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AnimatLab: A 3D graphics environment for neuromechanical simulations

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ABSTRACT

The nervous systems of animals evolved to exert dynamic control of behavior in response to the needs of the animal and changing signals from the environment. To understand the mechanisms of dynamic control requires a means of predicting how individual neural and body elements will interact to produce the performance of the entire system. AnimatLab is a software tool that provides an approach to this problem through computer simulation. AnimatLab enables a computational model of an animal's body to be constructed from simple building blocks, situated in a virtual 3D world subject to the laws of physics, and controlled by the activity of a multicellular, multicompartment neural circuit. Sensor receptors on the body surface and inside the body respond to external and internal signals and then excite central neurons, while motor neurons activate Hill muscle models that span the joints and generate movement. AnimatLab provides a common neuromechanical simulation environment in which to construct and test models of any skeletal animal, vertebrate or invertebrate. The use of AnimatLab is demonstrated in a neuromechanical simulation of human arm flexion and the myotactic and contact-withdrawal reflexes.

1. Introduction

A major goal of neuroscience is to understand how the nervous system is organized to control behavior. The nervous system gathers sensory information about the body's relationship to the world, and then makes decisions and issues motor commands which change that relationship. The dynamics of the interaction among the central nervous system, the body, and the world are central to the functional control of behavior (Chiel and Beer, 1997). To govern behavior correctly, the nervous system must both predict and respond to the consequences of the animal's own movements and behavior, and do so on a millisecond to second time scale.

Despite many experimental successes in the analysis of the nervous system and behavior, the dynamic relationship between nervous function and the body is poorly understood. The kinematics and dynamics of many behaviors have been described, and the neural circuitry for some of these behaviors has been mapped in anesthetized or restrained animals, or in isolated tissue preparations. However, we lack a means of predicting how the function and behavior of individual neural and body elements will affect the performance of the entire system and the behavior of the animal.

Neuromechanical simulation provides a new and promising approach to this problem. Computational models of the relevant neural circuits, body parts, and the physical world simulate the neural and biomechanical mechanisms of a behavior simultaneously in a physically accurate environment (Pearson et al., 2006). Here we introduce AnimatLab, a free, open-source, Windows®-based software tool written to provide a general simulator for neuromechanical processes of skeletal animals, both vertebrate and invertebrate. We first describe AnimatLab, its components and how they are used to construct models of the body and nervous system that interact to produce behavior in a virtual physical world. We then illustrate its use by presenting a model of spinal control of human arm flexion, the myotactic reflex, and the contact-avoidance reflex.

AnimatLab allows users to build neural circuit and biomechanical body models in a virtual physical environment, and then to record time-series of any variable(s) while viewing an interactive, 3D animation of the simulated behavior. Separate editors are used to build a model's body and nervous system, the objects and parameters that describe the surrounding physical world, and the patterns of physical and neural stimuli to be delivered to the model. Its interactive graphical user interface (GUI) permits users to view and

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interact with the model during the simulation, and to record and display data that describe its behavior. Both model construction and the simulations are carried out in an integrated environment. Construction of neural network models and 3D biomechanical body models use the point-and-click GUI in a way similar to professional CAD tools or 3D modeling tools like Maya or 3DS Max (www.usa.autodesk.com). Simulations and modules can be readily shared between investigators to allow others to examine and extend a simulation.

AnimatLab is available at www.AnimatLab.com with 45 video tutorials, and over 100 pages of help files that will guide new users in a click-by-click fashion through model construction and use of the program's different capabilities. AnimatLab requires no programming knowledge to use, but does assume a familiarity with neural and muscle physiology at the upper undergraduate/beginning graduate level. For those interested in adding new capabilities, AnimatLab's modular architecture makes it highly extensible via its pluggable, C++-based interface.

2. Methods

2.1. AnimatLab organization

AnimatLab has three interactive components: the GUI that enables model building and data graphing, coupled solvers for the neural circuit and biomechanics simulations, and an interactive 3D animation of the model's behavior in a virtual Newtonian world. In the model building portion, a "Project Workspace" (Fig. 1a) sets environmental parameters and provides access to editors for all the objects in the simulation: the nervous system and body of each animal, the ground and water surfaces, and all the fixed objects in the simulated environment. The "Body Plan Editor" (Fig. 1b) allows the user to assemble each model animal's body in a point-and-click, Lego®-like fashion from a variety of different part types. The "Behavior Editor" (Fig. 1c) allows users to construct the neurons and neural circuits that control the behavior of the model organism in a similar drag-and-drop fashion. Links are established between common elements (e.g., muscles, sensors) in the two editors, and the simulation is run by simultaneously operating and interacting solvers, the Vortex® simulator from CM Labs (http://www.vxsim.com/) for the biomechanics and a custom-made solver for neural interactions that uses an exponential Euler method (MacGregor, 1987) that is also used by GENESIS (Bower and Beerman, 2007). New neural solver plug-ins can be added by users, and each one can operate with a different integration time step from the others and from the physics engine. The model animal's movements in the virtual environment are under neural control as it responds to simulated physical and experimental stimuli. The autonomous behavior of the model is displayed graphically in a 3D animation (Fig. 1d) as the simulation runs, together with plots of the time-series responses of any designated set of neural or physical variables (e.g., membrane potentials, muscle forces and spatial displacements; Fig. 1e). Both the 3D animation and the data time-series can be recorded for off-line analysis, and the model parameter space can be explored by running multiple simulations with different parameter values simultaneously on different nodes of a grid computer.

2.2. Assembly of a body model

To build an animal model, users define rigid body parts in the Body Plan Editor (Fig. 1b), connect them with standard joints, enable them to move with actuators, and provide them with sensors to detect the environment. The connectivity of parts in the model is represented in a tree diagram (Fig. 1b, left). Several different types of body structures are currently available, including boxes, spheres, cones, cylinders, and polygon mesh models. A polygon mesh is a set of vertices and triangular faces that define the shape and volume for that part. All parts are assumed to have a uniform density, and the distribution of mass throughout the mesh volume determines the moment of inertia for that part. Meshes allow animal models to have more realistic structures, both visually and dynamically, by providing a more accurate representation of the body than is possible with simple geometric shapes. A wide array of mesh representations of animals' bodies can be purchased inexpensively from various graphics websites, including the human model presented (from www.exchange3d.com). Alternatively, a polygon mesh can also be obtained from a 3D laser scan of an animal's body using a computer-driven scanner (e.g., https://www.nextengine.com). Depending on the size of the animal and the scanner, the body can be scanned whole or as separate parts. For the body mesh to be used within AnimatLab, the body segments must be split into separate mesh files so that each can act as a single rigid body. For example, an arm would be split at the elbow to allow the upper and lower arms to be simulated with a joint between them. This reconstruction of the mesh file requires use of a 3D graphics program like Blender (www.blender.org). The separate body segment meshes are individually imported into AnimatLab and linked by the appropriate hinges to recreate the body with its moveable joints. Models of a human body, cat skeleton, and locust body are available at www.animatlab.com.

Rigid body parts have user-specified physical properties including dimensions, density, and drag; actuators include muscles, muscle spindles, motors, and springs; sensors include receptors for stretch, touch, odors, and tastes. Each body part is selected from a drop-down box and then placed, oriented, scaled, and shaped with a mouse in a 3D GUI. Joints are modeled as movement constraints that prevent any motion of the connected body parts that is not allowed by that joint type. The currently available joint types are planar hinge, ball and socket, one-dimensional sliding (prismatic), and fixed.

A fill-in "Properties" table (Fig. 1b, bottom left) can be used for exact placements and specifications of body parts and joints. A "description" cell in each properties table permits entry of text describing the object, or references to sources of the parameter values, or hyperlinks to those sources. Documentation of this sort is essential to distinguish between parameters and features based on experimental measurements from those that are made up to enable the model to work. This feature enables the model to be used as a knowledge base for the animal's neural circuitry and body structure.

Sensory receptors for touch, for stretch of a muscle spindle, and for chemosensory stimuli are implemented in AnimatLab (photoreceptors and auditory receptors are planned for a future version). Representations of each sensory receptor are created in both the body model and the neural circuit model to map the field of sensory receptors onto the population of sensory neurons. In the body model, single mechano- or chemoreceptors, or an array of such receptors, can be placed on the body surface where contact with an appropriate stimulus will activate it (Fig. 2a). Each mechanoreceptor has a 2D receptive field that describes its sensitivity to stimuli applied on the body surface in its vicinity. The distance from the contact to the center of the field is used to scale the force of the contact using a Gaussian function (Fig. 2a-2). In the neural circuit model, the corresponding representation of a body receptor is linked through a transduction adapter to a neuron compartment that represents the sensory neuron excited by the receptor. The scaled force produced at the receptor is transduced by a sensory adapter into a generator current (Fig. 2a-3) and passed into the sensory neuron (Fig. 2a-4). Receptors with overlapping receptive fields may detect the same physical contact and evoke spike responses in