

# Neurobotics: A strategic pillar of the Human Brain Project

Alois Knoll<sup>1\*</sup> and Marc-Oliver Gewaltig<sup>2</sup>

**N**eurobotics is an emerging science that studies the interaction of brain, body, and environment in closed perception-action loops where a robot's actions affect its future sensory input. At the core of this field are robots controlled by simulated nervous systems that model the structure and function of biological brains at varying levels of detail (1). In a typical neurobotics experiment, a robot or agent will perceive its current environment through a set of sensors that will transmit their signals to a simulated brain. The brain model may then produce signals that will cause the robot to move, thereby changing the agent's perception of the environment.

Observing how the robot then interacts with its environment and how the robot's actions influence its future sensory input allows scientists to study how brain and body have to work together to produce the appropriate response to a given stimulus. Thus, neurobotics links robotics and neuroscience, enabling a seamless exchange of knowledge between these two disciplines.

Here, we provide an introduction to neurobotics and report on the current state of development of the European Union-funded Human Brain Project's (HBP's) Neurobotics Platform (2, 3). HBP is Europe's biggest project in information communication technologies (ICT) to date ([www.humanbrainproject.eu](http://www.humanbrainproject.eu)) and is one of two large-scale, long-term flagship research initiatives selected by the European Commission to promote disruptive scientific advance in future key technologies. It will have a duration of 10 years and deliver six open ICT platforms for future research in neuroscience, medicine, and computing, aimed at unifying the understanding of the human brain and translating this knowledge into commercial products.

## History and current status of neurobotics

One of the first researchers to apply the concepts of neurobotics was Thomas Ross, who in 1933 devised a robot with a small electromechanical memory cell that could learn its way through a very simple maze via "conditioned reflex" (4). In his 1948 book *Cybernetics*, Norbert Wiener laid the theoretical foundation for robotics as "the study of control and communication in the animal and the machine" (5). Since then, however, robotics research has focused largely on industrial applications.

Recently, industry has again been advancing technology by building robotic bodies that are softer, more flexible, and more durable than before. However, despite numerous attempts, no robot today matches the cognitive or behavioral abilities of even the simplest animals, let alone humans. What is still missing after decades of effort? Robots are still lacking a brain that allows them to learn to adapt to and exploit the physics of their bodies.

Today, there are two main schools of thought in neurobotics research. The first focuses on *biologically inspired robots* with bodies, sensors, and actuators that mimic structural and functional principles at work in the bodies and organs of living creatures. The second concentrates on *brain-inspired control architectures*.

Biologically inspired robots are adaptable and can display rich perceptual and behavioral capabilities. In contrast to industrial robots, they often use compliant materials that make their mechanics intrinsically flexible. Examples of advanced biology-inspired humanoid robots are the iCub, a humanoid robot "child" (6); Kojiro, a humanoid robot with about 100 artificial muscles (7); and ECCEROBOT (Embodied Cognition in a Compliantly Engineered Robot), a humanoid upper torso that attempts to replicate the inner structures and mechanisms of the human body in a detailed manner (8). More recently, engineers have created Roboy, a soft human body with a spine and a head that can display several emotional patterns (9); the ASIMO robot (10); and, most recently Atlas, the latest agile anthropomorphic robot developed by Boston Dynamics (11). The last two are constructed from hard materials and implement research in machine walking. Such advances in multilegged robots have led to a renewed interest in applications for the military [BigDog, also from Boston Dynamics (12)]; disaster management [iRobot's PackBot (13), a snake-like robot developed by Hitachi-GE Nuclear Energy and IRID (International Research Institute for Nuclear Decommissioning) (14), and a scorpion-like robot from Toshiba (15)]; and entertainment [the NAO and Pepper robots from Aldebaran Robotics (16)]. Researchers have also developed robots that can mimic the characteristics of animals, such as locomotion in snakes and spiders, whisking in rodents, or jumping in frogs.

Brain-inspired control architectures are robotic control systems that on some level reflect properties of animal nervous systems. In general, they are tailor-made for a specific set of tasks, often using a combination of artificial neural networks, computer vision/audition, and machine learning algorithms. Early work in this field was done by Miyamoto et al. (17), who developed an artificial neural network with brain-inspired hierarchical architecture that could control an industrial manipulator by acquiring a dynamical model of the robot through the "feedback-error-learning" method. Later, Edelman et al. developed the "Darwin" series of recognition automata (18) to study different behavioral phenomena ranging from pattern recognition to association to autonomous behavior and sensorimotor coordination. Cox and Krichmar derived a robot controller based on the neuromodulatory systems of mammalian brains (19). Burgess et al. used a mobile robot

<sup>1</sup>Technical University of Munich, Department of Informatics, Chair of Robotics and Embedded Systems, Garching bei München, Germany

<sup>2</sup>Ecole Polytechnique Fédérale de Lausanne, Blue Brain Project, Campus Biotech, Geneva, Switzerland

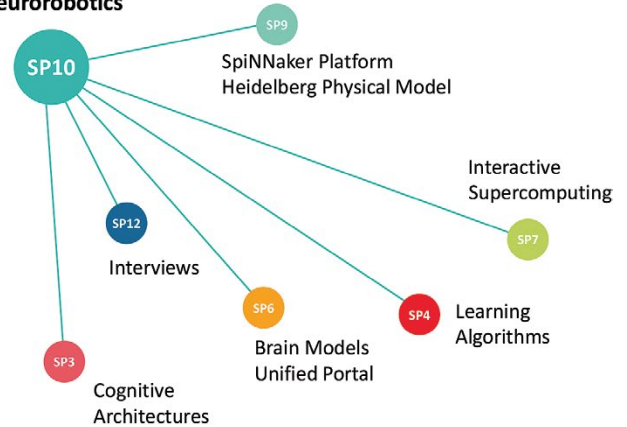
\*Corresponding Author: [knoll@in.tum.de](mailto:knoll@in.tum.de)

**FIGURE 1. A** schematic of the Human Brain Project showing collaborations between the neurorobotics subproject and other subprojects shown in the list on the left.

#### Main Collaborating Subprojects

- SP3 Systems and Cognitive Neuroscience
- SP4 Theoretical Neuroscience
- SP6 Brain Simulation Platform
- SP7 High Performance Analytics and Computing Platform
- SP9 Neuromorphic Computing Platform
- SP12 Ethics and Society

#### Neurorobotics



to test a model of the rat hippocampus (20). Ijspeert's group investigated low-level mechanisms of locomotion in vertebrates by constructing a salamander robot controlled by central pattern generators (21). Further work has included self-organizing synchronization in robotic swarms (22) and the learning of compositional structures from sensorimotor data (23).

Lund et al. used spiking-neuron models to derive a model for cricket phonotaxis that they evaluated on a mobile robot (24). Since then, spiking neural networks have become a standard tool in brain-based robotics and are used to control complex biomechanical systems such as the musculoskeletal model of the human body developed by Nakamura's group (25). For example, Sreenivasa et al. published a study on modeling the human arm stretch reflex based on a spinal circuit built of spiking neurons (26). Kuniyoshi et al. developed a fetus model to simulate the self-organized emergence of body maps in a nervous system of spiking neurons (27, 28). Finally, Richter et al. controlled a biomimetic robotic arm with a model of the cerebellum that was executed in biological real-time on the SpiNNaker neuromorphic computing platform (29, 30).

A third line of research that is usually not mentioned along with neurorobotics—but with which it greatly overlaps—is neuroprosthetics, which can in fact be viewed as the translational branch of neurorobotics. To advance neurorobotics further, a close collaboration between neuroscientists, roboticists, and experts in appropriate computing hardware is clearly mandatory.

#### The Human Brain Project's Neurorobotics Platform

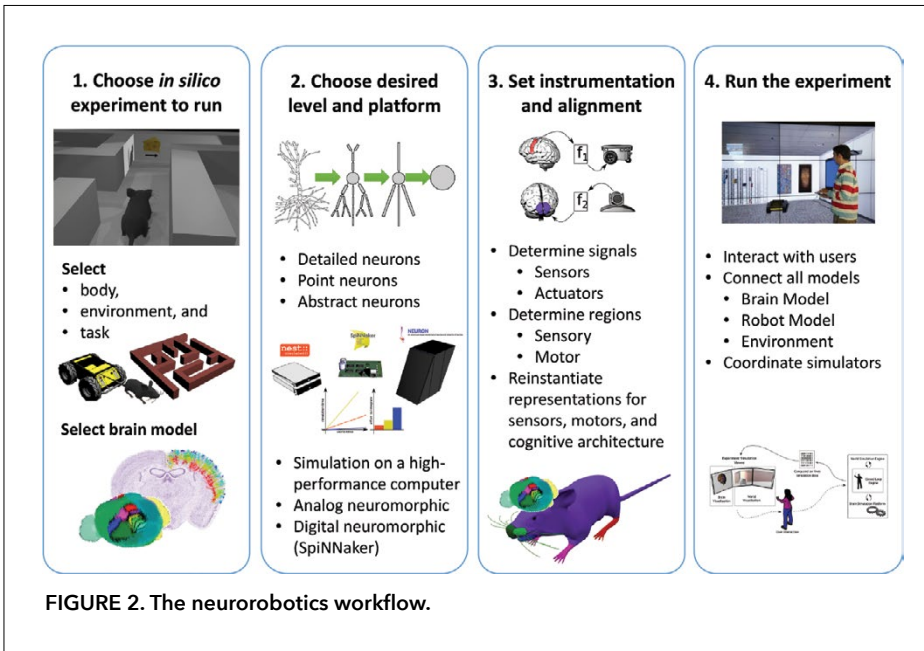
The Neurorobotics Platform (NRP) is a novel tool that allows scientists to collaboratively design and conduct *in silico* experiments in cognitive neuroscience, using a neurorobotics-focused approach. The NRP thus plays an integrative role in HBP as it provides the tools for all scientists to study brain models in the context of their natural habitat—the body.

The overarching goal of HBP is to help unify our under-

standing of the human brain and to use this knowledge to develop new products and technologies. HBP features a huge and diverse spectrum of research and development activities ranging from human and mouse brain-data collection to the discussion of ethical issues arising from brain simulation and brain-based technologies. These activities are organized in a network of closely collaborating subprojects. As shown in Figure 1, the neurorobotics subproject collaborates directly with almost all other subprojects. Six of these subprojects are to develop ICT platforms that will make technology developed within HBP available to the public. The Neuroinformatics Platform will deliver searchable brain atlases to enable access to a vast amount of digitized brain data. The Medical Informatics Platform will gather and process clinical data for research on brain diseases. The Brain Simulation Platform will provide detailed large-scale brain simulations that will run on the supercomputer infrastructure of the High-Performance Analytics and Computing Platform and on the novel neuromorphic hardware of the Neuromorphic Computing Platform. The NRP will connect the brain simulation and computing platforms through an advanced closed-loop robot simulator for neurorobotics experiments whereby robots can be controlled by a simulated brain model.

All these platforms contribute to the virtualization of brain and robotics research. Virtual brain research, when supported by powerful and well-calibrated models, will enable researchers to perform experiments impossible in the real world, such as the simultaneous placement of 1 million probes in a mouse brain. By the same token, the advantage of virtual robotics research is the enormous acceleration of experiment and development speed, alleviating dependency on real hardware in real environments. The possibility for smooth “mode changes” between real-world and virtual design phases is certainly essential, and only when this step becomes simple will an iterative give-and-take of insights between both worlds be possible.

In the remainder of the article we will introduce the “neurorobotics workflow,” a principled step-by-step ap-



proach to designing neurorobotics experiments for both roboticists and neuroscientists. The topics of the following section will cover details about the implementation of this workflow in the NRP, and the underlying tools and software architecture. We will then present a series of pilot experiments that were designed using the NRP to validate the workflow and to benchmark the performance and usability of its first public software release to the scientific community. Finally, we will summarize results achieved so far in the neurorobotics subproject and provide an outlook on the future development of the NRP.

## Methodology

The approach for the NRP consists of providing a number of design applications for models (of environments, robot bodies, and brains) and simulation engines that are integrated into a web-based frontend. Using this web frontend, users at different locations can rapidly construct a robot model, its brain-based controller, an environment, and an execution plan. We call this ensemble a “neurorobotics experiment.” The NRP also allows reusing and sharing of previously defined experiments, thus opening a new area of collaborative neurorobotics research.

Only through integration of the appropriate simulation engines can we expect to achieve meaningful results, especially if we want to close the loop between the brain, the robot, and its environment such that the simulated robot perceives its simulated environment through its simulated sensors and interacts with it through its simulated body. The simulation technologies used must provide the highest available fidelity and the best possible match between an observation in the real world and its counterpart in the virtual world.

In brain modeling, there are currently two extremes. The first are models that focus on the functional properties of

nervous systems. They define control architectures and neural network models, possibly trained by deep learning algorithms, with the aim of solving a particular set of tasks. Examples are the Spaun model (31) and control architectures commonly found in cognitive robotics. At the other extreme are digital reconstructions of neural circuits (32) or even entire brains of mice and rats, for example, based on experimental data. These models focus foremost on the structural and dynamical details of the reconstructed system and regard brain function as an emergent phenomenon of these brain reconstructions.

While many researchers argue in favor of one or the other position, we propose that the most productive route is to combine the two approaches. For example, many theories exist for higher-level brain functions like visual perception, but not all of

these theories can be true at the same time. Some may be appropriate for humans, whereas others may be applicable to cats or rodents. The only way to separate suitable theories from less suitable ones is to give researchers a tool that allows them to confront a given theory of brain function with the anatomical and physiological realities of a particular brain embedded in a concrete body, be it mouse, cat, or human. The NRP aims to be such a tool, following the time-tested approach of analysis by synthesis.

A typical neurorobotics experiment might involve the simulation of a rat as it navigates through a maze. In this case, the control architecture for the simulated rat could comprise sensory areas, a hippocampus, and a motor area to generate movements. Traditionally, these components are individually selected and specifically adapted to match the robot, the environment, and the task. The neurorobotics workflow departs from this approach: Rather than designing specific neural control architectures for each robot and each experiment, it provides elements for the rapid design and training of application-specific brains and for embedding these brains in appropriate robotic embodiments, with the theme of “modular brains for modular bodies.” It will incorporate both the experimenter’s own research as well as results from others.

The neurorobotics workflow starts with the choice of the system to be examined and ends with the execution of the experiment. It has four elementary steps, as described below and illustrated in Figure 2.

### Step 1: Choose *in silico* experiment to run

First, the researcher needs to specify the system to be investigated by deciding on the robot body, the environment, the task for the robot to solve, and the brain (the neural controller) that will control the body. We will refer to the specific combination of body, environment, and neural

system as a “neurorobotic system.” The concrete decisions for building each neurorobotic system will influence all other steps of the workflow.

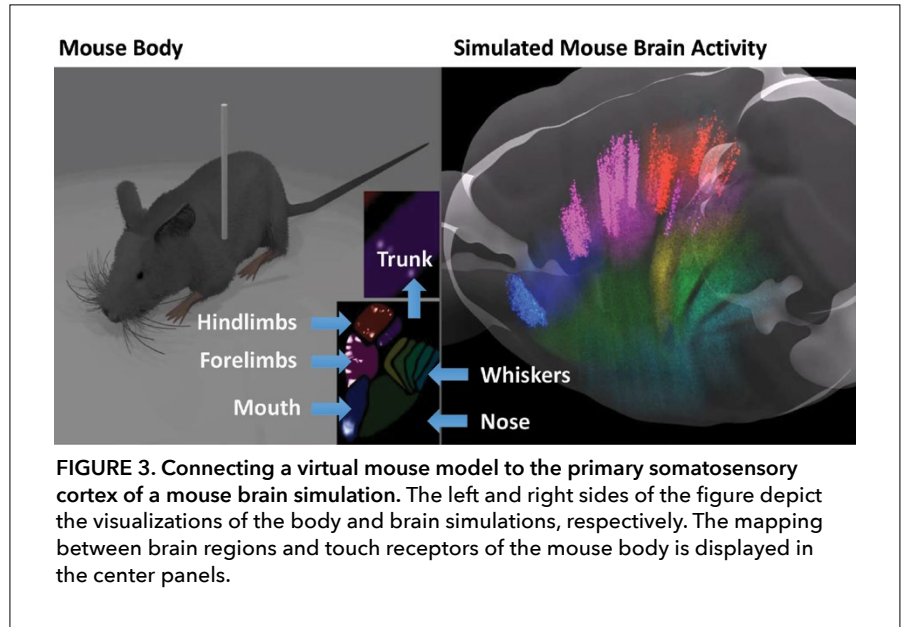
### Step 2: Choose desired level and platform

In the second step, the implementation of the neurorobotic system chosen in step 1 needs to be specified. The simulated nervous systems can be realized at varying levels of detail ranging from conceptual abstract models to spiking-point neuron models (33) or highly detailed neural simulations (32). Similarly, the robotic body can be built of stiff material with standard actuators from industrial robotics or can be based on a more complex design of soft structures (34), including biomimetic musculoskeletal actuators with many degrees of freedom.

Every component may be realized physically or in simulation. But why use simulated robots when our ultimate goal is a brain model that can control a real robot in a physical environment? Real robots have the advantage that all real-world complexities are considered. The same applies to the environments in which the robot is meant to perform its task. Computer models of robots and environments are complex and still inaccurate. However, robot simulations can be easily accessed without the need for purchasing expensive hardware. They also enable quick changes of the robot design and do not suffer from mechanical failure. During the simulation, the system state of the robot can be fully inspected at any point in time. Specific setups like the parallel execution of hundreds of simulations or the simulation of biological muscles cannot be realized at all in a physical setup. In the end, the decision whether to use simulated or physical robots is not influenced by scientific considerations, but rather by our ability to efficiently implement the brain model into the robot.

Like the robot, brain models can be executed either as a pure simulation or as a physical model, with the difference being that simulations tend to be more accurate than any physical model we can build to date. Thus, if we are interested in brain models that capture many of the properties of real brains, we must resort to simulation. These simulations, however, run much more slowly than real-time, and this limitation forces us to also simulate the combination of robot and environment, because we cannot slow down the physics that govern them. To test and implement simplified and abstracted brain models, we must find physical implementations that will also allow us to use real robots and environments.

In HBP, physical brain models are developed through the neuromorphic computing subproject, either by emulating neural dynamics based on analog integrated circuits (35) or by SpiNNaker, a digital neuromorphic system built of standard smartphone microprocessors interconnected by an efficient communication mesh (30).



**FIGURE 3. Connecting a virtual mouse model to the primary somatosensory cortex of a mouse brain simulation.** The left and right sides of the figure depict the visualizations of the body and brain simulations, respectively. The mapping between brain regions and touch receptors of the mouse body is displayed in the center panels.

### Step 3: Set instrumentation and alignment

After step 2 of the workflow, both the brain simulation and the robot are fully specified. Now, the researcher must define the connection between brain and body, specifically the mappings that translate the neural output of the brain into motor commands for the robot, and translate the sensor readings into input for the brain. An example of this mapping process is depicted in Figure 3, where touch receptors located on the skin and the whiskers of a mouse body are mapped to the corresponding cortical areas of a simulated mouse brain. Defining these mappings within the closed-loop integration of a brain simulation and a body model comprises the process stage that is the core of the workflow.

### Step 4: Run the experiment

In the final step of the workflow, the researcher executes the neurorobotics experiment. In this phase, the brain model and the robot model run in parallel with the output of one system being the input of the other and vice versa. It is of vital importance that both simulations are synchronized and run on the same timescale, since only then can the behavior observed in the neurorobotics experiment be validated with data from neuroscience and biology. During the execution of the experiment, the researcher can monitor and control all states and parameters of the experiment (brain, body, and environment) including the option to pause and restart it, which is technically impossible to achieve in the laboratory.

In essence, the NRP consists of different model designers and simulation engines that allow rapid construction of neurorobotics experiments. It enables researchers to design virtual robot bodies, to connect these bodies to brain models, to embed them in rich, virtual environments, and, ultimately to calibrate the brain models to match the specific characteristics of the

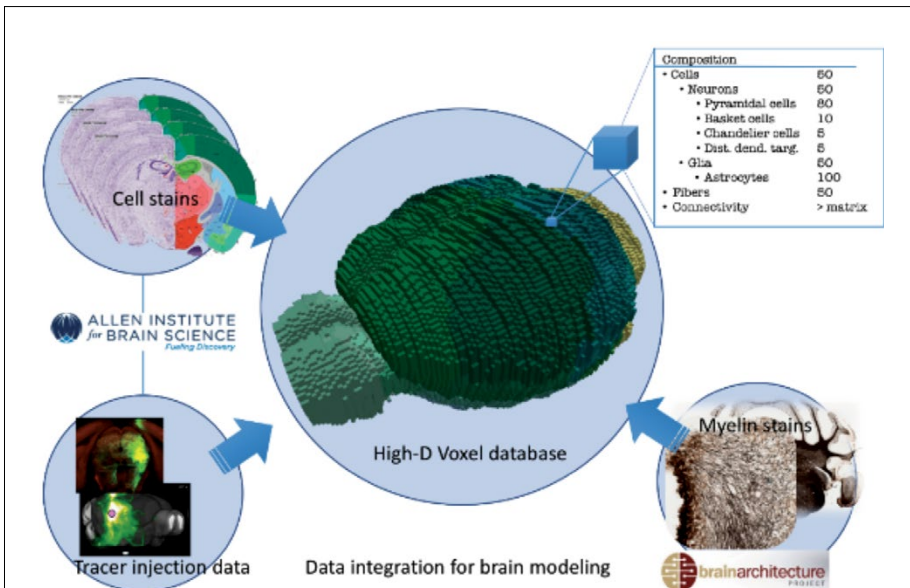


FIGURE 4. Schematic of brain modeling based on multiscale integration of data from different sources.

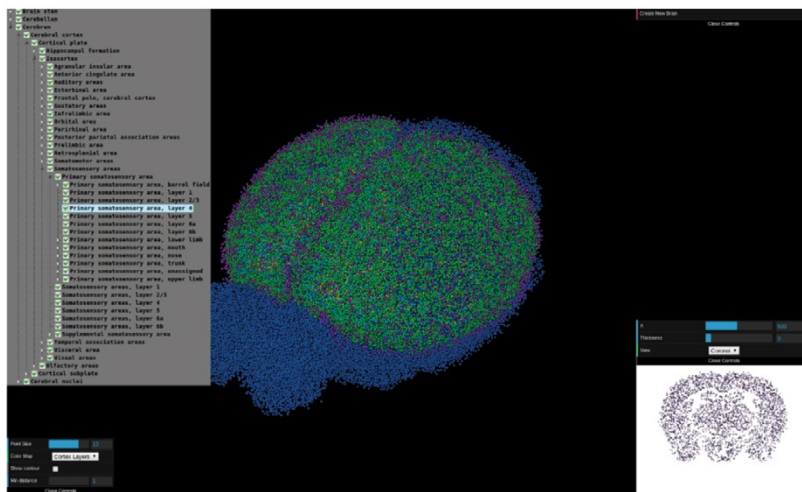


FIGURE 5. Synthesizing a brain model from measurement data.

robot's sensors and "muscles." Collections of predefined models for brains, bodies, environments, sensors, and actuators will also allow nonexpert users to quickly set up new experiments. Researchers will further be able to use traditional techniques from neuroscience, such as lesion studies or manipulations of single neurons, to identify the right control architecture for the specific task. The resulting setups allow researchers to perform *in silico* experiments, initially replicating previous work, but ultimately breaking new ground. The individual steps from the collection of brain data to synthesizing a brain model based on this data and finally to connecting the brain simulation to a body model are illustrated in Figures 4–6.

It goes without saying that for virtualized neurobotics research to be meaningful, the models for all constituents (environment, robot bodies, and brains) must reflect and integrate current knowledge of all entities, including knowledge about all abstraction levels of the brain, from the cell level to information processing. The neurobotics subproject will therefore openly collaborate with research groups worldwide—both within and outside HBP—and continuously integrate the state of the art in brain and robot research.

Even though the NRP is designed with a focus on simulation, it is important to realize that the virtual design and virtual execution tool chain implemented by the NRP can, at any step along the process, be translated to the real world; thus, real robots can be designed from their models in the virtual world. They will produce the same behavior as their virtual counterparts, provided the models are permanently calibrated. For industrial practice, this means there can be a very rapid design-test-revise cycle that produces robots with integrated behavior based on "brain-derived technologies."

## Implementation

The NRP consists of a frontend, called the "neurobotics cockpit," and a simulation backend. The cockpit gives access to a set of tools that implement the first three steps of the neurobotics workflow. The tools allow users to select and configure robots and environments, configure the brain model, and set up neurobotics experiments. Different visualization channels allow control and visualization of the simulation and interaction

with the experiment while it is running. The backend orchestrates the different tools for the simulation of robot, environment, and brain model, and manages the signal flow between these tools and the frontend. An overview of the complete system architecture is depicted in Figure 7.

### Frontend: Designers

The robot designer creates and adapts robot models, the environment designer sets up the virtual environment with which the robot will interact, the brain interfaces and body integrator (BIBI) specifies the mapping between the simulated brain and the sensors and actuators of the robot, and the experiment designer defines the neurobotics experiment.

The robot designer implements all functionality necessary to design robotic bodies, adapt their appearance, set their dynamic parameters, and equip them with sensors and actuators. Since users in neuroscience will be less interested in designing robotic bodies, needing them simply as tools for conducting closed-loop experiments, the designer includes libraries with ready-to-use models of robots, sensors, and actuators. In the current version of the NRP, users can choose from a model of the iCub robot (6), the six-legged walking machine LAURON (37), or the mobile robot Husky (38). Most importantly, the designer also includes a virtual mouse model that allows one-to-one comparison to experimental neuroscience studies. Future releases of the NRP will incorporate further refinements and improvements to this model, such as the addition of a realistic simulation of the musculoskeletal system. For the advanced user, the NRP offers a robot designer plugin for the popular open-source 3D modeling software Blender (36).

Similar to a real neuroscience experiment, a neurorobotics experiment is conducted in a specific environment. The environment designer is a tool for designing virtual environments tailored to the needs of the experiment. Moreover, users will be given the option to share their models with other scientists using the common HBP infrastructure.

The mapping between brain and body lies at the core of every neurorobotics experiment. In correspondence with step 3 of the neurorobotics workflow, BIBI provides tools for both spatial and representation mapping. Presently, there is only support for small brain models, which means that no spatial mapping is required. The representation mapping between the brain model and robotic sensing and actuation is accomplished by implementing so-called “transfer functions,” which translate the data exchanged between the brain simulation and the robot simulation. Beyond mere signal translation, transfer functions can also directly control the robot’s actuators in response to sensory input and thereby bypass further processing in the brain in a reflex-like manner.

We are now adding support for more realistic brain models in close collaboration with HBP’s brain simulation subproject, which is developing the brain builder and

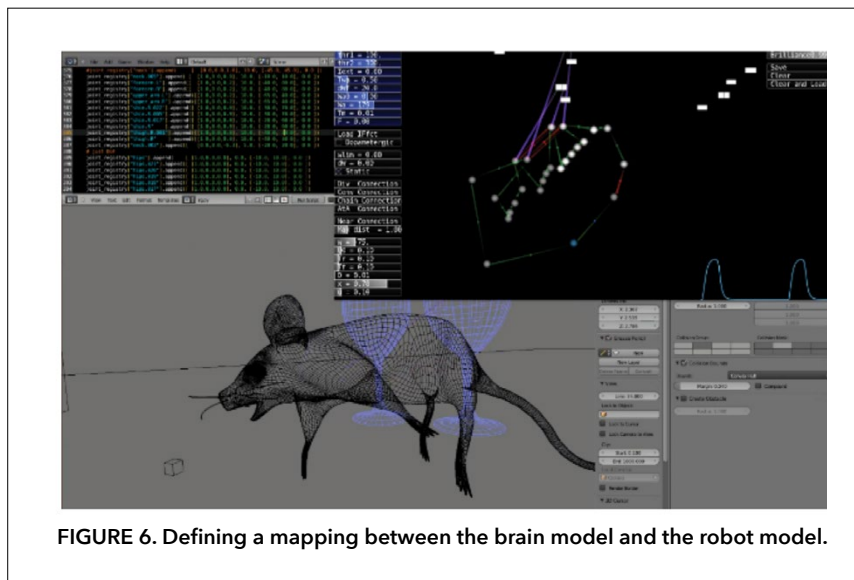


FIGURE 6. Defining a mapping between the brain model and the robot model.

the brain atlas embedding module as part of its Brain Simulation Platform. Following the paradigm of predictive neuroscience, this platform builds upon and extends the bottom-up biological reconstruction process to brain modeling, which has recently enabled the digital reconstruction of the microcircuitry of the rat somatosensory cortex (32).

The brain builder is at the core of this process. It allows researchers to synthesize brain models from a large-scale database delivered by the neuroinformatics subproject, which is designed to store the vast amount of available experimental knowledge about the brain. General principles of brain structure and function that are beyond the scope of experimental data are represented algorithmically and validated against biological knowledge. Depending on the intended application and the research question, the brain builder will support the generation of brain models at different levels of granularity ranging from the molecular level to microcircuits to whole brains. Both brain models and experimental data can be visualized and searched using the brain atlas embedding module.

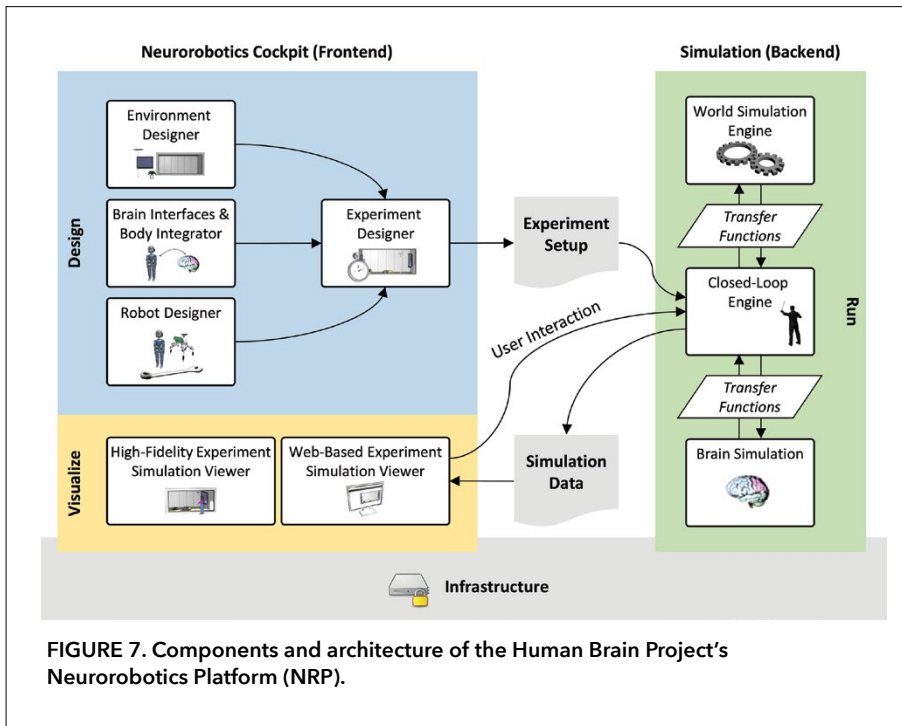
After selecting a brain model from this component, BIBI will allow researchers to set up a spatial mapping by selecting neurons graphically using the brain atlas embedding module, and to map these neurons to the robot model. The neurorobotics subproject will develop an open standard for storing and sharing the brain-body mappings created with the BIBI tool.

The experiment designer combines the output of the other three designers in a virtual protocol for neurorobotics experiments. Future releases of the NRP will contain an intuitive graphical user interface for setting the number of runs, terminating conditions, and measurement values to be recorded during experiments.

#### Frontend: Visualization

The second group of frontend software components addresses the visualization of the neurorobotics experiment. Depending on the experimental setup, this visualization can be computed from live data in a currently running simulation or generated from a previously recorded experiment.

The NRP supports two different types of visualization. The first is the web-based experiment simulation viewer, which runs in a browser and can therefore be used on any standard personal computer or even on mobile devices,



**FIGURE 7. Components and architecture of the Human Brain Project's Neurorobotics Platform (NRP).**

making the NRP easily accessible to interested users without the burden of buying dedicated hardware. However, compared to real-world experiments, the interaction is less intuitive and the fidelity of the visualization is limited by the screen size and performance of the graphics processing unit.

The second type of visualization supported by the NRP is the high-fidelity experiment simulation viewer, which delivers a much more immersive experience by rendering life-size visualization on a display wall or in a cave automatic virtual environment (CAVE). While this approach requires complex installation of displays and dedicated hardware, it delivers the highest degree of realism and even opens up the possibility for mixed-reality setups, where persons or objects in front of the display wall or CAVE can become part of the experiment.

### Backend: Simulation

The backend of the NRP processes the specifications of the experiment and coordinates the simulators. The world simulation engine computes and updates the states of the robot and the environment based on the system descriptions from the corresponding designers. It is based on the highly modular Gazebo simulator (39), which can be easily augmented with new simulation modules. The brain model is simulated by the well-established neural simulation tool (NEST) (40), which ensures that even brain models of the largest scale can be simulated using HBP's extensive computer resources. In the future, the user will not only be able to choose the desired brain model but also whether the simulation will be computed on standard hardware using a point-neuron simulator, on one of the two neuromorphic hardware simulators that are provided

by the neuromorphic computing platform, or on a supercomputer running a detailed simulator. Both simulations are coordinated and synchronized by the closed-loop engine that connects and manages the brain simulation and robot simulation according to the mapping defined in the BIBI component. In correspondence with the different levels of modeling supported by the brain builder, the brain simulation subproject offers different simulators for molecular-, cellular-, and network-level analyses. Whereas network-level simulations capture less detail about individual neurons and synapses, they are based on established point-neuron models that support large-scale models of whole brain regions or even complete brains.

The NRP is fully integrated into the HBP Collaboratory, a web portal providing unified access to the six ICT platforms developed in HBP. The portal implements a common set of services for storage or authentication that is

automatically available to users of the NRP and allows an easy exchange of data. The integration of the novel workflows and data formats developed into a common portal makes new research results immediately available to all members and collaborators. The NRP therefore automatically benefits from the work of the entire neuroscientific community, making it not only the most advanced tool in the field, but one that sets a new standard for state-of-the-art neurorobotics research.

### Experimental results

We validated both the neurorobotics workflow and the NRP in four different experiments that are available in the first public release of the platform. Because the interface to the brain simulation platform is under intense development, all experiments currently rely on simplified neural controllers simulated by NEST (40).

#### Basic closed-loop integration

The first proof-of-concept experiment carried out on the NRP was a simple Braitenberg vehicle (41), in a version designed for the Husky wheeled robot and the LAURON hexapod. The setup is based on a model of the Husky robot that is equipped with a camera and capable of moving around in a virtual room included in the NRP. The camera output is processed and forwarded to the NEST simulation of a neural network implementing basic phototaxis. As shown in Figure 8, the room contains two displays located on opposite walls. During the simulation, the user can interactively set the color of each display.

To demonstrate the modularity of our approach, the Braitenberg experiment was also implemented for the walking machine LAURON (Figure 8). Both the Husky

and LAURON robots were directed by the Braitenberg brain to walk in the direction of the red stimulus.

### **Simulation of a humanoid robot and a retina model**

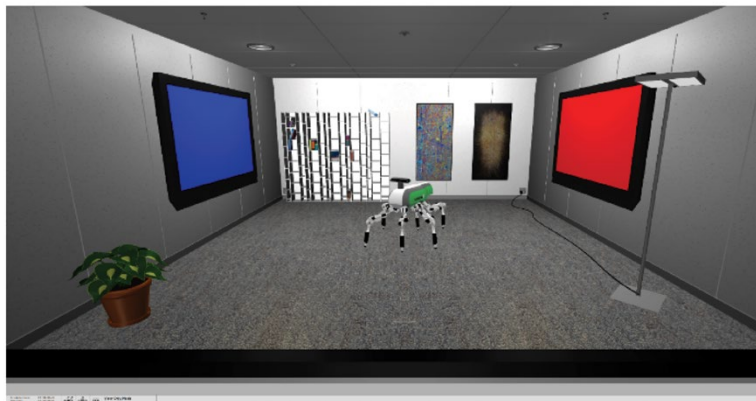
Studies of human brain models will require realistic humanoid embodiments. To this end, we integrated the iCub robot model delivered with the NRP. A sample experimental setup is depicted in Figure 9. The robot model is equipped with two cameras positioned at the eyes and is aimed toward one of the screens in the virtual room. Simple spiking neural networks similar to that used in the Braitenberg experiment control the eye motion. However, in this case, the network causes the robot's eyes to track a moving visual stimulus displayed on the screen. As can be seen in the figure, the user can not only display the spike raster plot, but can also access the recordings of the two cameras placed in the head of the iCub model. We are currently integrating a much more realistic model from a computational framework for retina modeling (42).

### **Mouse model and soft-body simulation**

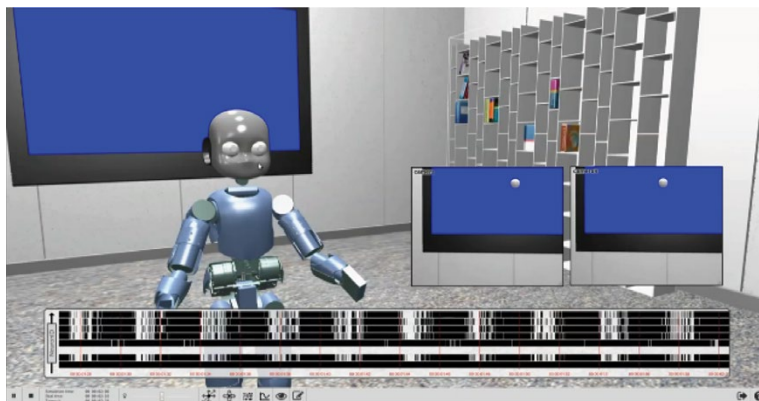
The virtual mouse model is an essential component of the NRP and a key to comparative studies bridging traditional neuroscience and virtual neurorobotics experiments. Compared to the other robot models considered thus far, the simulation of a mouse body is especially demanding due to its soft body structure. The mouse experiment included in the first release of the NRP therefore adopts the same simple protocol as the other prototype experiments and focuses on the soft-body simulation. The result is shown in Figure 10. The mouse model is placed at a junction point of a Y-shaped maze. Each direction leads to a dead end with a screen. As in the Braitenberg experiment, the neural controller directs the mouse to move its head toward the red stimulus. A more detailed, realistic-appearing mouse model has been completed, and a prototype that maps the sensory areas of this model to corresponding cortical areas of a detailed point-neuron model of the mouse brain has been successfully tested. The results will soon be available on the NRP.

### **Closed-loop neuromorphic control of a biomimetic robotic arm**

To complement the purely virtual experiments running on the NRP, we also implemented an initial physical neurorobotics experiment (29). The robot was a single-joint biomimetic arm with two antagonistic tendon-driven artificial muscles (Figure 11). It was assembled from design primitives of the modular Myrobotics toolkit (43), which allows the easy assembly of biomimetic robotic structures



**FIGURE 8.** Live visualization of the LAURON Braitenberg experiment in the web-based experiment simulation viewer.



**FIGURE 9.** Live visualization of the iCub eye-tracking experiment.

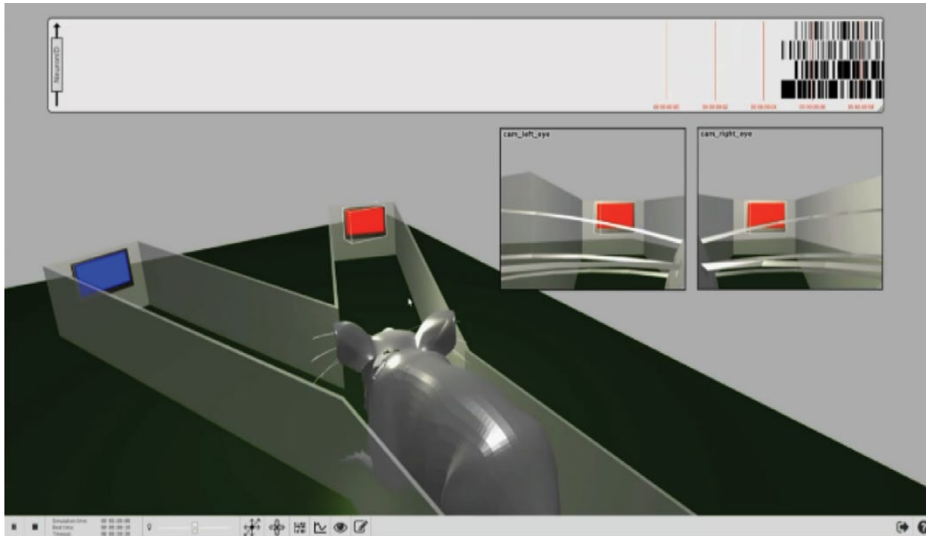
with arbitrary complexity. A SpiNNaker system (30) was connected to the robot via a dedicated hardware interface that translated between the communication protocols of SpiNNaker and Myrobotics (44). The arm was controlled by a cerebellum model simulation adapted to run on the SpiNNaker architecture from the system described by Luque et al. (45). In particular, we augmented the SpiNNaker software framework to support the supervised learning rule defined by the model. Based on this rule, the system successfully learned to follow a desired trajectory.

### **Conclusions and outlook**

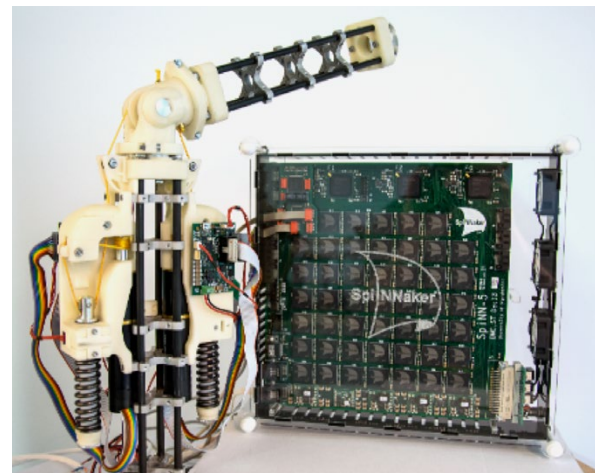
Following the neurorobotics subproject's overarching theme, "modular brains for modular bodies," we have successfully integrated the most advanced tools and technologies from brain simulation, robotics, and computing in a unified and easy-to-use toolset that will enable researchers to study neural embodiment and brain-based robotics. This integrative approach combines and connects the results of all HBP subprojects, rendering the neurorobotics subproject a strategic pillar of HBP.

The NRP (neurobotics.net) is the first integrated and Internet-accessible toolchain for connecting large-scale brain models to complex biomimetic robotic bodies.





**FIGURE 10.** Mouse model experiment with soft-body physics simulation and live visualization of spike trains.



**FIGURE 11.** Closed-loop neuromorphic control of a single-joint robot assembled from design primitives of the Myrobotics toolkit (left). The robot is controlled by a cerebellum model that runs on a SpiNNaker system (right). © 2016 IEEE. Reprinted, with permission, from (29).

Based completely on simulations, the platform enables the design and execution of neurobotics experiments at an unprecedented speed, which is accelerating scientific progress both in neuroscience and robotics. The neurobotics workflow guarantees that the results can be rapidly transferred to real robots.

A set of pilot experiments running on the first public release of the NRP has yielded positive results and helped to refine the development roadmap. In the upcoming releases, we will focus on the integration of more realistic brain models comprising a very large number of neurons.

To this end, we are currently augmenting the neural simulation interface with support for distributed setups in which many instances of NEST are running in parallel.

Additionally, we are implementing an interface to the SpiNNaker platform to allow neuromorphic simulation setups; an initial prototype system is already available. We are also making a concerted effort to ensure that the NRP is as attractive as possible to users. One example is a domain-specific language for defining transfer functions (46), which will serve as the basis for a graphical transfer function editor. On the modeling side, we will provide further environments and robots.

In the next phase of HBP, we will expand our collaboration with both internal and external partners to ensure that the NRP continues to reflect the cutting edge of both robotics and neuroscience. In particular, we are investigating embodied learning techniques, which are an essential prerequisite to endowing simulated brains with desired behaviors. We are also researching biomimetic robots with human-like musculoskeletal actuation, since these models are an important requirement for transferring results from the simulation to the real world.

We cannot stress enough that the development of the NRP and the neurobotics subproject are completely open to the entire scientific community. Interested researchers from both academia and industry are strongly encouraged to become involved and contribute. For the upcoming public release of the NRP, we are extending our hardware resources to accommodate as many users as possible. Regular meetings and workshops organized by our subproject are open to everybody, which will not only promote the NRP but also establish a community for neurobotics research.

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