Beyond Morphological Computation: an Ecological Approach to Control in Soft Robotics

Matteo Antonelli[1]

[1] University of Urbino, Urbino (PU) 61029, Italy

`m.antonelli17@campus.uniurb.it`

Extended Abstract for Presentation

This contribution addresses a fundamental issue in soft robotics: designing effective control strategies for adaptive behavior. Soft robotics is an emerging field of research that explores a wide range of new materials – including silicone, polymers, hydrogels, etc. – to build intelligent systems. A defining characteristic of soft robots is their ability to actively interact with the environment and undergo large deformations relying on inherent and structural compliance. While these features open unprecedented possibilities (for instance, the inherent compliance of soft robots improves safety in human-robot interaction, enables gentle manipulation of delicate items, and boosts locomotion by storing and releasing elastic energy), they also introduce significant challenges. Soft devices are notoriously difficult to model, and their large number degrees of freedom make them resistant to classical control approaches, which are typically based on rigid-body assumptions. Therefore, to fully harness the potential of soft robots, new control and design paradigms must be developed, capable of handling the complexity inherent to these systems.

One response to these challenges is the principle of morphological computation, which refers to a process of task distribution between the brain (the central controller in a robot), the body morphology of the agent and the environment. It proposes that control tasks typically regarded as complex in noisy, unstructured environments can be managed by comparatively simple controllers, since part of the computation is "offloaded" to the physical dynamics arising from the interplay between body and environment. A classic example is the passive dynamic walker, whose ability to walk is exclusively due to the downward slope of the incline on which it walks and the mechanical parameters of the walker, without requiring explicit control algorithms. However, while the notion of morphological computation has inspired a substantial body of work, I argue that describing such processes as "computation" – beyond the

purely metaphorical sense – is misleading. Body morphology supports control, but it does not perform any computation.

I propose ecological psychology as a more accurate conceptual framework for understanding the role of morphology in adaptive control. Rooted in the work of James J. Gibson, ecological psychology emphasizes the emergent nature of behavior from continuous, reciprocal interactions between an agent and its environment, without relying on computational processing over internal representations. Ecological psychology's theoretical foundation can be summarized by four core principles: (i) perception is direct; (ii) perception and action are continuous; (iii) affordances (i.e., meaningful possibilities for action specified by ecological information); and (iv) the proper unit of analysis is the spatiotemporal scale of organism and environment interaction. From this perspective, control is not a preprogrammed sequence of commands executed by the body, but rather an ongoing, dynamic negotiation with ever-changing external conditions.

The connection between this framework and soft robotics can be found in Nikolai Bernstein's classical analysis of motor control. Bernstein identified the core problem of action coordination as mastering the many degrees of freedom involved in a particular movement – a challenge that closely parallels two major problems in soft robotics: (i) designing complex systems capable of dexterous movements within their environments and, as a corollary, (ii) managing the large number of degrees of freedom inherent in compliant deformable structures. By employing an ecological reinterpretation of Bernstein's notion of synergy – a grouping of potentially independent anatomical elements that work together as a functional unit in exploiting information about affordances for a given behavior – I will outline a control architecture organized as a hierarchy of affordances and consider how notions such as affordances and direct perception can be rendered operational for robotic systems.

This operational reading of ecological psychology's notions allows me to formulate an ecological design principle for soft and tensegrity robots: the principle of Agent-Environment Duality. According to this principle, a robot's environment can be modeled as an affordance structure that is reciprocally isomorphic, or dual, to the effectivity structure of the robot (the set of capacities enabling it to act upon the world). Encouraging complementarity between robot and workplace, control is framed as keeping specific relations (affordances) within bounds given the robot's effectivities. In practical terms, this can allow designers to reduce computational burden (regulate task-level informational variables rather than reconstruct global state), align morphology and sensing with the structure of the physical world, and – potentially – lower energy demands. Furthermore, this ecological approach is scientifically generative: by building artifacts that rely on affordances and effectivities, we can test hypotheses about biological agents in the spirit of the synthetic methodology – understanding by building.

Notwithstanding these potential benefits, I will also outline several open problems and points of tension with the current state of the art. For example, the field of soft robotics already has control strategies (e.g., open-loop and closed loop control). Introducing a fundamentally different stance is by no means obvious, since teams face integration costs that must be offset by demonstrable gains in performance and robustness. Nonetheless, while such challenges are non-trivial, they appear tractable. At the same time, the promising outcomes – simpler controllers, lower energy demands, and behaviors more congruent with human and ecological contexts – indicate that the Agent-Environment Duality principle may allow artificial systems to operate seamlessly within the world, offering, in turn, a promising path for advancing soft robotics toward the construction of more resilient devices.

To summarize, this proposal introduces soft robotics and its challenges, critiques the limitations and potential misconceptions of morphological computation, and advances ecological psychology as a more comprehensive alternative. Finally, I introduce the Agent-Environment Duality design principle, aimed at guiding the development of more efficient, adaptive and intelligent soft robotic platforms.

Major References

Bernstein, N. A. (1996). *Dexterity and its Development.* (Latash M., L., & M., T., Turvey, Eds.). Lawrence Erlbaum Associates, Inc.

Favela, L., H. (2024). *The Ecological Brain: Unifying the Sciences of Brain, Body, and Environment*. Routledge.

Gibson, J. J. (1979). *The Ecological Approach to Visual Perception*. New York: Psychology Press, Taylor & Francis Group.

Hauser, H., Nanayakkara, T., and Forni, F. (2023), "Leveraging Morphological Computation for Controlling Soft Robots: Learning from Nature to Control Soft Robots," in *IEEE Control Systems Magazine*, vol. 43, no. 3, pp. 114-129, June 2023, doi: 10.1109/MCS.2023.3253422.

Laschi, C., Mazzolai, B., Cianchetti, M. (2016). "Soft Robotics: Technologies and Systems Pushing the Boundaries of Robot Abilities". *Sci. Robot.* 1, eaaah3690. DOI: 10.1126/scirobotics.aah3690 .

Müller, V., C., & Hoffmann, M. (2017). "What Is Morphological Computation? On How the Body Contributes to Cognition and Control", in *Artificial Life*, 2017 Winter; 23(1):1-24. doi: 10.1162/ARTL_a_00219. Epub 2017 Jan 31. PMID: 28140632.

Pfeifer, R., & Bongard, J. (2006). *How the Body Shapes the Way We Think: A New View of Intelligence*. MIT Press.

Profeta, V., L., S., Turvey, M., T. (2018). Bernstein's levels of movement construction: A contemporary perspective. *Hum Mov Sci*. 2018 Feb; 57:111-133. doi: 10.1016/j.humov.2017.11.013. Epub 2017 Dec 1. PMID: 29202312.

Turvey, M., T. (1992). "Affordances and Prospective Control: An Outline of the Ontology", in *Ecological Psychology*, 4:3, 173-187, DOI: 10.1207/s15326969eco0403_3.