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19 The Morphological Computation Principles as a New Paradigm for Robotic Design

Abstract: *A theory, by definition, is a generalization of some phenomenon observations, and a principle is a law or a rule that should be followed as a guideline. Their formalization is a creative process, which faces specific and attested steps. The following sections reproduce this logical flow by expressing the principle of Morphological Computation as a timeline: firstly the observations of this phenomenon in Nature has been reported in relation with some recent theories, afterward it has been linked with the current applications in artificial systems and finally the further applications, challenges and objectives will project this principle into future scenarios.*

The Observation of the Morphological Computation Phenomenon in Nature is the First Step for the Formalization of the Principle

When we see a dolphin swim, we are marveled by how such a rapid, elegant and strong movement can seem so simple. The dolphin motion has been subject of study since the time of Aristotle. In recent years, it has been found that the high velocities reached by these animals are possible thanks to the formidable mechanical properties of their body. The motion in water is extremely difficult due to the density and viscosity of the medium that imply an exceptional longitudinal force that slows the movement down. The combination of the skin structure, of the appendage shapes, and of the behavioral mechanism during motion allows reducing the drag force, enabling the effective and graceful movement that we all can admire [8]. In Nature, the shape, the geometry, the placement and the compliance properties of the body parts define the perception and the interaction with the environment, thus connecting such kind of features with the expressed behavior, synergistically. All these features can be gathered together in the term *morphology*. We could say that any transformation of information can be named as computing, and thus, in that sense, *Morphological Computation* endows all those behaviors where computing is mediated by the mechanical properties of the physical body [23, 22, 21]. There are at least three different cases we can use as reference to describe this transformation:

- **Shape**: the case in which the shapes, as body structure, specifies the behavioral response of the agent.
- **Arrangement**: the case in which the geometrical arrangement of the motors, perceptive and processing units implies specific computational characteristics.
- **Mechanical properties**: the case in which the mechanical properties allow emergent behaviors and highly adaptive interaction with the environment, impossible elsewhere.

The first point of view opens the way to all that kind of mechanical structures that facilitate the behavioral expression of a particular agent. A special structure allows many animals to move in the environment with elegant and coordinated gestures: the skeleton. All vertebrates share a similar organization evolved with the precise function to assist movements and in addition to protect internal organs. The term *Simplexity* has recently been used to explain the solutions that Nature found to simplify the control of complex phenomena [1]. For example, the S-shape characteristic of the animal backbone, and in particular the curvature of the neck, allows the disjunction of the rotations of the head respect to the rest of the body (Figure 1 left). This in turn allows the alignment of the head with the ground in order to stabilize the vision system and thus giving a reference for the control of movements. The complexity added in the morphology of the spine helps to simplify the control. A related example of morphology, but in sensing, is

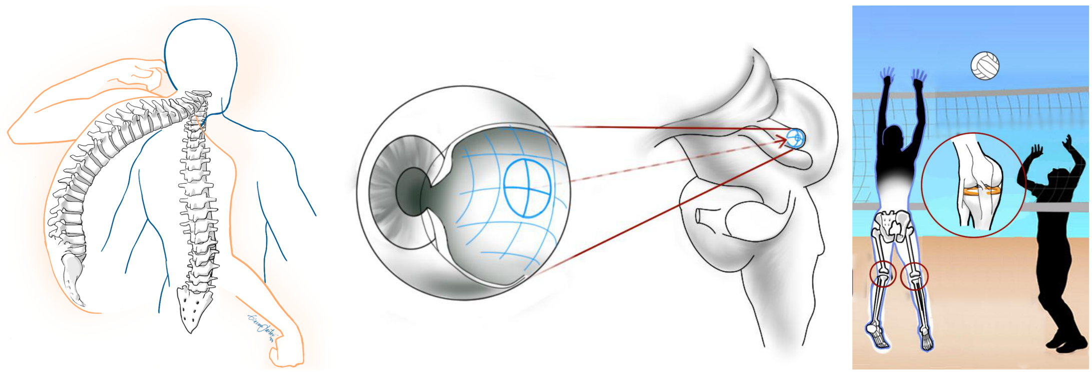

Figure 1: ***Examples of the three cases of Morphological Computation in Nature. Shape**, left. The S-shape of the backbone allows the disjunction of the rotations of the head respect to the rest of the body. **Arrangement**, centre. The geometrical arrangement of the perceptive units in the retina reflects the organization of the processing units into the Superior Colliculus, thus simplifying the processing and the control of eye movements. **Mechanical properties**, right. The mechanical properties of the muscle-tendon system allow emergent behaviors and highly adaptive interaction with the environment.*

given by the vestibular system, whose organs are precisely aligned with the Euclidean three-dimensional coordinates, thus facilitating gaze pointing in the Vestibular-Ocular Reflex.

The second possible aspect of Morphological Computation can be identified in the geometries of the brain areas, especially in those involved in perception and action. The solutions found by the evolution in these areas reflect the simplification of computation allowed by specific relative positions of the neural networks involved. Also this concept is in line with the definition of the term *Simplexity*. Actually, this term involves some high-order neural organizations, which simplify the complex nature of the environment comprehension in mammalian brains. However, from the Morphological Computation point of view, the geometry of the neural circuitry in the brain effectively reduces the complexity of computation both in perception and in action. A typical example is the geometry of the Superior Colliculus, a small agglomerate of neurons, which forms a major component of the vertebrate midbrain. The general function of this system is to direct gaze toward specific points in the egocentric space (Figure 1 centre). During the saccadic movement, the Superior Colliculus directly maps the stimulus onto an action response, thanks to the arrangement of neurons and synapses [26]. Hence such kind of complex behaviors, fundamental for the active perception of the world, share the same neural organization. Generally speaking, the way how certain neurons are positioned in the brain delineates the perception and the computation of the response. This knowledge is completely ignored by the most of the current vision systems that passively process the information in the images without considering the geometrical arrangement of the sensing elements and without integrating motion in perception.

The third case reflects the nature of the materials involved in the interaction with the environment. For example, in humans, this can be seen in the knee or in the elbow structures, which facilitate the compliant response of the limb during motion. Activities like walking, jumping or bringing a glass of water to the mouth are simplified by the elasticity present in the muscle-tendon system. Consequently, the higher cognitive functions of the animal brain, do not have to compute the exact amount of the force response. On the contrary, the brain can perform those complex tasks by controlling just a small number of parameters, such as the stiffness of the muscles (Figure 1 right). Therefore, the mechanical structure yields to a simplification of control and becomes an effective element of the whole computation system. Even the recent state of the art in robotics does not completely take advantage of this kind of phenomenon. Although is not the only possible approach, most current humanoid robots, for example, are able to reproduce the human walking exclusively by computing the exact position of each joint at each time step. This concept, known as Zero-Moment Point (ZMP) and theorized for the first time in 1969 [27], is the most famous and used algorithm used for humanoid walking robots. ZMP is still used since its first practical demonstration in Japan in 1984, at Waseda University, Laboratory of Ichiro Kato, in the first dynamically balanced robot WL-10RD of the robotic family WABOT.

It could be said, that, in the stated list, a fourth element is missed: the environment. However, the underline message that we are claiming is that the environment represents a crucial factor for all of the listed features. The environment contains information and the body, through its shape, elements arrangement, and mechanical properties, transforms this information for the agent's outcome.

In conclusion, the presented features are more intuitive in animals provided with small computing resources. For example, cockroaches rapidly move even in complex and rugged terrains. The simple brain-like controller provided in the cockroaches is coupled with a compliant leg system. The frequent collisions with the ground and obstacles are damped through the mechanical properties and the dynamical control of the legs [9]. The control of locomotion is not a simple cascade of events, where all the computation is made centrally, but both neural and mechanical systems play a role [7]. The computational burden is distributed also to the mechanical characteristics of its gait, avoiding the full control of the legs parameters from the limited central control system.

Current Applications and Technologies Emphasize the Role of Morphological Computation as a Design Principle

Morphological Computation can stand as a new approach to robot design. New methods for designing and developing robots, or other computational agents (such as prosthesis or exoskeletons), can exploit the principles of Morphological Computation by essentially transferring (a part of) the computational burden, from the control system to the morphology of the agent. It can be seen as an improvement of the design phase, with possible more complex solutions in the bodyware, for keeping the control to a low, manageable level of computational burden. This will lead to a simplification of control in adaptive behaviour, or as an enrichment of behaviour with same control complexity.

The extreme essence of Morphological Computation can be described as the simplification of movement control made possible by the presence of a bodyware able to cope with the informational content of the environment. The central processing unit is relieved of unnecessary computation which is indeed distributed toward the mechanical property of the body. The straightforward field of application of the principles of Morphological Computation results to be robotics, and all sectors where movement is involved. In robotics, Morphological Computation can dramatically influence the way robots are designed and controlled, and ultimately their effectiveness.

If the common paradigm for robot design is mechatronics, where mechanisms, electronics, control, sensors, and power supply are considered as the main components of the system and designed in an integrated way, Morphological Computation has the potential to establish a new paradigm, where control comes first and the mechanisms and sensors are designed with proper morphology and mechanical characteristics in order to obtain movement with fewer control parameters.

Morphological Computation could influence fabrication technologies, as well. The need for specific mechanical properties and morphologies, the use of soft materials, the required integration of components (sensors and actuators, primarily) is pushing forward technologies for building robots and robot components. An example of a fabrication technique, which results suitable for implementing Morphological Computation, is Shape Deposition Manufacturing (SDM). It is a Rapid Prototyping technology in which mechanisms are simultaneously fabricated and assembled as well as integrated with all the necessary remote components. The basic SDM cycle consists of iteratively depositing and shaping (basically machining) layers of part material and positioning the robot parts to be embedded in the subsequent step. These cycles result in three key features: (1) building parts in incremental layers allows a complete access to the internal geometry of any mechanism; (2) this access allows embedding actuators, sensors and other prefabricated functional components inside the structure; (3) by varying the materials used in the deposition process, the material properties of the entire structure itself can be spatially varied allowing the introduction of compliance at specific locations of the body. Locomotion techniques can be seen as one of the main topics where Morphological Computation and SDM can be successfully synergistically used for the design and fabrication of smart robots. An example is given by the *cockroach-inspired* robot developed by Mark Cutkosky at Stanford [3], where a fast running hexapod robot and its fast adaptation are obtained thanks to the mechanical reflex of its compliant knee joints, in analogy with the animal model. Another relevant example, which can be cited in this field, is the *the passive dynamic walking* [18]. This phenomenon can be obtained through a simple planar mechanism (the motion is two-dimensional) with two legs demonstrating the capability to walk stably down a slight slope with no other energy source, but gravity and no control. This system acts like two coupled pendula. The stance leg acts like an inverted pendulum, and the swing leg acts like a free pendulum attached to the stance leg at the hip. Given sufficient mass at the hip, the system will have a stable limit cycle, which is a nominal trajectory that repeats itself and will return to this trajectory even if slightly perturbed. An extension of the two-segment passive walker is to include knees, which provide natural ground clearance without need for any additional mechanisms. McGeer showed that even with knees, the system has a stable limit cycle [19].

Continuum soft limbs found in Nature demonstrated their capability of dexterous movements and soft and delicate interaction with the environment together with the possibility, when necessary, to change the (structure) stiffness and generate relatively high forces [13]. These peculiar capabilities were found in very simple animals, in evolutionary terms, suggesting the existence of an effective way of reducing the control efforts of such limbs. In the octopus, for example, the control of the 8 soft continuum arms with virtually infinite degrees of freedom is handled by a hierarchical (system) organization, where tissues, mechanical properties and their arrangement are of fundamental importance to achieve such performances. The density of the tissues, their packaging in a very particular manner ("muscular hydrostat") and the conical shape of the arms allow a synergetic exploitation of the environment characteristics and together with the use of control primitives allow the implementation of complex movement setting a very few parameters at central level [11]. The presence of all these characteristics and their perfect integration seem to play a fundamental role in the motor behavior and for this reason the octopus-like robot described in [2, 4, 15] took into account their function as well as their reciprocal interaction from a very early stage of design. Only soft or flexible materials have been used in order to leave to the robot the capability of adapting to the environment [14], in particular, when high deformability and squeezing are necessary requirements for the task to accomplish. But the soft nature of the robot is counter-balanced by a selective stiffening system, which allows the arms to actively change their mechanical properties and to exert forces on the environment. This is made possible by an actuation system based on Shape Memory Alloy springs and motor driven tendons arranged mimicking the octopus muscular system (muscular hydrostat), which is the key factor to transform deformation into motion, without the use of rigid supports (Figure 2).

Such a system has been successfully used to implement motor control primitives (such as the ones found in the real octopus), which, together with the geometrical shape of the arm, demonstrated the possibility to perform effective and energetically efficient movements, with a very low computational burden. This is a clear example of exploitation of Morphological Computation principles, where mechanical properties of the materials, the arrangement of the active elements (actuators) and the geometrical shapes are used to simplify the implementation of behaviors that otherwise would require a complex control system.

As described before, one of the main features of Morphological Computation is given by the arrangement of the system elements both in terms of sensors and actuators. *Neuromorphic engineering* is an emergent field, which focuses on the design and development of new generation of compact chips able to emulate the neural organization and function of thousands of neurons in electronic devices [20]. Silicon neurons (SiNs), hybrid analog/digital very large scale integration (VLSI) circuits, emulate in hardware the electrophysiological behaviour of real neurons and conductances. Neuromorphic SiN networks are much more efficient than simulations executed on general purpose computers and the speed of the network is independent of the number of neurons or of their coupling [24, 25]. Furthermore, spiking neural processing modules, distributed across multiple

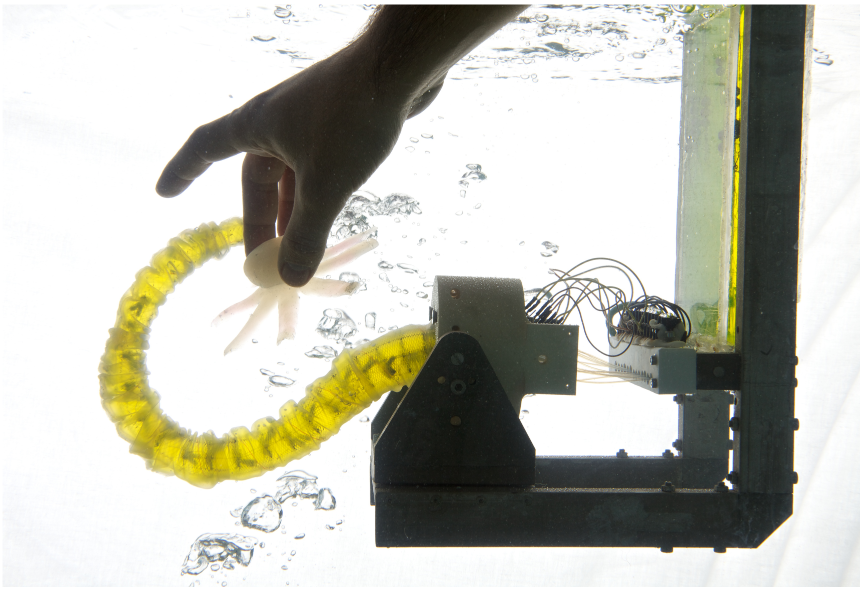

Figure 2: ***OCTOPUS robot arm.*** *The soft arm is able to mimic the real octopus arm capabilities by capitalizing on Morphological Computation and Soft Robotics technologies (credit: Massimo Brega - The Lighthouse).*

neuromorphic chips can be interconnected in a manner which is inspired by the nervous system [12]. This approach has been adopted for designing radically different spike-based vision and auditory sensors (e.g., silicon retinas, and silicon cochleas) [6, 16, 17]. Rather than capturing sensory signals in a sequence of static frames, these new bio-inspired devices produce real-time asynchronous spikes from the pixels or sensing elements that receive inputs, in the moment in which they are activated. As in biological sensors, the outputs of these devices are quite sparse, but with very high temporal resolution. The coding scheme used by these devices reduces redundancy and, as a consequence, minimizes computational requirements and power-dissipation figures. Specifically, the cost of processing the sparse output of neuromorphic sensors can be reduced by more than 2 orders of magnitude compared to the cost of processing the outputs of standard sensors [6].

Finally, mechanisms where the system has fewer inputs than degrees of freedom can be cases which exploits the principle of Morphological Computation approach, since the structure is designed to cope with a number of different interactions with the environment guaranteeing the success of the task accomplishment. Underactuated grippers are capable to conform to a wide variety of objects softly and gently, and to hold them with uniform pressure with a very simple control structure [10]. The arrangement of the tendons and the shape of the underactuated device (and partially its material properties) can be varied to increase the grasping flexibility and adaptability and at the same time to reduce the control complexity.

Next Horizons can be Deduced from Specific and Concrete Applications

The application of Morphological Computation principles in robot design can give rise to a new generation of robots with enhanced adaptability and limited number of required control parameters. They will be better suited for real-world applications and in this sense Morphological Computation will contribute to the progress of the broad field of service robotics. This is particularly important for unstructured environments when the external conditions are unknown and may present unpredictable obstacles becoming dangerous or inaccessible for human beings. This kind of scenario represents a challenging task for current robots, which usually show insufficient capabilities of adaptability. With respect to the classical robotics approach, Morphological Computation is able to cope with uncertainty exploiting the body characteristics to adapt to the environment and in some cases to exploit it providing an even richer repertoire of behaviors maintaining the same complexity in the control system.

Among the many hostile environments for humans, the underwater environment is one of the hardest to face. Here robots are being used for years, still in form of vehicles, in some cases with robotic manipulators, but with very limited usability where high dexterity should be shown together with soft interaction. Underwater manipulation tasks executed by traditional robot are made ineffective by the necessity of a very highly precise control, often not possible in such conditions. Thus, in many cases, the low capability of adaptability is compensated with a limited level of interaction. However, in some underwater tasks, the physical contact and the interaction with man-made structures or the sea bottom are mandatory: exploration or rescue in wrecks, maintenance of pipelines or other underwater structures, exploration of the sea bottom or reefs. In these cases, Morphological Computation principles could considerably increase the capability of dexterity maintaining the complexity of the control system at a manageable level.

Another harsh environment where robots play an essential role is space. Vacuum, extreme temperatures, radiations and different levels of gravity are some of the characteristics of this uncomfortable scenario. When the car-sized robotic rover *Curiosity* reached the Mars ground, one of the main challenges was to ensure the communication with its operative system from the Earth. Designing a robotic system able to autonomous interact with the environment following the Morphological Computation principle, while the human operator simply controls and decides some high level actions, would unload the data stream from the operator and the robot, reducing communication issues.

In biomedical applications, the use of Morphological Computation principles may result at least controversial, but it could lead to important improvements. In a broad field where robots are already used for surgery, endoscopy, rehabilitation and assistance, it is widely reasonable that the human operator, the surgeon or the nurse, should keep the finest and greatest control on every part of the tools used inside the human body. Thus, in such kind of applications, a robot which autonomously interacts with the internal tissues could be even dangerous. However, Morphological Computation principles shed new light in a broad field of technologies, which can be endowed in the biomedical field. To clarify this point, let us imagine a possible scenario with a surgeon executing a laparoscopic procedure [1]: the most suitable device should be able to safely interact with the environment letting the doctor concentrate only on the operation site. It should present a soft end-effector able to actively vary its stiffness in selected parts, while the support structure should actively interact with the body environment modifying its volume to adapt itself to the tissue walls [5].

In industrial robotics, as well, we may envisage an application of Morphological Computation principles. In many industrial productions there is still a part of the processes that needs to be performed by human operators. This is mainly due to the higher dexterity of human beings in those tasks where the object of the manipulation can change in shape or position and require some levels of adaptability. In some cases, this gives rise to mistreatment of human resources. Reaching human-like level of dexterity would allow a proper use of machines.

The Main Challenges and Ambitious Objectives Shed Light on the Future Scenarios

The concrete implementation of Morphological Computation principles in robots is still a creative process, widely left to the understanding and personal perception of the designer. More structured design guidelines or methods would probably help the design process and the development of robots, which incorporate Morphological Computation principles. The same stands for some fundamental enabling technologies related to materials and fabrication techniques: the need for specific mechanical properties and morphologies, the use of soft materials, the required integration of components (sensors and actuators, primarily) are pushing forward the technologies for building robots and robot components, which would bring a strong boost in the capability of exploiting the power of the Morphological Computation approach. New materials combining different properties (mechanical, but also electrical, chemical and thermal), composite materials and compounds would be the basic bricks to be combined with fabrication technologies like (but not limited to) SDM enabling the production of a wide range of possible new structures, mechanisms and systems.

Despite the described advantages coming from the shift of the adaptability control responsibility from the central processing unit to the mechanical characteristics of the peripheries, an evident limit arises when the agent has to tackle problems in which a fine control of the environment interaction is needed. As a child gradually learns to execute smooth and refined movements in controlling his own limbs, only applying the principles of Morphological Computation could result limiting and thus the design process should take into account the possibility to include specific learning mechanisms for precise and accurate, fully-controlled, movements. In animal brains two subcortical structures solve the problem of motor control. The *basal ganglia*[2] are specialized for learning from the

[1] A surgical procedure in which a fibre-optic instrument is inserted through the abdominal wall to view the organs in the abdomen or permit small-scale surgery, see also Laparoscopic surgery.

[2] The basal ganglia (or basal nuclei) comprise multiple subcortical nuclei, of varied origin, in the brains

reward/punishment signals coming after a specific action, thus formalizing an action selection mechanism which enables the organism to adapt to the different circumstances. The *cerebellum*[3] is instead specialized for learning from errors between sensory outcomes associated with motor actions and the relative expectations for these sensory outcomes associated with those motor actions. Therefore, the basal ganglia select one of the possible actions to perform, while the cerebellum refines the implementation of a given motor plan, to make it more accurate, efficient and well-coordinated. The presence of these neural structures in almost all the animal brains provides an elegant parallelism with the kind of challenges that robotics has to explore. As a consequence, in the Morphological Computation framework, the mechanical structure could likely be complex, but different strategies of motor control should co-exist at the same time, showing adaptation capability to uncertainty and learning behavior to specific movements across a wide range of motor tasks.

A final consideration concerns the interaction of humans and machines. Recent progresses of robotics are providing sophisticated systems which can perform complex tasks in the service of humans. If new robotics technologies allow to build robots with more degrees of freedom and improved dexterity, on the other hand the human users are facing an increasing complexity in operating high-tech robots. The reduction of the number of control parameters, without reducing the number of degrees of freedom and dexterity becomes an ideal solution in this perspective making Morphological Computation a fundamental ally in the robot design process.

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of vertebrates, which are situated at the base of the forebrain. The basal ganglia are associated with a variety of functions including: control of voluntary motor movements, procedural learning, routine behaviors or "habits" such as bruxism, eye movements, cognition and emotion. See also basal ganglia.

[3] The cerebellum (Latin for "little brain") is a region of the brain that plays an important role in motor control. It may also be involved in some cognitive functions such as attention and language, and in regulating fear and pleasure responses; its movement-related functions are the most solidly established. See also Cerebellum.

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