A model-based framework to investigate *morphological computation* in *muscular hydrostats* and to design soft robotic arms

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Extended Abstract

Soft Robotics is basically intended as building robots with highly compliant materials, but it is indeed more. Soft robots can safely interact with humans and with the environment and be able to adapt to different situations. These characteristics, combined with cheap materials and simple fabrication, candidate them to lead the next robotics revolution, when robots will massively move from the highly controlled industrial environments to the unpredictable real ones. As for the hardware, compliant materials such as silicones substitute stiff metals and rigid joints, following in under-actuated robots with virtually infinite number of degrees of freedom (DOF).

Controlling this extremely high dexterity using the same approach of hard robotics (i.e. a hierarchical top-down control) simply does not apply. On the contrary, a new vision of the coupling between body and intelligence has to be adopted. Instead of considering brain and morphology separated entities (with the first commanding and the second obeying) *morphological computation* (Pfeifer and Bongard, 2007) proposes a radically different standpoint. The nonlinearity and complexity of the body dynamics rather than problems are considered as part of the solution, as the produced richness of behaviors allow the morphology to carry part of the computational load, thus simplifying the required (central) control instead of complicating it.

This phenomenon is well observed in self-organization and embodiment of biological organisms, where characteristics like adaptability, robustness and agility are widely present without being explicitly controlled, and often without any (centralized) control. In the recent years many examples of embodiment in complex biological systems have been source of inspiration for robotics, ranging from cellular reproduction to the locomotion of more evolved animals like the salamander. A remarkable case where a central brain is present but still most of the sensory-motor control emerges from the body dynamics and the interaction with the environment is the octopus.

The octopus (*octopus vulgaris*) is an invertebrate sea animal showing high dexterity, variable stiffness and much more complex behaviors than expected from its position in the evolutionary scale. Its body has virtually infinite DOF, resulting in a very high computational cost if pretended to be fully controlled by its central nervous system. It has been proved instead that its relatively simple brain mainly sends actuation patterns and most of the computation is performed by a combination of the peripheral nervous system, the dynamics of the compliant body and the interaction with the environment (Yekutieli et al., 2005). The result is an under-actuated embodied system.

The element at the base of this system is the *muscular hydrostat*. It is an isovolumetric structure widely present in nature as a component of compliant animal bodies. Besides generating the forces for movements it also provides skeletal support, featuring extremely high dexterity and variable stiffness ability. It is composed by a combination of muscular fibers arranged in longitudinal, transverse and oblique directions (Fig. 1). The different activation patterns of these
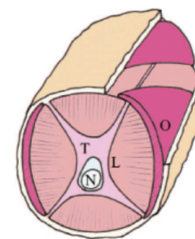

Figure 1: Longitudinal (L), transverse (T), oblique (O) muscular fibers and nerve cord (N) in muscular hydrostats.

muscular fibers generate all the basic movements performed by muscular hydrostats. The whole octopus body can indeed be considered as a complex system where the interaction above its elements and the environment lead to the emergence of the global behavior. The brain orients its outcome rather then controlling each intermediate step. Beyond being widely studied in biology, the octopus represents a rich source of inspiration for roboticists (Laschi et al., 2009), who want to reproduce its peculiar characteristics to build marine soft robots able to swim, manipulate, and move in

unstructured environments.

Understanding the principles underlying the behaviors of the octopus (and of other similar natural systems) is thus not only interesting from a biological standpoint but extremely useful for the design of a new generation of embodied soft robots. So far, this design has been mainly founded on bio-mimetics, meaning trying to reproduce biological structures in order to take advantage of their qualities. While this method has proven to be a powerful tool, it has two main shortcomings: the technological limits often encountered in reproducing biological structures (e.g., artificial muscles) and the challenge of applying embodiment principles to perform a defined task.

This reveals the need for a systematic design framework able to extract the basic principles of the embodied intelligence, transferring them into an artificial system while taking into account the technological limits and the (main) tasks to perform. In order to apply this *Design for Emergence* (i.e. shape the morphology so that the desired behaviors are likely to emerge) a modeling phase has to be included, where the complex characteristics of the system are synthesized and quantified and the technological constraints included.

In this work a lumped-parameters mathematical model of the nonlinear dynamics of a muscular hydrostat is proposed, inspired to the work of Yekutieli et al. (2005), where a similar model has been used to study the octopus reaching behavior. The presented model is realized as a complex network of masses and springs in order to reproduce the rich dynamics of the octopus arms (Fig. 2). Furthermore it is general, thus
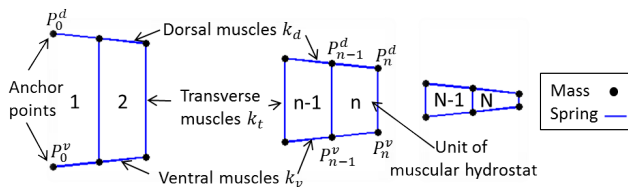

Figure 2: Scheme of the lumped-parameter arm model.

able to simulate a wide range of animal structures based on muscular hydrostats (e.g., octopus arm, elephant trunk) as well as, fittingly setting the parameters, soft robotic arms with muscle-like actuation (e.g., pneumatic, hydraulic).

Differently from other similar models, the equations of motion were obtained using an energy-based method (*Lagrangian mechanics*). The two main reasons are: have a set of equations where it is easy to add various constraints; energy and generalized coordinates provide a full description of the evolution of the system, the former at a global level, the latter at a local (*agent*) one. Constraints were applied to add the isovolumetric feature of muscular hydrostats and contacts (a novelty in these studies) to model the interaction with the environment (Fig. 3), opening to the investigation of grasping tasks and safe interaction with humans.
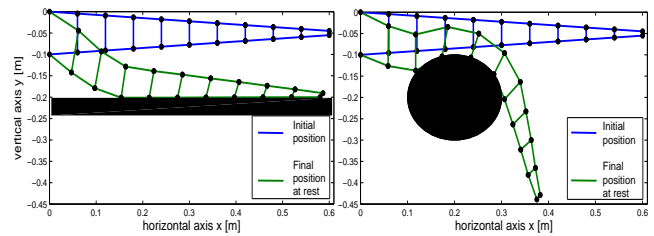

Figure 3: Soft arm free falling in contact with a hard plane (left) and sphere (right).

The proposed model is meant to be combined with evolutionary computation tools in a set-up for brain-body co-evolution (Lipson and Pollack, 2000): a genetic algorithm contemporary optimizing a neural controller (the brain) and the arm model parameters (the body), with the fitness mainly represented by the performance on an assigned task (e.g., reaching a point, grasping an object). Respect to other similar works the evolution is not from *tabula rasa*, as the design space, contemplating the different combinations of morphology and control, is extremely wide and with plenty of local minima. Thus, in order to simplify the genetic optimization process, bio-inspiration is used to focus the design space about biological systems well-suited for the desired tasks.

The aim of this set-up is twofold. First, the quantitative and task-related analysis of embodied intelligence and morphological computation in biological systems based on muscular hydrostats: thanks to the realized coupling the body parameters influence how the control is shaped by the genetic optimization and *vice versa*. Second, setting the model parameters to fit technological constraints (relative to a chosen actuation technology), the definition of a new framework for the Design for Emergence of soft robotic arms, where morphology and control are simultaneously optimized to reach the emergence of the desired global behaviors with the simplest software and hardware.

Acknowledgements

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