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Undulatory locomotion of polychaete annelids: mechanics, neural control and robotic prototypes[†]

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Abstract

The undulatory locomotion of polychaete annelid worms is studied as a biological paradigm of a versatile body morphology and effective motion control, adaptable to a large variety of unstructured and tortuous environmental conditions (water, sand, mud, sediment, etc.). Computational models of this type of locomotion have been developed, based on the Lagrangian dynamics of the system, on resistive models of its interaction with the environment and on neural control using central pattern generators. Simulation studies demonstrate the possibility to generate undulatory gaits, which are characterized by essential features of polychaete locomotion, based on these models. A lightweight robotic prototype has been developed, whose undulatory actuation achieves propulsion on sand.

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 endoscopic access to the human body to planetary exploration [Ayers, Davis & Rudolph, 2002], [Menciassi & Dario, 2003], [Hirose, 1993]. 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. The study of lower animals in particular (invertebrates, lower vertebrates), where complex forms of behaviour are controlled by relatively small groups of neurons, is proving beneficial in determining the principles of biological motion control [Orlovsky, Deliagina & Grillner, 1999], [Marder & Bucher, 2001].

(a) Nereis virens (b) Nepthys hombergi (c) Ventral nervous cord of some polychaete annelids

Figure 1: Polychaete annelid worms

A class of segmented worms, the polychaete annelids, offer an intriguing biological paradigm of locomotion, not only underwater, but also on sand, mud and sediment: they can be found living in the depths of the ocean, floating free near the surface, or burrowing in the mud and sand of the seashore. The variety of their morphology, sensory apparatus and nervous system structure is a direct consequence of their adaptation to so diverse habitats (Figure 1). Their locomotion is characterized by

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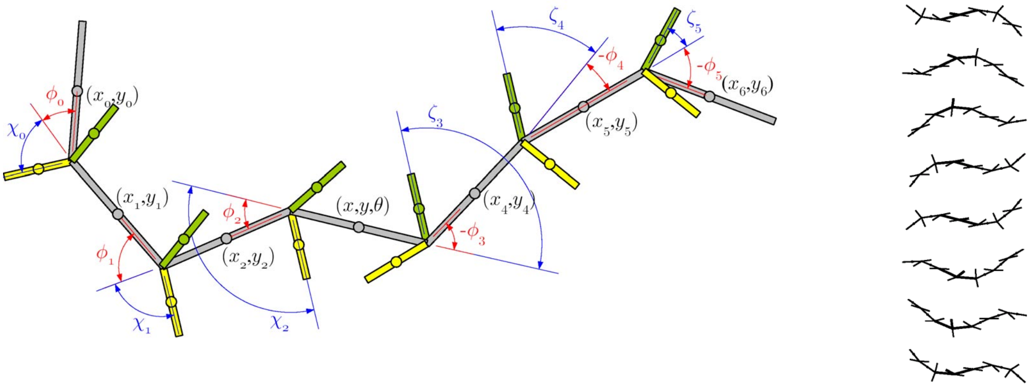
the combination of a unique form of tail-to-head body undulations, with the rowing-like action of the numerous lateral appendages, called parapodia, distributed along their segmented body. Both characteristics provide these worms with distinctive locomotory modes, increasing their terrain traversing capabilities [Gray, 1968], [Brusca & Brusca, 1990] and could benefit, if properly replicated, a robotic system.

The present work reports on the development of computational models of the mechanics and bio-inspired motion control of this type of locomotion and demonstrates the possibility to generate polychaete-like undulatory gaits. A reliable experimental platform is necessary to validate and refine these models; therefore, a robotic undulatory prototype has been developed, which is able of locomotion on sand.

Models of polychaete locomotion

Shape undulations are employed for locomotion by various organisms, spanning a wide range of body sizes and environmental habitats, as they perform satisfactorily over a significant range of Reynolds number values [Lighthill, 1975]. Taylor [Taylor, 1952] developed a theory to analyse the undulatory swimming of elongate animals, either with a smooth body (as in the anguilliform locomotion of eels) or with a rough one (as in the case of errant polychaete). In both cases, the body is assumed to be cylindrical in shape, with a small diameter compared to its overall length. The model used is a *resistive* one, whereby the local instantaneous force exerted on a segment of the undulating body depends (usually linearly or quadratically) on the instantaneous velocity of that segment relative to its environment. Such models can be used to simulate crawling over soft land, e.g. the terrestrial locomotion of snakes, and motion in fluids, e.g. anguilliform eel swimming. The lateral components of the segment frictional forces combine to yield a lateral force that generates sideways thrust, which tends to produce yaw. However, if we consider the whole organism, sideways forces are cancelled out, if an integer number of propulsive waves is present on the body. The components of the force along the direction of motion yield a net propulsive force when integrated along the body. The direction of motion depends on the relative size of the friction coefficients. For smooth animals (e.g. eel), the tangential friction coefficient is very small, rendering the tangential thrust contribution negligible. In this case, the animal achieves forward propulsion if the direction of the propulsive shape wave is from head to tail and can propel itself backwards by reversing the direction of the wave. Conversely, if the animal body is not smooth, as is the case with most errant polychaete (due to the laterally projecting parapodia), the tangential friction coefficient may be greater than the normal one and forward propulsion is achieved by a tail-to-head wave.



(a) Model of a 7-link undulatory mechanism with parapodia

(b) Shape undulations and parapodia movements

Figure 2: Model of an undulatory mechanism with parapodia

The polychaete and its locomotion are studied via computational models of planar undulatory mechanisms. Undulatory gaits, both for smooth- and for rough-body mechanisms, have been obtained, and related extensive parametric studies have been performed, on an especially-developed simulation environment, which is based on the Matlab/Simulink suite and on its SimMechanics toolbox. Figure 2 shows such a mechanism composed of a kinematic chain of 7 rigid links emulating the polychaete segments and 12 rigid links emulating the parapodia. Each of the joint angles is actuated independently.

The equations of motion of the system are obtained from its Lagrangian dynamics, with the kinetic energy used as the Lagrangian, after the reduction process described in [Bloch, Krishnaprasad, Marsden & Murray, 1996], [Krishnaprasad & Tsakiris, 2001], [Ostrowski & Burdick, 1998], [Cortes, Martinez, Ostrowski & McIsaac, 2001]. This reduction is based on the invariance of the system to changes in inertial position and orientation. The position and orientation of the central segment on the plane, with respect to an inertial frame, is an element g of the Special Euclidean group SE(2) of rigid motions on the plane. The corresponding element ξ of the Lie algebra *se*(2) of SE(2), defined as $\xi = g^{-1}\dot{g}$, is the body velocity. The segment joint angles φ_i and the parapodia link angles χ_i and ζ_i, constitute the system's shape variable vector r and are its control inputs. The equations of motion are then obtained in a body-fixed frame as:

$$\xi = -\mathbf{A}(r)\dot{\mathbf{r}} + \mathbf{I}^{-1}(r)p \quad , \qquad \dot{p} = \begin{pmatrix} \xi_3 p_2 \\ -\xi_3 p_1 \\ \xi_2 p_1 - \xi_1 p_2 \end{pmatrix} + \tau_\mathrm{T} + \tau_\mathrm{N} \ ,$$

where p is the body momentum, while τ_T and τ_N are the externally applied body forces obtained from the force model used, and originating from the tangential and normal component of each link's motion respectively. The matrix ***A(r)*** is the local form of the mechanical connection, which is only a function of the shape *r*. The locked inertia tensor ***I(r)*** describes the total inertia of the system when all joints are frozen at shape configuration *r*. The scheme obtained by the reduction process is computationally efficient and well suited to controller development. Extension to a larger number of links is straightforward, but quite involved.

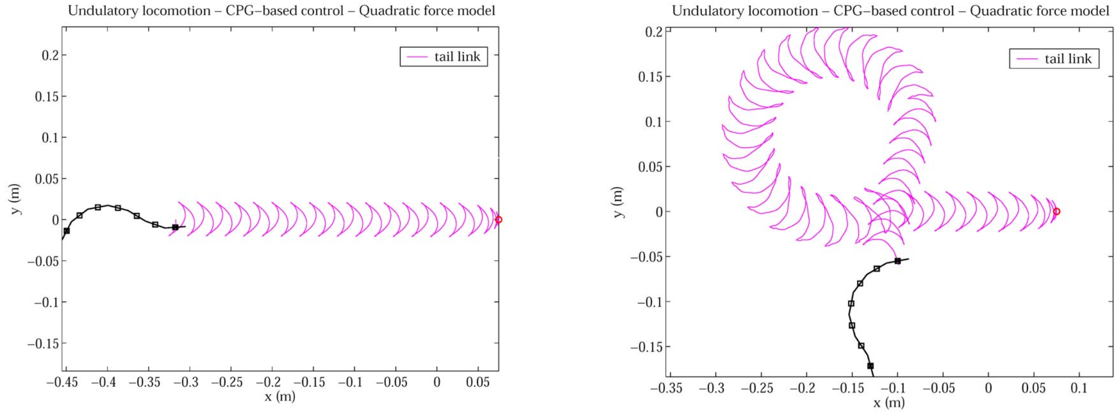
Direct implementation of various undulatory locomotion gaits can be achieved if a wave of joint activation is propagated along the mechanism, e.g. one generated by setting $\varphi_i\ (t) = A\ sin(2\pi ft + i\ \varphi_{lag}) - \psi,\ \ i=0,..,5,$ where A is the maximum angular deflection for each joint and φ_{lag} is the phase offset in the oscillatory motions between successive joints. The angular offset ψ provides a mechanism for steering the mechanism, and is set to $\psi = 0$ for propulsion along a straight line. Varying the joint angle amplitude A affects the wavelength and velocity of the travelling wave. Forward, turning, in-place-rotation and parallel-parking-like gaits were produced in simulation and studied parametrically. Closed-loop control schemes have been developed, based on the decoupled control of the mechanism's orientation and heading speed. In errant polychaete worms, the roughness of the body is due to the laterally extending parapodia, which can also play an active role in locomotion. Gaits involving the parapodial links of the undulatory mechanism demonstrate the increased manoeuvrability possible in this case. Following biological observations, the movement of the parapodial links is timed so that their power stroke occurs when they are at the crest of the body wave (Figure 2(b)) [Gray, 1968].

Neural Control

Evidence exists that annelid undulatory locomotion is based on Central Pattern Generators (CPGs), both for polychaete annelids [Lawry, 1970] and for hirudinidae annelids (medicinal leech) [Eisenhart, Cacciatore & Kristan, 2000], [Orlovsky, Deliagina & Grillner, 1999]. The CPGs are neuronal circuits able to produce rhythmic motor patterns in an organism (swimming, flying, breathing, etc.), even in the absence of sensory input or input from higher cognitive elements. The behavior of these networks depends both on the intrinsic properties of the neurons that form the network and on the properties of the synapses among them (connectivity, strength, etc.). In order to produce rhythmic motor patterns, the CPG network uses pre-motor interneurons to produce the oscillations and to drive motoneurons, which provide input to the muscles generating the rhythmic pattern. Input from sensors and from higher cognitive elements modulate the rhythmic activity of the CPG: they alter the synaptic strength and intrinsic properties of the CPG's neurons, thus affecting the timing characteristics of the CPG [Marder & Bucher, 2001]. From an engineering viewpoint, interest in biologically-inspired locomotion controllers based on CPGs stems, not only from their elegance, but also from their advantages over classical centralized approaches, like their potential to lead to distributed, thus fault-tolerant and robust, motion control architectures [Krishnaprasad, 1997], [Beer & Chiel, 2003] and to computationally efficient, fast and compact VLSI implementations [Lewis et al., 2003].

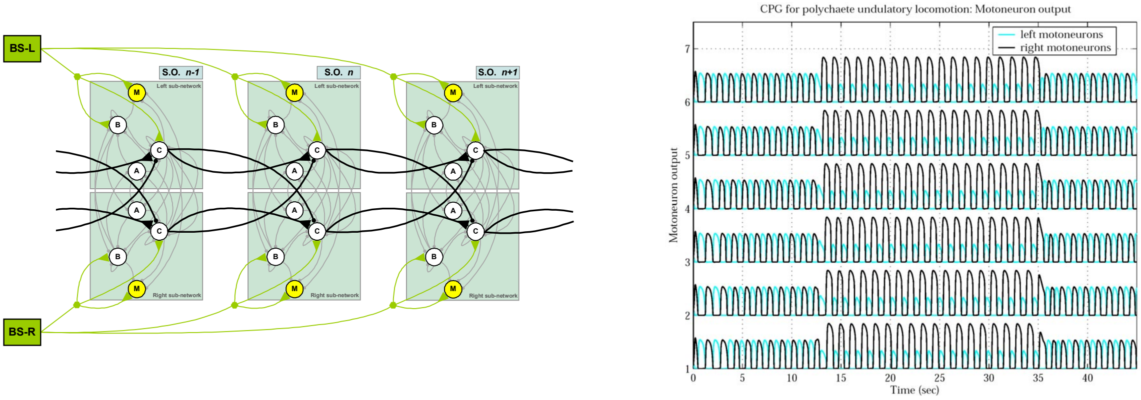
Inspired by models of the CPG which control the undulatory swimming of the lamprey [Carling, Bowtell & Williams, 1994]**,** [Ekeberg, 1993], [Orlovsky, Deliagina & Grillner, 1999], [Ijspeert, 2001], we developed connectionist models of the polychaete CPG, able to produce the undulatory patterns necessary for its locomotion. This involves modelling the following components of the CPG: the neurons that constitute the CPG, the segmental oscillator activating each segment of the polychaete, the connectivity of the segmental oscillators (intersegmental connectivity), which gives rise to the travelling wave of motoneuron activation, and, finally, the activation of the polychaete segment joints by the CPG motoneurons via antagonistic muscles. This neural control architecture is interfaced to the computational models of the system's mechanics, described earlier. As a first step, we considered the basic undulatory mechanism, without parapodial links, which we termed the ***polychaete body CPG***. The goal of the CPG is to produce the tail-to-head wave of muscle activation, which is characteristic of polychaete locomotion (compare this to the head-to-tail wave of the lamprey).

Each neuron of the CPG is modelled as a leaky integrator and is considered to encapsulate the effect of a whole population of functionally similar neurons in the biological CPG. Each segmental oscillator considered in our computational model is composed of two symmetrical sub-networks (denoted as left and right in Figure 3(c)), which create oscillations through mutual inhibition ("half-center oscillator"). With reference to the same figure, neuron units A, B and C represent three different types of interneurons, while M represents the motoneurons. Each sub-network receives a separate tonic (i.e. non-oscillating) input from the brainstem, denoted as BS-L and BS-R. The appropriate interconnection of the segmental oscillators gives rise to the polychaete body CPG, which is able to generate a wave of joint activation and generate the desired undulatory gaits. We consider both nearest-neighbour-type connections among segmental oscillators (as shown in Figure 3(c)) and more complicated connectivity patterns. Although the former give rise to relatively simple architectures, they are known for their poor transient properties, which can be improved when connections among more distant segments are considered [Kopell & Ermentrout, 2003]. Notice that this motion control architecture parallels the ladder-like organization of the ventral nervous cord of some polychaete species (Figure 1(c)) [Brusca & Brusca, 1990]. The torque applied to the body joints is determined by the outputs of the corresponding motoneurons, activating the antagonistic lateral muscles on the left and right side of the body. A spring-and-damper model is adopted for the muscle; then, the torque acting on the joint depends on the difference of the corresponding motoneuron outputs.



(a) Forward gait: trajectory of the tail link of the polychaete model

(b) Combination of forward and turning gaits: trajectory of the tail link of the polychaete model



(c) Intersegmental connectivity of the polychaete body CPG

(d) Combination of forward and turning gaits: Motoneuron outputs of all segmental oscillators of the body CPG which control joints.

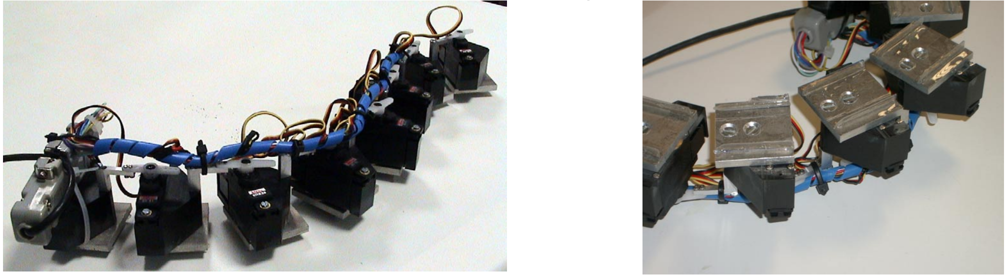
Figure 3: Polychaete model: CPG-based control generates forward and turning undulatory gaits by varying the tonic input

A series of simulations was performed to determine the capability of the developed neural architecture to generate polychaete-like locomotion gaits for the undulatory mechanism by a body CPG composed of 20 to 40 segmental oscillators. When equal tonic input is applied to both sides of the polychaete body CPG, the forward gait of the polychaete is obtained (Figure 3(a) shows the trajectory of the tail link). When the tonic input is varied, combinations of forward and turning gaits are obtained (Figure 3(b)). Figure 3(d) shows all the motoneuron outputs of the body CPG, which activate the joint angles. The transitions from forward gait (motoneuron outputs have the same amplitude) to turning gait (motoneuron outputs have different amplitudes) and vice-versa are evident.

Experiments with robotic prototypes

A robotic prototype of a polychaete annelid, based on the computational models presented earlier, was developed (Figure 4). The main features of the eight-segment lightweight undulatory mechanism are as follows:

- Each one of the eight segments is made out of *DELRIN* and the segments are interconnected by links made out of aluminium;
- The seven rotary degrees of freedom are actuated by *HITECH HS-81 micro-servo* motors. Each motor possesses an analog encoder (in order to find the starting zero position) and an integrated gear reduction system. Three wires are provided for each motor: two for the power supply, and the last for the control signal. The latter is a square wave of 50 Hz, which produces a sinusoidal variation of the joint angle;
- The control is based on a PIC 18F252 microcontroller with a LABVIEW interface through a serial bus: the frequency, amplitude and yaw of the joint sinusoidal variation can be altered in real time (the typical variation of the joint angle is +/-30° and the typical joint oscillation frequency is 2 Hz);
- The total weight of the prototype is 336 g;
- The link dimension (i.e. distance between two contiguous axes) is 47 mm.



(a) Polychaete robotic prototype

(b) Segment contact modules equipped with PET blades

Figure 4: Polychaete robotic prototype

The bottom part of each segment is in contact with the substrate and is used to impose different friction conditions, leading to various locomotion strategies. We call this component the Segment Contact Module (SCM). Currently we have developed two types of SCM, one made of a single block of polyurethane with a jagged edge at the bottom and another made of two flexible plastic blades (PET material) fixed at the bottom of the module (Figure 4(b)).

Figure 5: Polychaete robotic prototype moving on sand

The polychaete prototype moving on sand with an undulatory forward gait is shown in Figure 5. It is equipped with the PET blades, for which the frictional forces of a single segment on the sand are 0.329 N in the tangential direction and 0.479 N in the normal one. The grooves on the sand, traced by the moving segments of the mechanism, are very similar to the link trajectories in Figure 3(a).

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