Proceedings of the IASTED International Conference
APPLIED SIMULATION AND MODELLING
June 28-30, 2004, Rhodes, Greece

A SIMULATION ENVIRONMENT FOR UNDULATORY LOCOMOTION [†]

Michael Sfakiotakis and Dimitris P. Tsakiris

Institute of Computer Science – FORTH
Vassilika Vouton, P.O. Box 1385, GR-71110 Heraklion, Greece
{sfakios, tsakiris}@ics.forth.gr

Abstract

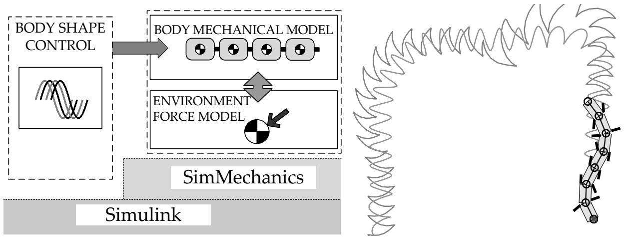
This paper presents a block-based simulation environment, developed on top of Matlab/Simulink^{TM} to facilitate research into various aspects of undulatory robotic locomotion in biology and robotics, including assessing the effect of different body configurations on gait generation. Simulations of snake-like mechanisms are made in this environment by connecting customisable body segment blocks via appropriate joint blocks, which are activated (either by explicit joint control blocks, or by neuromusclular control blocks) to propagate a travelling wave along the mechanism. Several force models are used to characterise the interaction with the locomotion environment, and emulate crawling, walking and swimming. Simulations of anguilliform swimming are presented to illustrate the versatility of the developed tools, and the potential of their use in a variety of domains, from robotics to computational neuroethology.

Key Words: Biomechanical modelling, undulatory locomotion, Simulink

1 Introduction

The development of undulatory robotic locomotors, namely serially connected, multilink articulated robots, propelling themselves by body shape undulations, has attracted significant interest in view of existing and emerging applications related to site inspection, search-and-rescue missions, mine clearance, and even endoscopy or planetary exploration. Advantages associated with undulatory robots include terrain adaptability, modularity and redundancy, as well as their potential for use as combined locomotors and end-effectors. Most of the existing such robots utilise passive wheels to realise serpentine locomotion, via the coupling of internal shape changes to nonholonomic constraints (see [1], [2] and references therein). Snake-like robots that crawl on their underside, and do not rely on wheels (e.g. [3], [4] and [5]), as well as undulatory swimming robots (e.g. [6] and [7]) have also been developed. Inspiration is provided by biological analogues, as locomotion by transversal whole-body waves is widespread among elongated, narrow animals. It is primarily an aquatic trait (termed *anguilliform* swimming), employed by animals ranging in size from larvae and marine annelids to sea snakes and eels. In the terrestrial environment, undulatory locomotion is utilised by snakes and lizards, and is also common among amphibians (e.g. salamanders, axolotls).

In this context, a simulation environment based on Matlab/Simulink^{TM} [8] has been developed, in order to facilitate research into various aspects of undulatory robotic locomotion, including assessing the effect of different body configurations, modelling the interaction with the environment, and applying neuromorphic control schemes. At the core of this development has been the SimMechanics physical modelling toolbox, used to create libraries containing elementary “body segment” blocks, which are serially connected to simulate the mechanics of planar articulated robots. The simulation environment, being versatile, expandable and relatively straightforward to work with, could have additional uses in computational neuroethology [9], or as a predictive tool in biological studies of undulatory locomotion [10].



(a) (b)

Figure 1. (a) Main components of the simulation environment. (b) Still frame from an animation, created with the results of a simulation of polychaete annelid locomotion.

2 The Simulation Environment

The simulation environment has been created on top of the Simulink substrate, to take advantage of its modular, block-based architecture, for building and integrating the main components involved in simulating an undulatory locomotor. These components are: (i) the body mechanical model, (ii) the body shape control model, and (iii) the force model of the body’s interaction with the environment (Fig. 1a).

Development is within Simulink’s graphical interface, using simple and intuitive drag-and-drop operations on the undulatory component blocks to construct the desired con-

---

[†] This research was supported in part by the European Commission through the IST project BIOLOCH (IST-2001-34181).

figurations. Furthermore, all the available Matlab/Simulink add-ons (toolboxes, coding options, etc.) can be used within this environment. This facilitates the implementation of open- and closed-loop control schemes, as well as the expansion with additional modules (e.g. implementing distance, vision, or other sensing modalities). A number of peripheral Matlab scripts facilitate tasks such as batch-run simulations and animation of results (Fig. 1b).

2.1 Mechanical Modelling of the Body

The body mechanics are modelled using the SimMechanics toolbox in Simulink. SimMechanics simulates rigid body motions, forces, and torques, employing the available numerical solvers to integrate Newton's equations of motion. These are formed by SimMechanics without the user having to derive an analytical model of the system. In order to simulate multi-segment organisms, libraries have been developed, containing elementary 2D segment blocks, with individual settings for their mass, shape (cylindrical or rectangular) and dimensions. Their internal structure is illustrated in Fig. 2. Each body block incorporates a planar revolute joint (block **b** in Fig. 2), through which segments are connected together to form serial chains (Fig. 3). SimMechanics offers special "joint actuation" blocks (Fig. 2-**c**), which are employed to determine the motion of the revolute joints, driven by the appropriate shape control module, either in terms of prescribed joint angle variations or by joint torque signals. Of particular interest is the simulation of the locomotion of segmented worms of the polychaete annelid class [5]. For this purpose, body blocks equipped with twin "parapodial" appendages (Fig. 2-**f**), placed at opposing sides along the body link (Fig. 2-**a**), and connected to it via active revolute joints, have also been created (visible in Fig. 1b). Special SimMechanics "body sensor" blocks (Fig. 2-**e**), provide direct access to the link positions, velocities and applied forces, and to the joint torques and angles, during the simulation. Apart from data logging, this information can also be used for control purposes.

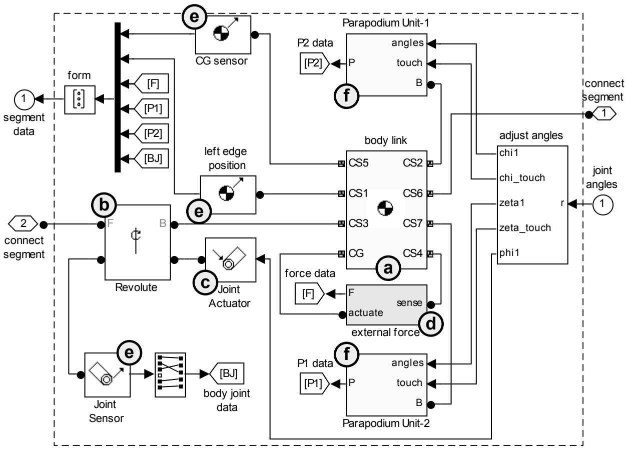


Figure 2. The internal structure of a polychaete body segment block, with parapodia.

The modular, library-based scheme allows for different body configurations to be implemented easily and with minimal troubleshooting. Mechanisms containing an arbitrary number of segments, each with different properties (even mixing plain and parapodia-bearing blocks), can be created very quickly, in order to evaluate their performance.

2.2 Modelling the Interaction with the Environment

Locomotion of an undulating body results from the coupling of its internal shape changes to external motion constraints. These constraints are usually due to external (frictional) forces, resisting the motion of the links and applied through the interaction with the locomotion environment. Three force models have been incorporated in our simulation environment, to approximate the characteristics of this interaction: a fluid drag model (detailed in section 3.1) is used to emulate swimming, while viscous or Coulomb friction models are used for motion over surfaces with the respective tribological properties. All three models are resistive, i.e. the force on a body segment depends on its velocity (rather than acceleration), and they all involve decoupled force components in the normal and tangential direction of motion. The blocks implementing the selected force model are embedded in the structure of the body segment blocks (Fig. 2-**d**) and they utilise special "body force" SimMechanics blocks to apply the external forces. The link velocities, necessary for implementing the resistive force models, are obtained directly from the "body sensor" blocks described in the previous section.

2.3 Modelling Body Shape Control

Fundamental to all undulatory locomotion schemes (both biological and robotic) is the propagation of a travelling wave along the locomoting body. A number of shape control blocks has been created, which implement different methods to generate the travelling wave, by controlling the joints in the body's mechanical model. Two of these methods (explicit joint actuation and neuromuscular actuation) are presented in some detail, within the context of elongated body swimming, in section 3.2.

3 Application: Elongated-Body Swimming

By appropriate choice of the various options available for the simulator components (e.g. body shape, travelling wave formulation, and force model used), different configurations for the undulatory mechanism, relating to a varying degree to biological analogues, can be studied. A primary motivation behind such efforts is the abstraction of biological locomotion features, in order to apply them to robotic designs. Alternatively, models which incorporate detailed shape and kinematic data of animals, could be used as predictive tools for understanding their control and dynamics.

An example of such an application is provided in this section. Simulations capturing the key aspects of anguilliform swimming are set up, using the developed simulation environment, and are presented here. An undulatory mechanism, comprising $N = 7$ identical links, each with a mass m uniformly distributed across its length l, was simulated using body blocks from the developed libraries (Fig. 3).

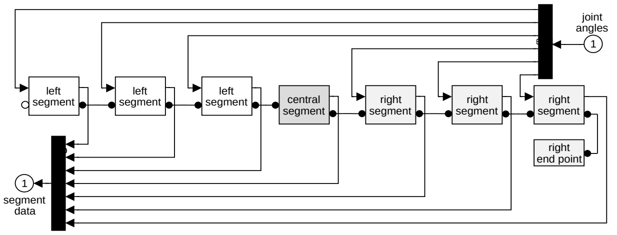


Figure 3. Mechanical model of the undulatory mechanism, constructed by serially connecting seven body segment blocks.

3.1 Fluid Drag Model

The interaction of the undulatory mechanism with the aquatic environment is simulated through a fluid drag model, which involves the following assumptions: (i) the Reynolds number is high enough for inertial forces to dominate over viscous effects (roughly for $400 < Re < 4 \cdot 10^5$), (ii) the fluid is stationary, so that the force of the fluid on a single link is due only to the motion of that link, and (iii) the pressure differentials (responsible for generating the drag forces resisting the link's motion) are considered independently for the tangential and normal directions. Then, the two components of the force applied to the ith link are respectively obtained as

$$\begin{aligned} F_T^i &= -\lambda_T \operatorname{sgn}(v_T^i) \cdot (v_T^i)^2 \\ \text{and} \quad F_N^i &= -\lambda_N \operatorname{sgn}(v_N^i) \cdot \left(v_N^i\right)^2 \end{aligned} \tag{1}$$

where v_T^i and v_N^i are the tangential and normal components of the ith link velocity. The drag coefficients associated with each force component are denoted as λ_T and λ_N. Their value can be estimated as

$$\lambda = \frac{1}{2}\rho C S \tag{2}$$

where S is the effective area of the link, ρ is the fluid density and C is a shape coefficient. The notion of decoupled forces in the normal and tangential direction of link motion can be traced to Taylor's resistive analysis of elongated animal swimming [11], and is considerably simpler to calculate and integrate with the body dynamics than any model which requires solving the Navier-Stokes equations. It has therefore been used quite extensively in the literature (e.g. [7], [12] and [9]), despite ignoring secondary effects of water movement. Since the assumptions of this model restrict its scope to the inviscous swimming of elongated animals, it cannot be applied to the undulatory swimming of microorganisms (e.g. nematodes and flagella), nor to the more sophisticated fish swimming modes [13].

The ratio λ_N/λ_T of the drag coefficients in Eqs. (1) is a key parameter in undulatory locomotion. The elongated body of anguilliform swimming animals (eels, amphibious snakes, etc.) is smooth and of elliptical cross-section, so that $\lambda_T << \lambda_N$ (Lighthill [14] estimates $\lambda_N/\lambda_T \simeq 10$ for a swimming grass-snake). Forward propulsion is then achieved by body waves propagating from head to tail [11]. Conversely, smooth elongated animals can swim backwards by reversing the propulsive wave [15]. If the animal body is not smooth, the propulsive component of the tangential force may be greater than that of the normal force (corresponding to $\lambda_N/\lambda_T < 1$). Forward motion would then be achieved by a tail-to-head wave [11]. This is indeed the case for the locomotion of errant polychaete (marine worms), whose body affords a significant amount of roughness, mainly due to the laterally projecting appendages (parapodia) distributed along their body [16].

3.2 Shape Control of the Body

3.2.1 Explicit Joint Angle Control

The most straightforward way to explicitly generate a travelling wave in a serial chain of N links is by having the joint angles vary sinusoidally, with a common frequency f and a constant phase lag ϕ_{lag} between consecutive joints:

$$\phi_i(t) = A_i \sin(2\pi f t + i\phi_{lag}) - \psi, \qquad i = 1, ..., (N-1) \tag{3}$$

where A_i is the maximum angular deflection for the ith joint (usually $A_i = A$ is assumed). The angular offset ψ provides a means for steering along curved paths, and is set to $\psi = 0$ for locomotion in a straight line. Propagation direction for the wave depends on the sign of the phase lag parameter, and is from link-N to link-1 for $\phi_{lag} > 0$. The condition $\phi_{lag} = \pm 2\pi/N$ yields (exactly) one wavelength of the propulsive wave across the undulating body, with beneficial effects on the propulsive efficiency. For links of identical length, the formulation of Eq. (3) produces a sinusoidal body shape, shown in Fig. 4 for the seven-link mechanism. The propagation velocity of the wave is calculated as $V = fw$, where w is the resulting wavelength.

3.2.2 Neural Control

A biologically-motivated body shape control method is based on central pattern generators (CPGs), which are neuronal circuits able to produce rhythmic motor patterns in an organism (for swimming, flying, breathing, etc.), even in the absence of sensory input or input from higher cognitive elements. Their behavior depends both on the intrinsic properties of the neurons that form the network, as well as on the properties of the synapses among them (connectivity, strength, etc.). Inspired by models of the CPG which