SIMUUN: A SIMULATION ENVIRONMENT FOR UNDULATORY LOCOMOTION

M. Sfakiotakis* and D.P. Tsakiris*†

Abstract

This paper presents SIMUUN, a block-based simulation environment, which has been developed on top of Matlab/Simulink^{TM}, in order to facilitate research into various aspects of undulatory locomotion in biology and robotics. Simulations of snake-like mechanisms are set up in this environment by connecting customizable SIMUUN body segment modules via appropriate joint blocks, which are activated either by explicit or by neuromuscular joint control modules, to propagate a travelling wave along the mechanism. Several force models are included in SIMUUN to characterize the interaction with the locomotion environment, and emulate crawling, walking and swimming. The simulation tools developed were used to study anguilliform swimming in robotics and in biology, and assess the effect of different body configurations on gait generation. Related simulation results are presented to illustrate the versatility of these tools and the potential of their use in a variety of domains.

Key Words

Biomechanical modelling, undulatory locomotion, robotics, biology, *Anguilla anguilla* eel.

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 emerging applications related to site inspection, search-and-rescue missions, mine clearance, and

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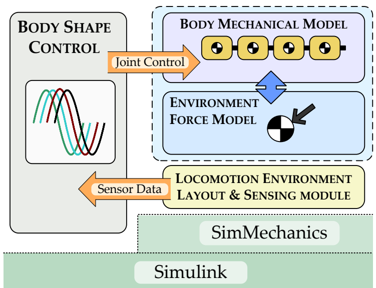
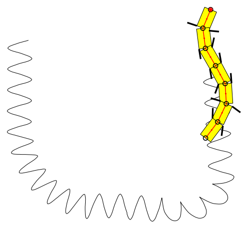
even endoscopy or planetary exploration. Advantages associated with undulatory robots include terrain adaptability, modularity and redundancy, as well as their potential for use as combined locomotors and manipulators. While most of the existing such robots utilize passive wheels to realize serpentine locomotion (see [1][2][3][4][5] and references therein), prototypes which crawl on their underside, and do not rely on wheels (e.g., [6][7][8][9]), as well as undulatory swimming robots (e.g., [10][11][2]) have also been developed. Inspiration is provided by biological organisms, since locomotion by transverse 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, but is also utilized by terrestrial (e.g., snakes and lizards) and amphibian (e.g., salamanders and axolotls) animals.

An undulating body (biological or robotic) can achieve locomotion through appropriate coupling of internal shape changes (typically a wave travelling along the body) to external motion constrains (typically frictional forces arising from the interaction with the locomotion environment). The effect of both these aspects needs to be considered when analyzing undulatory locomotion, in order to, for example, design efficient such robotic prototypes. The large number of parameters involved in this process (e.g., number and size of body links, travelling wave properties, characteristics of the interaction with the environment) is increased even further when more complex architectures (e.g., sensor-based reactive behaviours) are considered, thus highlighting the need for powerful and versatile software design tools.



(a)



(b)

Figure 1: (a) Main components of the simulation environment. (b) Robotic polychaete annelid with parapodia: still frame from an animation of its undulatory locomotion.

In this context, SIMUUN ("SIMUlator for UNdulatory locomotion"), a simulation environment based on the Matlab/Simulink^{TM} software suite [12], has been developed. The aim is to facilitate research into various aspects of undulatory robotic locomotion, which include assessing the effect of different body configurations, modelling the interaction with the environment, and applying neuromorphic control schemes. At the core of this development is the SimMechanics physical modelling toolbox of Simulink, used to create libraries with integrated "body segment" modules, which are serially connected to create a block diagram representation of the articulated robot mechanics. The developed set of tools has already facilitated the design, simulation and analysis of the polychaete-like undulatory robotic prototypes presented in [8][9]. Since SIMUUN is versatile, expandable and relatively straightforward to work with, it can have additional uses in computational neuroethology [13], or as a predictive tool in biological studies of undulatory locomotion [14]. Moreover, since SimMechanics allows construction of the mechanical models without the user having to derive the associated equations of motion (an error-prone and time-consuming process), the simulation environment can also be used by researchers from fields other than robotics, even with limited mechanical background.

Section 2 of the paper presents the main SIMUUN components and their implementation with respect to the Simulink/SimMechanics framework. Example applications are then provided, involving the use of SIMUUN to develop an undulatory reactive behaviour (section 3) and to replicate biological studies of eel swimming (section 4).

2. The Simulation Environment

SIMUUN has been created on top of the Simulink substrate, to take advantage of its modular, block-based architecture and of the numerous related software tools for building and integrating the main components involved in simulating an undulatory locomotor. These components, shown in Fig. 1a, 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. A distance sensing module, coupled to a model of the locomotion environment layout, has also been created, to facilitate the study of sensor-based, closed-loop control schemes.

Development of SIMUUN simulations is performed within Simulink's graphical interface, using simple and intuitive manipulations of the undulatory component modules to construct the desired configurations. Setting up a basic simulation of an undulatory mechanism involves the following steps: 1) The mechanical model of the body is initially created, by serially connecting "body segment modules", using simple drag-and-drop operations. 2) This is then linked to an appropriate "body shape control module", which provides the joint actuation signals for the undulatory mechanism.

3) The environment force model to be used, along with various other parameters of the simulation (e.g., its time range), are set in a Matlab script file. 4) Additional "sensing blocks", coupled to Matlab script files describing the layout of 2D wall-like features in the locomotion environment, may also be incorporated in the Simulink model. 5) The simulation is then run in standard Simulink fashion, under the "forward dynamics" mode of SimMechanics, to calculate the motion of the mechanism resulting from the applied forces/torques and constraints. During the simulation, a number of variables (link positions, joint velocities, applied forces, etc.) is being recorded, to allow post-processing of the results. Various peripheral Matlab scripts facilitate tasks such as batch-run simulations and animation of results (an example is shown in Fig. 1b).

Standard Simulink/SimMechanics blocks have been used to create the SIMUUN modules, whose internal structure can be easily modified by the user, and tailored to the requirements of particular applications, should such a need arise. Furthermore, all the available Matlab/Simulink add-ons (toolboxes, coding options, etc.) can be used within this framework to implement additional features. Simulations involving multiple undulatory mechanisms, e.g., for developing cooperative behaviours, are also readily supported in SIMUUN.

2.1 Mechanical Modelling of the Body

The body mechanics are modelled using the SimMechanics toolbox in Simulink, which provides so-called "physical modelling" blocks to represent physical components and their geometric and kinematic relationships directly. These are connected together using non-directional "connection lines" via special "connection ports" on the blocks, to form a block diagram representation of the modelled mechanical system. After this has been set up, SimMechanics automatically derives the equations of motion and, under the forward dynamics analysis mode, employs the selected Simulink numerical solver (in SIMUUN the `ode45` variable step continuous solver [12] is commonly used) to integrate them for the specified forces and torques applied to the system. Details on the setup of the equations of motion and on the algorithms internally employed by SimMechanics to formulate and solve these equations are provided in [15].

In order to simulate multi-segment undulatory mechanisms in SIMUUN, a "body segments library" (BSL, for short) has been developed, which is shown in Fig. 2. The library contains integrated 2D body segment modules, with individual settings for their mass, shape (cylindrical or rectangular)

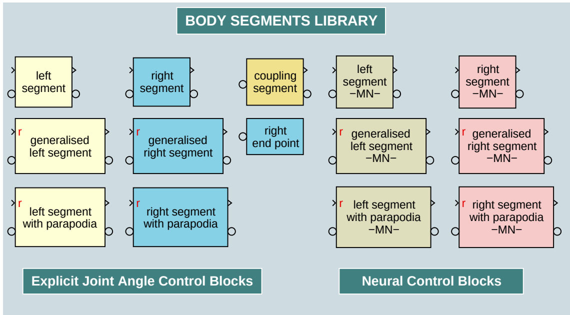


Figure 2: The body segments library (BSL) of the simulation environment.

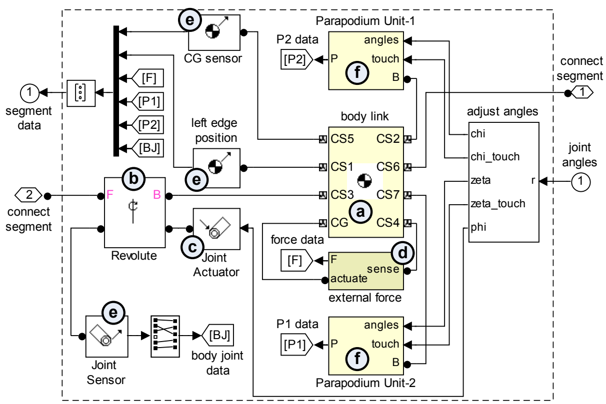


Figure 3: The internal structure of a body segment module with parapodia.

and dimensions, whose internal structure is illustrated in Fig. 3. Each BSL module incorporates the main body link (block **a** in Fig. 3) with a planar revolute joint (Fig. 3-**b**), through which segments are connected together to form serial chains (Fig. 4). Two different variants of the body segment blocks are provided, on the basis that the "joint actuator" SimMechanics block (Fig. 3-**c**) offers two modes for driving the revolute joint: either by applying a specific torque signal, or as an explicit motion driver. In the latter case, explicit Simulink signals of the angular position $\phi(t)$, the angular velocity $\dot{\phi}(t)$ and the angular acceleration $\ddot{\phi}(t)$ of the joint, are required to determine its prescribed motion. Of particular interest is the simulation of the locomotion of segmented worms of the polychaete annelid class [8][9]. For this purpose, additional BSL modules have been created, which are equipped with twin "parapodial" appendages (Fig. 3-**f**, visible in Fig. 1b), placed at opposing sides along the body link, and connected to it via active revolute joints. Special SimMechanics "body/joint sensor" blocks (Fig. 3-**e**), provide direct access to quantities such as the position and velocity of the body segment, or the angular velocity of the revolute joint, during the simulation. Apart from data logging, this information is used to implement the distance sensor modules, presented in section 2.4.

The plane of motion is represented in SIMUUN by the SimMechanics "ground" block. A special "coupling" body segment, provided in the BSL, incorporates a planar joint, through which the mechanism is coupled as a whole to the motion plane. Hence, the undulatory mechanisms constructed in SIMUUN have an acyclic graph structure, and therefore benefit from the particularly efficient manner that such systems are handled by SimMechanics [15].

This modular, library-based scheme allows for different body configurations to be set up easily and with minimal troubleshooting, using simple drag-and-drop operations. 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, which are usually due to external (frictional) forces, resisting the motion of the links and applied through the interaction with the locomotion environment. Two different force models, developed to approximate the characteristics of this interaction both for aquatic and for terrestrial locomotion, have been incorporated in SIMUUN. In both models, the force on a body segment is assumed to depend on its velocity, and the force components in the normal and tangential direction of motion are assumed to be decoupled. A fluid drag model (detailed in section 2.2.1) is used to emulate swimming, while for crawling a more general friction model has been developed. The latter combines stiction, Coulomb and viscous damping, as well as the Stribeck effect and anisotropic characteristics, in an effort to allow coverage of the wider range of tribological phenomena encountered in different terrestrial substrates [16]. The blocks implementing the selected force model are embedded in the structure of the BSL modules (Fig. 3-**d**) and they utilize 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.

2.2.1 Fluid Drag Model

The fluid drag model, used in SIMUUN to simulate the interaction of undulatory mechanisms with the aquatic environment, is a first approximation of the hydrodynamics involved, assuming that: (i) fluid forces are mainly inertial (roughly for a Reynolds number $400 < Re < 4 \cdot 10^5$), (ii) the fluid is stationary, so that its force on a single link is due only to the motion of that link, and (iii) the tangential

(F_T) and normal (F_N) components of the fluid force are decoupled. These are then calculated, for individual links, as:

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

where v_T^i and v_N^i are the tangential and normal components of the velocity of the ith link. Estimates for the associated drag coefficients λ_T and λ_N may be obtained as $\lambda = \frac{1}{2}\rho CS$, where S is the link's effective area, 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 [17], and has been used quite extensively in the literature (e.g., [10][18][13]), despite ignoring secondary effects of water movement. Since the assumptions of this fluid drag model restrict its scope to the inviscid swimming of elongated animals, it cannot be applied to the undulatory swimming of microorganisms (e.g., nematodes), nor to the more sophisticated swimming modes encountered in fish [19].

The ratio λ_N/λ_T of the drag coefficients in (1) is a key parameter in undulatory locomotion. The elongated body of eel-like animals is smooth and of elliptical cross-section, so that $\lambda_T << \lambda_N$ (e.g., $\lambda_N/\lambda_T \simeq 10$ in swimming grass-snakes [20]). The overall locomotion direction is then opposite to that of the wave direction, and therefore, forward propulsion is achieved by body waves propagating from head to tail; reversing the propulsive wave enables backwards swimming [21]. If the animal body is not smooth (as in the polychaete annelids, see [22]), the propulsive component of the tangential force may be greater than that of the normal force (corresponding to $\lambda_N/\lambda_T < 1$). Hence, for such rough-body configurations, locomotion is along the direction of wave propagation, i.e. forward motion is achieved by a tail-to-head wave [8][9].

2.3 Modelling Body Shape Control

Fundamental to undulatory locomotion (both biological and robotic) is the propagation of a travelling wave along the locomoting body. In SIMUUN, the "shape control library" (SCL, for short) comprises a number of modules, built with standard Simulink blocks, which implement different methods of generating the travelling wave, by controlling the joints in the body's mechanical model. For simulations involving undulatory mechanisms with parapodial appendages, the respective SCL modules also provide the control signals for the parapodial joints. As demonstrated in section 3, the developed modules may also be used in closed-loop control schemes.

Two of the implemented methods for generating the body wave are presented next, within the context of elongated body swimming. The first method is based on the assumption of direct control of the mechanism's joint angles, while the second one is a neural control scheme, where the control inputs are the joint torques. Their presentation here is facilitated by introducing a basic undulatory mechanism, constructed with BSL segments (Fig. 4), and comprising $N = 7$ identical links, whose mass is uniformly distributed across their length.

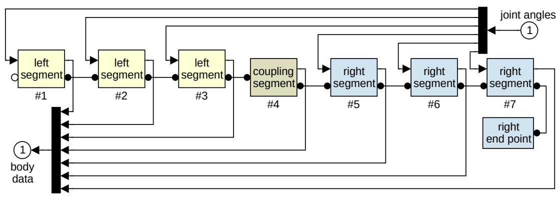


Figure 4: SIMUUN mechanics setup of a seven-link undulatory mechanism.

2.3.1 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:

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

where A_i is the maximum angular deflection for the ith joint. The angular offset ψ provides a means for steering along curved paths, and is set to $\psi = 0$ for locomotion in a straight line. The 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 locomotion efficiency. For links of identical length, the formulation of (2) with $A_i = A$ produces a "serpenoid" body shape [1], which is shown in Fig. 5 for the seven-link mechanism. The propagation velocity of the wave is calculated as $V = fw$, where w is the resulting wavelength. Series of simulation runs over various ranges of these body wave parameters can identify their effect on locomotion efficiency, and are easy to set up in SIMUUN using Matlab scripts [23].

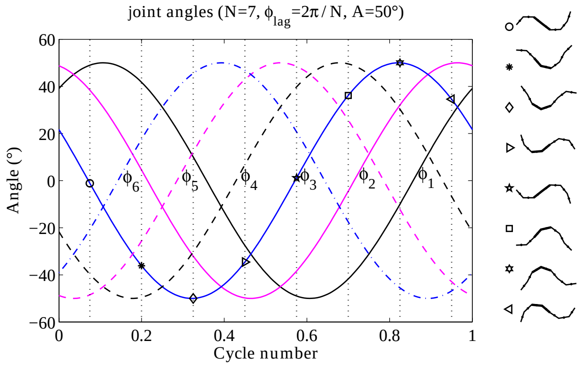


Figure 5: Relationship between the joint angles and the overall body shape. The markers follow the variation of ϕ_3, the joint angle between links 3 and 4.

Closed-loop control schemes utilizing (2) may also be set up, whereby the parameters A and f are used to alter the speed of locomotion, while changes in ψ impose orientation changes. Appropriate such SCL modules have been created, which receive input by "controller" blocks, typically developed by the user for implementing e.g., sensor-based reactive behaviours. In all cases, the joint velocities $\dot{\phi}_i(t)$ and joint accelerations $\ddot{\phi}_i(t)$, required in the BSL blocks, are obtained from the joint angles $\phi_i(t)$ by numerical differentiation, employing a filtered derivative Simulink block to reduce noise due to the differentiation.

2.3.2 Neural Control

A biologically-motivated body shape control method can be based on the central pattern generator (CPG) neuronal circuits, which produce rhythmic motor patterns (for swimming, flying, etc.) in various organisms. Their behaviour depends both on the intrinsic properties of the constituent neurons, as well as on the properties of the synapses among them. Inspired by models of the CPG which controls the undulatory swimming of the lamprey (e.g., [18][13]), SCL modules realizing neuromuscular body shape control were developed. These are based on a connectionist CPG circuit, which is modelled as a chain of (identical) segmental oscillators, properly interconnected to generate a wave of joint activation. Each segmental oscillator comprises interneurons and motoneurons (all of which are modelled as leaky integrators [13]), arranged in two symmetrical sub-networks, which create oscillations through mutual inhibition. The torque eventually applied to each of the body joints is determined by the outputs of the corresponding motoneurons, after they activate a pair of antagonistic lateral muscles, which are simulated using a spring-and-damper muscle model (Fig. 6). The characteristics of the motoneuron outputs can be altered by tonic (i.e. non-oscillating) inputs to the left and right sub-networks of the segmental oscillators [8].

The developed SIMUUN modules comprise blocks implementing the basic segmental oscillator units, which are serially connected to form the desired CPG circuit (Fig. 7). Both the interneuronal and the intersegmental CPG connectivities are defined via Matlab scripts, thus facilitating the investigation of different architectures, e.g., by evolutionary computation methods.

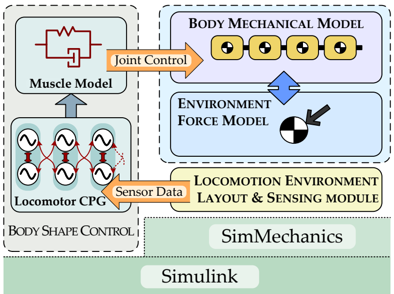


Figure 6: SIMUUN setup for neuromuscular control.

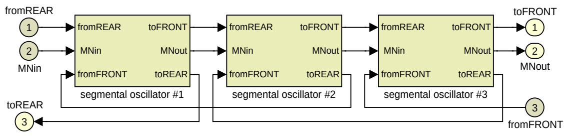


Figure 7: CPG circuit construction within SIMUUN.

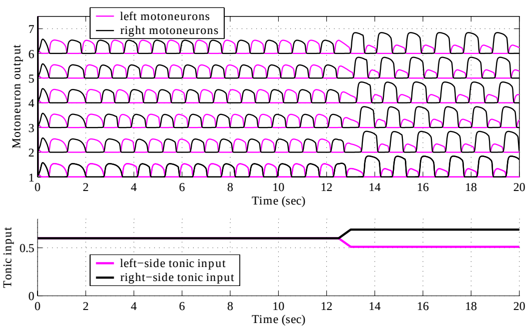


Figure 8: Tonic input and resulting motoneuron outputs of the CPG segmental oscillators, controlling the body joints.

For simulations involving the basic seven-link mechanism, a body CPG comprising 20 segmental oscillators was constructed. The motoneuron outputs from (roughly) every third oscillator were utilized to provide torque signals to the six body joints, through the antagonistic muscles. Motion in a straight line is obtained by symmetric activation of the two sides of the body CPG, via equal tonic inputs, while turning motions are instigated by unequal tonic input to them (Fig. 8). Rapid transition in the motoneuron outputs, when varying the tonic input, is a key feature for smooth steering of the mechanism, closely related to the type of intersegmental coupling in the CPG structure. The scheme was successfully applied to both smooth- and rough-body configurations. Since this approach provides torque signals to the joints, their exact angular motion depends on the segments' mechanical properties, as well as on the parameters of the force model used. The resulting joint angles may therefore be quite different from the explicitly defined ones (cf. Figs. 9 and 5). This fact, along with the non-straightforward relationship between the tonic input level and the properties of the motoneuron outputs (i.e. frequency and amplitude), renders the precise tuning of the travelling wave parameters difficult, and highlights the benefits of using SIMUUN for design purposes, particularly when setting up CPG-based closed-loop control schemes, such as the one described in section 3.

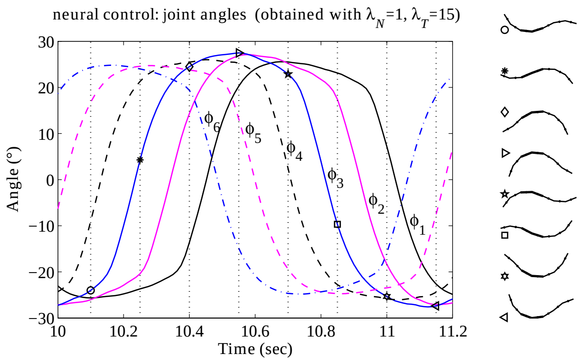


Figure 9: Joint angles and body shape, obtained using neural control to generate the travelling wave.

2.4 Locomotion Environment Model and Sensing Module

The current version of SIMUUN includes modules which emulate distance sensing elements, and implement simple 2D models of the world that the mechanism is presumed to be operating in, typically a maze-like environment. The latter is defined in terms of (consecutive) line segments, by providing their 2D position coordinates in a Matlab script file. The sensor modules then operate by calculating the distance of the geometric centers of the mechanism's links (whose coordinates are readily available from the "body sensor" SimMechanics blocks) from these line segments. The developed modules assume one or more pairs of distance sensors, mounted on each link center, and aiming at user-defined angles with respect to the main axis of the link, to realize the full sensing array of the undulatory mechanism (an example is shown in Fig. 11). Variations of the sensing subsystem to consider noise in the distance measurements, or to implement simpler whisker-like sensors are also available.

An example application utilizing the sensing blocks is described in section 3. Additional sensory modalities and locomotion environments are easy to incorporate in SIMUUN, based on the flexibility of Matlab/Simulink, and will be included in future versions of the simulation environment.

2.5 SIMUUN Validation

Validation of the SIMUUN simulation framework against analytical approaches used to model the mechanics of undulatory locomotion is deemed important, in view of the fact that the SimMechanics process of deriving the equations of motion of the simulated mechanisms is automatic and totally transparent to the user. Within this context, the equations of motion for the seven-link mechanism under explicit joint angle control, were analytically derived from its Lagrangian dynamics, following the reduction process described in [5][9][10]. These were formulated for both viscous and fluid drag models of interaction with the environment, and were subsequently implemented in Matlab. Simulations were then carried out for different waveform parameters in (2), and for different Simulink ODE solvers, to compare the resulting trajectories of the mechanism against those obtained by the respective equivalent SIMUUN setups. In all cases, the main factor to obtaining a close match in the results was identified as the low-pass bandwidth P of the filtered derivatives, utilized to calculate numerically $\dot{\phi}_i(t)$ and $\ddot{\phi}_i(t)$ (see section 2.3.1). Indicative results demonstrating its effect are shown in Fig. 10, where the trajectory of the mechanism's tail link, calculated using the reduced dynamics approach (shown in the upper part of Fig. 10) is used as a reference for plotting the deviation, in terms of their Euclidean distance e, of the respective trajectories obtained in SIMUUN for different values of P, over a simulation time of $10\,\mathrm{sec}$.

3. Simulations of a Reactive Centering Behaviour

This section demonstrates the use of SIMUUN to develop a reactive, sensor-based undulatory behaviour, facilitated by the Simulink framework of the simulation environment. The specific behaviour presented here 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. This has inspired the implementation of reactive centering schemes 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

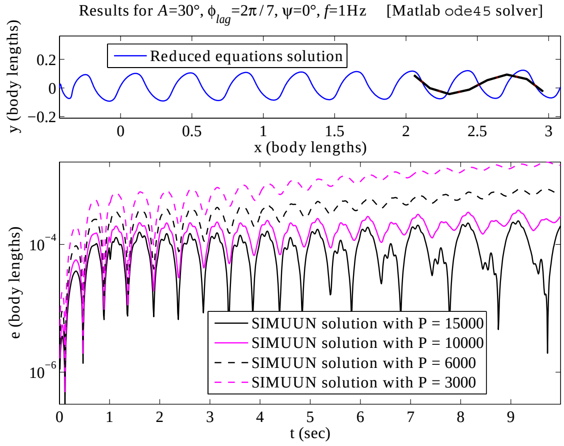


Figure 10: Validation of SIMUUN simulation results againsts those obtained by the reduced equations analytical approach.

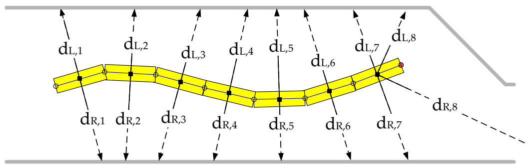


Figure 11: Example configuration of a sensor array for a seven-link undulatory mechanism.

control loop [24]. Adaptation of such sensor-based control schemes to the significantly more complicated dynamics of undulatory robots involves balancing the weighted sum of the distance sensor outputs to the left and right sides of the robot.

For our purposes, the previous seven-link undulatory mechanism, coupled to the locomotor CPG described in section 2.3.2, is considered. Assuming M pairs of distance sensors (see section 2.4), and denoting $d_{L,j}$ and $d_{R,j}$ $(1 \leq j \leq M)$ the outputs for such a sensing array (Fig. 11), the control law to realize the undulatory centering behaviour is then implemented via the tonic input signals applied to the left and right sides (I_L and I_R, respectively) of the CPG, so that:

$$I_L(t) = 1 - kD(t) \text{ and } I_R(t) = 1 + kD(t) \tag{3}$$

where $k > 0$, and

$$D(t) = \frac{1}{\sum_{j=1}^{M} q_j d_{L,j}(t)} - \frac{1}{\sum_{j=1}^{M} q_j d_{R,j}(t)} \tag{4}$$

The weights q_j in (4) determine the relative contribution of the M sensor pairs in calculating the distance metric $D(t)$.

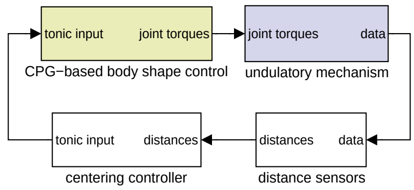


Figure 12: Undulatory centering behaviour: constructed SIMUUN block diagram.

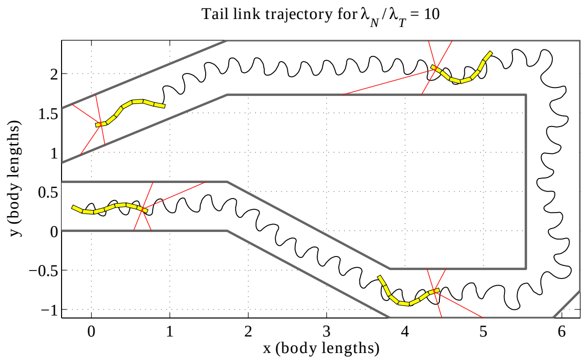


Figure 13: Undulatory centering behaviour: trajectory of the mechanism.

The block diagram constructed within SIMUUN to implement the CPG-based undulatory centering behaviour is shown in Fig. 12. The centering scheme considered inputs only from the two sensor pairs mounted on the head link of the mechanism, and aiming at $\pm 45°$ and $\pm 90°$ with respect to the link's main axis. The controller based on (3) and (4) was implemented using standard Simulink blocks, and a maze-like environment was created, as described in section 2.4, to test the setup. The performed simulations demonstrated, both for smooth-body and for rough-body configurations of the seven-link mechanism, the successful application of the neural control scheme. Indicative results for the smooth-body case (with $\lambda_N/\lambda_T = 10$), obtained for $q_7 = q_8 = 1$ in Fig. 11 and for $k = 0.03$, are shown in Figs. 13-14.

4. Simulations to Replicate Biological Data

This section demonstrates the use of SIMUUN to replicate biological data for organisms locomoting by undulations, highlighting its potential as a tool, both for the analysis of such data and for designing new related biological experiments.

Simulations were set up based on the detailed biological data from filmed sequences of swimming of the *Anguilla anguilla* eel, which are provided in [21]. A biomechanical eel model was constructed, composed of 20 cylindrical links of equal length, but unequal radius, reflecting the analysis framework

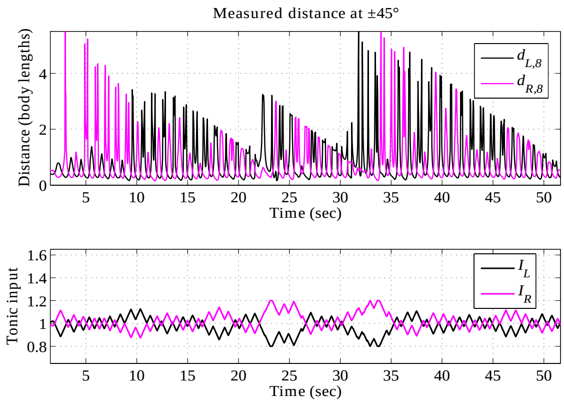


Figure 14: Undulatory centering behaviour: Output from one of the two sensor pairs utilized (top) and the respective tonic input signals (bottom).

in [21] and incorporating the biometric measurements reported therein (total body length $22\,\mathrm{cm}$, total mass $13\,\mathrm{g}$). The Reynolds number for the reported eel swimming kinematics is $Re \simeq 3 \cdot 10^4$, thus validating the use of the fluid drag model in the simulations; the drag coefficients were calculated (section 2.2.1) and set to $\lambda_N = 0.5\,\mathrm{kg/m}$ and $\lambda_T = 0.01\,\mathrm{kg/m}$. The explicit joint angle control scheme is used to generate the travelling wave in the developed eel model.

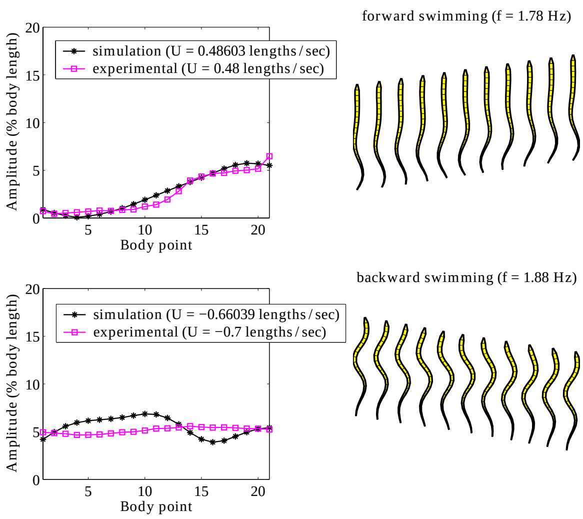


Figure 15: Amplitude profiles (left) and body contour plots (right) for simulations of forward and backward eel swimming. Body points refer to the endpoints of the eel sections considered in [21].

Two simulation runs are presented here, corresponding to two of the representative eel swimming sequences analyzed in [21], one for forward, and one for backward propulsion. From the pool of biological data for the two selected sequences, the reported frequencies and maximal angles between segments, along with the body contour plots provided, were used to set the parameters f, A_i and ϕ_{lag} in (2). Results were then evaluated by comparing the attained velocities and body amplitude profiles obtained in simulation, against the corresponding measurements in [21]. For both swimming sequences, a very good match has been obtained, as indicated in Fig. 15. A number of additional observations made in [21], on the eel swimming kinematics and on their relation to body shape and mass distribution (regarding, for example, the orientation changes of the head), can also be reproduced with the SIMUUN computational models.

5. Conclusions

The simulation environment presented in this paper aims to facilitate the study of undulatory locomotion principles, both in biological organisms and in related robotic implementations. Further immediate extensions to SIMUUN will include the expansion to 3D mechanisms and motions, to multiple undulatory mechanisms, to additional models for the interaction of the system with its environment, and to more refined neuromuscular control schemes.

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Related resources (papers, videos of experiments, etc.) regarding applications of SIMUUN can be found at the Web site *www.ics.forth.gr/simuun*, where the biomechanical eel model presented in section 4 is also available.

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Biographies

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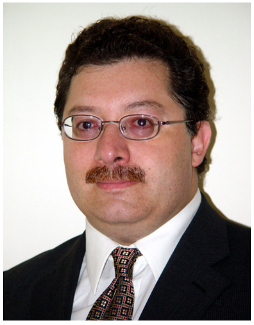

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