phase space of the dynamical system at large. In a morphofunctional system, morphological parameters can change, thus changing the functional aspects of morphology and the dynamics of interaction. Changes in morphological parameters would thus result in the transient dynamics of a variable structure system (VSS) [10].

In control and robotics practice, changing configuration parameters during run time poses severe controllability issues. One reason why parameters normally remain fixed is that this allows us to model the behavior of the individual components. The overall sensory-motor dynamics of the system can be deduced from the behavior of particular subsystems, and so reliable action can be generated by activating the right components. Changing almost any configuration parameter will most likely have disruptive consequences in any robotic system. In fact, tuning of configuration parameters is one of the central tasks of a robotic experiment, at least one that requires a large effort.

Control of VSSs is thus challenging, but integral to the concept of effective morphofuncionality. As we see in the next section, strategies exist in control engineering that allow designers to deal with variable dynamical structures. These are widely used, mainly for making low-level control more robust through active compliance. Scaling these control strategies toward cognitive or emotional control

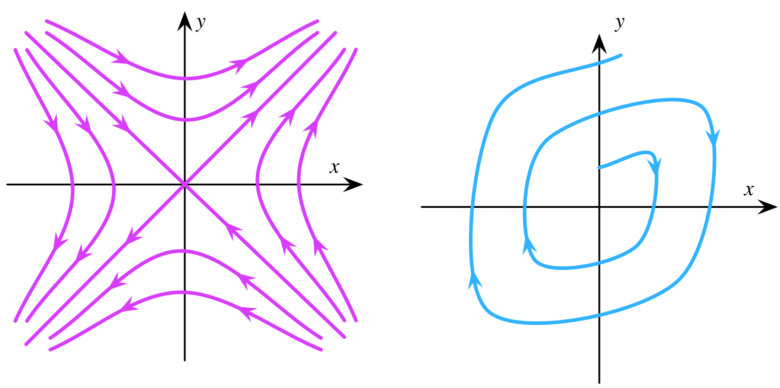

Figure 1. The behavior of the system can be conceptualized by visualizing its trajectories within the state space. Different morphological configurations may give rise to different phase diagrams, depending on state values and configuration parameters.

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is not straightforward, but considering these techniques will allow us to hypothesize about the control requirements of a morphofunctional system.

4 Morphofunctional Control

In the previous analysis, morphological reconfigurations may temporarily transform the overall dynamics of the system, transforming the state space dynamics—while behavior control performs trajectories within the state space. A morphofunctional system thus must integrate motor control, used for executing actions, and system regulation, which is used on a different time scale to prepare the system for different types of behavior.

In this section, we analyze the control requirements and existing techniques, and we hypothesize two features of morphofunctional control. First, whereas the space of morphological configurations may be considered continuous, control of the system's dynamics may be based on its discretization. As we will see later, the reduced number of basic emotions is an indicator of this evolutionary trend. Emotions emerge as a pattern-based mechanism of system metacontrol, selecting within a finite set of control organizations.

The second feature is the loose integration of morphofunctional and behavioral control. By loose integration, we informally mean that both control tasks could be executed by distinct control systems, whose operation is at some level decoupled. In biological agents, we find this in the coordination of nervous and endocrine systems in controlling body dynamics, dealing with behavior generation mechanisms and morphofunctionality, respectively. The two are fairly independent, albeit subject to continuous reciprocal regulatory processes.

Both hypotheses may be derived from the control requirements of morphofunctional system, which, as we have seen, constitutes a variable structure system. A VSS is a discontinuous nonlinear system that behaves like different continuous nonlinear systems in different regions of its state space; at the boundaries of such regions the dynamics change qualitatively. A VSS can be manageable if transitions between regions can be integrated in control.

Several approaches exist to make the problem of VSSs tractable in control theory. One such approach is sliding mode control [49]. Here the state space of the VSS system can be represented as divided into different regions, each containing the phase diagram corresponding to the regional dynamics. A discontinuous control signal forces the system to slide to configurations in which the dynamics are altered (see Figure 2). The sliding mode allows designers to suppress uncertainties due to parametric variations, as well as external disturbances and variable payloads [17], by adapting the compliance of the system.

In effect, sliding mode control discretizes the system's transient dynamics, simplifying control. In general, systems that exhibit both continuous and discrete dynamics are called hybrid systems. They

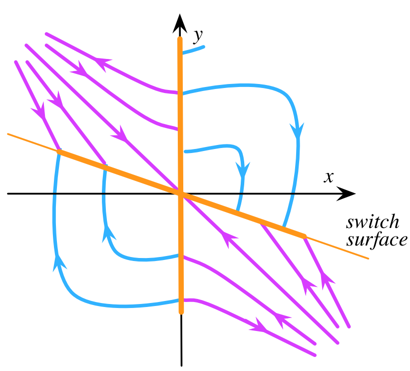

Figure 2. Combined state space trajectories for a system with variable structure. For each operating region, the dynamics is defined by a different phase portrait. In this case, that is easily visualizable because of the existence of a simple switching surface.

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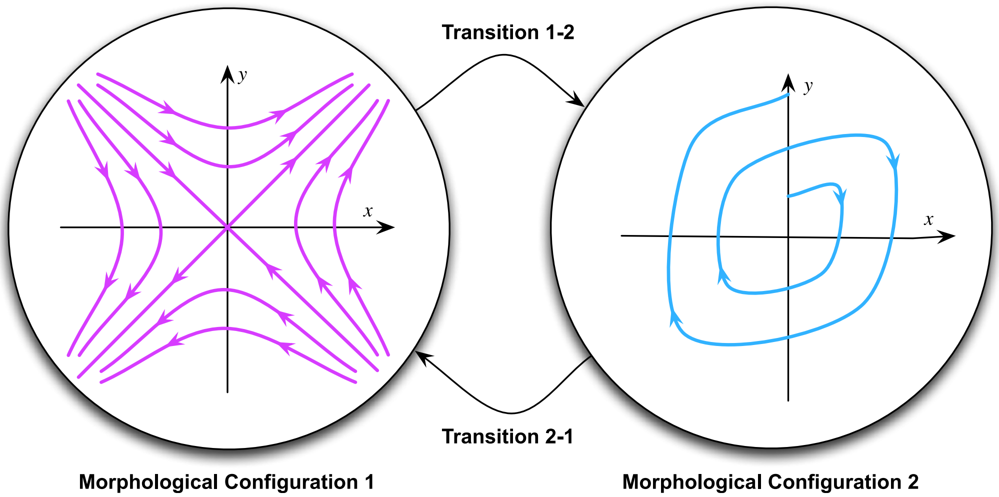

Figure 3. Finite state automaton with two states that correspond to two states of morphological configuration, each one characterized by a different dynamical behavior. Transitions imply a morphofunctional change and hence a behavioral change.

may be modeled as hybrid automata, which partition the system into a continuous state (grasping the continuous-time dynamics of its relationship with the environment) and a discrete state (describing the mode of the system) (cf. [1]). Such a model should determine the possible state spaces of the system, the dynamics for each of the states, and the transition between them (Figure 3).

Hybrid systems are common in engineering. For instance, consider a car with different gears, which ultimately is controlled by the driver. For a driver, there are four main control variables: wheel turning, pressure on brake and gas pedals, and gear setting. The first three determine the behavior of the car: the direction and rotational speed of the wheels, and consequently the car's movement through space. The gear mechanisms change the morphological structure of the car so that the relationship between motor revolutions and wheel movement changes. In turn, each gear defines a different region of state space, and the gear changes facilitate the transitions between them. The dynamics of the system could be represented by different state spaces, one for each gear.

Control of a car can therefore be decomposed into two control tasks. First, determine what gear is most adequate for the expected interaction. This should take into account many different feedback variables: internal, such as motor speed (to ensure that the motor can cope with current activation), and externally appraised, such as the need for torque (e.g., if we need to go up a hill, we might need to prepare for it), controllability (e.g., on an icy surface), or stability (for instance, what we expect from a bend ahead). Second, determine how we can control the car through modifying its speed (through accelerator and brakes) and direction (through wheel turning), given the gear we are in (Figure 4).

The potential separability of the two tasks is made explicit in automatic transmission cars, in which the driving per se is controlled by the driver, while the gear change task is delegated to an automatic system. They are of course not totally independent, because both forms of control have to be integrated in the system as a whole. They are loosely coupled control systems because they operate independently of each other—that is, the behavior of one of the systems does not determine the behavior of the other.

This feature can also be found in a decentralized variable structure control (DVSC) [22]. In this approach, hierarchical control topologies are used to decompose a large control problem into parts, such that each subsystem is stabilized with local discontinuous controllers; higher-level supervisory/corrective control is designed to take into account the emerging effects of interactions among the subsystems. Arguably, this form of control shares some features with biological emotion, in that here the stabilization of physiological changes is not centrally controlled, as it depends on multiple feedback connections between different physiological subsystems.

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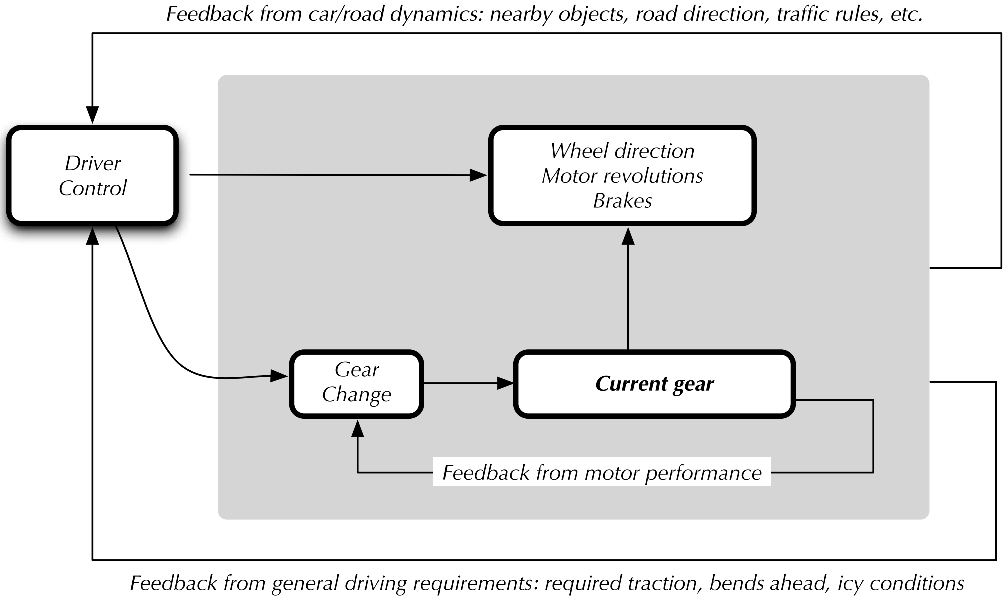

Figure 4. Tasks involved in controlling a car.

In Figure 5 we adapt a variable structure control system to include the features mentioned, with the aim of controlling a robot. A morphofunctional controller (MC) produces modifications in morphological parameters, affecting all systems. The homeostatic switching element (HSE) moves the control device toward one of several discrete functional configurations (A1, … , A*n*), which support particular forms of interaction with the environment. The control device (CD) is in charge of the robot's mission, which is strongly conditioned by the current morphological configuration.

5 Refocusing Emotion

The morphofunctional approach presented is a novel, possibly controversial framework for modeling emotion. The guiding research question was posed by Pfeifer long ago: "Given certain behaviors that we find interesting (e.g., because we characterize them with emotion terms), what are the

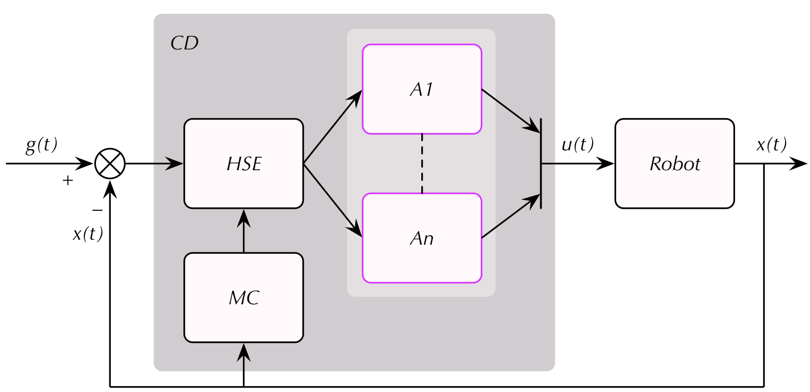

Figure 5. Block diagram of a morphofunctional robot controller. The control device (CD) operates on a robot using several patterns of morphological configuration (A1, …, An) managed by a homeostatic switching element (HSE) and a morphofunctional controller (MC).

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underlying mechanisms?…What we can say is that the way the complete system is organized enables it to display certain adaptive behaviors" [31]. Our thesis is that the underlying mechanisms are those that control morphofunctionality, from which the main features of emotion emerge.

Emotion is a phenomenon that spreads across agent and environment, and is expressed in behavior, cognition, and interaction. This is in line with approaches that characterize emotion "as an emergent pattern of component synchronization, preparing adaptive action tendencies to relevant events, as defined by their behavioral meaning and aiming at establishing control precedence over behavior" [41]. "A prototypical emotional episode is a complex set of interrelated subevents concerned with a specific object…: core affect; overt behavior of the right sort (flight with fear, fight with anger, etc.) in relation to the object; attention toward, appraisal of, and attributions to that object; the experience of oneself as having a specific emotion; and, of course, all the neural, chemical, and other bodily events underlying these psychological happenings" [37].

A morphofunctional autonomous robot must always regulate its morphological configuration, providing an underlying action readiness—this is a process that cannot be put on hold. To be effective in favoring the generation of adaptive behavior, such changes must be synchronized and, given the control requirements, discretized. In other words, the system must select from a finite, evolutionarily selected set of control organizations [40].

The picture in Figure 6 aims to represent a cognitive architecture with two interconnected control systems, the action control system and the morphofunctional control system. First, the morphofunctional control system can modulate the physical systems involved in action control (one instance of which is neuromodulation in animals). Also, feedback from morphofunctional control (e.g., interoceptive feedback, as-if body loops [9]) provides vital information for embodied appraisal. The action control mechanism effects morphofunctional control (i.e., changes in the physiological structure) through the process of appraisal. The physiological processes that define the morphological configuration of the body are nevertheless subject to distributed control (homeostatic feedback loops between the different components in the case of animals). Feedback from the agent-world dynamics is crucial both for action control (through sensory-motor loops) as well as for morphofunctional control.

The morphofunctional approach has implications for the question of appraisal, but also regarding behavior generation and feeling. We will discuss each of the three in more detail in the rest of this section.

5.1 Appraisal

If the robot could at all times predict its interaction with the environment, it could always choose the best-suited configuration. A true autonomous agent, though, is expected to deal with situations that

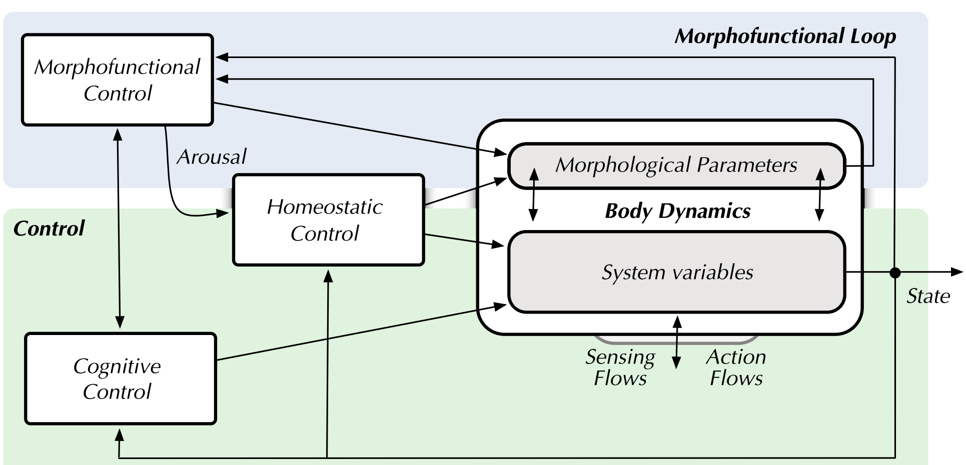

Figure 6. Cognitive architecture representing the components required for the emergence of emotion and the reciprocal causal connections.

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are not fully predictable. Adaptive morphofunctionality must make an assessment of what configuration is appropriate to deal with a situation, which is a nontrivial problem. There might not be a universal control solution to the problem of predicting dynamics for creating action readiness—this is a computationally complex inverse problem—which suggests that the control of morphofunctionality may be dynamic, suboptimal, and decentralized.

There must be mechanisms designed or evolved to maximize the utility of a state of readiness, whatever the uncertainties of the situation. Such mechanisms may be implicit in the self-stabilization of dynamic patterns of interaction, in part independent from the actual processes of cognition and behavior generation. This directly relates to perhaps the most asked question in emotion theory: How much cognition is required for emotion?

Whereas the fact that cognitive evaluations can trigger emotional responses is uncontested, there are more difficulties in accepting that physiological processes can themselves have a content. This is defended in the thesis of embodied appraisal, where physiological states are considered as representations of *core relational themes*, that is, organism-environment relations that bear on well-being [35].

As Prinz rightly points out, this thesis requires that "changes in the body are reliably caused by the instantiation of core relational themes" [35]. Nevertheless, he offers no concrete indication of the causal connections that make this possible. In the morphofunctional approach, the causal link is found between physiological states and action-readiness, and between this and dynamical features of the interaction, which form core relational themes.

Let us clarify what we mean by a concrete hypothesis: Changes in the dynamical structure of interaction can themselves lead to an emotional response, without any cognitive processing. Changes that originate in the situation can trigger the self-stabilization morphofunctional mechanisms. The agent's behavior and morphofunctional setup go through a period of instability until a new configuration and behavioral strategy are consolidated: An emotion has emerged. For instance, imagine a robot that uses sensory-motor prediction mechanisms for regulation: Whenever prediction fails, a process of reconfiguration is triggered, until prediction becomes successful again. This may have involved slight or qualitative changes in both behavior and morphology.

This reciprocal causal connection between morphofunctional organization and agent-environment relations means that changes in cognitive processing, morphofunctional regulatory processes, or environmental events can be sufficient to trigger a multidimensional process of emotion. The question of whether emotion precedes cognition or vice versa cannot be answered in general. In this view, *primary appraisal* refers to a process of morphological reconfiguration per se, with its underlying ascription of significance to the event in the form of readiness. *Secondary appraisal* is hence the process of cognitive assessment of the situation.

5.2 Emotions and Behavior Generation

Morphofunctionality radically changes the question of the main features of emotional behavior. Most models in robotics, in line with basic emotion theories (cf. [41]) have considered the issue of the dynamicity of behavior as secondary. These theories postulate the existence of pre-fixed servomotor affect programs, with relatively rigid execution; the agent response can be assumed to be a stereotyped action pattern, suitable for the appraised situation and brought about by a specialized module. Introducing morphofunctionality nevertheless allows us to understand the adaptive properties of emotional behavior as an emergent pattern that involves cognitive, morphofunctional, and interactive processes. This is a novel interpretation of the embodiment of affect programs and how they develop for the generation of emotional behavior.

The morphofunctional perspective must seek to understand the dynamics of action readiness and behavior generation. The underlying action readiness conditions behavior generation—the same behavior can acquire different qualities depending on the state while it is executed. This also explains how sometimes ongoing behavior has to be interrupted, when the underlying state no longer provides the attentional and physical effort required. A new behavior decision, possibly exploiting the underlying readiness, may emerge, which would now be characterized by emotional behavior.

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5.3 Emotion and Feelings

Another area that can be affected by the morphofunctional approach is that of machine consciousness—a connection we simply sketch here. Among the four aspects of emotion—appraisal, physiology, behavior, and feeling—the last one, the experiential character of emotional states, is at the same time important and elusive. It is the most important (at least for humans) because most conscious motivations derive from the phenomenic state of the person.

It is elusive because (besides the tricky nature of the problem of experience [7]), the enormous variety of emotional experiences, the heterogeneity of feelings, makes it extremely difficult to find a cohesive theoretical model of them. Machine consciousness research nevertheless pursues the design of systems with self-x properties, that is, technical functions enabling the system to manage itself in an autonomous way by exploiting a model of that system [8].

The morphofunctional approach to emotion offers a straightforward path to models of feelings based on the realization of metaobservational, interoceptive loops in the agent. This is in line with higher-order thought (HOT) theories of consciousness and second-order cybernetics [19]. Essentially, phenomenic experience is produced by the instantiation of a third-level observational loop that is able to perceive and valuate the morphofunctional state of the agent [39, 40]. Feelings are the signals used at this ultimate, value-oriented, metacontrol level.

6 Conclusion

Morphofunctionality, the variation of parametric structures that define the functionality of morphology, offers a novel approach to emotion-based robotics. We have argued that it can perform functions analogous to physiological processes, favoring states of action readiness, and allowing the emergence of emotion. Biological systems are very different to engineering systems in that their morphology is highly dynamic and their interactions with the environment present very different dynamics at different time scales. Arguably, plastic morphologies provide animals with flexibility and eventually autonomy. Understanding how functional control is effected in biological systems may allow us to understand what is required to move from rigid morphologies of machines to dynamic ones.

Real-world engineering systems require predictability. This is needed because these systems offer services to people who trust them. Control engineering deals with the provision of mechanisms to improve systems' dependability in the presence of disturbances. Variable structure systems—the class of systems addressed in this article—are less predictable and more difficult to control than single-structure systems.

By looking at the phenomenon of emotion, we can grasp the challenge of controlling activity and controlling morphofunctionality. Motor control produces different forms of movement toward executing goal-oriented actions, normally through a sequencing of patterns that use some form of feedback mechanisms for control. Morphofunctional control, a slower-time-scale process that has consequences for behavior over longer periods of time (minutes in biological systems), provides the system with timely action readiness.

Control strategies for variable structure systems support the hypothesis that emotions emerge as pattern-based mechanisms of system metacontrol that select from a finite, evolutionarily selected set of control organizations [40]. Furthermore, *action generation* and *preparation for action* appear as two loosely coupled control tasks. That they are separable means easier constructability (or evolvability), but it also means that their integration poses a control problem, from which emotions emerge. In contrast with other approaches where emotion and cognitive control are considered competing routes for behavior generation, we explain potential discrepancies as the loose coordination of these dual control tasks.

The challenge for morphofunctional design is thus to understand how different organization patterns may be functionally advantageous for an agent, and how the agent can autonomously reconfigure itself. If emotions are indeed necessary for autonomy, as researchers argue, they offer a strategy for the organization of a morphofunctional modulatory network of processes to be leveraged in the real world for better robot adaptation.

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Further work is required to consolidate the morphofunctional approach to emotion. At the moment we have only hinted at some of the problems posed by morphofunctionality, some of the potential solutions, and how these may relate to emotional processes. Development of the tools in the context of robot behavior generation is required to understand what will be the real problems such a system would face. A morphofunctional theory of emotion requires a model that allows us to explain, through system analysis, emotional processes in better ways than other models. We consider the arguments presented sufficient to motivate new possibilities for research in the area of morphofunctional machines and emotion.

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