The Si elegans Project – The Challenges and Prospects of Emulating Caenorhabditis elegans*

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Abstract. *Caenorhabditis elegans* features one of the simplest nervous systems in nature, yet its biological information processing still evades our complete understanding. The position of its 302 neurons and almost its entire connectome has been mapped. However, there is only sparse knowledge on how its nervous system codes for its rich behavioral repertoire. The EU-funded ***Si elegans*** project aims at reverse-engineering *C. elegans*' nervous system function by its emulation. 302 in parallel interconnected field-programmable gate array (FPGA) neurons will interact through their sensory and motor neurons with a biophysically accurate soft-body representation of the nematode in a virtual behavioral arena. Each FPGA will feature its own reprogrammable neural response model that researchers world-wide will be able to modify to test their neuroscientific hypotheses. In a closed-feedback loop, any sensory experience of the virtual nematode in its virtual environment will be processed by sensory and subsequently interconnected neurons to result in motor commands at neuromuscular junctions at the hardware-software interface to actuate virtual muscles of the virtual nematode. Postural changes in the virtual world will lead to a new sensory experience and thus close the loop. In this contribution we present the overall concepts with special focus on the virtual embodiment of the nematode. For further information and recent news please visit http://www.si-elegans.eu.

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1 Introduction

The *C. elegans* hermaphrodite, a soil-dwelling worm, is comprised of exactly 959 cells, including 95 body wall muscle cells and 302 neurons. The morphology, arrangement and connectivity of each cell including neurons have been completely described and are found to be almost invariant across different individuals. There are approximately 7000 chemical synaptic connections, 2000 of which occur at neuromuscular junctions, and approximately 600 gap junctions [2]. Despite its simplicity, the nervous system of *C. elegans* does not only sustain vital body function, but generates a rich variety of behavioral patterns in response to internal and external stimuli. The *Si elegans* project aims at providing a comprehensive artificial *C. elegans* emulation system from which the principles of neural information processing underlying its behavior can be derived.

2 Si elegans Concepts

The *Si elegans* project will provide the 302 neurons of the *C. elegans* nervous system as highly reconfigurable FPGA-based hardware modules. In contrast to popular serial communication protocols (*e.g.*, address event representation (AER), network-on-chip (NoC)), individual FPGA neurons will be linked by free-space electro-optical or acoustic interconnection concepts. They will not only replicate the known connectome of *C. elegans* to result in the complete and correctly wired neural circuitry of the nematode, but allow for a genuinely parallel axo-synaptic information flow between neurons. A single FPGA will be utilised per *C. elegans* neuron, thus allowing for highly detailed and biologically plausible neuron and synaptic models to be implemented. Intuitive drag-and-drop configuration from primitives (*e.g.*, synapses, integration algorithms) as well as import modules for existing models from common simulation engines (*e.g.*, NEURON, BRIAN, NeuroML) will be provided. This hardware nervous system will be embodied by a virtual representation of the nematode (including correct biophysics, sensors and actuators) being situated in a virtual environment with programmable stimuli for real-time behavioural studies. Web-accessible services will include the software for defining neural response models, for designing virtual behavioural experiments and for transcoding models into HDL code. They will connect to a dedicated computer running the virtual arena (VA) and interfacing to the *Si elegans* hardware framework for its programming and for the real-time, closed-loop run-time streaming of sensory input stimuli and motor output commands between the virtual worm and the respective sensory and motor neurons of its 'hardwired' nervous system. The system will be designed for scalability to allow for the emulation of larger nervous systems.

3 The Virtual Arena

The VA is devoted to the realistic virtualization of the nematode including its muscles, its environment, all relevant chemical and mechanosensory stimuli, and the resulting behaviors. The simulation is based on the real biophysics of the *in vivo* model. Its interaction with the simulated environment will map experience (stimuli) onto a sensory input matrix of the emulation hardware. The virtual arena is interactive. All parameters can be defined by researchers through the same web portal where the simulation output will be rendered as well. This will permit to define experiments and validate neurocomputational and behavioral hypotheses. The environment description includes different terrains or fluids which influence the locomotion of the nematode. The complex biomechanical and fluid dynamic-based simulation will be based on the high-level middleware SOFA [1] in a workstation directly connected with the FPGA architecture (Fig. 1).

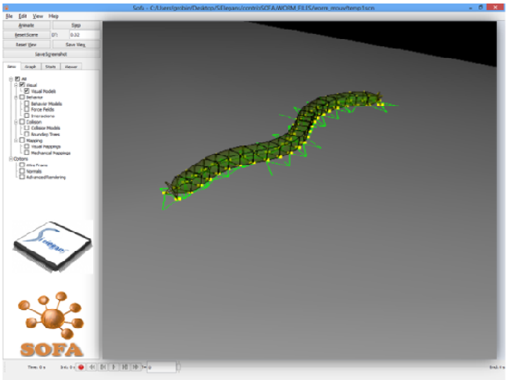

Fig. 1. First prototype of the virtual arena in SOFA. The visual output of the simulation is rendered in the *Si elegans* (Fig.1) web browser using WebGL. This allows for a fast rendering (animation) on the research client of the virtual arena simulation. The SOFA engine, which uses CUDA, allows the realistic interaction between deformable objects and has the ability to simulate fluid dynamics. The modeling strategy for the 95 muscles is based on mass spring dampers.

The rendering of the simulation in SOFA runs at 65 frames per second (FPS) while the rendering of the WebGL animation will be slower. In a future version, we will implement more complex locomotion models and more environmental features (*i.e.* terrains features, obstacles, chemical gradients, etc.).

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