

Towards animal phenotype transfer into biomimetic robots: the LAMPETRA project

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Abstract

Biorobotics aims at developing artifacts as synthesis and simulation of living systems. Herein, an autonomous agent inspired to *Lampetra fluviatilis* that was developed in the framework of the LAMPETRA Project, has been described. Lampreys are established models for studying higher vertebrate locomotion, including humans. The LAMPETRA robotic artifact mimicked the flexibility, as well as the passive dynamic movement of the real animal, thanks to the muscle-like actuation system relying on the use of direct magnet interaction, and closely mimicking the central pattern generators (CPGs) architecture of the animal spinal cord. Furthermore, the robot included a binocular vision system to track objects and avoid obstacles, as well as an artificial skin that made it waterproof and compliant. This biomimetic agent can be used to interact with abiotic and biotic components of aquatic ecosystems, as well as could be interfaced with the central nervous systems of real fish creating a biohybrid configuration.

Introduction

Biorobotics, by drawing from fundamental principles of biological systems, aims at creating innovative engineering design rules to develop life-like artifacts for reactive behaviour in the physical world (Yang, et al. 2018). This approach has provided new methodologies in biological research, including the use of neurobiological models to develop artifacts as synthesis and simulation of living systems (Aguilar et al. 2014). Furthermore, the use of biological principles in engineering has led to advancement in several technological contexts, including materials, mechanisms, sensors, actuators, energy efficiency, and control. The literature provides a number of outstanding studies describing the development of robots that were inspired to living organisms, including inchworms and earthworms (Kotay & Rus 2000; Chowdhury et al. 2017), snakes (Dear et al. 2020), caterpillars (Amiri et al. 2021), jumping animals (Mo et al. 2020), and fish (Yu et al. 2018).

Herein, we describe an autonomous agent inspired to the lamprey, that was developed in the framework of the LAMPETRA Project (Stefanini et al. 2012; Manfredi et al. 2013). This biomimetic agent can be used to interact with abiotic and biotic components of aquatic ecosystems, as well as could be interfaced with the central nervous systems of real lampreys.

Animal model

Lampreys belong to the superclass of Agnatha, among the oldest group of living vertebrates (Tytell et al. 2010). So, Agnatha can be considered as a 'prototype' of vertebrate, presenting the same basic neuronal structures of the higher vertebrate species. In particular, the robot was inspired to *Lampetra fluviatilis* Linnaeus (Petromyzontiformes: Petromyzontidae) a species widely distributed in western Europe, from southern Norway to the western Mediterranean, that has been used to investigate goal-directed locomotion control, along with related neural control mechanisms.

Lampreys are excellent biological models, as they have simple morphological and neuronal characteristics that can be easily reproduced in bioinspired robots (Grillner et al. 2007). These animals are easier to study than other vertebrates, but still presenting the main features of more evolved animals. For this reason, lampreys have become an established model for studies on higher vertebrate locomotion, including humans. Furthermore, their relative simpler nervous system allows to identify the neuronal circuits mainly involved in goal-directed locomotion.

Biomimetic artifact

The bioinspired mechanics of the LAMPETRA artifact robot mimicked the flexibility, as well as the passive dynamic movement of the real animal, via custom-designed actuators (Stefanini et al. 2012; Manfredi et al. 2013). The body of the robot had a distributed electronic digital control to closely mimic the central pattern generators (CPGs) architecture of the animal spinal cord. Furthermore, the robot was endowed with a stereo vision system, implementing models of visuo-coordination for goal-directed locomotion. A high energy efficiency was achieved in both the mechanical and the

electronic design, ensuring an autonomy of up to 5 hours. The bioinspired robot was developed with dedicated technologies to produce a highly bioinspired artificial agent successfully performing its tasks. The robot, 860 nm long, included 21 segments, and moved thanks to a new kind of muscle-like actuation system that relied on the use of direct magnet interaction (Figure 1).

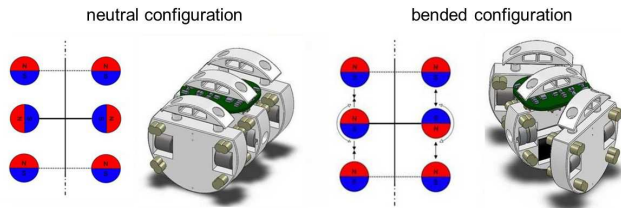


Figure 1: the muscle-like actuation system.

This allowed to produce actuation forces with marginal energy losses and backdrivability. The control system of the robot was based on CPG locomotion to optimize reactive behaviours, and to produce travelling waves for forward locomotion with variable speed and waveform. Furthermore, the robot included a binocular vision system to track objects and avoid obstacles. The robot was covered by an artificial skin that made it waterproof and compliant thanks to the mechanical properties of the artificial skin that did not hamper the undulatory movements during locomotion. The artificial skin was fabricated by using a silicone rubber, and it presented a multi-layer configuration where each silicone layer was alternated with a release agent layer. This configuration improved impermeability, as well as resistance to cracks. Information on the reciprocal angular position of segments was provided by an intra-vertebral distance sensors system. Also, the robot presented a multi-layer fiberglass tail improving its fluid dynamic performance, and propulsion (Figure 2).

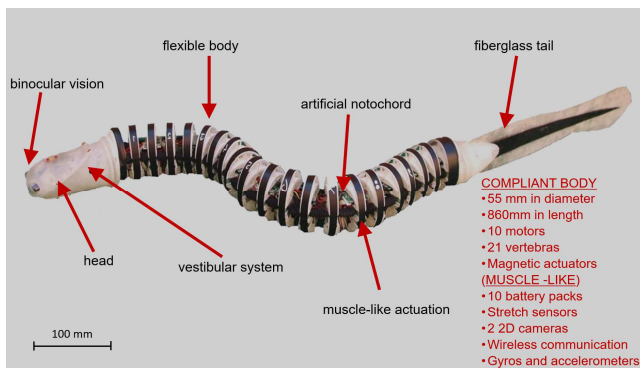


Figure 2: the LAMPETRA artifact.

Discussion

The LAMPETRA project provided an innovative robotic platform for biological model validation “*in artefacto*”. The developed system was designed to locomote in the environment, achieving a natural interaction with it.

This robotic system allowed to test the CPG hypotheses, and to investigate goal-directed locomotion, by exploiting visual input from its vision system that processed the video streaming.

Biorobotics-base paradigms propose an integrative approach combining the advantages of biology and engineering strategies to investigate the evolution of animal locomotion and behaviour. Excellent examples are the recent studies where biorobots have been used to reconstruct the locomotion of extinct vertebrates (Nyakatura et al. 2019; Talori et al. 2019). In another interesting research authors focused on high-frequency biological swimming to develop bio-inspired underwater vehicles with such fish-like performance (Zhu et al. 2019).

Our swimming robotic platform opens up many research applications including: (i) investigating goal-directed behaviour in a controlled environment; (ii) using a realistic setting to test the CPG models (i.e. within a realistic feedback loop); (iii) measuring the descending command activity, with the verification of control hypotheses like those of simpler signals (and possibly fewer pathways activated) during steady-state locomotion, compared to non-steady-state locomotion; (iv) exploring how different sensor modalities can interact each other; (v) perturbing selected modalities, to study behavioural effects.

Envisioned further studies include the interface between the robot and the real animal. This can be achieved by bidirectionally coupling the electrophysiological signals of the animal to the robot controller in real time. This biohybrid approach can enable the direct tuning of internal parameters of the hardware that is based on the neural activity of the animal. The biohybrid configuration could pave the way to new approaches to create artificial life forms (Aguilar et al. 2014) investigating locomotor programs expressing different motor pathways.

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