Neural Control of Reactive Behaviors for Undulatory Robots [†]

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Abstract Undulatory locomotion is studied as a biological paradigm of versatile body morphology and effective motion control, adaptable to a large variety of unstructured and tortuous environmental conditions (e.g. the polychaete annelid worms move equally efficiently in water, sand, mud and sediment). Computational models of this type of locomotion have been developed, based on the Lagrangian dynamics of the system and on resistive models of its interaction with the environment, and have been validated on a series of lightweight robotic prototypes, whose undulatory actuation achieves propulsion on sand. The work described here extends these models of locomotion and motion control in two directions: one is the generation of sensor-based reactive behaviors, based on appropriate sensory information, and the second is motion control via biomimetic neuromuscular control, based on central pattern generators. This leads to *reactive neuromuscular control schemes*, which are used to generate the behaviors necessary to traverse corridor-like environments and maintain the cohesion of swarms of undulatory robots. Simulation studies demonstrate the possibility to generate undulatory reactive behaviors for such systems based on information from distance sensors. The expansion of our undulatory prototypes with an appropriate sensory apparatus, in order to validate such reactive control schemes, is in progress.

Keywords motion control, central pattern generators, polychaete annelids, undulatory locomotion, biomimetic robotics.

Introduction

Control of locomotion is one of the most significant problems for emerging robotic applications dealing with unstructured and tortuous environments, which range from endoscopy to planetary exploration [1–4]. Drawing inspiration from biology, where this problem has been effectively addressed by the evolutionary process, can help the design of agile robots able to adapt robustly to a variety of environmental conditions.

A marine worm species, the polychaete annelids, offer an intriguing biological paradigm of locomotion, characterized by the combination of a unique form of tail-to-head body undulations, with the rowing-like action of the numerous lateral appendages, called parapodia, distributed along their segmented body [5,6]. Both characteristics provide these worms with distinctive locomotory modes, increasing their swimming, terrain traversing and burrowing capabilities over sand, mud and sediment. Undulatory locomotion in annelids and other animals, as well as in robots, is achieved through appropriate coupling of internal shape changes (typically a traveling body wave) to external motion constrains (typically frictional forces from the interaction with the locomotion environment). Evidence exists [7–9] that annelid undulatory locomotion is based on Central Pattern Generators (CPGs), which are neuronal circuits able to produce rhythmic motor patterns in an organism (swimming, breathing, etc.), even in the absence of sensory input or input from higher cognitive elements. Such input may alter the synaptic strength and intrinsic properties of the CPG's neurons, thus modulating its rhythmic activity [10]. From an engineering viewpoint, interest in CPG-based locomotion controllers stems, not only from their elegance, but also from their potential to lead to distributed, thus fault-tolerant and robust, motion control architectures [1, 11–13].

The literature on undulatory robotics has mainly focused on mechanical design and open-loop control. However, in order for such devices to be able to operate in the complex environments for which they are intended, they require exteroceptive sensors to implement more complex behaviors, either for single robots (e.g., obstacle avoidance, pursuit of moving targets), or for multi-robot swarms (e.g., formation control, cooperative exploration). Many potential applications for undulatory robots (e.g., site inspection, search-and-rescue missions) involve tasks which could be efficiently addressed by multiple robotic agents operating as a swarm. A significant body of work is available regarding the dynamics and control, as well as relevant sensor-related aspects, for swarms of conventional mobile robots and of underwater or aerial vehicles; however, swarms of undulatory robots do not appear to have been investigated (see [14, 15] and references therein).

Neuromuscular Control for Undulatory Robots

The main components involved in modeling an undulatory locomotor have been implemented in this work as follows:

Body mechanics: An articulated mechanism model is adopted, comprising rigid 2D links, serially connected via revolute joints. Details of the system's Euler-Lagrange equations of motion appear in [4].

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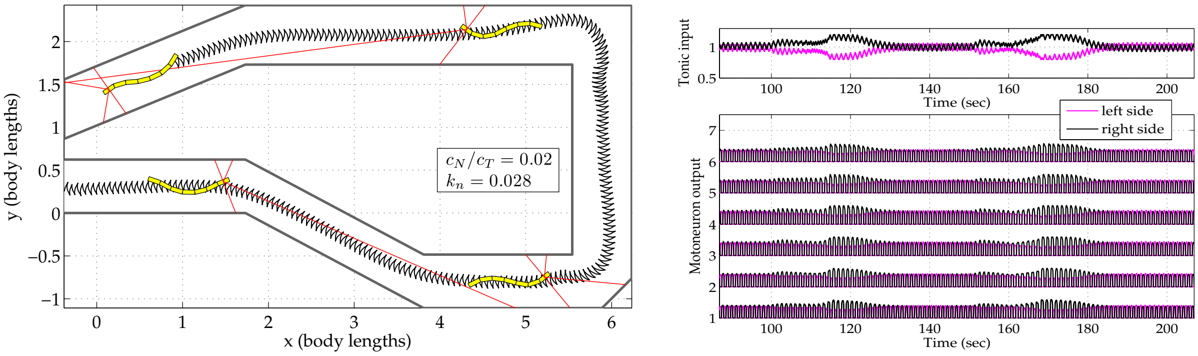
Interaction with the environment: A viscous friction model is used, where the tangential and normal components of the force applied to the ith link are obtained as $F_T^i = -c_T v_T^i$ and $F_N^i = -c_N v_N^i$, with v_T^i and v_N^i being the respective components of the link's velocity. The ratio c_N/c_T of the force coefficients determines whether the overall locomotion is in the opposite (for $c_N > c_T$, *eel-like* mode) or in the same (for $c_N < c_T$, *polychaete-like* mode) direction as the propulsive wave [4, 13].

Propulsive wave generation: Neuromuscular body shape control schemes have been developed [12, 13], based on models of the CPG which controls lamprey swimming (see, e.g., [16]) and implementing a connectionist CPG, formed as a chain of (identical) segmental oscillators, which are properly interconnected to generate a wave of joint activation. Each segmental oscillator comprises interneurons and motoneurons (modeled as leaky integrators), arranged in two symmetrical sub-networks that create oscillations through mutual inhibition. The torques applied to the body joints are determined by the outputs of the corresponding motoneurons, after activating a pair of antagonistic lateral muscles (modeled as spring-and-damper elements). The motoneuron output characteristics can be altered by tonic (i.e., non-oscillating) inputs to the left and right sub-networks of the segmental oscillators (I_L and I_R, respectively) [12]. Coupled to the body's mechanical model, the locomotor CPG yields motion in a straight line for $I_L = I_R$, while turning motions are instigated by unequal tonic inputs to the two CPG sides. These tonic inputs are exploited, as described below, to generate reactive behaviors.

Reactive Behaviors for Undulatory Robots

The elongated articulated body of undulatory robots, whose locomotion involves a continuously changing shape, complicates the generation of reactive behaviors. We consider here distance sensors placed on each robot link and employed to dynamically adjust the propulsive wave amplitude, while the head link incorporates additional sensors (e.g., vision), utilized in steering the mechanism. This approach parallels the distribution of sensory structures in, e.g., polychaete annelid worms [5, 6].

The SIMUUN computational tools for undulatory locomotion [13], were employed to set up the simulations presented here. These consider an undulatory mechanism composed of seven identical links, each equipped with a distance sensor pair aiming at $\pm 90^\circ$ with respect to the link's main axis, while the head link features an additional distance sensor pair, aiming at $\pm 45^\circ$ (Fig. 1a). The locomotor CPG comprises 20 segmental oscillators, with the motoneuron outputs from (roughly) every third oscillator utilized to provide torque signals to the six joints, through the activation of antagonistic muscles.

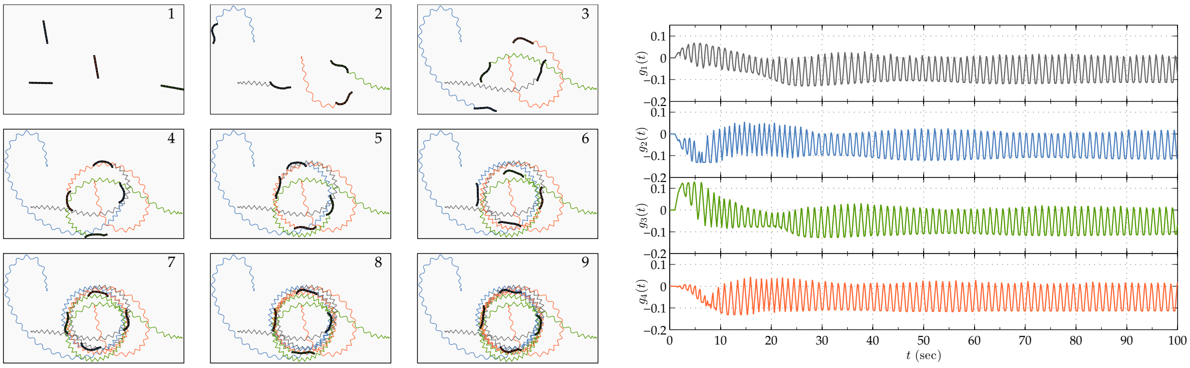


(a) Tail link trajectory (b) Neural control

Figure 1: Neural control of the undulatory centering behavior, for polychaete-like locomotion: (a) trajectory of the mechanism, and (b) the corresponding tonic input signals and motoneuron outputs of the locomotor CPG.

Reactive Centering Control: This reactive behavior is inspired by the centering response exhibited by bees when flying through narrow gaps, which has been attributed to their balancing the retinal motion perceived by each of their two wide field-of-view compound eyes. It was originally implemented for nonholonomic mobile robots, whereby optical flow information from several distinct "looking" directions in the field of view of an onboard panoramic camera is employed directly in the control loop [17]. Adaptation to the dynamics of undulatory robotic locomotors relies on balancing the weighted sum of the distance sensor outputs to the left and right sides of the robot [15]. Assuming M pairs of distance sensors, and denoting by $d_{L,i}$ and $d_{R,i}$ ($1 \leq i \leq M$) the outputs for such a sensing array, the control law to realize the undulatory centering behavior is then implemented via the tonic input signals applied to the left and right sides of the CPG as $I_L(t) = 1 - k_n s(t)$ and $I_R(t) = 1 + k_n s(t)$, where $k_n > 0$. The distance metric is obtained as $s(t) = \left(\sum_{i=1}^{M} w_i d_{L,i}(t)\right)^{-1} - \left(\sum_{i=1}^{M} w_i d_{R,i}(t)\right)^{-1}$, with the weights w_i determining the relative contribution of the M sensor pairs. A series of simulations demonstrates the ability of the integrated neural control scheme to successfully navigate the robot through various corridor-like courses, both for eel-like and for polychaete-like interaction with the environment, when utilizing sensory information from the head link. Indicative results are shown in Fig. 1.

Formation Control of Undulatory Swarms: A variation of the "circling" control law, proposed in [14] for multiple unit-speed vehicles, is employed, where a circling formation emerges by steering controls alone, based on range and relative orientation data. Adaptation to a swarm of n undulatory mechanisms, each under neural control, involves setting the tonic drive of the jth swarm member to $I_L^j(t) = 1 - g_j(t)$ and $I_R^j(t) = 1 + g_j(t)$. The sensor-modulated component is obtained as $g_j = \frac{1}{n}\sum_{k \neq j}(-\eta \sin\varphi_j + f(\rho_{jk})\cos\varphi_j)$ with $f(r) = a\left[1 - \left(\frac{r_0}{r}\right)^2\right]$ (η, a and r_0 are all positive constants). Considering the (j,k)th-pair of undulatory robots, ρ_{jk} denotes the distance between their head link centers, while φ_j and φ_k is the orientation of the head links with respect to the direction perpendicular to the baseline connecting the centers of the head links. Indicative simulation results for an undulatory swarm under this formation control law, are shown in Fig. 2.



(a) Emergence of the circular formation

(b) Sensor-modulated tonic input component

Figure 2: Neural control of a swarming behavior, for eel-like locomotion: Circular formation control.

References

[1] J. Ayers, J. Davis, and A. Rudolph, Eds., *Neurotechnology for Biomimetic Robots*. MIT Press, 2003.

[2] A. Menciassi and P. Dario, "Bio-inspired solutions for locomotion in the gastrointestinal tract: background and perspectives," *Philos. Trans. R. Soc. Lond. Ser. A*, vol. 361, pp. 2287–2298, 2003.

[3] S. Hirose, *Biologically Inspired Robots: Snake-Like Locomotors and Manipulators*. New York: Oxford University Press, 1993.

[4] D. Tsakiris, M. Sfakiotakis, A. Menciassi, G. La Spina, and P. Dario, "Polychaete-like undulatory robotic locomotion," in *Proc. IEEE Int. Conf. on Robotics and Automation (ICRA'05)*, Barcelona, Spain, 2005, pp. 3029–3034.

[5] J. Gray, "Annelids," in *Animal Locomotion*. London: Weidenfeld & Nicolson, 1968, pp. 377–410.

[6] R. Brusca and G. Brusca, *Invertebrates*. Sunderland: Sinauer Associates, 1990.

[7] J. Lawry, "Mechanisms of locomotion in the polychaete *Harmothoë*," *Comp. Biochem. Physiol.*, vol. 37, no. 2, pp. 167–179, 1970.

[8] F. Eisenhart, T. Cacciatore, and W. Kristian Jr., "A central pattern generator underlies crawling in the medicinal leech," *J. Comp. Physiol. A*, vol. 186, pp. 631–643, 2000.

[9] G. Orlovsky, T. Deliagina, and S. Grillner, *Neuronal Control of Locomotion: from Mollusc to Man*. Oxford: Oxford University Press, 1999.

[10] E. Marder and D. Bucher, "Central pattern generators and the control of rhythmic movements," *Curr. Biol.*, vol. 11, no. 23, pp. R986–R996, 2001.

[11] E. Niebur and P. Erdös, "Modeling locomotion and its neural control in nematodes," *Comm. Theor. Biol.*, vol. 3, no. 2, pp. 109–139, 1993.

[12] D. Tsakiris, A. Menciassi, M. Sfakiotakis, G. La Spina, and P. Dario, "Undulatory locomotion of polychaete annelids: mechanics, neural control and robotic prototypes," in *Abstracts book of The Annual Computational Neuroscience Meeting (CNS*2004)*, Abstract #288, Poster #M69, Baltimore, USA, 2004, p. 89.

[13] M. Sfakiotakis and D. Tsakiris, "SIMUUN: A simulation environment for undulatory locomotion," *Int. J. Modelling and Simulation*, IASTED/Acta Press, in press.

[14] E. Justh and P. Krishnaprasad, "Equilibria and steering laws for planar formation," *Syst. Contr. Lett.*, vol. 52, no. 1, pp. 25–38, 2004.

[15] M. Sfakiotakis, D. Tsakiris, and A. Vlaikidis, "Biomimetic centering for undulatory robots," in *Proc. 1st IEEE/RAS-EMBS Int. Conf. on Biomedical Robotics and Biomechatronics (BioRob 2006)*, Pisa, Italy, 2006, (to appear).

[16] A. Ijspeert, "A connectionist central pattern generator for the aquatic and terrestrial gaits of a simulated salamander," *Biol. Cybern.*, vol. 85, no. 5, pp. 331–348, 2001.

[17] A. Argyros, D. Tsakiris, and C. Groyer, "Biomimetic centering behavior for mobile robots with panoramic sensors," *IEEE Robot. Automat. Mag.*, vol. 11, no. 4, pp. 21–30, 2004.