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Morphological computation for adaptive behavior and cognition

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Abstract. Traditionally, in robotics, artificial intelligence and neuroscience, there has been a focus on the study of the control or the neural system itself. Recently there has been an increasing interest in the notion of embodiment not only in robotics and artificial intelligence, but also in the neurosciences, psychology and philosophy. In this paper, we introduce the notion of morphological computation, and demonstrate how it can be exploited on the one hand for designing intelligent, adaptive robotic systems, and on the other hand for understanding natural systems. While embodiment has often been used in its trivial meaning, i.e. "intelligence requires a body", the concept has deeper and more important implications, concerned with the relation between physical and information (neural, control) processes. Morphological computation is about connecting body, brain and environment. A number of case studies are presented to illustrate the concept. We conclude with some speculations about potential lessons for neuroscience and robotics. © 2006 Elsevier B.V. All rights reserved.

Keywords: Morphological computation; Sensor morphology; Rapid locomotion; Cheap grasping

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1. Introduction

While in the past the focus in the field of robotics has been on precision, speed, and controllability, more recently there has been an increasing interest in adaptivity, learning and autonomy. The reasons for this are manifold, but an important one is the growing attention the research community is devoting to using robots for studying intelligent systems and to the development of robots that share their ecological niche with humans. If

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we are to design these kinds of robots, embodiment must be taken into account. Now there is a trivial meaning of embodiment, namely that "intelligence requires a body". In this sense, anyone using robots for his or her research is doing work on embodiment. It is also obvious that if we are dealing with a physical agent, we have to take gravity, friction, torques, inertia, energy dissipation, etc., into account. However, there is a non-trivial meaning of embodiment, namely that there is a tight interplay between the physical and the information theoretic aspects of an agent, or generally, the information theoretic implications of embodiment. One simple but fundamental insight, for example, is that whenever an agent behaves in whatever way in the physical world, it will by its very nature of being a physical agent, affect the environment, and in turn be influenced by it, and it will induce–generate–sensory stimulation. A fish, for example, as it moves, will induce currents and turbulences in the water which then affect its own motion. The sensory signals caused by the movement will, depending on the kind of behavior, have certain properties, and typically they will be correlated. For example, if you walk in the street optic flow will be induced in your visual sensors, and tactile and proprioceptive stimulation in your feet and motor system. Optic flow is about correlations in the visual sensors, proprioceptive and tactile stimulation about rhythmic patterns, also containing important correlations. An additional point is that because of the intrinsic physical dynamics there will be certain preferred walking patterns, corresponding to energy-efficient movement. Thus, there is a continuous tight interaction between the motor system and the various sensory systems, a sensory-motor coordination. Typically, behaviors in natural agents are sensory-motor coordinated.

Before we continue, a short note on terminology is required. By information theoretic implications of embodiment we mean the effect of morphology, materials and environment on neural processing, or better, the interplay of all these aspects. It turns out that materials, for example, can take over some of the processes normally attributed to control, a phenomenon that is called "morphological computation". There is no taxonomy of morphological computation yet, but we can roughly distinguish between sensor morphology taking over a certain amount of computation, similarly for shape and materials, and for the interaction with the environment.

In an embodied agent, by the mere fact of its being physical, all aspects–sensors, actuators, limbs, the neural system–are always highly connected: changes to one component will potentially affect every other component. From this perspective we should never treat, sensory and motor system separately. However, for the purpose of investigation and writing, we must isolate the components, but at the same time we must not forget to view everything in the context of the complete agent. Having said that, we now proceed with a few case studies. We start with sensor morphology, followed by two locomotion examples, and we conclude with a study of grasping with an artificial hand. Finally, we will discuss what has been achieved, what lessons there might be for neuroscience and robotics research.

2. Sensor morphology

In previous papers we have investigated in detail the effect of changing sensor morphology on neural processing (e.g., [1–4]). Here we only summarize the main results.

The morphology of sensory systems has a number of important implications. In many cases, when the morphology of the sensory systems is suited for the particular task environment, more efficient solutions can be found. For example, it has been shown that for many tasks (e.g., obstacle avoidance) motion detection is all that is required. Motion detection can often be simplified if the light-sensitive cells are not spaced evenly, but if there is a non-homogeneous arrangement, a phenomenon that is studied in the field of space-variant vision (e.g., [5,6]). For example, Franceschini et al. found that in the house fly the spacing of the facets in the compound eye is denser toward the front of the animal [7]. This non-homogeneous arrangement of the light-sensitive cells, the ommatidia in the case of the insects, in a sense, compensates for the phenomenon of motion parallax, i.e. the fact that at constant speed, objects on the side travel faster across the visual field than objects towards the front; it performs the "morphological computation", so to speak.

It has been shown in experiments with artificial evolution on real robots that certain tasks, e.g., keeping a constant lateral distance to an obstacle, can be solved by proper morphological arrangement of the ommatidia, i.e. frontally more dense than laterally [1]. See Fig. 1.

Note that all this only works, if the agent is actually behaving in the real world and therefore generating sensory stimulation. Once again, we see the importance of the motor system for the generation of sensory signals, or more generally for perception. It should also be noted that these motor actions are physical processes, not computational ones, but they are computationally relevant, or put differently, relevant for neural processing, which is why we use the term "morphological computation".

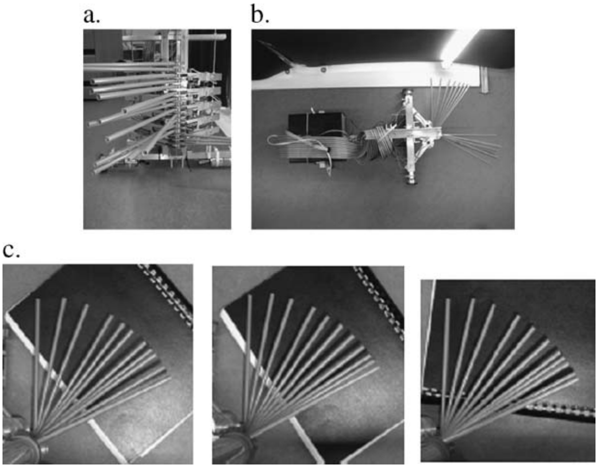


Fig. 1. Evolving the morphology of an "insect eye". (a) The Eyebot used for experiments on motion parallax. (b) The experiment seen from the top. The robot has to maintain a minimal lateral distance to an obstacle (indicated by the vertical light tube) by modifying its morphology, i.e. the positioning of the facet tubes. This is under the control of an evolutionary strategy. The same EMDs are used for all pairs of facets. (c) Final distribution of facets from three different runs. The front of the robot is towards the right. In all of the runs, the distribution is denser towards the front than on the side.

3. Locomotion

In this section two case studies, the quadruped “mini dog”, and the artificial fish “Wanda” demonstrating the exploitation of materials and dynamics of the system–environment interaction for locomotion, will be introduced.

3.1. Muscles: control from materials—the running quadruped

We now present a case study where a very simple kind of artificial “muscle” in the form of a normal spring is used. One of the fundamental problems in rapid locomotion is that the feedback control loops, as they are normally used in walking robots, can no longer be employed because the response times would be too slow. One of the fascinating aspects of the quadruped “mini dog” is that not only fast but also robust locomotion can be achieved with no sensory feedback [8].

The robot’s design was inspired by the spring-mass model studied in biomechanics. Each leg has one standard servomotor located at the shoulder and a series of two limbs connected through a passive elastic joint. A small weight on the top was used to adjust the weight distribution of the body. Fig. 2 shows the robot use for the experiments.

The controller of the robot is extremely simple: each motor oscillates through sinusoidal position control. No sensory feedback is used for this controller; therefore it does not distinguish between the stance/flight phase, acceleration, or inclination. Nevertheless, the robot maintains a few stable periodic gaits by properly exploiting its intrinsic dynamics as shown in Fig. 3. Because it has only little friction on the feet, it will self-stabilize in response to small perturbations. The morphological computation in this case is the result of the complex interplay of agent morphology, material properties (in particular the “muscles”, i.e. the springs), control (amplitude, frequency), and environment (friction, shape of the ground, gravity). Exploiting morphological computation makes cheap rapid locomotion possible because physical processes are fast and for free! (For further references on cheap locomotion, see e.g., [9–11].)

Now, if sensors–e.g., pressure sensors on the feet, angle sensors in the joints, and vision sensors on the head–are put on the robot, structured–correlated–sensor stimulation will be induced that can potentially be exploited.

3.2. Behavioral diversity from system–environment interaction—“*Wanda*”

The artificial fish, “Wanda”, built by Marc Ziegler and Fumiya Iida [12], a very recent development in our laboratory, exploits the interaction with the environment in

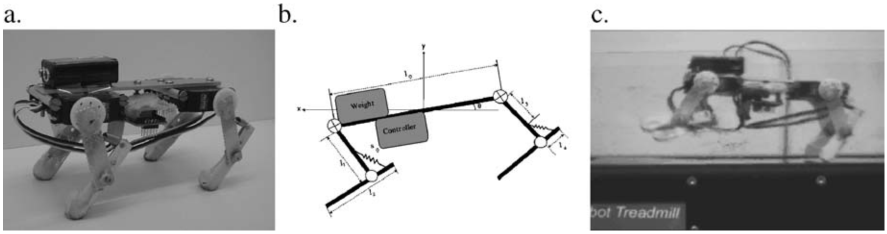
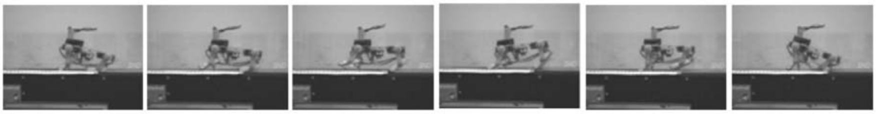


Fig. 2. The quadruped “mini dog”. (a) Picture of the entire robot. (b) Schematic of the robot’s design. (c) Image captured with a high speed camera installed at the lateral side to observe the running behavior of the robot.

gait 0



gait 1

Fig. 3. Gait 0: slower velocity and higher hopping. Gait 1: faster and lower hopping height.

interesting ways (Fig. 4). The fish has one single degree-of-freedom of actuation: it can basically wiggle its tail fin back and forth. The tail fin is built from elastic materials such that it will on average produce maximum forward thrust. It can move forward, left, right, up and down. Turning left and right is achieved by setting the zero-point of the wiggle movement either left or right at a certain angle. The buoyancy is such that if it moves forward slowly, it will sink, i.e. move down. The speed is controlled by the wiggling frequency and amplitude. If it moves fast and turns, its body will tilt slightly to one side which produces upthrust, so that it will move upwards. The fascinating point about this fish is the behavioral diversity that can be achieved through morphological computation: instead of having more complicated actuation and thus more complex control, the interaction with the environment can be exploited to achieve the task.

4. Grasping

“Cheap” grasping—the “Yokoi hand”: the 13 degrees-of-freedom “Yokoi hand” [13] that can be used as a robotic and a prosthetic hand, is partly built from elastic, flexible, and deformable materials (Fig. 5). For example, the tendons are elastic, the finger tips are deformable and between the fingers there is also deformable material.

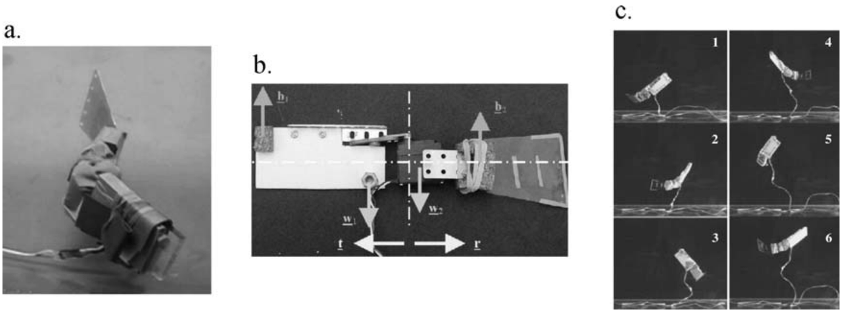


Fig. 4. The artificial fish. (a) “Wanda” with one degree-of-freedom for wiggling the passive tail fin. (b) The forces acting on its body are illustrated by arrows. (c) A typical sequence of an upward movement.

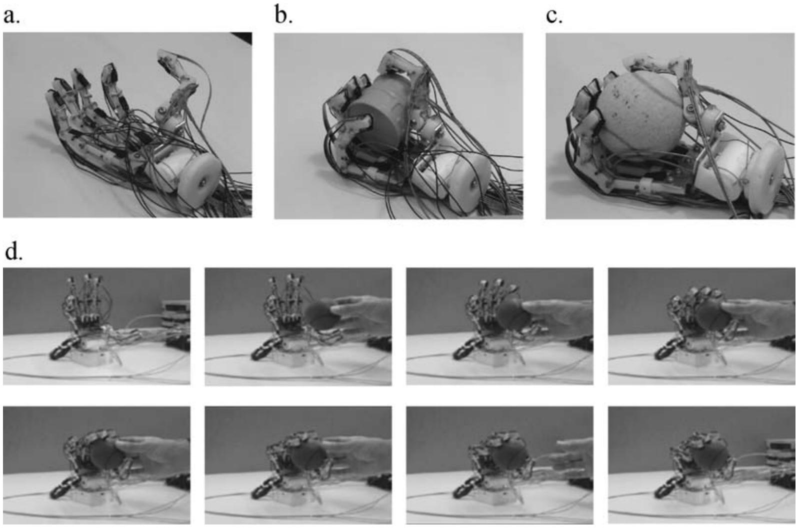


Fig. 5. "Cheap" grasping: exploiting system–environment interaction. (a) The Yokoi hand exploits deformable and flexible materials to achieve self-adaptation by the interaction between environment and materials. (b, c) Final grasp of different objects. The control is the same, but the behavior is very different. (d) Sequence of a typical grasping experiment.

When the hand is closed, the fingers will, because of its anthropomorphic morphology, automatically come together. For grasping an object, a simple control scheme, a "close" is applied. Because of the morphology of the hand, the elastic tendons and the deformable fingertips, the hand will automatically self-adapt to the object it is grasping. Thus, there is no need for the agent to "know" beforehand what the shape of the to-be-grasped object will be. The shape adaptation is taken over by morphological computation performed by the morphology of the hand, the elasticity of the tendons and the deformability of the fingertips, as the hand interacts with the shape of the object. Because of this morphological computation, control of grasping is very simple, or in other words, very little brainpower is required for grasping. For prosthetics, there is an interesting implication. If EMG signals, which are known to be very noisy, are used, control cannot be very precise and sophisticated. But by exploiting morphological computation, there is no need for very precise control, at least for grasping. Pressure and bending sensors have been added to the hand and feedback signals can be provided to the agent (the robot or the human) that can be exploited by the neural system for learning and mutual adaptation (e.g., [14,15]).

5. Conclusions: lessons for neuroscience and robotics

We introduced the concept of morphological computation which can be characterized as performing a kind of "task distribution" between the brain (neural system), or the controller in a robot, the morphology of the agent (shape, sensors, actuators, materials) and the environment. We showed that by exploiting morphology, materials and system–environment interaction, hard tasks such as rapid locomotion or grasping can be achieved in a "cheap" manner. Let us speculate a bit what potential lessons there might be for neuroscience and for robotics. While some of these points are entirely obvious, it is interesting to note that in practical everyday research, they are normally not considered, or not considered sufficiently.

First, by looking at the neural system only the function of the neural system cannot be understood: we must take the way it is embedded into the agent and the specific types of interactions with the environment into account as well (e.g., the case study on motion parallax). Secondly, not everything needs to be controlled by the brain: the morphological computation takes over, or distributes computational or control functions to the morphology, materials, and system–environment interaction (e.g., self-stabilization in "mini dog's" running behavior, self-adaptive grasping in the Yokoi hand). Thirdly, the interaction with the environment takes over essential aspects of the control task, which simplifies not only the control, but also the morphology of the agent (e.g., the artificial fish "Wanda"). If we are interested in the brain function, i.e. the role the brain plays in subtending behavior, the entire agent and the interactions with the environment must be taken into account. Recent insights in biomechanics, for example, suggest that in rapid locomotion in animals, an important role of the brain is to dynamically adapt the stiffness and elasticity of the muscles, rather than very precisely controlling the joint trajectories. This way, the muscles can take over some of the control function, e.g., the elastic movement on impact and adaptation to uneven ground (e.g., [9,10]). For robotics, the idea of morphological computation provides new ways of looking at behavior generation; in the past the focus has been very much on the control side.

One problem with the concept of morphological computation is that while intuitively plausible, it has to date defied serious quantification efforts: We would like to be able to ask "How much computation is actually being done?" [16]. The first very crude approximation would be to compare a system that exploits morphological computation with one that does not. For example, how much computation is required for the controlled forward movement of a leg in biped walking compared with a passive swing? Another problem is that the notion of computation in the context of morphology or dynamics may in fact require fundamental reconceptualization, which is in itself a challenging research topic.

In summary, we hope to have demonstrated the power of morphological computation as a new way of designing robots and of understanding biological systems, thus giving the term "embodiment" a non-trivial meaning that goes substantially beyond "intelligence requires a body."

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