Soft Robotics in Underwater Legged Locomotion: From Octopus–Inspired Solutions to Running Robots

Marcello Calisti

Abstract This chapter reports on the conceptual design of an octopus-inspired robot. The investigation started from slow speed gaits, such as the crawling locomotion of octopuses, and was followed by faster gaits such as bipedal walking and hopping. Results envisage that this novel locomotion can be exploited to increase the mobility of underwater robots in the benthic realm.

1 Underwater Legged Locomotion

Marine robotics experienced a steady growth over last years, fostered by the increased request of underwater natural resources, as well as the number of scientific, exploration and search and rescue missions performed in collaboration with underwater robots. Although manipulation, interaction and motion are among the key system abilities requested to underwater robots, the vast majority of those vehicles move in what is called *pelagic* realm, i.e. the portion of the ocean ranging from above the seabed to the water surface, and when they need to interact with underwater structures or surfaces, for example in inspection, sampling, and manipulation tasks, the control complexity (and autonomy) drastically increases (or decreases) [11]. On the contrary there exist a category of underwater vehicles, called generically crawlers [19], which is purposely designed to explore the *benthic* real, i.e. the bottom of the sea and some sub-surface layers. Crawlers are used to track mineral resources, operates in close-contact with structure or to provide high resolution information of the benthos [16, 19]. They are usually rover-like vehicles, with wheels or tracks, and their design should take into account water-related forces, which can tilt the vehicle over and decrease the friction, resulting in reduced performance [19]. Moreover wheels or tracks can get stuck in complex, uneven surfaces, thus reducing the motion capability of the robot, or they can cause serious damages to fragile substrates. On the other hand, there is a great number of benthic animals which swiftly move onto

M. Calisti (✉)
The BioRobotics Institute, Scuola Superiore Sant'Anna, Viale Rinaldo Piaggio 34, 56025 Pontedera, PI, Italy
e-mail: m.calisti@sssup.it

C. Laschi et al. (eds.), *Soft Robotics: Trends, Applications and Challenges*,
Biosystems & Biorobotics 17, DOI 10.1007/978-3-319-46460-2_5

the seabed or rocks, and gently interact with the environment: among them, we can recognized several species of crab, lobsters, worms, shrimps, sea cucumbers, starfish and octopuses.

Recently, octopus-inspired solutions attracted several researchers, especially in the soft robotics niche: the amazing properties of the octopus arm, which are exploited to manipulate objects and to move, have been source of inspiration for soft robotics manipulators [12] and suckers [27], in addition to mobile soft vehicles. Octopuses move in several different ways ranging from swimming by jet propulsion [25] or sculling [26], to crawling [9] and bipedal walking [5, 6]. Octopus-like robots are among the few pioneering prototypes of underwater legged machines, together with other few examples [1, 3, 20], and this chapter presents three bioinspired solutions for underwater legged locomotion. To begin with, the slowest movement of the octopus was studied, called crawling, which is mainly used in shallow waters and on multiple surfaces; then a faster locomotion, named bipedal walking, was investigated; and finally an hopping-based locomotion is formulated, inspired by punting locomotion, where the contact time is minimal and a flight (swimming phase) is clearly shown. In the next sections I will report the principles of these kinds of underwater legged gaits, while in Sect. 2 I will conclude the chapter and illustrate further developments.

1.1 Crawling

Octopus crawling appears as a cluttered sequence of pushing and pulling actions, without a timely and organized coordination [23], however recent studies demonstrated that octopus crawling relies on a few fundamental principles:

1. thrust tangential to the direction of elongation of the arm [9]
2. non-rythmical arm coordination made of instantaneous decision on which arm to recruit to move in a certain direction [21]
3. stereotyped sequences of arm motions [9]

These three principles are illustrated in Fig. 1; practically, if the octopus wants to move to the right, it elongates the arms to the left and pushes the body in the opposite direction Fig. 1a; if a target suddenly appear, a novel set of arms is recruited to push in the proper direction Fig. 1b, thus that an overall eight-arm coordination emerges from single arm recruitment; and finally it is shown how the pushing action is based on four repeated phases: a shortening motion (when the arm is shortened), an attaching phase (when the arm sticks to the ground by means of the suckers), an elongation action (when the arm elongates and pushes the body), and eventually a detaching phase, Fig. 1c. These findings significantly reduce the features required to build a soft arm devoted to locomotion: that arm should only be capable of shortening/elongating and attaching/detaching. By taking as a reference these design objectives, a conical arm made of silicone and cables was developed: the first version embedded one axial steel cable and one longitudinal nylon cable, with two different functions. Thanks to the

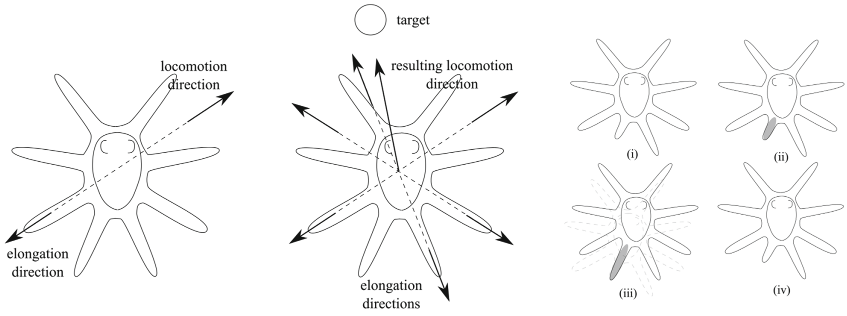

Fig. 1 Biological findings guided the development of the octopus inspired robot: **a** radial pushes, **b** multi-arm recruitment, and **c** four phases pushing action

coiling or uncoiling of the steel cable, the arm reduced or increased its length, whereas the longitudinal cable was used to bend the arm in a spiral like configuration. The bending action was used to lift the arm (or to lie it) onto the ground, thus providing a attaching/detaching mechanism, while the shortening/elongating strategy was used to push the robot. Implementation and design details are reported in [9].

Following this seminal work, a further version of the arm was developed by using the axial cable as a bar of a three-link mechanism, illustrated in Fig. 2: thanks to this design, only one motor was needed to perform the sequence of actions required to push the body forward. Moreover, a rotation in anti-clockwise direction allowed the arm to push the robot, while a rotation in the opposite direction entailed a pulling motion. By using this novel design it was possible to attach, in a radial configuration, several copies of the compliant arm on a central rigid platform, which allowed the underwater robot to move in every direction [4, 8]. Moreover, bioinspired control strategies were implemented by taking into account the non-rythmical coordination behaviour discovered in the animal. The positions of a target (balloon) on the frame of an omni-directional camera were collected as input, while the actuations of the corresponding arm were used as output of a goal-oriented sensory-motor coordination strategy which was implemented on a six-arm robotic platform. This reactive control strategy leaded to a reliable behaviour which allowed the robot to reach the target in every position of the space, and moreover a two-arm coordination emerged when the target was in between the direction of two pushing arms [22].

1.2 Bipedal Walking

The crawling solution, even if it was effective on several grounds [12], lacks the dexterity and speed desired in underwater mobile robots, hence we tried to exploit the compliant actuation mechanism developed for crawling in novel configurations, with the goal of improving the mobility of the robot. A novel platform, called PoseiDRONE, was developed for this purpose [2]: it featured only four-arms, but

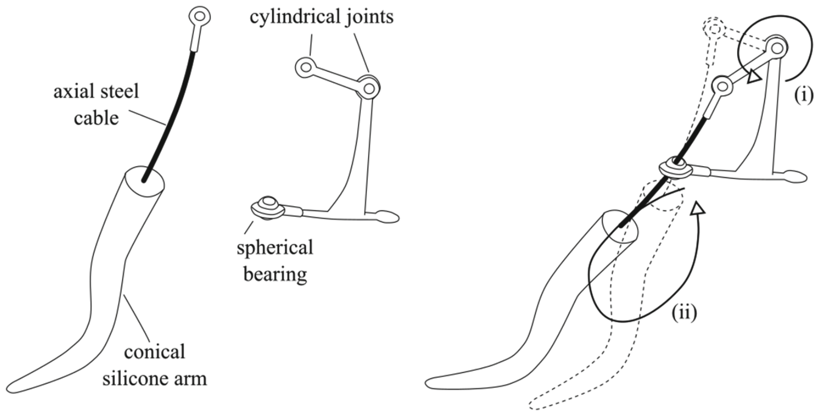

Fig. 2 The compliant arm is used as a bar of a three-link mechanism. The rotation of the crank (*i*) entails a pseudo-elliptical loop in the arm (*ii*), which allow the robot to push or pull the ground

with robot geometries optimized (via evolutionary design) to realize faster gaits [5, 13, 14]. The work was again inspired by a gait performed by the octopus: the bipedal walking. In this gait, the animal stands in a bipedal-like posture and, in a roughly coordinate action, it uses a couple of arms to push forward the body [17, 18]. By lodging over the body of the robot a controllable floating module, we tested a bipedal actuation and reported the speed the robot, which was considerably higher than the crawling one, while the behaviours was qualitatively influenced by sculling movements as well [6]. Particularly, we noticed that it was possible to exploit body/water relationships to design improved underwater legged robots [13, 14], and that the duty factor drastically decreased, due to long swimming phases after short pushing phases, as the buoyancy contribution increased. This motivates the investigation of a pushing-based motion which employed very brief, impulsive, pushing phases followed by gliding phases, as to reduce to the minimum the contact with the environment yet to increase the speed of the robot.

1.3 Underwater Hopping

Such desired dynamic motion was similar to the one-leg hopping behaviour implemented on a pogo-stick machine to study terrestrial running [24]. Similar to the terrestrial counterpart, we expected that it was possible to obtain reliable self-stabilizing running behaviours also in underwater legged locomotion, and a monopedal running model was developed to test this hypothesis [10]. The model was based on the successful Spring Loaded Inverted Pendulum (SLIP) template, which was extensively used as a reference for the control of running machines [15]. The novel model, called Underwater-SLIP (U-SLIP), included water related contributions such as the drag, buoyancy forces, and the added mass. Results demonstrate how the U-SLIP reaches a self-stabilizing periodic behaviour, even when moving over uneven terrains with random disturbances. Based on those results, a monopedal robot was design, developed and tested on several grounds, confirming the high stability of underwater robots employing such hopping locomotion [7].

2 Conclusion

Underwater legged locomotion is using tools and strategies of soft robotics to increase the interaction and motion capabilities of underwater robots. By using bioinspired design, soft solutions can be quickly developed and tested, while more focussed design methods can be used to properly exploit water/soft-body relationship. The qualitative solutions presented envision the long term goal of demonstrating quantitatively augmented capabilities related to stability of the locomotion, reduced damage to the environment and improved motion on the benthic realm.

Acknowledgments This work was funded within the framework of the EU RoboSoft Coordination Action, under the contract FP7-ICT-2013-C project # 619319.

References

1. Akizono, J., Tanaka, T., Nakagawa, K., Tsuji, T., Iwasaki, M.: Seabottom roughness measurement by aquatic walking robot. In: MTS/IEEE Conference Proceedings, OCEANS 1997, vol. 2, pp. 1395–1398 (1997). doi:10.1109/OCEANS.1997.624200
2. Arienti, A., Calisti, M., Serchi, F.G., Laschi, C.: Poseidrone: design of a soft–bodied rov with crawling, swimming and manipulation ability. In: Proceedings of the MTS/IEEE OCEANS. MTS/IEEE (2013)
3. Ayers, J., Witting, J.: Biomimetic approaches to the control of underwater walking machines. Trans. R. Soc. A **365**, 273–295 (2007)
4. Calisti, M., Arienti, A., Renda, F., Levy, G., Mazzolai, B., Hochner, B., Laschi, C., Dario, P.: Design and development of a soft robot with crawling and grasping capabilities. In: Proceedings of the IEEE Interenational Conference on Robotics and Automation, pp. 4950–4955. IEEE (2012)
5. Calisti, M., Corucci, F., Arienti, A., Laschi, C.: Bipedal walking of an octopus-inspired robot. In: Duff, A., Lepora, N.F., Mura, A., Prescott, T.J., Verschure, P.F.M.J. (eds.) Biomimetic and Biohybrid Systems, pp. 35–46. Springer International Publishing, Cham (2014)
6. 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), 046012 (2015). http://stacks.iop.org/1748-3190/10/i=4/a=046012
7. Calisti, M., Falotico, E., Laschi, C.: Hopping on uneven terrains with an underwater one-legged robot. IEEE Robot. Autom. Lett. **1**(1), 461–468 (2016). doi:10.1109/LRA.2016.2521928
8. Calisti, M., Giorelli, M., Laschi, C.: A locomotion strategy for an octopus-bioinspired robot. In: Prescott, T.J., Lepora, N.F., Mura, A., Verschure, P.F.M.J. (eds.) Living Machines. Lecture Notes in Computer Science, vol. 7375, pp. 337–338. Springer, Heidelberg (2012)

9. Calisti, M., Giorelli, M., Levy, G., Mazzolai, B., Hochner, B., Laschi, C., Dario, P.: An octopus-bioinspired solution to movement and manipulation for soft robots. Bioinspiration Biomimetics **6**(3), 036002 (2011)
10. Calisti, M., Laschi, C.: Underwater running on uneven terrain. In: OCEANS 2015, Genova, pp. 1–5 (2015). doi:10.1109/OCEANS-Genova.2015.7271366
11. Christ, R.D., Wernli Sr., R.L.: The ROV Manual: A User Guide for Observation Class Remotely Operated Vehicles. Elsevier, Oxford (2011)
12. Cianchetti, M., Calisti, M., Margheri, L., Kuba, M., Laschi, C.: Bioinspired locomotion and grasping in water: the soft eight-arm octopus robot. Bioinspiration Biomimetics **10**(3), 035003 (2015). http://stacks.iop.org/1748-3190/10/i=3/a=035003
13. Corucci, F., Calisti, M., Hauser, H., Laschi, C.: Evolutionary discovery of self-stabilized dynamic gaits for a soft underwater legged robot. In: 2015 International Conference on Advanced Robotics (ICAR), pp. 337–344 (2015). doi:10.1109/ICAR.2015.7251477
14. Corucci, F., Calisti, M., Hauser, H., Laschi, C.: Novelty-based evolutionary design of morphing underwater robots. In: Proceedings of the 2015 Annual Conference on Genetic and Evolutionary Computation, GECCO 2015, pp. 145–152. ACM, New York (2015). doi:10.1145/2739480.2754686. http://doi.acm.org/10.1145/2739480.2754686
15. Dadashzadeh, B., Vejdani, H., Hurst, J.: From template to anchor: A novel control strategy for spring-mass running of bipedal robots. In: 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2014), pp. 2566–2571 (2014). doi:10.1109/IROS.2014.6942912
16. Henthorn, R.G., Hobson, B.W., McGill, P.R., Sherman, A.D., Smith, K.L.: Mars benthic rover: in-situ rapid proto-testing on the monterey accelerated research system. In: OCEANS 2010 MTS/IEEE SEATTLE, pp. 1–7 (2010). doi:10.1109/OCEANS.2010.5664381
17. Huffard, C.: Locomotion by abdopus aculeatus (cephalopoda: octopodidae): walking the line between primary and secondary defenses. J. Exp. Biol. **209**, 3697–3707 (2006)
18. Huffard, C.L., Boneka, F., Full, R.J.: Undewater bipedal locomotion by octopus in disguise. Science **307**, 1927 (2005)
19. Inoue, T., Shiosawa, T., Takagi, K.: Dynamic analysis of motion of crawler-type remotely operated vehicles. IEEE J. Oceanic Eng. **38**(2), 375–382 (2013). doi:10.1109/JOE.2012.2225292
20. Kim, J.Y., Jun, B.H.: Design of six-legged walking robot, little crabster for underwater walking and operation. Adv. Robot. **28**, 77–89 (2013)
21. Levy, G., Flash, T., Hochner, B.: Arm coordination in octopus crawling involves unique motor control strategies. Curr. Biol. **25**(9), 1195–1200 (2015). doi:10.1016/j.cub.2015.02.064. http://dx.doi.org/10.1016/j.cub.2015.02.064
22. Li, T., Nakajima, K., Calisti, M., Laschi, C., Pfeifer, R.: Octopus-inspired sensorimotor control of a multi-arm soft robot. In: IEEE Mechatronics and Automation, pp. 948–955. IEEE (2012)
23. Mather, J.: How do octopuses use their arms? J. Comp. Psychol. **112**, 306–316 (1998)
24. Raibert, M.H.: Legged Robots That Balance. The MIT Press, Cambridge (1986)
25. Serchi, F.G., Arienti, A., Laschi, C.: Biomimetic vortex propulsion: towards the new paradigm of soft unmanned underwater vehicles. IEEE/ASME Trans. Mechatron. **18**, 1–10 (2013)
26. Sfakiotakis, M., Kazakidi, A., Pateromichelakis, N., Tsakiris, D.P.: Octopus-inspired eight-arm robotic swimming by sculling movements. In: 2013 IEEE International Conference on Robotics and Automation (ICRA), Karlsruhe, Germany, 6–10 May 2013. IEEE (2013)
27. Tramacere, F., Kovalev, A., Kleinteich, T., Gorb, S.N., Mazzolai, B.: Structure and mechanical properties of octopus vulgaris suckers. J. R. Soc. Interface **11**(91) (2014)