Morphosis – Taking Morphological Computation to the Next Level

Helmut Hauser and Francesco Corucci

Abstract Morphological Computation is a concept used in robotics that sees physical bodies of robots as means to carry out computations that are relevant for their successful interaction with the environment. It is inspired by observations in nature where we can see that the morphology (i.e. the shape as well the dynamic properties of the body) of biological systems is playing a crucial role for the emergence of intelligent behavior. Although there are a number of successful implementations of this concept in robotics, there are still challenges to overcome. One is that any functionality implemented in a morphology is deemed to be fixed. However, truly autonomous robots should be highly flexible and are expected to be able to adapt to changes in the environment and to new tasks. In case of morphological computation, in order to change the desired computation to be carried out, the underlying morphology has to be altered. A solution is to introduce mechanisms that enable the robot to make these changes online, often referred to as *morphosis*. We introduce and discuss a general notion of morphosis from the view point of dynamical systems theory, highlight the concept by examples from robotics, and elaborate on the wide-reaching implications with respect to the design of highly autonomous robots.

Helmut Hauser
University of Bristol, Depart. of Engineering Mathematics, Woodland Road, BS8 1UB,Bristol, UK
Bristol Robotics Lab, Frenchay Campus, Coldharbour Lane, Bristol, BS16 1QY, UK
e-mail: helmut.hauser@bristol.ac.uk

Francesco Corucci
The BioRobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy
Morphology, Evolution & Cognition Lab, University of Vermont, Burlington, VT, USA
e-mail: f.corucci@sssup.it

1 Introduction

There are numerous robotic examples that apply morphological computation as design principle. They all use the robot's body dynamics to carry out (implicitly, or explicitly) relevant computational tasks including nonlinear processing, transforming, and transmitting information. Successful implementations include highly robust locomotion, like running [17], swimming [22, 7], flying [18], as well the combination of different locomotion modes [3, 2, 4]. It has also been shown that morphological computation is useful in the context of grasping [1], sensing [13], as well facilitating communication [15, 16] and control [14]. Although morphological computation has been successfully applied, and, theoretically, there is almost no limitation with respect to which computations can be carried in morphological structures [9, 10], there are still a number of challenges that have to be addressed. One is the limitation that once a computation is implemented in a certain morphology, it will be fixed. This is a problem if we want to build highly autonomous systems that are able to adapt to changes in the environment or to new tasks. Recently, there has been an effort to incorporate mechanisms that overcome this limitation by enabling the robot to dynamically reconfigure its morphology. Often referred to as *adaptive morphology* or *morphosis*, this concept has strong implications regarding the possibility to build highly robust systems, simplifying control, and implementing hierarchical control structures that might form the basis for higher cognitive functions.

2 Morphosis from the perspective of dynamical systems theory

A number of mechanisms have been proposed to vary morphological parameters online. These include simple variable impedance and damping systems that can help to increase the range of conditions in which a robot is able to work properly, e.g. as in [20]. Some robotic systems go beyond that by allowing a reconfiguration of the morphological structure that results in a qualitative change in the behaviour of the robot [21, 5, 6]. Both approaches implement the idea of morphosis. To better understand this concept, we propose to look at it from the dynamical systems' point of view.

For the sake of simplicity, let's consider an arbitrary stable one-dimensional dynamical system (note that the underlying concepts are scalable). The left part of Figure 1A (i.e. behaviour A) shows an example of the attractor landscape of such a system with one stable equilibrium point located at the bottom of the ”valley”. If the system is perturbed, its own body dynamics will bring it automatically back to this point (blue arrow). By changing the parameters of the dynamical system (i.e. changing morphology), we can get a different response. For example, we can make the valley steeper if we make the mechanics stiffer. If the dynamics of the body are complex enough, we can have two (or more) equilibrium points, representing different (locally) stable behaviours, see both sides of Figure 1A. The question is how can we move from one equilibrium point (i.e. one behaviour) to another? As it turns out

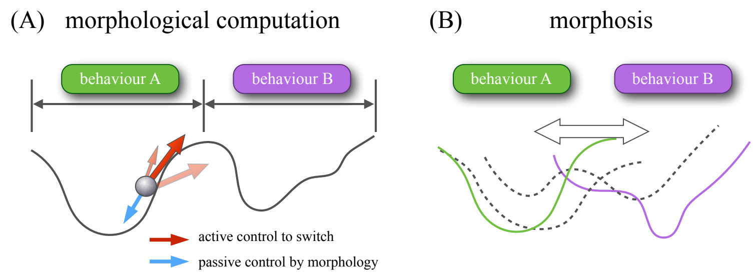

Fig. 1 Dynamical systems view of morphological computation and morphosis. (A) Two fixed behaviours implemented in one morphology (B) Morphosis enables smooth switching between two behaviours by reshaping the attractor landscape.

this is very simple: The system has to get pushed into the right direction to get over the energy hump between them. Note that the required control is low-dimensional and it can be rather imprecise. The direction of the force can vary (compare red arrows in Figure 1A) and the amplitude just needs to be big enough to overcome the hump between the two valleys. The rest is done by the attractor landscapes of the local equilibrium points. Also, energy is only required during the change. While this is very promising and has a great potential (see [11, 10] for examples), this is not morphosis yet. Now, instead of having a fixed attractor landscape we can imaging morphosis as a way to dynamically reshape the attractor landscape online (see Figure 1B). By reshaping (”reprogramming”) the body, morphosis enables the robot to easily switch among a set of different behaviours. As before, the control can be low-dimensional, imprecise, and is typically very energy efficient. Morphosis therefore further simplifies the control problem by outsourcing parts of the control to the morphology in form of attractor landscapes. It also provides a form of abstraction that implements implicitly a control hierarchy. As a consequence, building upon morphological computation and morphosis might lead us the way to achieve higher cognitive functions. Having discussed the notion of morphosis in the context of dynamical system theory, we are now ready to look at three robotic examples to underline the idea and to demonstrate its potential.

Example 1: Morphosis to achieve energy efficient locomotion

The most straightforward implementation of morphosis in locomotion consists in changing leg stiffness. A number of different variable compliant mechanisms have been proposed for that. One of them, MESTRAN [19], was used in the knee joint in the hopping robot leg shown in Figure 2A. The idea of this setup was to mimic a behavior observed in humans and other animals, which adapt their leg stiffness depending on ground conditions in order to locomote in an energy efficient manner. The experimental setup in Figure 2A allowed to vary systematically the stiffness of the ground. The robot leg was driven by a simple sinusoidal control signal applied at the hip motor. The knee joint was passive, but it was possible to adjust its stiffness.

It was shown that there exist one optimal stiffness for each of the explored different ground stiffness values, resulting in minimal energy consumption [20]. This points to the great potential of morphosis to increase energy efficiency and versatility of robots over a wide range of environmental conditions.

Example 2: Morphosis to change gait

Locomotion in different environments (slopes, steps, roughness of the terrain, etc.) calls for different leg and foot trajectories. Vu et al. [21] developed a robot platform to explore this idea with the help of morphosis. The basic leg design was a crank-slider mechanism translating a simple control signal (i.e., constant rotational velocity) into two-dimensional leg trajectories (compare Figure 2B). The morphosis mechanism changed the way the rotational movement was translated, while the control remained unchanged. The result was a range of different end point trajectories (see Figure 2B) that can be useful for different terrains. Note that morphosis only takes place when there is a need for a change as opposed to the continuously running, rotational hip motor. As a result, the morphosis motor could be small, not very demanding, and could even be switched off during stable locomotion. This robotic prototype demonstrates how morphosis can help to increase the number of possible behaviors (gaits, in this case) within one robot design.

Example 3: Automated evolutionary design targeting morphosis

A complete design pipeline targeting morphosis was introduced in [5]. The case study is the locomotion of a soft underwater robot (PoseiDRONE, see [2, 3]) (Fig. 2C). A model of the robot dynamics was developed and fed into an evolutionary engine that, by tweaking a number of morphological parameters (24 in total), discovered thousands of alternative robot designs by maximizing a metric of behavioral novelty. This novelty metric was computed in a behavioral space defined by some locomotion-specific features. A clustering procedure was then implemented in the space spanned by the morphological parameters that evolution could modify, in order to identify groups of similar morphologies. At this point, an algorithm searched inside each cluster for similar morphologies that maximally differ in their behavior (i.e. that are far apart in the behavioral space): these are good candidates for morphosis. The procedure was able to discover several configurations in which the robot was able to dramatically and qualitatively change its behavior by slightly adjusting a single morphological parameter, in presence of a constant open loop control. For example, by slightly rearranging their bodies, discovered robots could switch from walking to swimming, from crawling to hopping (compare Figure 2C), and others. Moreover, once morphosis was triggered, the transition between one morphology (and its associated behavior) to another did not have to be actively and precisely controlled, and relied in fact on the robustness and self-stabilizing properties of the attractor landscapes shaped by morphosis.

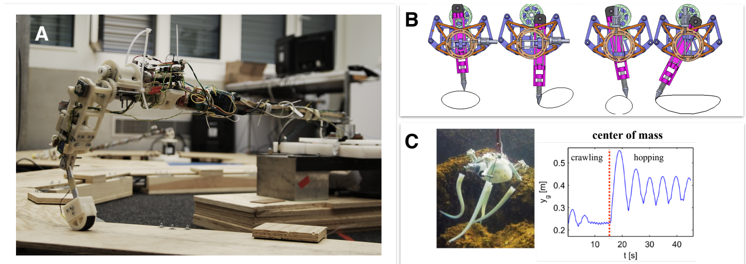

Fig. 2 Three examples of morphosis in robotics. Increase (A) versatility in locomotion, (B) number of gaits, and (C) behavioral repertoire (plot of CoM, switch at $t = 15s$ from crawling to hopping).

3 Outlooks and conclusions

The concept of adaptive morphology/morphosis has been discussed from the view point of dynamical system theory. The presented robotic examples suggest a number of advantages. Morphosis can increase the range of operative conditions in which a robot is able to work. It also enables the implementation of different (robust) behaviours that resort on the power of morphology instead of on complex controllers, implying a new way to design versatile robots. Morphosis also implicitly establishes a hierarchical control structure, further reducing the control complexity. It also allows for imprecise high-level control signals, which can help robot to operate in noisy, real-world scenarios. Looking more into the future, morphosis will play a crucial role in artificially growing [8] and self-healing systems. Control systems will benefit from adaptive and reconfigurable bodies, that will take care of most of the low level control thus freeing resources for higher level and, ultimately, cognitive tasks. In order to exploit these ideas, processes to optimize morphologies will be needed [12, 8], allowing them to adapt during their lifetime and react to environmental stimuli [8]. Ultimately, these concepts will enable more robust, adaptive and intelligent robots, helping robotic technology to become truly pervasive.

Acknowledgements This works has been partly supported by the EU project RoboSoft – Future and Emerging Technologies Open Scheme (FP7-ICT-2013-C project #619319).

References

1. Brown, E., Rodenberg, N., Amend, J., Mozeika, A., Steltz, E., Zakin, M.R., Lipson, H., Jaeger, H.M.: Universal robotic gripper based on the jamming of granular material. Proceedings of the National Academy of Sciences **107**(44), 18,809–18,814 (2010)
2. Calisti, M., Corucci, F., Arienti, A., Laschi, C.: Bipedal walking of an octopus-inspired robot. In: Conference on Biomimetic and Biohybrid Systems, pp. 35–46. Springer (2014)
3. Calisti, M., Corucci, F., Arienti, A., Laschi, C.: Dynamics of underwater legged locomotion: modeling and experiments on an octopus-inspired robot. Bioinspiration & Biomimetics **10**(4),

046,012 (2015)

4. Corucci, F., Calisti, M., Hauser, H., Laschi, C.: Evolutionary discovery of self-stabilized dynamic gaits for a soft underwater legged robot. In: Advanced Robotics (ICAR), 2015 International Conference on, pp. 337–344 (2015). DOI 10.1109/ICAR.2015.7251477
5. Corucci, F., Calisti, M., Hauser, H., Laschi, C.: Novelty-based evolutionary design of morphing underwater robots. In: GECCO2015 (2015)
6. Corucci, F., Calisti, M., Hauser, H., Laschi, C.: Shaping the body to shape the behavior: a more active role of the morphology in the brain-body trade-off. 13th European Conference on Artificial Life (ECAL2015), Late Breaking Proceedings pp. 7–8 (2015)
7. Corucci, F., Cheney, N., Lipson, H., Laschi, C., Bongard, J.: Evolving swimming soft-bodied creatures. In: ALIFE XV, The Fifteenth International Conference on the Synthesis and Simulation of Living Systems, Late Breaking Proceedings (in press) (2016)
8. Corucci, F., Cheney, N., Lipson, H., Laschi, C., Bongard, J.: Material properties affect evolution's ability to exploit morphological computation in growing soft-bodied creatures. In: ALIFE XV, (in press) (2016)
9. Hauser, H., Ijspeert, A.J., Füchslin, R.M., Pfeifer, R., Maass, W.: Towards a theoretical foundation for morphological computation with compliant bodies. Biological Cybernetics **105**(5-6), 355–370 (2011)
10. Hauser, H., Ijspeert, A.J., Füchslin, R.M., Pfeifer, R., Maass, W.: The role of feedback in morphological computation with compliant bodies. Biological Cybernetics (2012). DOI 10.1007/s00422-012-0516-4
11. Hauser, H., Nakajima, K., Füchslin, R.M.: Morphological Computation – The Body as a Computational Resource. In: H. Hauser, R.M. Füchslin, R. Pfeifer (eds.) E-book on Opinions and Outlooks on Morphological Computation, chap. 20, pp. 226–244 (2014)
12. Hermans, M., Schrauwen, B., Bienstman, P., Dambre, J.: Automated Design of Complex Dynamic Systems. PLoS ONE **9**, e86,696 (2014). DOI 10.1371/journal.pone.0086696
13. Johnson, C., Philippides, A., Husbands, P.: Active Shape Discrimination with Physical Reservoir Computers. In: ALIFE 14, vol. 14, pp. 176–183 (2014)
14. Nakajima, K., Li, T., Hauser, H., Pfeifer, R.: Exploiting short-term memory in soft body dynamics as a computational resource. Journal of The Royal Society Interface **11**(100), 20140,437 (2014). DOI 10.1098/rsif.2014.0437
15. Owaki, D., Kano, T., Nagasawa, K., Tero, A., Ishiguro, A.: Simple robot suggests physical interlimb communication is essential for quadruped walking. Journal of The Royal Society Interface (2012). DOI 10.1098/rsif.2012.0669
16. Rieffel, J.A., Valero-Cuevas, F.J., Lipson, H.: Morphological communication: exploiting coupled dynamics in a complex mechanical structure to achieve locomotion. Journal of the Royal Society Interface **7**(September 2009), 613–621 (2010). DOI 10.1098/rsif.2009.0240
17. Rummel, J., Iida, F., Smith, J.A., Seyfarth, A.: Enlarging regions of stable running with segmented legs. In: Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on, pp. 367–372. IEEE (2008)
18. Shim, Y., Husbands, P.: Feathered flyer: Integrating morphological computation and sensory reflexes into a physically simulated flapping-wing robot for robust flight manoeuvre. In: F.A. e Costa et al (ed.) ECAL, pp. 756–765. Springer Berlin / Heidelberg (2007)
19. Vu Quy, H., Aryananda, L., Sheikh, F.I., Casanova, F., Pfeifer, R.: A novel mechanism for varying stiffness via changing transmission angle. In: ICRA 2011, pp. 5076–5081 (2011)
20. Vu Quy, H., Hauser, H., Leach, D., Pfeifer, R.: A variable stiffness mechanism for improving energy efficiency of a planar single-legged hopping robot. In: ICAR 2013, pp. 1–7 (2013). DOI 10.1109/ICAR.2013.6766488
21. Vu Quy, H., Ramstein, G., Casanova, F., Aryananda, L., Hoffmann, M., Sheikh, F.I., Hauser, H.: Gait Versatility Through Morphological Changes in a New Quadruped Robot. In: 5th International Symposium on Adaptive Motion of Animals and Machines (2011)
22. Ziegler, M., Iida, F., Pfeifer, R.: "Cheap" Underwater Locomotion: Roles of Morphological Properties and Behavioural Diversity. In: CLAWAR (2006)