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Neuromuscular 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. Computational models of undulatory locomotion have been developed, and validated on a series of robotic prototypes propelling themselves on sand. The present paper explores in simulation neuromuscular motion control for these undulatory robot models, based on biomimetic central pattern generators and on information from distributed distance sensors. This leads to reactive control schemes, which achieve (i) traversal of corridor-like environments, and (ii) formation control for swarms of undulatory robots.

Keywords: Neural control; Central pattern generators; Biomimetic robotics; Undulatory locomotion; Sensors; Closed-loop control; Polychaete annelids

1. Introduction

Motion control is one of the most significant problems for emerging robotic applications dealing with locomotion in unstructured environments, which range from endoscopy to planetary exploration [4,13,31,34]. 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. Such an intriguing biological paradigm is offered by the polychaete annelid worms, whose locomotion is characterized by the combination of a unique form of tail-to-head body undulations, with the rowing-like action of numerous lateral appendages, called parapodia, distributed along their segmented body [6,11]. This provides the worms with distinctive locomotory modes, increasing their swimming, terrain traversing and burrowing capabilities over water, sand, mud and sediment. These locomotory modes have been modeled computationally and validated via robotic prototypes propelling themselves on sand [30,31,34].

Undulatory locomotion in annelids and other organisms, 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 [21,9,27] that motion control of the annelid undulatory locomotion is based on central pattern generators (CPGs), which are neuronal circuits able to produce rhythmic motor patterns in an organism, even in the absence of sensory input or of input from higher cognitive elements; such inputs may modulate the rhythmic activity of the CPG [23,2]. The typical morphology of annelids [11,6,27] hints at a sequential, modular and distributed sensing and control architecture, not unlike that of the CPG controlling the undulatory swimming of lamprey eels, which has been extensively studied in neurobiology [27,12] and modeled at various levels of detail [10,12,14,24,18,19,28]. From an engineering viewpoint, interest in CPG-based locomotion controllers, especially for undulatory mechanisms, stems not only from their elegance, but also from their potential to lead to distributed, fault-tolerant and robust motion control architectures [4,30,26,33,7,22,15,16].

The literature on undulatory robotic systems has mainly focused on mechanical design and open-loop control (gait generation). However, in order for such devices to be able to operate in the complex environments for which they are intended, they require exteroceptive sensing to close the

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loop and 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) [32]. This paper presents computational models of CPG-based neuromuscular control for undulatory robotic systems in Section 2, and explores in simulation the use of sensory information from distributed sensors for the generation of reactive behaviors (centering and body wave shaping in corridor environments) in Section 3. This modulation of the CPG dynamics by sensory information appears not to destroy rhythmogenesis, although it may alter its characteristics.

Many potential applications for undulatory robots (e.g., site inspection, search-and-rescue missions, ocean sampling) involve tasks which could be more efficiently addressed by multiple robotic agents operating as a swarm. A significant body of work is available regarding swarms of conventional mobile robots and of underwater or aerial vehicles (see [32,17,29] and references therein); however, swarms of undulatory robots do not appear to have been investigated. Swarming behavior is important for biological organisms (e.g., for mutual protection, like the fish "bait-ball" rotating formations). This paper, then, also considers in Section 3 the extension of the developed neuromuscular control schemes to formation control problems for swarms of undulatory robots.

2. Neuromuscular control for undulatory robots

The main components involved in modeling an undulatory locomotor are: (i) the body mechanical model, (ii) the body shape control strategy and (iii) the force model of the body's interaction with the environment. The implementation of these components in the present study is described next.

2.1. Body mechanics

Undulatory locomotors can be modeled as multi-link articulated robots comprising serially connected links, the equations of motion of which can be obtained from their Lagrangian dynamics [34]. A computational model of a planar undulatory mechanism has been developed, based on a serial kinematic chain of N identical rigid 2D links, with the center of mass for each link being at its middle (we consider N odd; the case of $N=7$ is shown in Fig. 1). The links are interconnected by planar revolute joints, which are independently actuated, via applied torques, to control the shape of the mechanism.

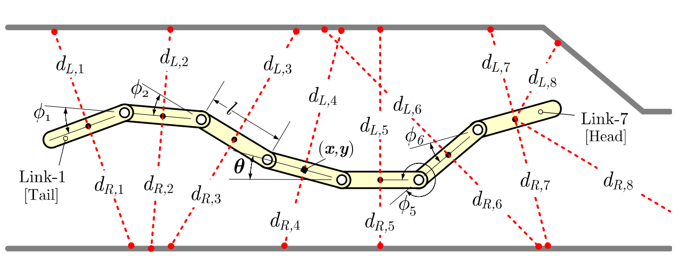

Fig. 1. Computational model of a seven-link undulatory mechanism and its sensor array (distance sensors).

The position (x, y) and orientation θ of the central link describe the global pose of the mechanism with respect to an inertial coordinate frame on the plane, and can be represented by an element g of the group $G = SE(2)$, the Special Euclidean group of order 2. The Lie algebra element, corresponding to g, is $\xi \triangleq g^{-1}\dot{g} \in \mathcal{G} = se(2)$ and describes the *body velocity* of the central link. The joint angle vector $r = (\phi_1, \ldots, \phi_{N-1})$ describes the system's body shape.

The Euler–Lagrange equations of motion can be *reduced* [34,5,20,8,25] by exploiting the invariance of the mechanism to changes in inertial position and orientation, expressed as *Lie group symmetries* exhibited by the system (for details see [34]):

$$\begin{aligned}
&\dot{g} = g[-\mathbf{A}(r)\dot{r} + \mathbf{I}^{-1}(r)p],\\
&\dot{p} = ad^{*}_{\xi}p + f_T + f_N,\\
&\tilde{M}(r)\ddot{r} + \dot{r}^{\mathrm{T}}\tilde{C}(r)\dot{r} + \tilde{N} = B(r)\tau,
\end{aligned} \tag{1}$$

where the matrices $\mathbf{A}(r)$ and $\mathbf{I}(r)$ are the local forms of the *mechanical connection* and the *locked inertia tensor*, respectively; p is the body momentum; f_T, f_N are the external frictional forces in the tangential and normal directions of the central link, which are obtained from the frictional force models described in Section 2.3. The first two equations in (1) describe the effect of body shape changes and of the interaction with the environment on the global pose of the mechanism. The third equation describes the evolution of the body shape, as a function of the control input, which is the joint torques τ. In the present model, these torques are provided, for each joint, by a pair of antagonistic muscles, which are driven by the motoneuron outputs of the locomotor CPG described in Section 2.2. These computational models may be extended to polychaete-like mechanisms by the inclusion of parapodial links [31].

2.2. CPG-based propulsive wave generation

Neuromuscular body shape control schemes have been developed [33,30], based on connectionist models of the CPG which controls lamprey swimming (see, e.g., [10,14]), formed as a chain of (identical) segmental oscillators (S.O.s), properly interconnected to generate a wave of joint activation. Each S.O. comprises interneurons, which produce the rhythmic pattern, and motoneurons, which transmit the rhythmic pattern to the muscles activating a joint. Each of the S.O. neurons is modeled as a leaky integrator [2,14], where the mean membrane potential m_j of neuron j is

$$T_j \frac{\mathrm{d}m_j}{\mathrm{d}t} = -m_j + \sum_k q_{j,k} M_k + I_j, \tag{2}$$