Subproject 10: Neurorobotics

Deliverable D10.7.2

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Abstract:	This document describes the progress made in the first half of the first SGA.
Keywords:	Neurorobotics, virtual robotics, *in silico* experiments

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1. Preamble

This is a revision of D10.7.2, including changes and clarifications in response to the reviewer's comments on the first version.

2. SP Leader's Overview

2.1 Key Personnel

Subproject Leader: Alois KNOLL (TUM)

Subproject Deputy Leader: Marc-Oliver GEWALTIG (EPFL)

Subproject Manager: Florian RÖHRBEIN (TUM)

Scientific coordinators: Letizia ALLEGRA (SP1, LENS), Stefan ULBRICH (FZI), Alexander KUHN (TUM)

2.2 Overview

Subproject 10 develops and operates the HBP Neurorobotics Platform (NRP), one of six research platforms of the Human Brain Project (see Figure 1). The NRP is our vehicle to operationalise the goals of SP10 in the HBP; see our mission statement at https://www.humanbrainproject.eu/en/robots.

Figure 1: Concept visualisation of the Neurorobotics Platform "Holodeck". The user experience is amplified by a uniform look and feel for all NRP experiments.

The NRP is a powerful integration of models, simulation tools, visualisation environments and hardware-/software-in-the-loop facilities that allows neuroscientists and roboticists to connect brain models of different complexity to biological or technical robot bodies, real or virtual, that operate in complex virtual dynamic spaces. The NRP is the only platform worldwide, i.e., an integrated software environment, which aims at building, operating and monitoring virtual robots of arbitrary complexity and making these models easily accessible both to neuroscientists and roboticists. It will also enable them to find "common ground" over using those robots together in simulated (or partly or fully real) environments, i.e., a basis for the exchange of ideas and concepts. To this date, such common ground hardly exists.

Since there is no such platform anywhere in the world, the design of the NRP is an advanced research project in its own right. Quite obviously, its design process cannot be compared to standard software development, such as the coding of a new database systems, for which clear specifications based on many years of experience exist, and strict timeframes can be set. For example, the NRP is the only platform that was designed form the start for cloud use, for supporting output devices ranging from smart phones to CAVEs, as well as sophisticated groupware functionality, making use of the specification of the HBP Collaboratory. Unfortunately, not all of these materialised, partly because the goals were too far reaching and not implementable with the available resources, but partly also because the necessary base functionalities were not provided by others.

Now, after some further research alleys have been explored – some successful, others not – we have a stable specification of the NRP, and it will be used within the HBP Collaboratory as part of the proposed “HBP Joint Platform” (once that becomes available). Currently, it is mainly distributed as a local installation, using local HPC resources.

The Neurorobotics Platform integrates four key components: a robot and world simulator (GAZEBO from the Open Source Robotics Foundation), a neural network simulator (NEST from the NEST initiative)), a closed-loop engine (CLE from SP 10) – or “director” – for the operation of the different simulators, and a web cockpit (from SP10) to interactively design, run and analyse both neurorobotics experiments and realistic physical robot scenarios.

Neuroscientists may benefit from the NRP in a large number of ways. The high-fidelity body models in the NRP allows them to produce photo-realistic and sufficiently complex sensory stimuli for their brain models. This is important, for example, for the study of sensory learning and perceptual learning. The body model allows to investigate how dynamic processes in brain models produce realistic and sufficiently complex motor responses – but also how the body changes the environment and how this recursive relationship shapes the brain of the robots. The Neurorobotics Platform is, thus, a unique tool to study the interactions and synergies between brain, body and environment.

The NRP supports both data-driven and functional brain models. Data-driven models are digital reconstructions of the brain, based on anatomical, electrophysiological, or imaging data. Most models developed in the SP6 “Brain Simulation” fall into this class. Functional models try to reconstruct a particular brain function (such as navigation or object recognition) from known functional principles of the brain. Many models studied in SP3 Cognitive Neuroscience and SP4 Theoretical Neuroscience fall into that class. Thus, neuroscientists can also study *hybrid* models, where parts of a functional model are replaced by a data-driven model, or where parts of a data driven model are replaced by a functional model. For example, a reconstructed model of the visual cortex may use stimuli that are generated by filtering images to mimic retinal and thalamic processing, or a data-driven model of the cerebellum can be connected to a functional model of spinal motor control.

Similarly, roboticists benefit from the NRP, because the NRP offers a familiar modelling and visualisation environment (GAZEBO/ROS) but bundled with powerful and user-friendly programming and user interfaces. Moreover, they can develop neural control models alongside traditional robot controllers. Finally, they can control a robot with a brain simulated in the NRP, or they can feed in live data streams into the virtual environment of the HBP. The borders between real and virtual entities can be changed arbitrarily (this feature, however, is not yet fully implemented).

All scientists benefit from the NRP’s collaborative features. Using the HBP Collaboratory, scientists can design and edit experiments from different locations. They can run and analyse experiments together and they can easily share their models with others. This facilitates the development of open and reproducible benchmark experiments in robotics, similar to OpenAI Gym, but with realistic robot and environment models.

The Ramp-Up Phase (RUP) was concluded with the first release of the NRP to the scientific community. It was more a prototype, but we were overwhelmed by the demand. This led to serious performance issues, and in the end, we had to temporarily block access to external users. The main objective for SGA1 is therefore to develop the NRP into a reliable research infrastructure and demonstrate its usefulness with state-of-the-art neurorobotics research.

SP10 is now using an approach that is called *participatory design* or *co-design,* where the users of a product are tightly integrated into the development process.

SP10 has co-design users inside the SP, mainly in WPs 10.1, 10.2, and 10.4, within HBP as part of CDPs 1,4, and 4 as well as from SP3 and SP9, and now again outside of the HBP. These users work together with our engineering team (WPs 10.5 and 10.6) to propose, specify and finally test new features of the NRP. Users and developers meet regularly at SP10 meetings, SP10 User Workshops, as well as HBP events such as the HBP Code Jam and HBP Young Researcher's Event. The feedback from the users is extremely positive and encouraging (see WP10.5 below for details).

The paramount importance and relevance of the NRP to the HBP and research in related fields in general becomes clear when we look at the competitors that have emerged since the project started in 2013. We mentioned OpenAI Gym, though its functionality is much smaller than the NRP's. A start-up in Barcelona is using a platform very similar to the NRP with regard to our robot programming features, called *ROS Development Studio* (http://www.theconstructsim.com/rds-ros-development-studio/) to teach ROS. NVIDIA is offering a commercial robot simulation platform, called Isaac (https://www.nvidia.com/en-us/deep-learning-ai/industries/robotics/). A project was also launched by Google Deep Mind (https://deepmind.com/blog/deepmind-and-blizzard-open-starcraft-ii-ai-research-environment/). While this system uses computer games rather than realistic robot and environment models, it shares NRP's vision to connect brain (or AI) models to agents in dynamic environments.

The HBP Neurorobotics Platform is still ahead of its competitors in scope and ambition. No other platform offers such a unique combination of realistic physics based robot simulations and multi-scale neural network modelling. Only the NRP is collaborative, open access and open source. The integration of the NRP into the HBP Collaboratory gives all users access to an unprecedented amount of data and models that can be used in neurorobotics experiments as well as access to supercomputing resources in Europe (via SP7).

In the remainder of this section, we give a high-level summary of the progress from the perspective of the SP Leaders and how it addresses the comments and recommendations expressed by our reviewers in their second periodic review report of August 7 2017. The detailed results and their relation to the Description of Action (DoA) are then summarised in the sections of the individual Work Packages and Tasks:

- WP10.1 Closed-loop experiments (data-driven brain models)
- WP10.2 Closed-loop experiments (functional/control models)
- WP10.3 Components of closed-loop experiments
- WP10.4 Translational Neurorobotics
- WP10.5 Simulation and visualisation tools for neurorobotics
- WP10.6 Neurorobotics Platform
- WP10.7 Scientific coordination and community outreach

2.3 Progress M1-M12

In their second periodic review report, the reviewers gave a number of recommendations for the phase of SGA1 which we have tried to consider by a number of concrete measures.

A main concern that needed to be addressed was the usefulness of the NRP for both neuroscience and robotics researchers. In particular, the reviewers wished to see more challenging pilot experiments that should "*allow the experimenter to "ask questions" using the* *knowledge embedded in the models and should help to explain how a specific function is implemented in the brain and why it is implemented in that way*". Along similar lines were the reviewers' requests to consider the re-structured SP3 and its legacy closed-loop cognitive (robotics) models which need to be integrated into the HBP Platform landscape in general and the NRP in particular.

We have addressed these comments in Work Packages 10.1 to 10.4 which focus on neurorobotics research at different levels of description – from reconstructed brain models at the point-neuron level to high-level functional models. They act as internal *co-design* projects that define the development roadmap of the Platform tools. WP10.1 *Closed-loop experiments (data-driven brain models)* is almost entirely devoted to the HBP wide co-design project 1 (CDP-1) and addresses two particularly challenging Use Cases. In the first we attempt to reproduce (the mechanics and protocol of) an existing experiment from the field of neuro-rehabilitation in simulation. This *in silico* experiment not only includes a scaffold whole-brain model (developed by SP6), but also the embodiment of the brain model into a neuro-muscular-skeletal system with spinal motor circuits and a complex stimulation and observation protocol. The full implementation of this CDP will clearly require several SGA periods. In the first 12 months of SGA1, WP10.1 has successfully modelled the hardware platform from the rehabilitation experiment (the so-called M-platform) along with its kinematics. In the second use-case, we address the topics of posture control and locomotion that are highly relevant for neuro-prosthetics research. Here WP10.1 has delivered a neuro-muscular-skeletal model to move the rodent's limbs during locomotion and later during reaching. In parallel, WP10.3 has developed a highly accurate rodent skeleton model that will replace our previous rodent model.

WP 10.2 *Closed-loop experiments (functional/control models)* has successfully extended and integrated the detailed visual perceptual grouping model (RUP WP11) with the iCub robot in the NRP. This pilot experiment convincingly demonstrates a number of important aspects of SP10's work: first, it illustrates how the behaviour of a (visual) model changes if the input is changed from idealised synthetic input (images) to more realistic (still synthetic) stimuli that result from sensory sampling of an environment; second, it demonstrates the integration of complex neural architectures into the NRP. Thus, after 12 months of SGA1, SP10 can demonstrate a number of exciting state-of-the-art experiments in the NRP with complex brain or control models. The details can be found in the respective Work Package and Task descriptions below.

WP 10.4 Translational Neurorobotics is aiming to translate control principles from neuroscience into physical robotic applications. SP10 has developed a clear strategy for this work which has been described in detail in our M6 Deliverable D10.7.1. In the first 12 months, WP10.4 has focused on interfacing neuromorphic hardware such as SpiNNaker (SP9) and Dynamic Vision Sensors for use in real-time experiments, as well as on adapting the Roboy/MyoRobotics soft-body robots for integration into the NRP. These efforts address one of the reviewers' recommendations to intensify the collaboration with SP9 to better harness the power of neuromorphic computing. Again, the detailed results are described below.

WP10.5 *Simulation and visualisation tools for neurorobotics* and WP10.6 *Neurorobotics Platform* focused on developing, deploying and operating the NRP. We have made great progress in developing the NRP software toolchain according to the requirements of the Platform users and also in supporting new users to use the platform for their research.

Noteworthy are the numerous NRP User Workshops and *Platform Install Parties* where users and interested researchers had the opportunity to meet and interact with the Platform developers. The NRP tools are released every 6 months and are available to the scientific community from a public BitBucket repository.

As mentioned in our implementation plan, SP3 has a number closed-loop cognition models that existed prior to HBP and that lives outside the HBP Platform Ecosystem (e.g. Shewbot and MiRo). We are in close contact with SP3 to migrate these legacy models into the NRP and have made great progress. These activities address the reviewers' wish to more strongly involve users in the development of the NRP tools.

SP10 has also started a close co-design collaboration with SP7 to deploy the NRP on the supercomputers in Lugano, using the Docker virtualised container system. Progress here has been slower than expected, since the high security standards on production servers require more work on the NRP architecture than expected. These efforts directly address the reviewers' recommendation to deepen the collaboration between SP10 and SP7.

2.4 Challenges, consequences, and priorities

Establishing a productive and ongoing co-design activity between researchers and developers is not easy and needs constant attention by the responsible Work Package and Task Leaders. To facilitate and structure the knowledge transfer from the scientific users of the NRP (within and outside SP10) to its developers, we have set up a *Science Kanban* team that closely collaborates with the Software Development SCRUM Team. In this process, the Science Kanban produces requirements in the form of feature requests and reference prototype which are delivered to the Product Owner of the software Development Team who then translates these requests into a development roadmap. Every three months, users and developers meet in person to review the progress and refine the roadmap. The details of this process are defined in our Implementation Plan (D10.7.1).

Setting up this process took longer than anticipated, mainly due to two factors: first, the delayed start of SGA1 resulted in severe recruiting problems for some Partners and as a result, Tasks that should have started simultaneously were in fact starting out of sync. Second, it took longer than expected to *train* the scientists in Kanban and to convince them to participate in the regular meetings. However, we observe good progress and are confident that the process will run very productively during the second half of SGA1.

Finally, difficulties were experienced in the operation and support of the NRP services on the cloud servers. These difficulties have two main sources. The first source is lacking resources as the NRP was running on a relatively small cluster in Lugano. This problem will be solved once the migration of the NRP to the larger servers in Lugano is completed. The second problem is that operating a software as a service for 24/7 requires considerable resources that we did not anticipate to that extent. Some of these extra resources are needed to adapt the software (such as the NRP) to the hard- and software- setup of the particular deployment system. Others are needed to ensure that the software is running smoothly, that it gets restarted in cases of hard- and software failures, and to offer user support.

Most of these activities will be very similar for the other HBP Platforms that offer software as a service (such as SP5, SP6, SP7, and SP8). Thus, introducing a HBP wide "DevOps" team will benefit from an economy of scale that cannot be achieved if each platform SP addresses these problems independently. This solution should be addressed in the context of the HBP Joint Platform that is proposed for SGA2.

As a temporary mitigation strategy, SP10 will scale down its NRP cloud service to a level that is compatible with its resources and at the same time encourage the on-site installation of the NRP software. This has the additional benefit, that we can empower Platform users to actively contribute to the Platform development and we find that many are excited to do so.

3. WP10.1. Closed-Loop Experiments (Data-Driven Brain Models)

3.1 Key Personnel

Work Package Leader: Marc-Oliver GEWALTIG (EPFL)

Other Researcher: Letizia ALLEGRA (SP1, LENS)

3.2 WP Leader's Overview

WP10.1 aims to develop a scaffold model of the sensory-neuro-muscular system of the mouse, to be used in conjunction with the scaffold whole mouse brain model, developed in SP6. Thus, WP also aims to demonstrate how simulation methods can help theoretical and experimental neuroscientists alike in reconstructing and understanding the different systems that are involved in sensorimotor tasks. To this end we look at two different experiments: a pulling (and later grasping) task that involves sensorimotor control of the forelimbs and assisted hind lib (and later quadruped) locomotion. Both experiments will be share a large part of their components, developed in different tasks of WP10.1 and WP10.3.

All Tasks in WP10.1 are linked by three criteria: first, focus on the reconstruction of sensory-motor systems in mammals, and more specifically in mice; and second, each Task targets a different component of the sensory-motor loop, so that all Tasks together cover the entire animal; and third, all Tasks should help to design or improve the Neurorobotics Platform.

For the end of the SGA1 period, it is planned, to replicate the mechanics (the protocol) of this experiment in the NRP. In other words, scientists should be able to experiment with a virtual mouse (that has a virtual brain) inside a virtual setup, set the same stimuli as in the original experiment and observe the same quantities as in the original experiment. Thus, it becomes possible to observe the activity of a reconstructed brain model to realistic dynamic sensory signals coming from the virtual body and environment. From the disagreements (initially) and the agreements (later) between in silico and in vivo data, it is then possible to determine where and how the brain model needs to be improved.

The pulling experiment is part of CDP-1 which aims to deliver a simplified model of the mouse brain and an associated brain atlas. The tools and models developed in SP10 will allow neuroscientists (in SP1, SP4, SP6, and SP10) to constrain and refine data-driven brain models by dynamic sensorimotor data. The integration of the pulling experiment is subject of T10.1.4.

The first year of SGA1 was devoted to developing the various parts of the experiment setup and to integrating them into the NRP. Scientific progress has been very good and prototype models for all parts of the experiment have been developed and demonstrated during the two SP10 Performance Shows in 2017 (January and May).

In parallel, the NRP has been extended by new features to facilitate the integration of all parts of the pilot experiments. In particular, the NRP has added support for OpenSim, a physics engine for muscular-skeletal modelling.

On the managerial side, coordination between the groups was good given the fact that some partners were new to the project, and that SP5 was re-structured considerably.

Particularly noteworthy is the role of WP10.1 as SP-internal co-design driver. During the first few months of SGA1, the scientists in WP10.1 developed prototypes of the models that contribute to the two pilot experiments (treadmill locomotion and the stroke-rehabilitation experiment). These prototypes were then used in close collaboration with the development team of WPs 10.5 and 10.6 to specify new NRP requirements and to implement them along a roadmap with user-defined priorities.

The impact of WP10.1 was thus manifold: Scientifically, great progress was made in modelling the rodent neuro-muscular-skeletal system. This is substantiated with one publication in *Neuron*. WP10.1 then contributed substantially to the progress of CDP1 and to the progress of the NRP development.

In the remainder of SGA1, the focus is clearly on integrating all described parts into a small number of pilot experiments that demonstrate the utility of *in silico experimentation* with bio-mechanical body models and reconstructed brain models in the Neurorobotics Platform. Well progressed are the already mentioned stroke rehabilitation experiment (T10.1.6) as well as the treadmill locomotion experiment. However, other experiment setups will become possible as well.

3.3 Milestones

Table 1: List of Milestones for WP10.1 - Closed-Loop Experiments (Data-Driven Brain Models)

MS No.	MS Name	Leader	Expected Month	Achieved Month	Comments
10.1.1	Implementation plan for WP10.1	EPFL	M02	M06	This Milestone has been achieved with the submission of Deliverable 10.7.1
10.1.2	Draft model of mouse brain (SP6) connected to a mouse body (SP10)	EPFL	M12	M12	Closed loop spinal cord stimulation experiment with mouse hind limb musculoskeletal model. Currently installed on NRP platform on a local machine. Will be soon integrated with web platform.
10.1.4	Draft implementation of the motor-rehabilitation experiment	EPFL	M12	M12	The initial version of the motor-rehabilitation experiment has been integrated in the NRP. Currently installed on NRP on a local machine, it will be soon integrated with web platform (see https://hbpneurorobot-icsblog.wordpress.com/2017/05/17/the-virtual-m-platform/)The CAD model of the main components (i.e. linear actuator, linear slide, handle) of the mouse stroke rehabilitation platform (M-Platform), was converted in a suitable format for the Gazebo simulator. Physical properties of the models have been set up according to the real characteristics of the slide. The modelled components of the M-Platform have been included in a simulated experiment with a closed loop involving a spiking neural network. In addition to this, a biological model of proprioceptive sensory information, implementing a computational model of neural activity of sensory fibres connected to muscle spindles, has been designed and tested with a simulated mouse in the NRP.

3.4 T10.1.1 Locomotion and posture

3.4.1 Key Personnel

Task Leader: Grégoire COURTINE (EPFL)

Other Researcher: Silvestro MICERA (SSSA)

Other Researcher: Auke IJSPEERT (EPFL)

3.4.2 SGA1 DoA Goals

This Task aims at reconstructing the control of posture and locomotion using the rodent model developed in T10.3.1 and T10.3.2, as well as the corticospinal integration from T10.1.3.

The overreaching goal of this Task is to ensure the convergence of the computational models of spinal circuits, the descending motor control inputs from supraspinal structures, sensory models of proprioception and light touch and muscoloskeletal models of the mouse hind limbs. The integration of these inputs will support simulations of standing and locomotion in the mouse (and potentially other species).

We will initiate this work with assisted walking on a treadmill. We will then extend the model to unassisted walking onto flat surfaces. The model will be constrained and validated using muscle activity (EMG) recordings and high-resolution motion-capture data. Using this information, we will reach the following goals:

(1) Providing comprehensive dataset on the kinematics, EMG and kinetics underlying locomotion in mice (and other species).

(2) Perform closed-loop simulations using a neurobiomechanical model of the mouse hind limbs through the computational platform.

This Task contributes to CDP1.

3.4.3 Component Progress

3.4.3.1 Muscle Spindle Feedback Network

Development of a NEURON-based muscle spindle feedback network of the spinal cord. This component is linked to GOAL 2.

Component Progress:

We have completed and published this component in the journal *Neuron*:

The muscle spindle feedback model has been fully developed, his results and applications are summarised in the publication**:** Moraud et al. Mechanisms underlying the neuromodulation of spinal circuits for correcting gait and balance deficits after spinal cord injury. Neuron (2016), http://dx.doi.org/10.1016/j.neuron.2016.01.009".

The model has also been shared online and is available at the following link: https://senselab.med.yale.edu/ModelDB/showmodel.cshtml?model=189786

The Neuron code is currently translated into a NEST compatible model that will allow the full integration of the model in the platform (see also Figure 2).

Quality Control:

DOWNSTREAM

- Model of spinal cord using reservoir computing for real-time control T10.4.5 - Joni DAMBRE - **Model is completed and available online (**https://senselab.med.yale.edu/ModelDB/showmodel.cshtml?model=189786**).**
- Basic Spinal Cord Model T10.1.3 - Röhrbein Florian - **Model is completed and available online (**https://senselab.med.yale.edu/ModelDB/showmodel.cshtml?model=189786**).**

- Sensory Models T10.1.2 - Cecilia LASCHI - **Model is completed and available online (https://senselab.med.yale.edu/ModelDB/showmodel.cshtml?model=189786).**

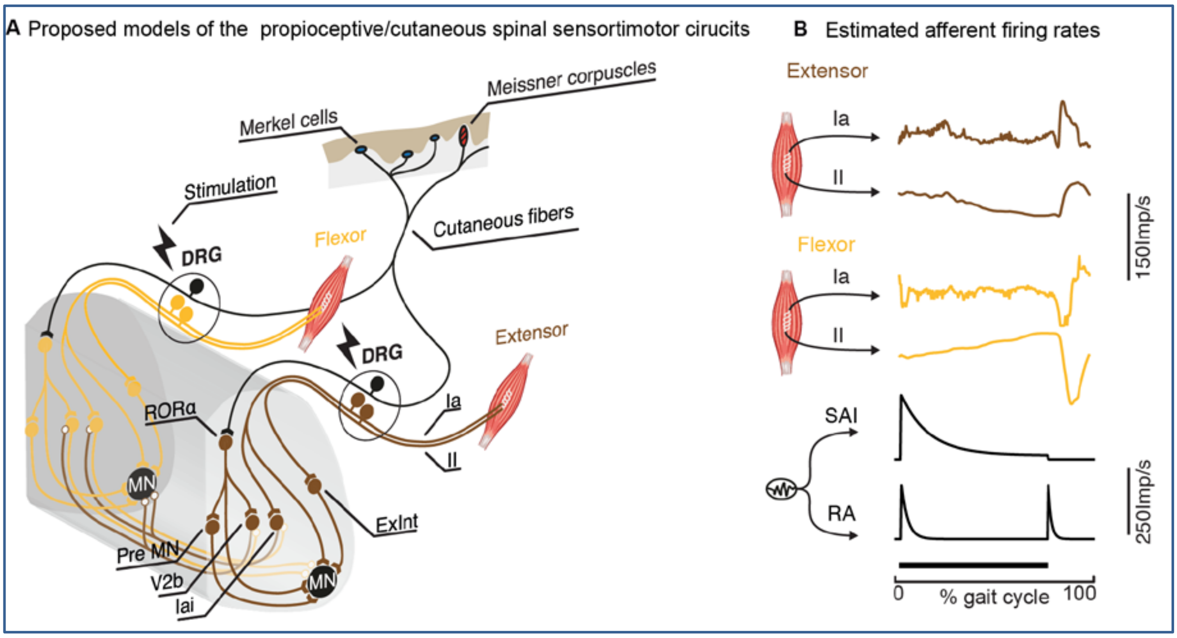


Figure 2: Muscle Spindle Feedback Model

A current design of the sensorimotor circuit model of the spinal cord. The model includes spindle afferents and touch mechanoreceptors models of the foot as well as detailed motor neuron pools of flexors and extensors muscles of the ankle. B simulation of afferent firing rates during one gait cycle on the treadmill using a rat musculoskeletal model to compute muscle stretch and touch pressure information. This model has been adapted to the mouse and is currently being optimised in NEST for full integration with the platform Error! Reference source not found.

3.4.3.2 Muscle activity and Kinematics Data underlying mouse locomotion

Behavioural experiments in intact and spinal cord injured mice. Bipedal locomotion on a treadmill and quadrupedal locomotion over ground. Recording of continuous muscle activity signals and 3D Kinematic data for model constraints and validation.

Component Progress:

A comprehensive database of bipedal and quadrupedal locomotion in mouse has been fully acquired and processed. The database is available upon request.

Quality Control:

DOWNSTREAM

- Model of spinal cord using reservoir computing for real-time control T10.4.5 - Joni DAMBRE -**data is acquired and available upon request.**
- Basic Spinal Cord Model T10.1.3 - Florian ROHRBEIN - **data is acquired and available upon request.**
- Musculoskeletal models of rodents for the Neurorobotics Platform T10.3.2 - Auke IJSPEERT - **data is acquired and available upon request and has been and will continue being used for models design and validation**

3.4.3.3 Muscle activity and Kinematics Data underlying rat locomotion

Behavioural experiments in intact and spinal cord injured rodents. Bipedal locomotion on a treadmill and quadrupedal locomotion over ground. Recording of continuous muscle activity signals and 3D Kinematic data for model constraints and validation.

Component Progress:

A comprehensive database of bipedal and quadrupedal locomotion in rat has been fully acquired and processed. The database is available upon request.

Quality Control:

DOWNSTREAM

- Musculoskeletal models of rodents for the Neurorobotics Platform T10.3.2 - Auke IJSPEERT - **data is acquired and available upon request and has been and will continue being used for models design and validation**

3.4.3.4 Muscle activity and Kinematics Data underlying human locomotion

Behavioural experiments in intact and spinal cord injured humans. Bipedal locomotion on a treadmill and over ground. Recording of continuous muscle activity signals and 3D Kinematic data for model constraints and validation.

We will use kinematic and muscle activity data underlying human locomotion to build neuromechanical models. The neuromechanical model of human locomotion will support the study of locomotor control in healthy and pathological conditions, such as spinal cord injury and stroke. Lower limb musculoskeletal data necessary for simulations of human locomotion have been published.

(see also F. Dzeladini, J. Van Den Kieboom and A. Ijspeert. The contribution of a central pattern generator in a reflex-based neuromuscular model. *Frontiers in Human Neuroscience*, **8**, 2014.)

Component Progress:

Kinematic and muscle activity Data underlying human locomotion is currently being acquired at the university hospital Lausanne, and will be made available soon.

Quality Control:

DOWNSTREAM

- Musculoskeletal models of rodents for the Neurorobotics Platform T10.3.2 - Auke IJSPEERT - **Data will be provided for models design and validation**

3.4.3.5 Closed Loop Simulation of locomotion a treadmill

Execution of a closed-loop Neurobiomechanical simulation using the mouse model.

The aim is to reproduce locomotion on a treadmill using the Platform. For this, we built a spinal cord model that receives inputs from corticospinal modules and muscle spindle feedback circuits. This model controls the recruitment of muscles in a biomechanical model of the lower limbs.

The primary goal is to implement a closed loop model capable to reproducing locomotion in mice. However, simulations involving the rat models and human models may also be used for further development and clinical applications.

This task requires inputs from T10.3.1, T10.3.2 and T10.1.3, provides outputs to T10.1.2 and T10.4.5

Component Progress:

The spinal sensorimotor circuit model developed in Component 1 of this Task is currently being integrated with models developed in T10.3.2 of the mouse hind limb and data of Component 2 to generate a closed-loop simulation of locomotion on a treadmill. Currently, we are tuning the synergy between the biomechanical and neural components (COURTINE, MICERA, IJSPEERT).

We constrained hind limb kinematics with data from Component 2 and 3, and firing rates of sensory afferents and motor neuron output predicted by the model in Component 1. These simulations produce alternated motor activity resembling locomotor-like movements (see Figure 3).

Adaptation of the network to realistic mouse biomechanics required more time than initially expected. Because of this delay, the release of the component has been partially executed. We expect to fully release this component together with component 6 at Month 24.

Quality Control:

UPSTREAM

- Musculoskeletal models of rodents for the Neurorobotics Platform T10.3.2 - Auke IJSPEERT – **Biomechanical model is tuned and functional.**
- Musculoskeletal models of humans for the Neurorobotics Platform T10.3.2 - Auke IJSPEERT - **These models will be integrated when the mouse models are completed**
- Rodent Body Model for the Neurorobotics Platform T10.3.1 - Matthias CLOSTERMANN - **The body model will be integrated once tuning of the biomechanical/neural model is performed**
- Model of spinal cord using reservoir computing for real-time control T10.4.5 - Joni DAMBRE - **We proceeded using the spinal cord model developed in component 1 of T10.1.1**

DOWNSTREAM

- Sensory-Motor Maps T10.1.2 - Cecilia LASCHI - **We have not released the component yet**
- Sensory Models T10.1.2 - Cecilia LASCHI - **We have not release the component yet**
- Cognitive models for complex behaviours T10.2.2 - Cecilia LASCHI - **We have not released the component yet**

Model of spinal cord using reservoir computing for real-time control T10.4.5 - Joni DAMBRE - **We have not released the component yet**

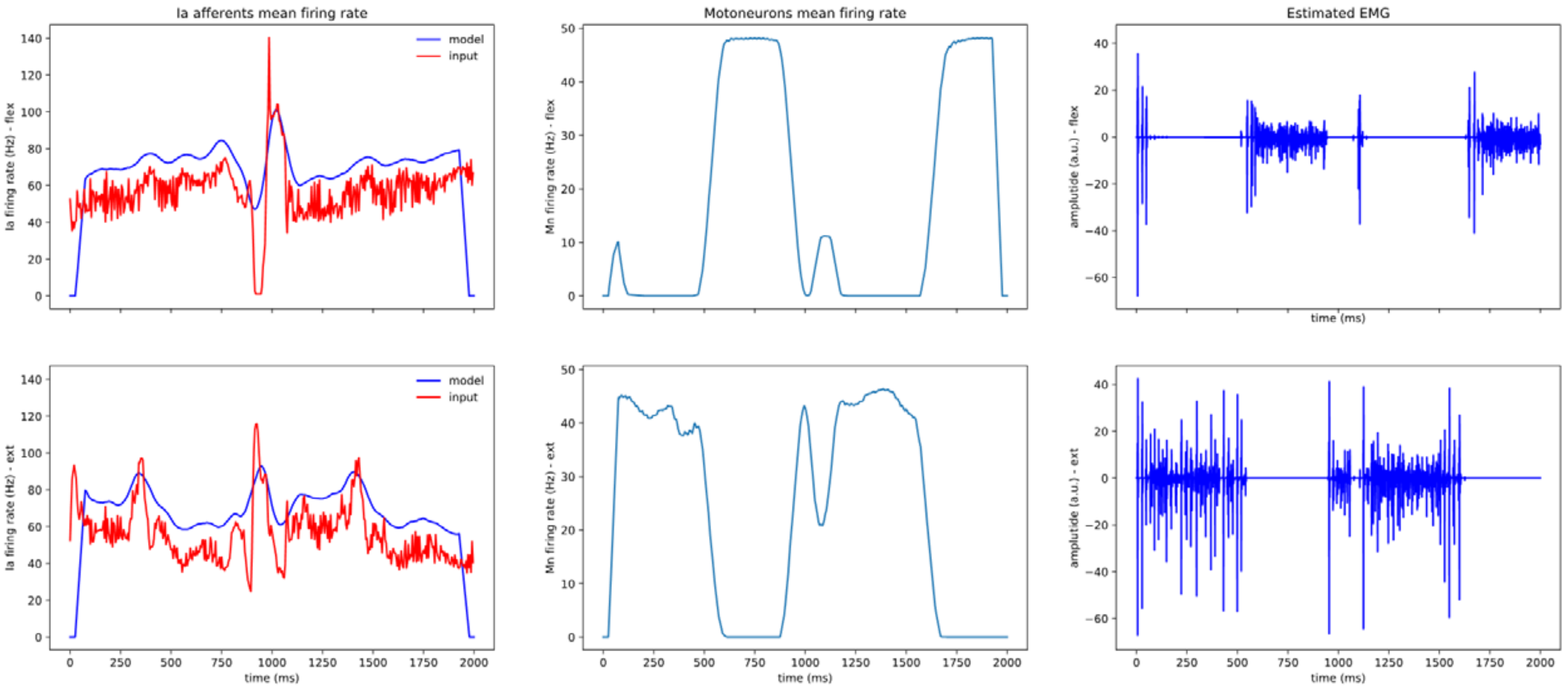


Figure 3: Ia afferents and motor neuron firing rates of flexors (top row) and extensors (bottom row) motor pools of the ankle during treadmill walking

On the Left in red the muscle stretch during locomotion is estimated using the biomechanical model of the rodent hind limb. The stretch information is provided as input to the muscle spindle sensory model and the afferent population firing rate (Ia fibres in blue) is computed. In the right panel, sensory inputs estimated using the biomechanical model of the rodent hind limb combined to the sensory model of proprioceptive afferents is processed by the spinal circuit model implemented in NEST and alternate recruitment of flexors and extensors motor neurons is produced.

3.4.3.6 Closed Loop Simulation of locomotion over ground

Execution of a closed loop neurobiomechanical simulation using the mouse model. Using the Platform, the aim is to reproduce over ground locomotion. A spinal cord model receiving inputs from corticospinal modules and muscle spindle feedback circuits produces the recruitment of muscles in the biomechanical model of the legs. The primary goal is to implement a mouse closed loop model. However, rat models and human models may be used in further development or as starting point for the neurobiomechanical integration infrastructure. This Task requires inputs from T10.3.1, T10.3.2 and T10.1.3, provides outputs to T10.1.2 and T10.4.5.

Component Progress:

While data has been acquired, integration requires the prior release of Component 5. The development of this component is thus contingent on the progress of Component 5. See Progresses in Component 5 for reference.

Quality Control:

UPSTREAM

- Musculoskeletal models of rodents for the Neurorobotics Platform T10.3.2 - Auke IJSPEERT - **Models are currently being tuned by our joint groups.**
- Musculoskeletal models of humans for the Neurorobotics Platform T10.3.2 - Auke IJSPEERT - **These models will be integrated when the mouse model is completed**
- Rodent Body Model for the Neurorobotics Platform T10.3.1 - Matthias CLOSTERMANN - **The body model will be integrated once tuning of the biomechanical/neural model is performed**
- Model of spinal cord using reservoir computing for real-time control T10.4.5 - Joni DAMBRE - **We proceeded using the spinal cord model developed in component 1 of T10.1.1**

DOWNSTREAM

- Sensory Models T10.1.2 - Cecilia LASCHI - **We have not released the component yet**
- Cognitive models for complex behaviours T10.2.2 - Cecilia LASCHI - **We have not released the component yet**
- Model of spinal cord using reservoir computing for real-time control T10.4.5 - Joni DAMBRE - **We have not released the component yet**

3.5 T10.1.2 Sensory-motor integration

3.5.1 Key Personnel

Task Leader: Cecilia LASCHI (SSSA)

3.5.2 SGA1 DoA Goals

This Task develops technologies to map sensors and motors to selected parts of SP6 scaffold brain models to enable sensory control voluntary movements. In particular, sensors and motors will be selected to support the strategic use cases: proprioceptive, visual, inertial and tactile sensors will be included in the implemented sensory-motor maps together with a set of actuation mechanisms defined in the Task 10.1.1.

The main goal of this Task is to provide a basic neural implementation of sensorimotor maps and integrate them into a closed loop for the control of simulated agents (mouse or robotic platforms, see T10.1.6). Investigations will be performed in order to exploit learning mechanisms for adapting the maps to body changes (i.e., growth or lesion) or interaction with the environment (i.e. tool use). A possible approach may involve developmental robotics to analyse the impact of body development on the formation of sensorimotor maps. This Task contributes to the following use case of CDP1: CDP1-P4, A virtual lab app.

3.5.3 Component Progress

3.5.3.1 Sensory models

This component aims to provide models of early sensory processing that will be used in sensory-motor integration tasks. Models of proprioceptive, visual, inertial and tactile sensors will be provided with suitable neural interfaces for brain models.

CDP to which Component contributes: CDP1; in detail, it is part of the product CDP1-P4, A virtual behaviour lab app, and the use case "Mouse rehabilitation experiment in NRP".

Progress on Component:

A biologically inspired translation model for proprioceptive sensory information was developed. The translation is achieved implementing a computational model of neural activity of type Ia and type II sensory fibres connected to muscle spindles. The model also includes activity of both static and dynamic gamma-motor neurons, that provide fusimotor activation capable of regulating the sensitivity of the proprioceptive feedback, through the contraction of specific intrafusal fibres (Proske, 1997[1]).

The proposed model is an extension of a state-of-the art computational model of muscle spindle activity (Mileusnic, 2006[2]). The model developed by Mileusnic and colleagues, albeit complete and validated against neuroscientific data, was completely rate based, thus it was modified in order to be integrated in a spiking neural network simulation. In particular, a spike integration technique was employed to compute fusimotor activation and the generated rate was used to generate spike trains. As a first step, we developed a MATLAB Simulink model whose results were directly comparable with the ones reported in (Mileusnic, 2006). Then, we compared the results, in terms of afferent rates, with two different implementations (on Nest and SpiNNaker), with the Simulink reference, by executing the same tasks, in terms of fibre stretch and fusimotor stimulations (see Figure 4 and Figure 5). After the execution, the spike trains were recorded and the rate was computed by sorting them into bins of fixed time intervals (30ms) and counting them to compute the average rate for the bin. In order to provide the fusimotor stimulations in NEST and SpiNNaker simulations, we employed already existing Poisson spikes generators, connected to the appropriate synapses types.

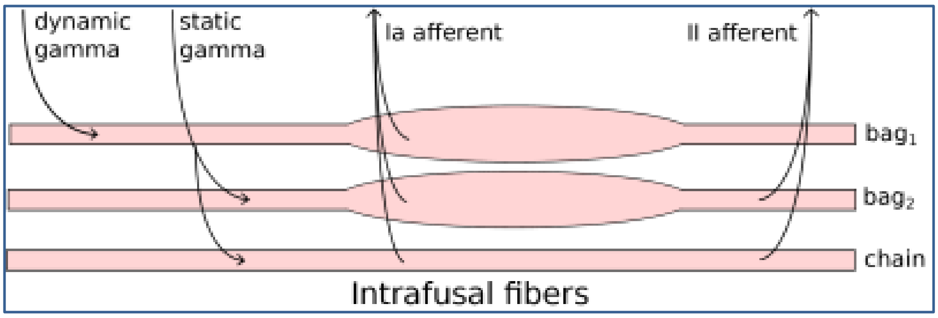


Figure 4: Intrafusal fibres

The implementation in NEST has been tested in closed-loop experiments using the Neurorobotics Platform on the mouse model and on the iCub robot (see Figure 5). The proposed component can be coupled to both biomechanical models, like musculoskeletal systems, and common robotic platforms (via suitable conversions from encoder values to simulated

[1] Proske, U. (1997). The mammalian muscle spindle. Physiology, 12(1), 37-42.
[2] Mileusnic, M.P., Brown, I.E., Lan, N., Loeb, G.E. (2006). Mathematical models of proprioceptors. I. Control and transduction in the muscle spindle. Journal of neurophysiology, 96(4), 1772-1788.

muscle length). In particular, this model will be used, as part of CDP1, to provide sensory feedback from the virtual mouse body. In our tests, we employed the proposed model to convert information coming from motor encoders.

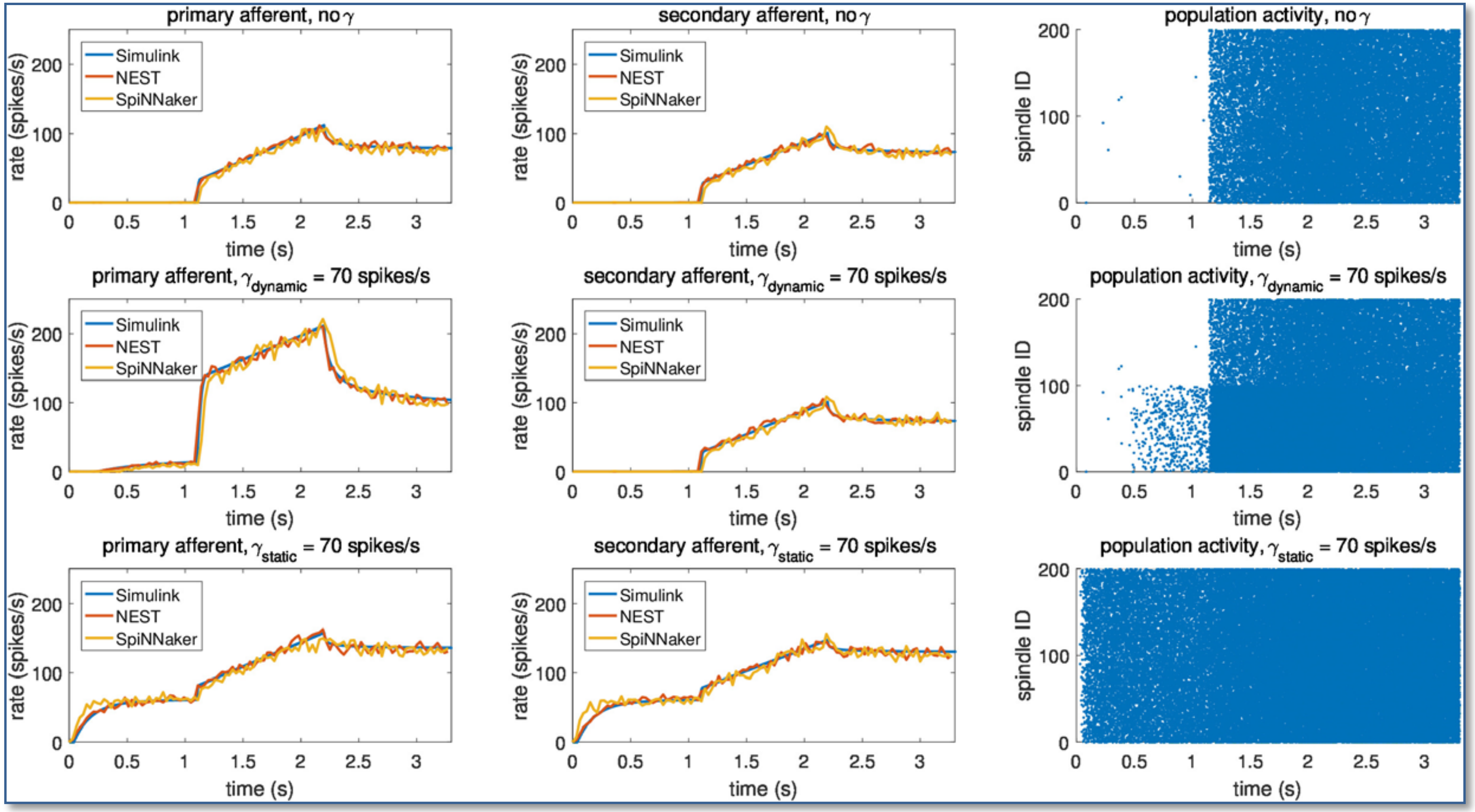


Figure 5: Comparison between the different implementations (Simulink, NEST and SpiNNaker) for a stretching task with different fusimotor activities (no activity, dynamic at 70spikes/s and static at 70spikes/s)

The rows correspond to the different fusimotor activations. The first column shows the Ia afferent activity, in terms of spike rates, the second II afferent activity and the third one the raster plots of the neural population relative to the task, as produced by SpiNNaker. Spindles 0-99 simulate Ia activity, while spindles 100-199 simulate II activity. In order to improve visibility in the raster plots, only activity of 20\% of the units of the spindle populations is displayed.

In principle, every joint connecting two links can be considered actuated by an agonist-antagonist pair of muscles. Therefore, sensory information should be translated in terms of stretches of such muscles. We employed the spindle model to translate information received from encoders into afferent activities for an antagonistic pair of simulated muscles. Further details about these implementations can be found in this paper:

Lorenzo Vannucci, Egidio Falotico and Cecilia Laschi (2017), Proprioceptive Feedback through a Neuromorphic Muscle Spindle Model, Frontiers in Neuroscience, vol 11, pp 341: http://journal.frontiersin.org/article/10.3389/fnins.2017.00341/full

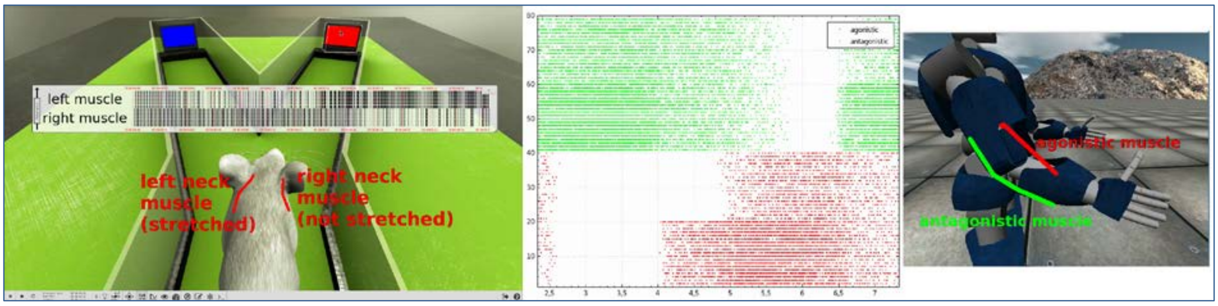


Figure 6 Application of the touch sensor model to the mouse (left) and the iCub (right).

For the translation of touch sensors, a neurorobotic framework to study neural coding at the different levels of tactile sensing is being developed. Force detected at the sensor (see)was transformed into current linearly. Primary afferent signals are processed by second order neurons in the cuneate nucleus (CN) of the brainstem, which constitutes the main synaptic relay along the somatosensory pathway from the fingertip to the central nervous system.

The spiking neural network consists of LIF neurons. The network model was composed of two neuronal populations: 4 inhibitory interneurons and 16 pyramidal neurons and was simulated in C++. The network connectivity was random with 0.2 probability of directed connection between any pair of neurons, so that more than 80 excitatory and inhibitory synapses have considered in the network. We simulated a 3*3 sensorised skin and thus we consider only 6 neurons in the output layer.

Stimulation of the sensor located in the second row and second column of 3*3 sensorised skin is shown in . In this simulation, we stimulated one of the sensor by the rectangular pulse with different pulse widths and fixed amplitude. As can be seen, the firing rate of the corresponding neurons in the output layer has increased and the winner neuron can be determined just by counting the number of spikes for the duration of stimulation. Indeed, in this case we apply a fixed force with different time scale, and thus firing activities of the output spiking neurons are increased accordingly. The colour plot is obtained by adding the number of spikes generated by the neurons for corresponding row and column. An implementation of the model is available in Matlab and we are currently working to implement it in NEST in order to test it in the NRP.

The development of touch sensor models allows also to face issues related to contact points and pressure information requiring a strong effort from a simulation point of view. Other robotic experiments (i.e. grasping tasks) can benefit from the outcome of this work.

Model descriptions, videos and code repositories are available here: https://hbpneurorobot-icsblog.wordpress.com/2017/05/17/sensory-models-for-the-simulated-mouse-in-the-nrp/

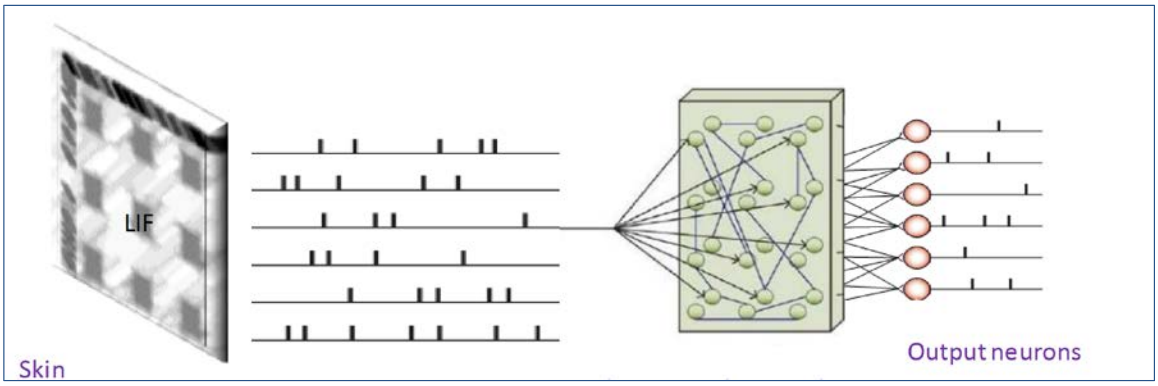


Figure **7:** Encoding touch signals from the skin. Force detected at the sensor is linearly transformed into a current, driving the sensor neurons. Primary afferent signals are processed by second order neurons in the cuneate nucleus (CN) of the brainstem, the main synaptic relay along the somatosensory pathway from the fingertip to the central nervous system.

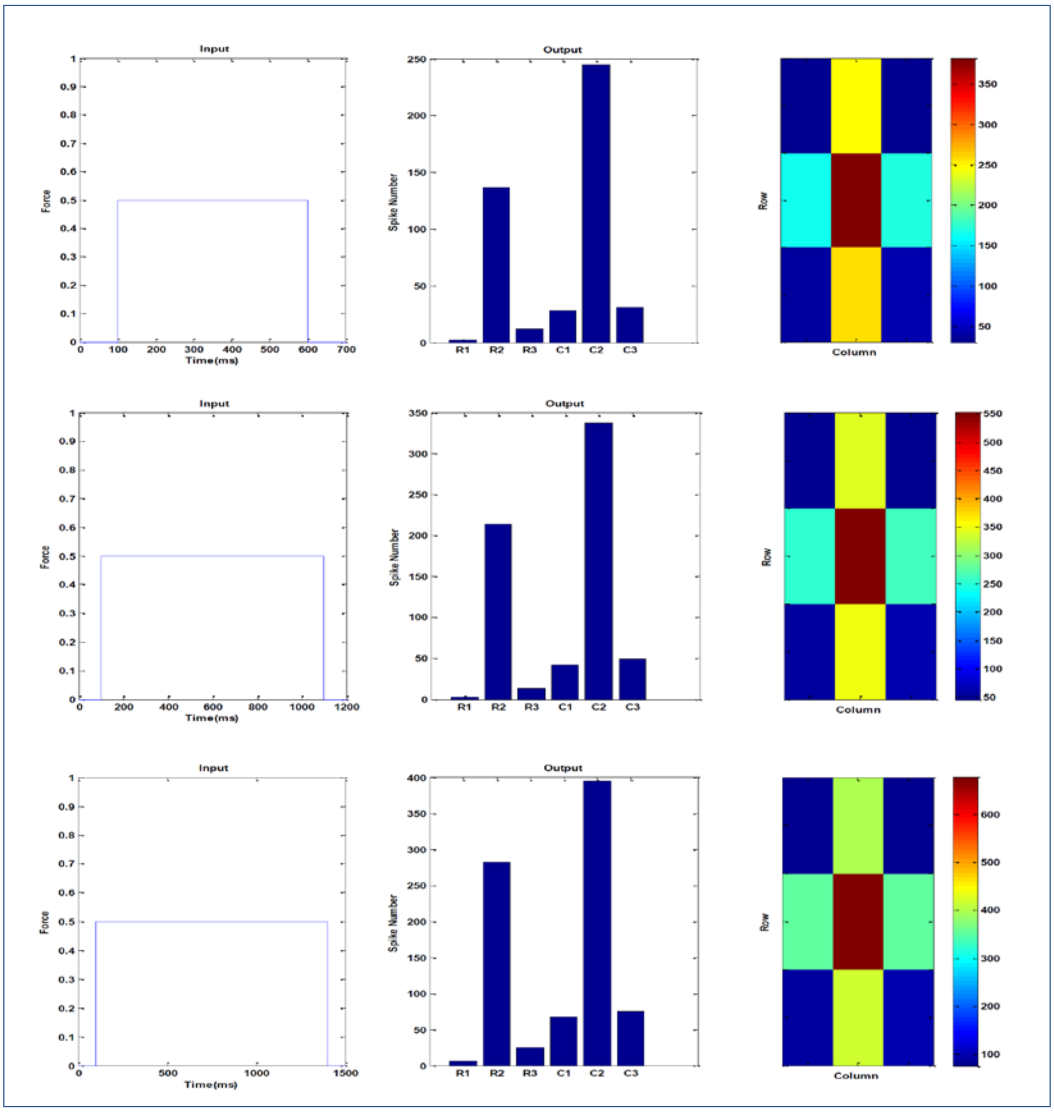


Figure 8: Stimulation of the sensor located in the second row and second column of 3*3 sensorised skin.

3.5.3.2 Sensory-motor maps

The main goal of this Component is to provide a basic neural implementation of sensorimotor maps and integrate them into a closed loop for the control of simulated agents (mouse or robotic platforms), using sensory models developed in this Task, simplified brain models from T6.2.2 and T6.2.3, as developed in T6.2.7, and motor primitives provided by T10.1.1.

Further investigation could be performed in order to exploit learning mechanisms for adapting the maps to body changes (i.e., growth or lesion) or interaction with the environment (i.e. tool use).

CDP to which Component contributes: CDP 1, A virtual behaviour lab app.

Progress on Component: The work for this Component will start at M13.

3.5.3.3 Related Publication

Vannucci L, Falotico E, Laschi C, “Proprioceptive feedback through a neuromorphic muscle spindle model”, *Frontiers in Neuroscience*, vol 11, pp341

3.6 T10.1.3 Corticospinal Integration

3.6.1 Key Personnel

Task Leader: Patrick VAN DER SMAGT (FORTISS)

3.6.2 SGA1 DoA Goals

The objective of this Task is to connect the neurorobotic models to the brain simulation. An interface module will have to be devised which can interpret cortical signals.

This will be achieved in two steps.

The first step will implement a 5-neuron-per-muscle model in Python, based on previous work by Loeb et al (2010; 2014) and using the open-source Musculoskeletal Modelling Software (MSMS) model. This will be integrated with the NRP that is developed in WP10.5. The model will include features as self-stabilising against external forces and motor limits (limits force/load in muscles), and thus mimic spinal cord control, which is necessary as interface between the NRP and the brain simulation.

As a primary example for this implementation the currently available mouse model is targeted. We intend to adapt existing joint and motor models to biologically correct models, and include our spinal model for joint movement generation. The output of the mouse brain model will be fed into the spinal cord to induce movement.

Once the model is running, in the second step, it will be replaced by a deep learning-based neural network model, which can mimic and then generalise the behaviour of the spinal cord model. The neural network will be bootstrapped from our spinal model. In particular, this will be used to extend the spinal cord model to its application to general robotic systems.

3.6.3 Progress

In the reporting period models from Patrick VAN DER SMAGT (FORTISS) and Shravan Tata RAMALINGASETTY (EPFL) have been compared and the latter one was selected for later integration in M13-14. The reasons for this decision are:

- modelling with spiking instead of artificial neural networks
- already ported from NEURON to NEST and thus allows for an easy integration in the neurorobotics platform
- unproblematic regarding licensing

This Task is delayed since Patrick van der Smagt left the team for a position in industry in 2016.

3.7 T10.1.4 Cerebellar Motor Control

3.7.1 Key Personnel

Task Leader: Eduardo ROS (UGR)

3.7.2 SGA1 DoA Goals

The practical goal of this task is to develop and integrate a biologically relevant model of cerebellar motor control in an accurate movement task implemented in the NRP. The task will then be used to address specific scientific questions such as how specific properties of cells, system network topology (in particular the ones being studied in SP6, Task 6.2.3 and UNIPV) and synaptic adaptation mechanisms play a role in the process of integrating sensory-motor information and the construction of dynamic models. This also allows further investigating how specific properties of the cells, network topology and synaptic adaptation mechanisms complement each other in the particular architecture of the cerebellum.

Furthermore, in this task we aim to research also on how the cerebellum is integrated within the sensory-motor pathways, for example cerebellum as an inverse model capable of generating control terms in the framework of accurate control tasks. This scientific question still remains controversial in the field of cerebellar research. We believe that neurorobotic simulation can facilitate a better understanding of the biological control loop, and thus our approach to answering the above question is as follows:

- Three incremental cerebellar models will be implemented on NEST simulator.
- The first one will include data-driven model (SP6) of the cerebellar connectivity accounting the experimental evidence of neuron density, morphological details of the axons/dendrites extension and connectivity ratios but only static synapses (no learning rules).
- The second one will add plasticity at the synaptic sites between the parallel fibres and Purkinje cells. This plasticity mechanism will be driven (supervised learning rule) by the complex spikes occurring in the Purkinje cells.
- The third model (distributed learning) will be extended with plasticity at the cerebellar nuclei, including the connections between mossy fibres (cerebellar main input) and cerebellar nuclei cells and between Purkinje cells and cerebellar nuclei cells.
- These three models will be integrated in the NRP to control the movement of an artificial avatar for accurate movements. The influence of the plasticity mechanisms in the performed task will be evaluated. The scientific question that is addressed is to understand how the different plasticity mechanisms complement each other and how they are supported by the neurobiological substrate. The NRP offers the unique opportunity to simulate neural systems (in this case a cerebellar model) connected to a robotic avatar within a close-loop control. Usually, neural systems are simulated using input patterns (for instance well defined input spike trains), then the neural system produces output patterns (that are analysed). These synthetic simulations are rather constrained when it comes to evaluate how the neurobiological substrate supports the performance of actual biologically relevant tasks.

3.7.3 Progress

The first and second cerebellar models have already been implemented in NEST and tested with synthetic data. The integration in the NRP has already started and the experimental set-up will be available soon.

NRP provides a unique opportunity of integrating neural system simulation within a control loop with an artificial agent. This enables us to define specific experimental set ups to study how specific features of the cerebellar neurobiological substrate supports certain task capabilities. In particular:

- We evaluated sensorial information representation (with synthetic inputs) in the cerebellar granular layer as a first step for learning. Status: Completed.
- We set up an experimental set up with cerebellar operation with theoretically calculated weights and synthetic inputs. Status: Completed. (D'Angelo et al. 2016)
- We implemented cerebellar learning with synthetic inputs and supervised learning rule enabled. Status: Completed.
- We implement cerebellar learning with synthetic inputs and parallel fibres and cerebellar nuclei learning rules enabled. Status: Ongoing.
- We evaluate sensorial information representation in the cerebellar granular layer when performing an accurate movement task. Status: Ongoing. (Luque et al. 2016)
- We will study the processes of gain adaptation and learning consolidation supported by different cerebellar features. Status: To be performed.
- We evaluate several control loops including the cerebellum working as an inverse model. Status: To be performed.

In terms of platform development, our approach should attract users to the NRP insofar as closed-loop testing with NEST enables biologically realistic simulation of the cerebellum in relation to the activity of a simulated agent. This will allow groups from other SPs (for instance, SPs dealing with accurate movements and manipulations tasks) to test a wide variety of brain models under the most realistic conditions, and to probe the functional influence of a host of biological parameters. Conversely, this will allow roboticists to identify which characteristic of the cerebellar circuitry are most relevant to those same motor tasks. Ongoing discussions are already taking place to integrate this type of approach in our SGA2 planning.

3.7.4 Publications

Luque, N.R., Garrido, J.A., Naveros, F., Carrillo, R.R., D'Angelo, E., Ros, E. (2016). Distributed cerebellar motor learning: a spike-timing-dependent plasticity model. *Frontiers in Computational Neuroscience*, 10.

Garrido, J.A., Luque, N.R., Tolu, S., D'Angelo, E. (2016). Oscillation-driven spike-timing dependent plasticity allows multiple overlapping pattern recognition in inhibitory interneuron networks. *International Journal of Neural Systems*, 26(05), 1650020.

D'Angelo, E., Antonietti, A., Casali, S., Casellato, C., Garrido, J.A., Luque, N.R., ... Rizza, M.F. (2016). Modeling the Cerebellar Microcircuit: New Strategies for a Long-Standing Issue. *Frontiers in Cellular Neuroscience*, 10.

Richter, C., Jentzsch, S., Hostettler, R., Garrido, J.A., Ros, E., Knoll, A., ... Conradt, J. (2016). Scalability in Neural Control. *IEEE Robotics & Automation Magazine*, 1070(9932/16).

3.8 T10.1.5 Sensory-guided neuromotor control

3.8.1 Key Personnel

Task Leader: Florian RÖHRBEIN (TUM)

Other Researcher: Florian WALTER (TUM)

3.8.2 SGA1 DoA Goals

This Task will implement the spiking model of CDP4 in a neurorobotic engine achieving biologically-inspired closed-loop motor control. This project aims at a comprehensive visuomotor and somatosensory brain model of complex motor control. The sensorimotor modelling will, in collaboration with other SPs, be integrated with the development of algorithms for multi-modal guidance of robotic motor control with feed-forward and feedback loops.

3.8.3 Component Progress

3.8.3.1 Experimental Setups for the Evaluation of Cognitive Models on the Neurorobotics Platform

This Component comprises a suite of experimental setups for the NRP that are set up to reflect the specific requirements of the neural models developed in CDP4. Every of these experiments contains a robot model which is placed in an environment. Both the robot and the environment model are selected to match the requirements of the corresponding sensorimotor integration models in terms of actuators and sensory modalities. There will be an individual experiment for every sensorimotor integration model.

Progress on Component:

At the beginning of the reporting period, all CDP4 collaborators met at a workshop held at the EITN in Paris. Participants from other CDP4 Tasks were given an introduction to the NRP. Initial discussions revealed that the current feature set implemented by the Platform would be sufficient to implement a neural model for saccadic eye movements. Another tutorial on the NRP with a focus on possibilities for integrating the saccade models was given at the 2016 HBP Summit in Florence. At this meeting, it was decided that the iCub robot model would be used for the first closed-loop experiment with the saccade generation model. During a visit from CDP4 collaborator Marion SENDEN in Munich, an early version of the saccade generation model was successfully connected to the robot model in a prototype experiment. The saccade generation model is simulated by a beta release of NEST with support for analogue neuron models that output continuous-valued numbers instead of spikes. The full closed-loop setup will require a saliency map model that is currently developed by the collaborators from the Maastricht University. A full integration into the release version of the NRP will therefore only be possible when the new neuron types are being fully available in upcoming releases of NEST and PyNN.

In preparation for more advanced neurorobotics experiments for visuomotor integration, we also investigated closed-loop simulations with realistic neuromusculoskeletal models. To this end, we implemented an interface between the musculoskeletal simulator OpenSim and NEST. Based on this setup, a biomechanical model of a human arm was extended to study basic stretch reflexes. The neural circuits for these reflexes were implemented in NEST.

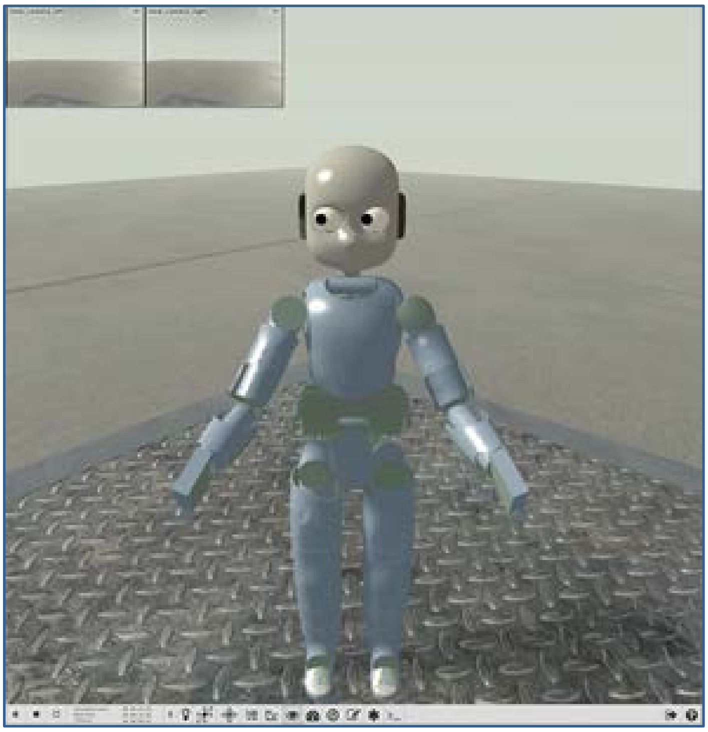


Figure 9: iCub robot model simulated on the Neurorobotics Platform

The eyes are controlled by the saccade generation model developed by Marion Senden at Maastricht University.

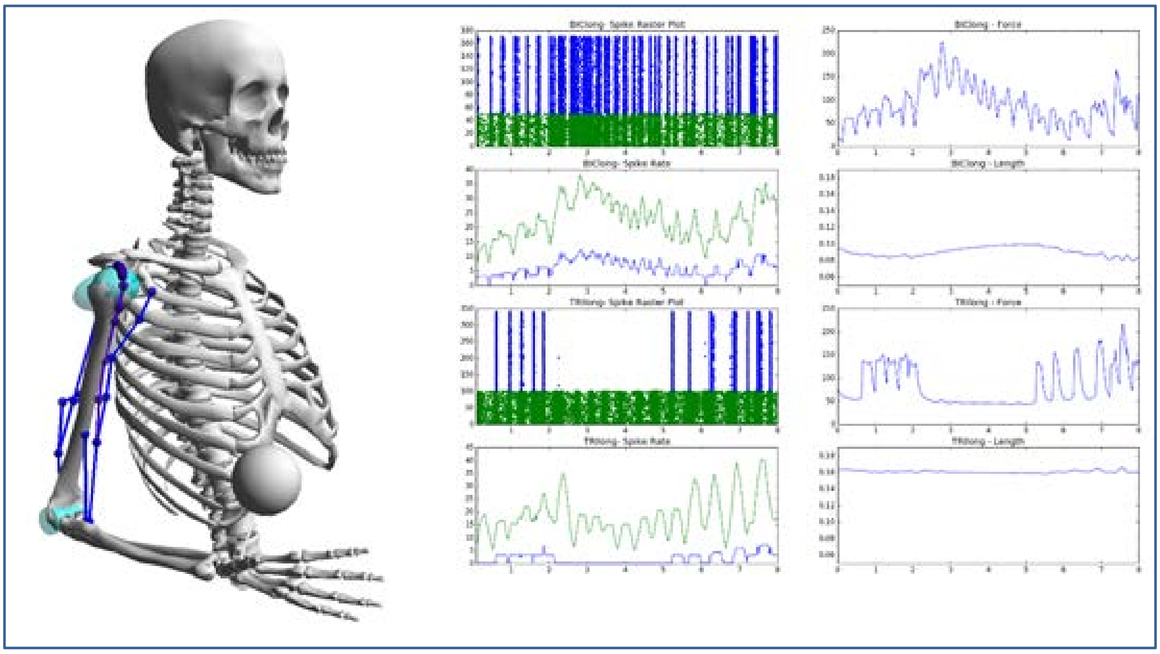


Figure 10: Prototype for closed-loop neuromusculoskeletal simulation

Left: Visualisation of the adapted biomechanical arm model in OpenSim. Right: Spike raster plots and average activity of the neural populations in the reflex circuit.

3.8.3.2 Measurements from Cognitive Experiments Performed *in Silico* on the Neurorobotics Platform (CDP 4, Visuo-Motor Integration)

The models of sensorimotor integration developed in CDP4 will be evaluated *in silico* on the NRP. Each execution of an experiment will yield measurement data that can be stored, shared and validated.

Progress on Component:

Work on the Component has not started since the complete saccade model is not finished yet. However, the NRP already contains all technical infrastructure required to record experimental data. Progress will therefore be made quickly is soon as the final saccade generation model is available and integrated in a closed-loop experiment.

3.9 T10.1.6 Simulation of motor rehabilitation experiment in rodents

3.9.1 Key Personnel

Task Leader: Silvestro MICERA (SSSA)

3.9.2 SGA1 DoA Goals

Define and replicate a robot-based rehabilitation scenario for rodents able to simulate real experiments performed with the M-Platform in the NRP. The M-Platform is a robotic device able to train mice to perform a retraction movement with their forelimbs (pulling experiment) and this experiment is the basis Use-Case of the CDP1 in the SGA1. The validated simulation of the platform and the integration with the model of the mouse allows to start motor rehabilitation experiments also taking into account clinical considerations and data. We use this experiment to align the different Tasks in WP10.1 and, as part of CDP1, to define and improve the features for the Brain Simulation Platform and the Neurorobotics Platform. The detailed model of the experiment will enable the extension and improvement of the whole-brain models, developed in SP6 by adding constraints from closed-loop dynamics.

The draft implementation of the M-Platform, as described in the MS 10.1.4, is currently installed on NRP on a local machine and will be soon integrated with the web NRP.

(see https://hbpneuroroboticsblog.wordpress.com/2017/05/17/the-virtual-m-platform/).

3.9.3 Component Progress

3.9.3.1 Specifications of the motor rehabilitation experiment and characterisation of the real M-Platform

The aim of this Component was to upgrade the M-Platform improving some of its critical Components to provide precisely data to be then used on the simulation.

Progress on Component:

<u>Components of the M-Platform and experimental protocol</u>

The M-Platform is a robotic system that allows mice to perform a retraction (i.e. pulling) movement of their forelimb. The M-Platform is composed of a linear actuator, a 6-axis load cell, a precision linear slide and a custom-designed handle fastened to the left wrist of the mouse. The handle is screwed on the load cell allowing a lossless transfer of the forces to the sensor during the training session. Each training session is divided into “trials”, repeated sequentially and consisting of five consequent steps. First, the linear actuator moves the handle forward and extended the mouse left forelimb by 10 mm (full upper extremity extension). Next, the actuator quickly decouples from the slide and informs the mouse about the initiation of the task. If able to overcome the static friction, the animal voluntarily pulls the handle back by retracting its forelimb (i.e. forelimb flexion back to the starting position). Upon successful completion of the task, the animal is given access to a liquid reward, i.e. 10 µl of sweetened condensed milk, before starting a new cycle.

Experiments and data related to this part:

Completed CAD projects and requirements have been optimized and provided for simulation (status completed, see Figure 11 A).

<u>Characterisation of the friction force levels:</u>

Although the M-Platform has been proficiently used as efficient tool both to identify motor deficits and to administer motor training, the possibility to precisely set the static friction the animals have to overcome was not possible. A precise characterization of the level of friction acting on the M-platform was thus the crucial point to be investigated to increase the repeatability and stability of the device and provide precisely data to be then used on the simulation.

<u>Experiments and data related to this part:</u>

- Design of a Component providing a variable level of friction to the slide. The movement of the slide is reduced by the application of a force, through a felt pad placed on screw, acting perpendicular to the movement of the slide. Thus, the level of the friction to be estimated depends on the angle of screw joining of the felt on the slide. Design and implementation of a rigid component to link the linear actuator to the handle, connected to the load cell. This rigid component mimics the effect of the retraction movements performed by the animal (status completed, see Figure 11 B).

- Definition and implementation of a protocol to assess the static and dynamic frictions acting on the linear slide. Repeated cycles of 15 forward/backward movements have been performed by the linear actuator for different velocities and screw joining of the felt on the slide. The static friction has been defined as the force peak needed to cause a first movement of the slide, while the dynamic friction has been identified as the constant force value after the static peak where the speed of the slide was kept stable. A parabolic relation between the static friction (the most important friction component in this experiment) and the level of contact of the felt pad on the slide was found (status completed, see Figure 11 C).

- Design and implementation of an actuated system to dynamically and precisely modulate the level of static friction. The felt pad was connected to a servo-motor controlled by a PWM logic through a microcontroller. The parabolic relation previously found, was used to specify the level of static friction by changing the voltage sent to the motor (status completed, see Figure 11 D).

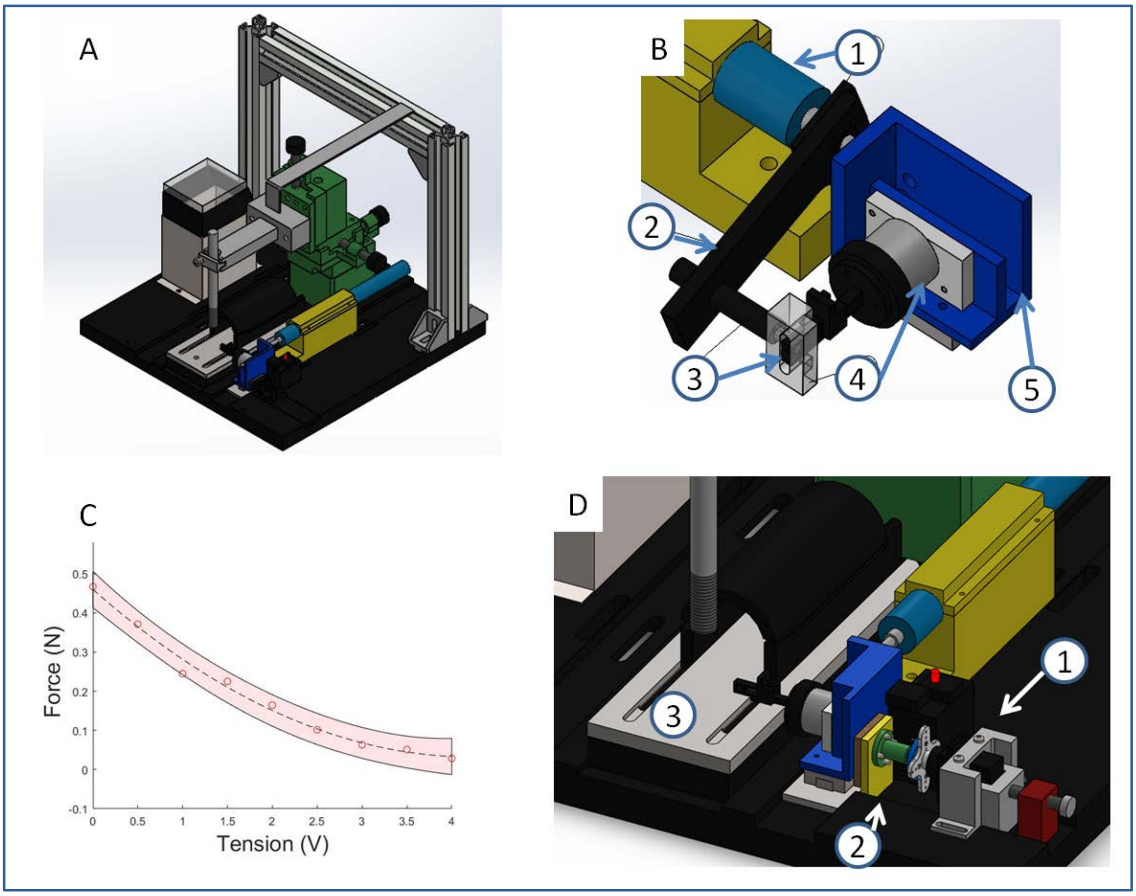


Figure 11: (A) CAD project of the real M-Platform. (B) New component (2) linking the actuator shaft (1) to the handle (3) connected to the force sensor (4) placed on the linear slide (5). (C) Parabolic curve estimated through the experimental trials which define the relation between the static friction force of the slide and the voltage controlling the servo-motor (linked to the level of contact of the felt pad on the slide). (D) The new component of the M-Platform used to finely control the static friction acting on the slide movement. It is composed of felt pad contacting the slide (2) moved by a screw connected to a servo motor (1), controlled by a microcontroller. The working area of the animal (3) is not obstructed by the new component.

3.9.3.2 Simulation of a motor rehabilitation scenario (Joint work with Laschi's group)

The aim of this Component was to define a first prototype of M-Platform in the simulated environment.

Progress on Component:

<u>A first prototype of the virtual M-Platform in the NRP</u>

We provided all the specifications requested to develop the virtual model of the M-Platform in the NRP. The first example provides the execution of a simple task of pulling of the slide, resulting from the application of a constant force to the handle of the robot. This study has been carried out as a joint work with the Prof. LASCHI's group (SSSA, member of SP10).

Experiments and data related to this part:

The CAD model of the main components of the M-Platform (i.e. linear actuator, linear slide, handle), previously designed (see section 1.1) was converted in a suitable format for the Gazebo simulator. To transfer properly the dynamic properties of the platform into the model, such as joint limits, values of friction, forces, as well as the possibility to model confounding influences of the setup onto the experiment, a graphical interface has been set up and properties of the model have been adjusted according to the real characteristics of the slide. The actuator was connected to a PID controller whose parameters have been tuned to reproduce the behaviour of the real motor (status completed, see

Figure 12 A).

A simple experiment has been designed in the NRP, for testing the behaviour of the obtained model. The experiment includes a 100 neurons brain model, divided in two populations of 90 and 10 neurons respectively. In this closed loop experiment, the first neuron population spikes randomly, and the spike rate of the population is converted to a force value picked out of a predefined range, compatible with the range of forces possibly performable by the mouse through its forelimb.

The computed force values are continuously applied to the handle and can move the slide until the starting position. Once there, the second neural population, wired to suppress the first population spike rate when active, is triggered, so there's no more force acting on the slide. The motor pushes the slide until the maximum extension position and it then comes back to its starting position, letting the loop start again (status completed, see

Figure 12 B-C).

Calibration of the virtual M-Platform in the NRP

The virtual model of the robotic platform has to accurately reproduce movements of the slide according to the applied force at different values friction force levels. The friction levels, that in the M-Platform are modulated with an actuated system, are reproduced on the virtual model regulating the friction coefficient of the slide. A precise calibration of the model based on the estimation of the friction has been performed. This study has been carried out as a joint work with the Prof. Laschi’s group.

Experiments and data related to this part:

A simple experiment has been designed using the rigid component that links the linear actuator to the handle (see Figure 11Figure 11 A). In this test, the slide was moved by the actuator forward and backward; the cycle was repeated for 20 times. During the test, position and applied forces were recorded. Later an offline analysis was performed: the signal was segmented and the average of the force signal was computed. This mean value was applied to the virtual model and the position of the slide in the NRP was compared to the recorded position of the M-Platform. The intrinsic limit of Gazebo in simulating low friction contact force between surfaces reduced the possibility to achieve simulated results adequately fitting the data collected. Moreover, we think that these results are due to the difficulties to model the inertial force of the linear slide acting on the real M-Platform, one to two orders of magnitude lower than the friction force and the force performed by the actuator. The model could then be better validated by using dataset of simulated data (forces) ranging into a physiological interval (related to real force measurements from mice performing the task) but that should be adjusted based on the characteristics of the simulator.

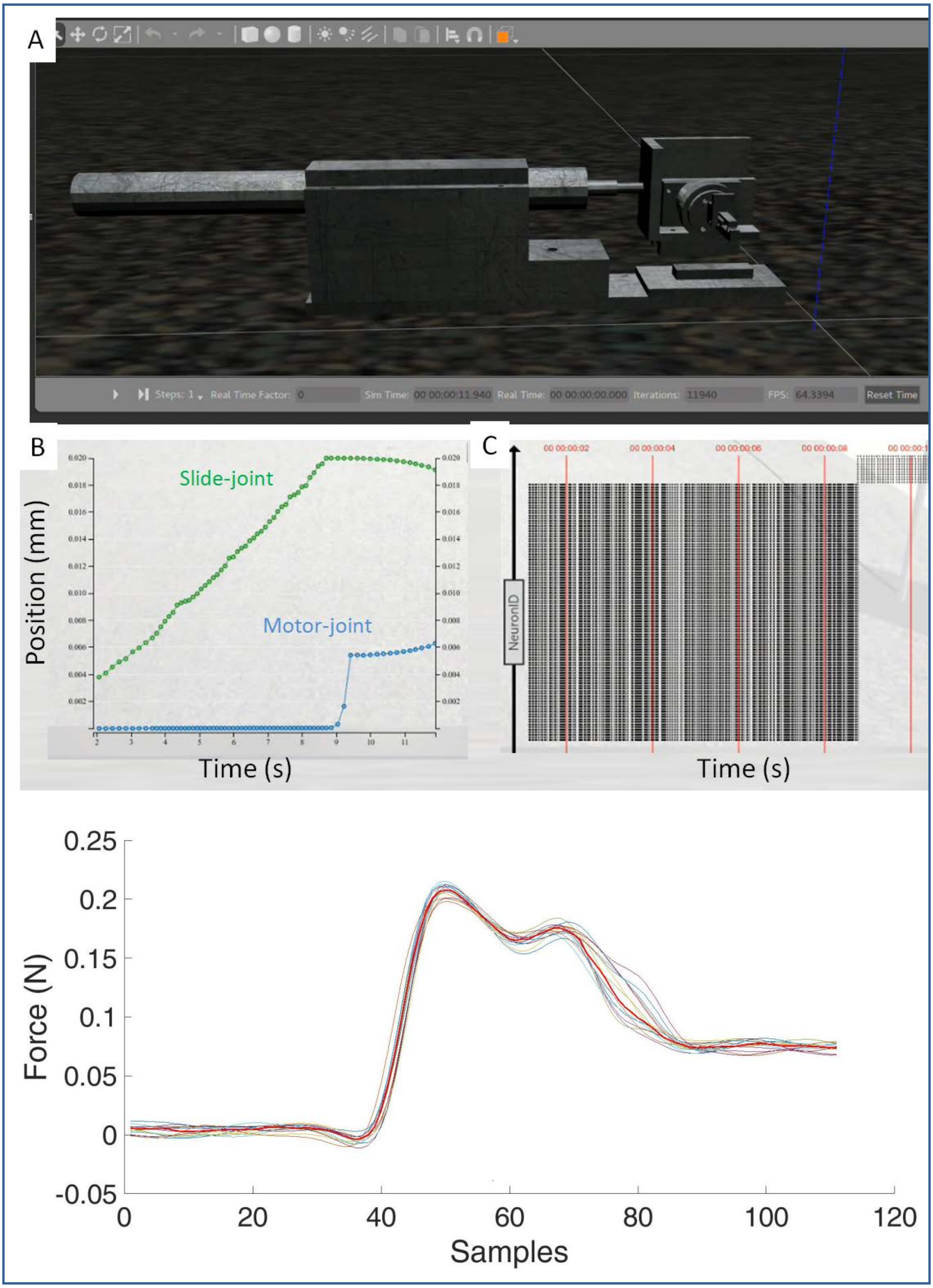


Figure 12: (A) M-Platform on the Gazebo Simulator. (B) The position of slide-join is changing because of the application of a force converted from the spiking activity of neurons population (in C) as explained on the text. (D, bottom) The segmented recorded signal of force, the red line is the mean signal used as input to the model in NRP

3.10 T10.1.7 WP Lead

3.10.1 Key Personnel

Task Leader: Marc-Oliver GEWALTIG (EPFL)

This Task involves no personnel costs, only the travel costs of the WP leader are budgeted. For a report see the WP Leader's Overview at the beginning of this section.

4. WP 10.2. Closed-Loop Experiments (Functional / Control Models)

4.1 Key Personnel

Work Package Leader: Cecilia LASCHI (SSSA)

4.2 WP Leader's Overview

This WP focuses on the development of a set of strategic top-down models of sensory-motor processing used to control virtual and physical body models. In particular, this WP aims to develop control models through a set of functional components that can be implemented by means of basic neural networks or classic control techniques and can be functionally replaced by data-driven brain models. The work is composed of three functional parts:

1) models of visual perception (T10.1.2) including a cortical model for early visual processing;
2) models of sensory-motor coordination using incremental functional models (T10.2.2) including models for the control of eye-head coordination in gaze stabilisation tasks;
3) learning models of body representation (T10.2.3) including models of short-term visual prediction, learning body model and force control.

The developed models are so far not integrated, but already implemented and tested in the NRP. The final goal is to have a library of these models (functional components) that can be selectable and usable in the NRP (an initial version of this library has been released according to M10.2.2). These models will be integrated during the second year of the SGA1 in order to generate complex behaviours. All the developed models and implementations are innovative and lead to submissions of articles in journals or international conferences (most of them are still under review). This work has been carried out by means of collaborations among SP10 partners (i.e. the gaze stabilisation model developed in the framework of the T10.2.2) or across SPs (i.e. neural model for short-term visual prediction implemented in the framework of the T10.2.3). There have been no deviations from the work plan.

Model descriptions, videos and code repositories are available here: https://hbpneurorobot-icsblog.wordpress.com/2017/05/05/functional-components-for-control-and-behavioural-models/

4.3 Priorities for the remainder of the phase

In the remaining part of SGA1 we plan to focus on two main goals:

1) Embedding the developed models in the NRP and making them easily usable and configurable for the user needs;
2) Design experiments that can demonstrate the effectiveness of the models and their integration. In particular, these experiments will allow to generate complex behaviours involving manipulation or postural tasks.

In order to achieve these goals intermediate steps are needed. These include the development of new models of sensory-motor control (i.e., predictive controllers), learning mechanisms for the automation of the articulations of hands and the corresponding body and the refinement of the existing models and the definition of a common interface to allow a seamless integration.

4.4 Milestones

Table 2: Milestones for WP 10.2 - Closed-Loop Experiments (Functional/Control Models)

MS No.	MS Name	Leader	Expected Month	Achieved Month	Comments
10.2.1	Implementation plan for WP10.2	SSSA	M02	M06	This Milestone has been achieved with the submission of deliverable 10.7.1
10.2.2	First version of the functional components library	SSSA	M12	M12	A first functional framework composed of functional models for brain mechanisms, perception mechanisms and robotic controllers has been defined. This framework allows users to design basic and complex functional behavioural models. We implemented some basic behavioural models using building blocks that have now been embedded in the framework. The behavioural models have been tested with simulated and real experiments, including visual perception, gaze stabilisation, balancing, and grasping tasks. Further details on the experiments can be found in the last semester report. More details about the framework architecture and some examples and demos of the experiments are available on the HBP Neurorobotics blog https://hbpneurorobotics.wordpress.com/2017/05/05/functional-components-for-control-and-behavioural-models

4.5 10.2.1 Early sensory processing

4.5.1 Key Personnel

Task Leader: Michael HERZOG (EPFL)

4.5.2 SGA1 DoA Goals

Task 10.2.1 continues work on a cortical model for early visual processing that started during the RUP (Laminart model). The model is a biologically plausible, multi-layered neural network that uses recurrent processing to segment a visual stimulus into several separated perceptual groups (see Figure 13). The main goal of the task is to integrate the model in the NRP as part of a closed-loop simulation of perceptual-cognitive-motor systems. Once embedded in a virtual experiment, the model will project its output to higher cortical areas to generate a motor response, recurrently updating the visual stimulus. The model contains hundreds of thousands of neurons, and is (to date) the largest simulation in the neurorobotics platform. It is a benchmark that the platform can operate a model with such many neurons and simulate a complex cortical model and human performance in a closed loop fashion.

The second goal of the task for SGA1 is to increase physiological realism by connecting the Laminart model to a retina model that is already implemented in the NRP.

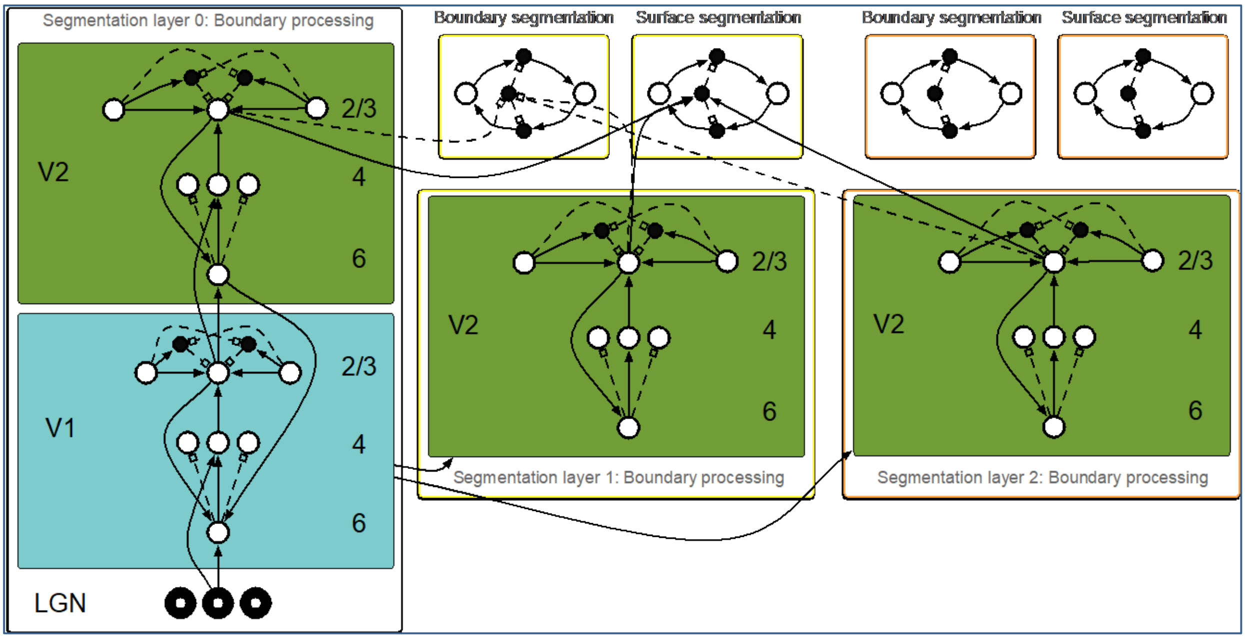


Figure 13: Laminart model

Neurons in V1 (blue) project to three segmentation layers in V2 (green). Each segmentation layer represents a different perceptual group. Boundary and surface segmentation networks segment the visual field into these perceptual groups and allow activity to spread within the segmentation layers. Segmentation is initiated by top-down signals. V2 activity projects to 3 different copies of V4 (not shown), which generate the output of the model.

4.5.3 Progress

The following concrete steps were defined in order to fulfil the overarching goals described above in SGA1:

- Integrate the model in the NRP.
- Design visual experiments to test and explore the models in realistic conditions within the NRP.
- Based on the model's performance in the NRP, implement the adequate modifications to the model, so that it detects objects in realistic scenes.
- Connect the cortical model to a retina model to increase physiological realism, by taking into account the retinal magnification factor for central and peripheral vision and pre-processing the input with a basic gain control (Weber's law).

Current progress on the work being carried out to achieve these steps is described below:

- In order to integrate the Laminart model to the NRP, we translated the original model code (written in NEST) to PyNN. Status: Completed
- Together with Alessandro Ambrosano from SSSA, we started to translate the model code to SpiNNaker code for higher computational performance, when compatibility between the NRP and SpiNNaker is achieved. Status: Ongoing
- In collaboration with Jacques Kaiser from FZI and Alessandro Ambrosano from SSSA, we integrated the Laminart model on the NRP. We could test the basic behaviours of the model on the platform. Status: Completed - computation of illusory contours, boundary segmentation and surface segmentation worked exactly as in the original version of the model.

- To be able to simulate the Laminart model in descent conditions on the NRP, we reorganised the code to shorten the time needed to setup the network by a factor of 100. Together with Alessandro Ambrosano, we also made modifications to speed up the simulation of the network by a factor of 10. Status: Completed
- To ensure that the model can handle realistic objects, we made the model sensitive to eight orientations. Status: Completed – the network can represent edges oriented with an angle of 22.5°, 45°, 57.5°, etc., just as it would do for vertical and horizontal bars; however, to detect so many orientations, the model needs the compatibility between the NRP and SpiNNaker.
- We provided scale-invariance to the boundary and surface segmentation processing. Status: Completed – segmentation spread can now be done at any scale (which means: much faster if the configuration of the visual stimulus allows it), without breaking the inherent behaviour of boundary and surface segmentation.
- We used the video stream viewer to generate and display real-time images of different layers of the network (e.g. layer 2/3 of area V2) in response to the environment. Status: Completed – see Figure 14: the output of the video stream viewer corresponds exactly to what could be generated with the original version of the model.
- We set up a simple closed-loop experiment using the output of the network (brightness layer of area V4) to generate a simple motor response that influences the network's input. Status: Completed - see Figure 14.

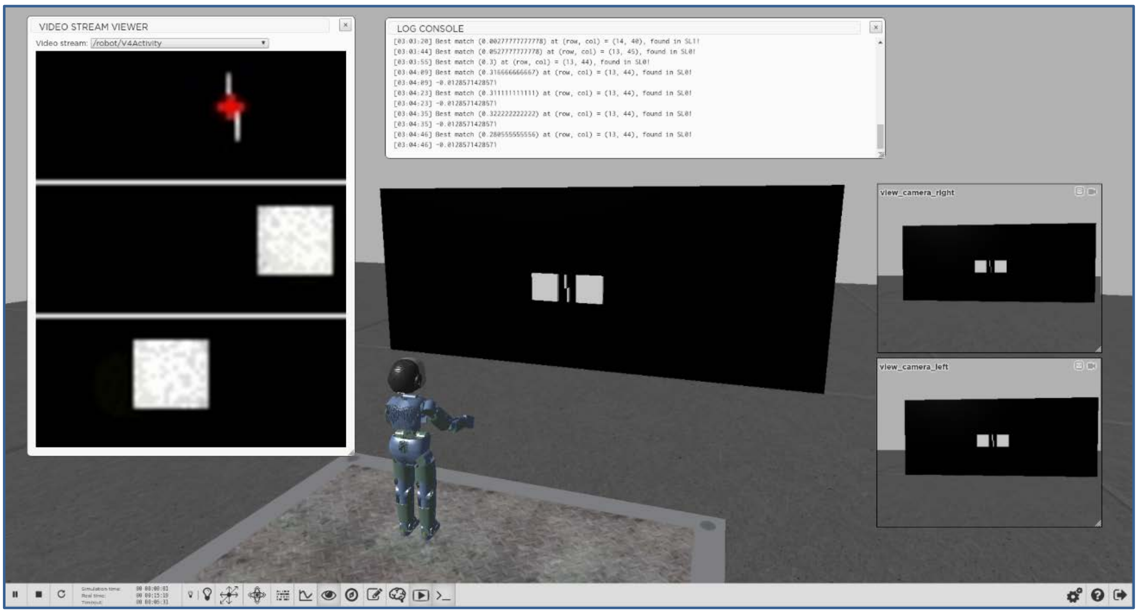


Figure 14: The robot views a line target surrounded by two flanking squares, which impair target detection

The task is to detect the target. This is only possible when the squares are successfully segmented by the surface segmentation signals. When the target is detected (red cross), the robot moves its eyes towards the target location, recurrently updating the visual stimulus. The output of the video stream viewer is the activity of the segmentation layers in the area V4.

- We connected the Laminart model to a framework used to create retina models (NEST module by Prof. Eduardo Ros) and checked for smooth information flow between both models. Status: Completed – the complex made with the retina model had a behaviour that was consistent with the standalone version of the Laminart model.
- Then, in collaboration with Alessandro Ambrosano from SSSA, we started to connect the cortical model to the same retina framework, on the NRP. From there it was planned to build a closed-loop segmentation experiment involving both cortical and retina models. Status: Ongoing.

Platform development:

- We performed an experiment on the NRP involving the model with at least 50,000 neurons and 300,000 connections (input image of 20 by 20 pixels, network sensitive to 2 orientations). This is a benchmarking experiment for the platform that proves the NRP can handle simulations of that scale. Status: Completed
- We then repeated the simulation with more neurons and connections and real-time images of the network activity. Up to now, the implementation of the network on the NRP has been tested with an input image of 30 by 70 pixels and 2 detectable orientations, for a total number of 450,000 neurons and 4,350,000 synaptic connections. Status: Completed
- While we were integrating the Laminart model to the platform, we delivered various feature requests and extensive tests to the NRP. Status: Ongoing

One of the goals for SGA1 is to achieve the connection between the cortical and the retina model. We plan to use this connection to model how segmentation can be performed in low-contrast condition, and how the model should use colour information to segment the visual space (using the retina model further, for colour opponent processes).

Taking advantage of the fact that HBP promotes the collaboration between different labs, we also plan, after all SGA1 goals are fulfilled, to connect our cortical model to the other models that are developed in WP10.2 (saccade generation, gaze stabilisation, object detection, motor control). Finally, as a plan for SGA2, we have established future connections to SP2 (saliency model by Prof. Rainer Goebel, comparison with monkey experiments about texture segmentation by Prof. Pieter Roelfsema) and SP4 (predictive coding model by Prof. Wulfram Gerstner), which are planned for SGA2. All these collaborations were accepted by the aforementioned groups and were officially integrated to the project life-cycle application. The feedback we received from them indicates that our model is of interest to them. We think our model will be a component integrated by many groups into their simulations because a biologically realistic visual module will be crucial to many applications on the NRP.

We think that the connections thus established will be crucial for the whole field of vision research, because we believe that having a whole model of the visual system is necessary to even model how the most basic computations are made by human vision (see Figure 16). The NRP provides a unique and very convenient framework to connect so many different models together.

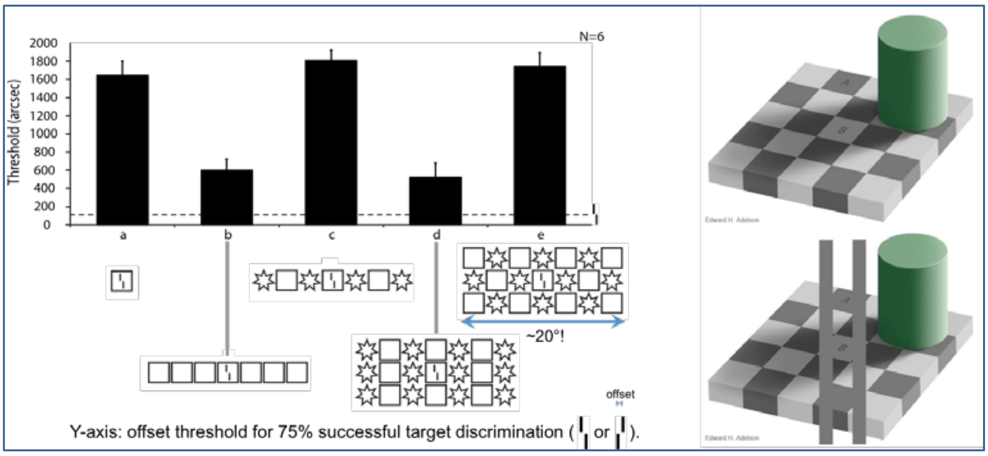


Figure 15: Left: behavioural experiments done in our laboratory

The stimuli shown on the *x*-axis are briefly presented to human observers in the periphery of their visual field. Observers have to identify the direction of the offset of the target (small tilted bars). The whole configuration of the flankers (shapes around the target) have an indisputable influence on the observer's performance. Right: the perceived colours of A and B depend on the whole context of the scene. In both cases (left and right), the content of the whole visual field has an effect on simple, local computations.

Platform use cases:

- Visual tracking experiment: the iCub robot, equipped with the cortical model, tracks a moving target. The robot is expected to keep a stable, non-retinotopic representation of the target object by the computation of illusory contours and a constantly active and adapting segmentation process, even if the object is partially occluded by non-target objects. The location of the segmentation signals adapts to the eye movements, ensuring that the representation of the perceptual groups is non-retinotopic. The future plan is to connect the Laminart model to a model for gaze stabilisation from SSSA (task 10.2.2), to ensure a stable visual environment, even if the head moves. It is also planned to connect the Laminart model to several models for motor control, provided by tasks 10.2.2 and 10.2.3 (saccade generation, smooth pursuit, object-related movement prediction).
- Catching experiment (collaboration with tasks 10.2.2 and 10.2.3): use the visual tracking experiment to connect the output to higher visuomotor cortical areas (saliency detection, saccade generation, smooth pursuit generation, object related movement prediction, target detection, decision making), to track and predict the pathway of a moving target object to catch.

Related publications:

- Francis, G., Manassi, M., Herzog, M. H. (2017). Neural Dynamics of Grouping and Segmentation Explain Properties of Visual Crowding, *Psychological Review*.
- Manassi, M., Hermens, F., Francis, G., Herzog, M. H. (2015). Release of crowding by pattern completion. *Journal of vision*, 15(8), 16-16.
- Francis, G. (2015). Contour erasure and filling-in: Old simulations account for most new observations. *i-Perception*, 6(2), 116-126.
- Clarke, A. M., Herzog, M. H., & Francis, G. (2014). Visual crowding illustrates the inadequacy of local vs. global and feedforward vs. feedback distinctions in modeling visual perception, *Frontiers in Psychology*.

4.6 T10.2.2 Behaviour generation

4.6.1 Key Personnel

Task Leader: Cecilia LASCHI (SSSA)

Other Researcher: Henrik H. LUND (DTU)

4.6.2 SGA1 DoA Goals

This Task focuses on the development of functional components needed to allow the agent to generate a proper behaviour in response to complex sensory stimuli. Such behaviours will include incremental functional models; starting from the basic perception and action functions of the robot, specifically the visual, proprioceptive, vestibular and tactile sensory systems and the actuators for the eye, head, body and limbs movements.

4.6.3 Component Progress

4.6.3.1 Cognitive models for complex behaviours

This Component will provide integration of previously developed functional and data-driven models in order to generate complex behaviours. A set of experiments will guide the selection of the mentioned models and their integration (i.e. spinal cord models for locomotion, basal ganglia and cerebellum models for manipulation or gaze control). This component can take advantage from sensory and motor models developed in T10.1.1 and T10.1.2.

Progress on Component:

The work for this Component will start in M13.

4.6.3.2 Reactive perception-action loops

This Component will provide functional behavioural models of reactive perception-action loops (i.e. reflexes and feedback-based actions, based on cerebellar motor control). These behaviours will be tested on simulated robotic platforms (humanoids or modular) or simulated mouse and human models. The models will have a modular structure, so that parts of them can be substituted by brain models provided by T10.1.2.

Progress on Component:

We focus our work on reflexes used by human for gaze stabilisation. In particular, we implement on humanoid robots a model of gaze stabilisation based on the coordination of vestibulocollic reflex (VCR) and vestibulo-ocular reflex (VOR) and optokinetic reflex (OKR). The model, inspired on neuroscientific cerebellar theories, is provided with learning and adaptation capabilities based on internal models. This model is tested on two sets of experiments. The first set of experiments focuses on the model response to a set of disturbance frequencies along the vertical plane. The other set of experiments were carried out to test the capability of the proposed model to stabilise the gaze in locomotion tasks. The first set has been validated in the NRP as well as in a real humanoid robot (SABIAN). For this experiment, the SABIAN head has been placed on an oscillating platform (see Figure 16) able to rotate along the pitch axis, with different frequencies, in order to produce a disturbance.

Figure 17 shows the results on the SABIAN robot in a task with a disturbance of 1 Hz along the pitch axis applied to the head with VOR and VCR active. It shows that the model is able to reject the disturbance strongly decreasing the retinal slip (velocity of the image on the retina) and the position error on the camera.

The effectiveness of the controller was also tested in a realistic situation by employing the biped humanoid robot SABIAN for a walking task consisting of 8 steps in a straight line. In order to compute the camera error and the retinal slip, a target was placed in front of the robot, at the same height as the robot head. The target was kept static during these trials, thus the OKR module have been disabled. The VCR is active only on the roll and pitch axis (due to a drift of the inertial sensor along the yaw axis) and the VOR is active only along the vertical axis (tilt motion). We employed the offline learning strategy by creating a training set consisting in inertial data recorded during 4 locomotion trials. All the collected data were glued together to create a new offline task lasting 32 s. Then, the controller was executed on such trial and the learnt internal models were saved.

Finally, the modified version of the controller for the execution phase was employed on a new walking task. A comparison between a stabilised walk and a non-stabilised one can be seen in Figure 18.

Further details about the data related to gaze stabilisation during locomotion can be found in this recently accepted paper:

Lorenzo Vannucci, Egidio Falotico, Silvia Tolu, Vito Cacucciolo, Paolo Dario, Henrik Hautop Lund and Cecilia Laschi (2017), A comprehensive gaze stabilisation controller based on cerebellar internal models, *Bioinspiration & Biomimetics* (accepted, available online)*:* http://iopscience.iop.org/article/10.1088/1748-3190/aa8581

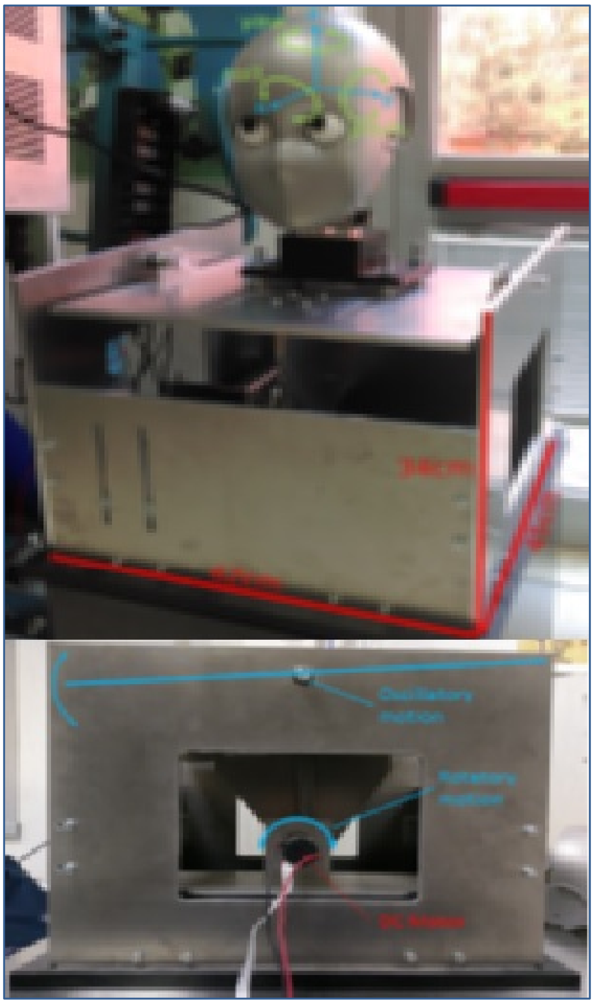


Figure 16: The oscillating platform. In the SABIAN head mounted on the platform (top), with its inertial reference frame is shown. The transmission of motion from the DC motor to the oscillating platform (bottom)

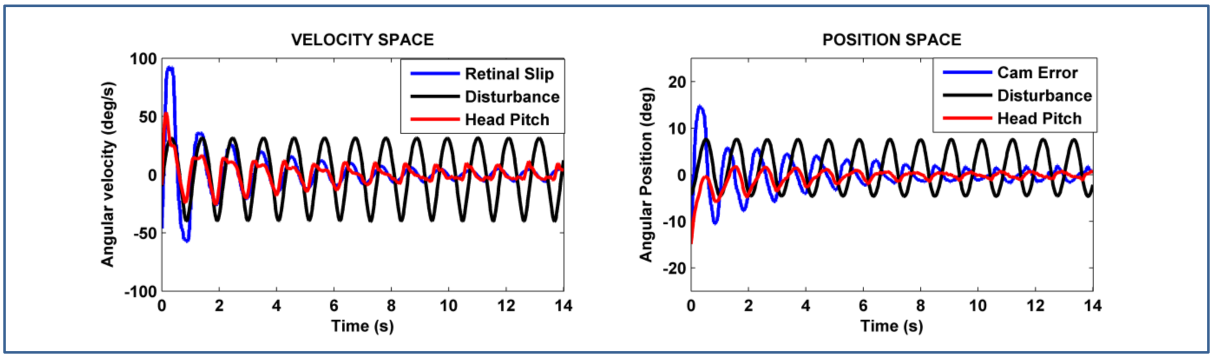


Figure 17: Execution trial for *f* = 1 Hz. Results for the inertial readings and camera error in the velocity and position spaces

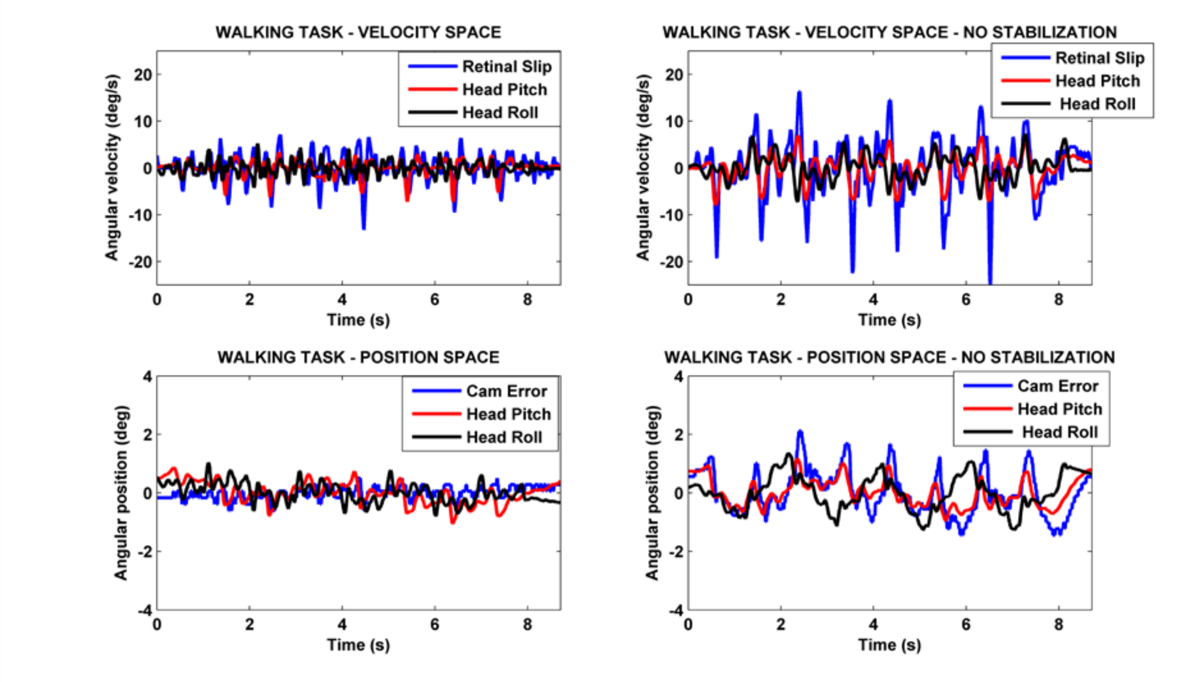


Figure 18: Stabilisation during a straight walking task: comparison between stabilised and non-stabilised gaze

4.6.3.3 Anticipative perception-action loops

This Component will provide functional behavioural models of anticipative perception-action loops. These behaviours will be tested on simulated robotic platforms (humanoids or modular) or simulated human models. The models will have a modular structure, so that parts of them can be substituted by brain models provided by T10.1.2.

Progress on Component:

We designed models of prediction of target trajectory of moving objects in tracking tasks. These models have been integrated in a visual tracking model in order to provide it with the capability to overcome the delays of the sensory-motor loop allowing a more accurate tracking of the objects. Preliminary tests have been carried out on a simulated humanoid robot in the NRP.

4.7 T10.2.3 Learning body and movement representations for grasping and manipulation

4.7.1 Key Personnel

Task Leader: Rüdiger Dillmann (FZI)

4.7.2 SGA1 DoA Goals

The main goal of this Task during the first 12 months of SGA1 was the development of a small library of brain models (i.e., spiking neural networks) dedicated to the control of classical robots. In contrast to the majority of models handled in WP10.1, their development is much lesser data-driven and instead, they are rather engineered for functionality based on well understood and reliable principles. In the NRP, such *functional* models offer new insights into the process of conceptualisation, design and execution of meaningful and challenging experiments that were designed to develop and evaluate novel, brain-based technologies.

Consequently, previously unpredicted requirements for the platforms could already be identified during the design of our experiments and the development of the neural controllers.

We designed the controllers and experiments to be easily integrable into the NRP once these features are implemented. During the remainder of SGA1, we will continue this research and transform it into pilot experiments that serve as showcases of the NRP, mainly targeting engineers.

Our pilot experiments will be centred around early grasping and manipulation experiment in the Platform and feature an industrial arm with an anthropomorphic hand (Schunk LWA arm and SVH hand) and neuromorphic sensors (Dynamic Vision Sensor cameras) both physically available to the Consortium. We designed the experiments to be able to demonstrate and evaluate learnable body and movement representations, and in order to achieve this, we identified several necessary building blocks each of which is represented by a Component in T10.2.3.

- Functional brain model for visual perception
- Learnable body model representations
- Neuromorphic Visual motor coordination
- Functional brain model for humanoid grasping
- Functional body and movement learning
- Functional model of Symbolic perception
- Library for Human Motion Data

4.7.3 Component Progress

4.7.3.1 Functional brain model for visual perception

This Component creates a functional brain model (not data-driven but inspired by Machine Learning approaches) for visual perception. It relies not only traditional cameras but also a novel technology: Address event sensors like the Dynamic Vision Sensor (DVS) camera. Obviously, this raised the requirement of the ability to simulate this sensor which has been addressed in T10.3.3. To create the brain model, we considered popular techniques such as convolutional networks (e.g., for detection) and the more biologically plausible Reservoir Computing (for motion prediction).

Progress on Component:

We first evaluated the construction of neural models for visual perception in simulation and published our results. The scenario chosen for this early study was an end-to-end controller capable of lane following in a self-driving vehicle. The advantage of using a car is that its control is simpler than a full robot arm. This experiment was used to showcase our novel interfaces to spiking networks: simulated event-based vision and muscles. Indeed, due to the similarities to biological information flows, we developed a visual encoder from camera images to spikes heavily inspired by the DVS Dynamic Vision Sensor which is often referred to as silicon retina. This idea evolved later into new sensor model for the NRP (cf. T3.3.3). For the control of the vehicle, we implemented a steering wheel decoder based on a virtual agonist antagonist muscle model. The resulting control principles are general with respect to being able to be transferred easily to different embodiments such as an anthropomorphic robot system. In the remainder of SGA1, this showcase will be transformed into an experiment in the NRP to highlight its benefits in many fields of research.

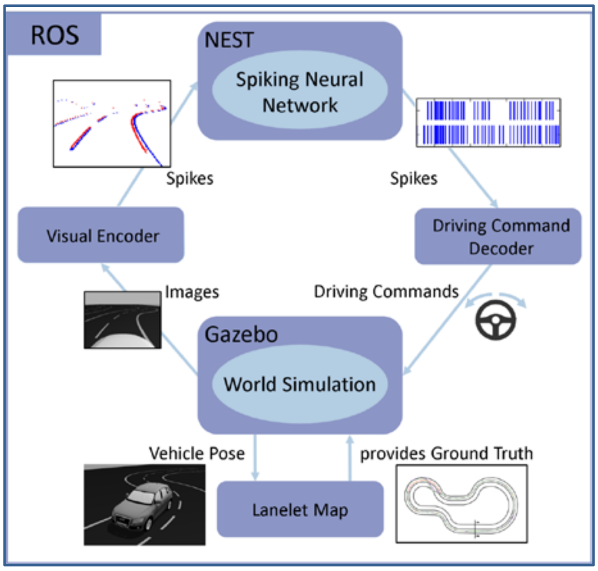


Figure 19: End-to-end controller for lane following for a self-driving vehicle

We continued the research on functional visual perception models in cooperation with SP4 (W. Maass, TU Gratz). Here, we developed neural model for short-term visual prediction, which will be of importance later in the manipulation experiments developed in this Task. It allows anticipating upcoming states of the environment and therefore, renders planning significantly more efficient. In more depth, we applied models based on liquid state machines (LSM) developed in SP4 and put them into a neurorobotics context. LSM are a biologically inspired method to perform asynchronous prediction without a model. We combined this model on raw stream of events created by a simulated and physical DVS camera. The results have been submitted for publication.

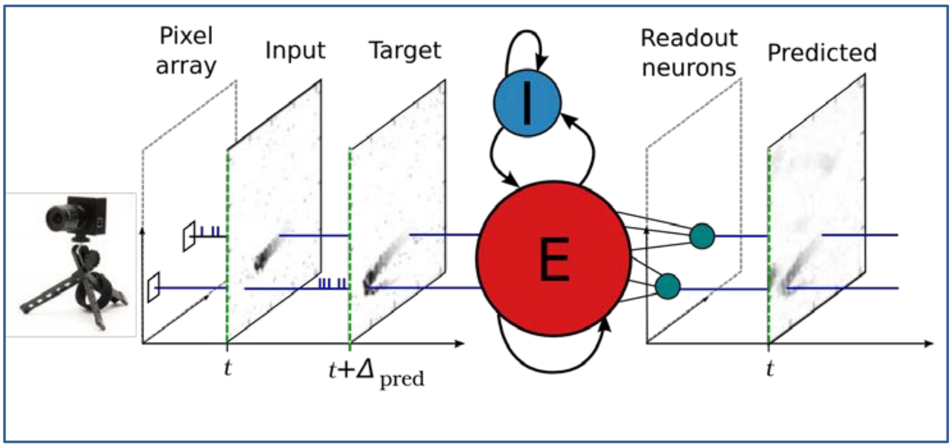


Figure 20: Neural model for short-term visual prediction

In parallel to the integration of predictive models, further effort in developing visual perception models involved the transfer of currently very popular deep learning techniques into spiking neural networks compatible with SP6's neural simulator (NEST/PyNN) simulator and therefore, the NRP and eventually, the neuromorphic hardware developed in SP9. We therefore augmented a recently published unsupervised learning rule to train spiking Restricted Boltzmann Machines. It is based on synaptic plasticity and was modified to learn features directly from event streams as produced by the DVS silicon retina. We extend this approach by adding convolutions, lateral inhibitions and multiple layers, and evaluated our method on a self-recorded DVS dataset containing objects with different affordances, as well as the Poker-DVS dataset. Our convolutional method performs better compared to the original approach with fewer parameters. It also achieves comparable results to previous event-based classification methods while learning features are learned from unlabelled data (unsupervised learning). These results are published.

Finally, we investigated functional, neural models for object recognition based on networks of spiking neurons which are inspired by another popular deep learning technique (HMAX). Unlike the previously presented network, it does not rely on event-based sensor but processes classical (synchronous) camera images converted into spikes based on pixel intensities. We created a model which extracts intermediate-level features in images from a set of classes in an unsupervised manner and uses them to later learn new, unrelated classes with just a few training examples. This process of very fast learning is called one-shot learning. The learning of the classes happens in a continuous manner, without scripted interruptions and external interventions to the neuron states during simulation. This increases the biological plausibility and negates the need for modifications to the NEST simulator used in the NRP.

The high quality of the learned features is confirmed by achieving a close to state-of-the-art F1 score of 97% during the recognition of the same classes, while obtaining a score as high as 72% for one-shot learning. These results have been submitted for publication.

4.7.3.2 Neuromorphic Visual motor coordination

Description: We plan to implement a reasonably sized neural network that interfaces two DVS directly from neuromorphic computation hardware (SpiNNaker) to control a specially designed robotic head on which the cameras are mounted. The network will be manually crafted (i.e., without learning) to investigate scientifically relevant tasks such as saccades and fast, smooth pursuit. We will use dedicated hardware developed in WP10.4 to overcome bandwidth limitations between the hardware components.

Progress on Component:

While work related this Component started, it was focused on the physical simulation only: A virtual model of the robotic, anthropomorphic head has been created in collaboration with WP10.4 (TUM, Jörg Conradt) and integrated in the NRP including a simulation of the dynamic vision sensor during the first months. Therefore, this effort is reported in more detail in the context of T10.3.3.

4.7.3.3 Learnable body model representations

This component creates a functional brain model (not data-driven but inspired by Machine Learning approaches) for mapping from generative joint and later, muscle spaces (configuration space) to the resulting Cartesian or work space. In terms of classical robotics, these brain models correspond to the direct and inverse kinematics.

Progress on Component:

For a model-based approach to generate motion for grasping and manipulation, we investigated the transformation of the Kinematic Bézier Maps (KBMs) [5] into networks of spiking models. KBMs linearise the complex trigonometric relations in robots which dramatically speeds up learning and renders them a promising candidate for a neural implementation. For evaluation purposes, we integrated this algorithm as a classical Python library that can directly be used for comparison in the NRP. For the translation of the mathematical model into neural networks, the Neuro-engineering Framework (NEF) has been first considered and has been augmented for multivariate multiplication and polynomial function approximation. This approach contributed to discussion of opening the platform for different simulators. The results of this approach are published in [6].

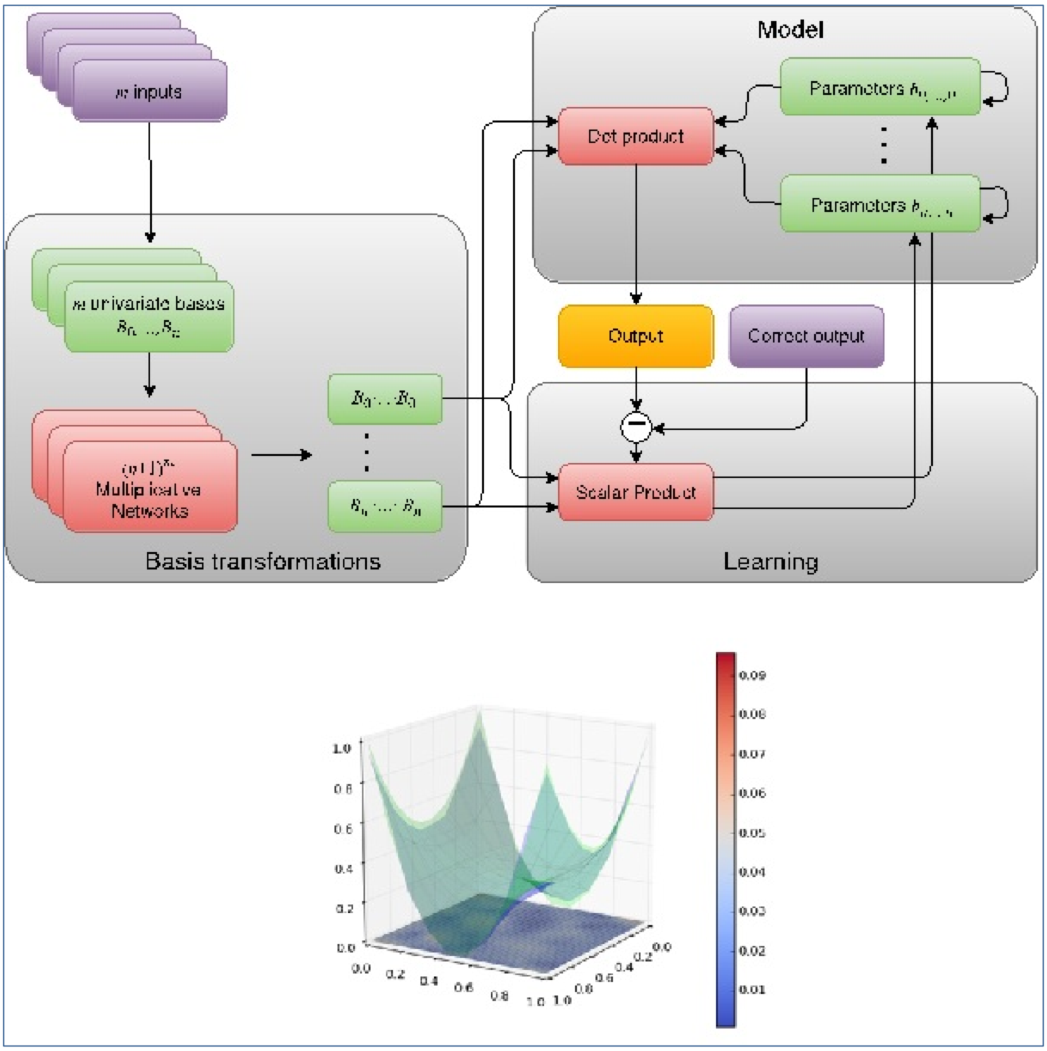


Figure 21: Architecture of a functional brain model (top) capable of multivariate polynomial function approximation (bottom). This model is the basis for learnable body representations.

In the remainder of SGA1, this model will be completed and transformed into a NEST model for the NRP

4.7.3.4 Functional body and movement learning

This Component is a functional brain model (inspired by Machine Learning approaches) for mapping from joint and muscle spaces to Cartesian space (direct and inverse kinematics). Unlike the network described earlier, it is not model-based and capable of learning movements.

Progress on Component:

During the work on the Component, we encountered shortcomings of the NRP, which we were able to resolve and demonstrate in an experiment. At that time, the NRP supported only the actuation of joints via classical (i.e., non-neural) PID controllers for either the position or the velocity of individual joints. This abstraction is generally useful for a researcher who is not directly working on motion. When the joints are to be directly controlled by a brain model, the PID controller needs to be bypassed. In our case, we wanted to apply torques to specific joints depending on the activation dynamics of the brain model. Although the underlying physical simulation already provides force/torque-based control, this feature was not exposed and documented in the NRP so far. The NRP was enhanced accordingly and example was added to the experiment library.

The experiment demonstrates a simple force-based spiking interface for an anthropomorphic robot hand (Schunk SVH). Two joints of the index finger are exemplary controlled by two motor neurons each (antagonist and synergist) to reach a desired configuration. Therefore, we apply a simple muscle model to convert activation dynamics to joint efforts in the physical simulation. This early experiment demonstrates one of the possible mechanisms for implementing force-based control in the paving the way to more complex muscle model simulations in the future. In the remainder of SGA1, this experiment will be extended to support more complex control methods.

Starting from this simple experiment, we developed a neural network capable of learning arm motions with reinforcement learning based on dopamine regulation. This mechanism available in the NEST simulator (developed in SP6) and consequently, also in the NRP. The resulting network is capable of learning how to move the end-effector to a target location and can control multiple degrees of freedom in real-time. The results are currently prepared for publication.

4.7.3.5 Functional brain model for humanoid grasping

This component creates a functional brain model for encoding motion primitives for finger movements with spiking neural networks which can be used for grasping.

Progress on Component:

During the first 12 months of SGA1, we investigated methods for representing and executing grasping motions with spiking neural networks that can be simulated in the NEST simulator and therefore, the NRP. For grasping in particular, humans can remember motions and modify them during execution according to the shape and the intended interaction with the object. We developed a spiking neural network with a biologically inspired architecture to perform different grasping motions. At first, it learns in simulation via neural plasticity and input from human demonstration. Later, it can be used to control a humanoid robotic hand. The network consists of two types of associative networks trained independently. The first represents single fingers and learns joint synergies in form of motion primitives. The second network represents the entire hand and coordinates multiple networks of the first type to execute a specific grasp. Both receive the current joint states as proprioceptive input using population encoding. In addition, the networks for the individual fingers also receives tactile feedback for the inhibition of output neurons and interruption of the motion upon contact with an object. The results are published.

4.7.3.6 Library for Human Motion Data

This Component represents a library for motion capture data and EMG data during motions. It will combine data produced by the HBP and existing libraries such as the HuMoD, CMU and KIT full body motion libraries. The intent of the interface to a motion library is to be able to validate and train the models with human captured data. These data will gain particular importance for the future human locomotion models.

Progress on Component:

The work for the library component will start at M13.

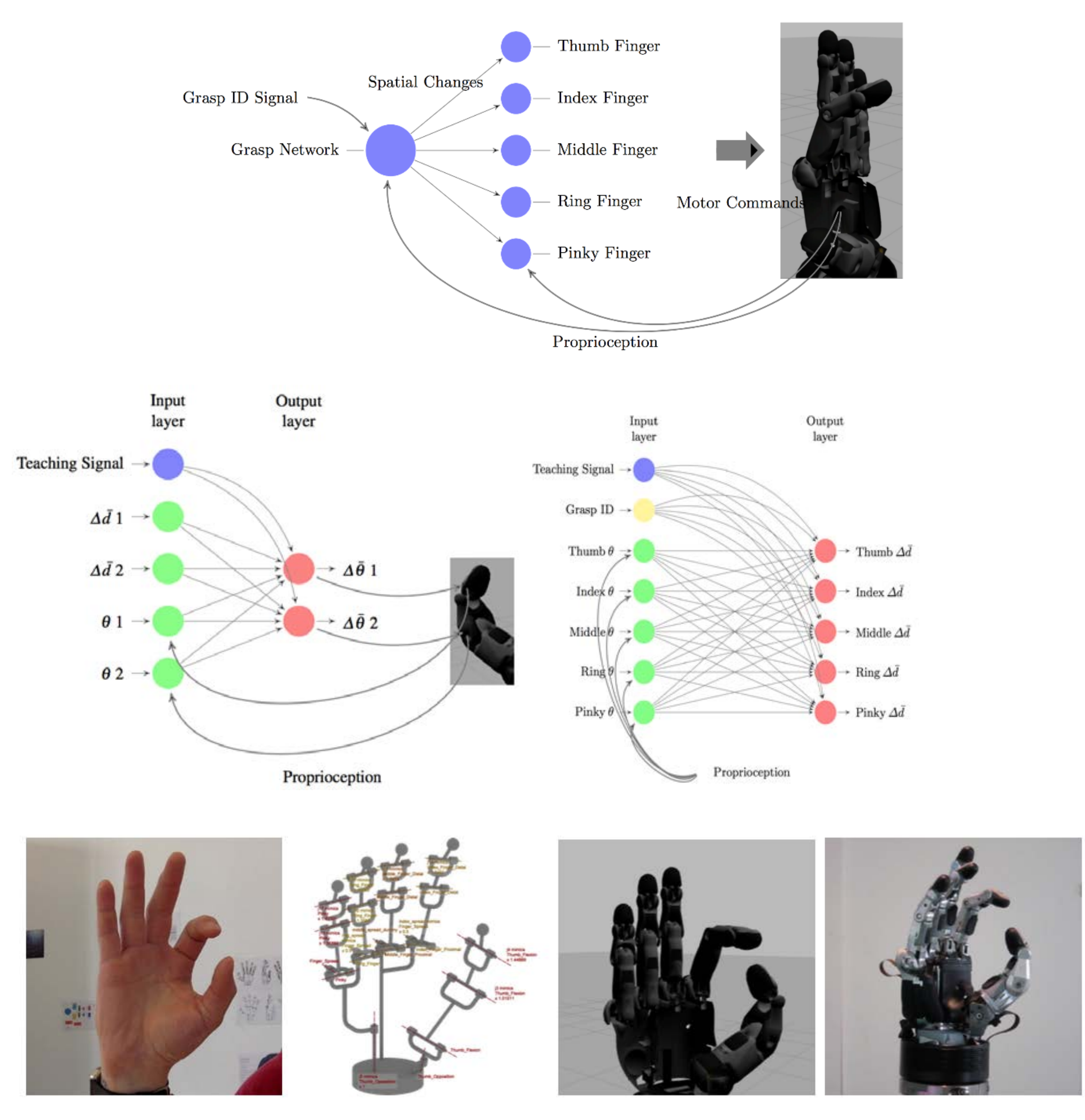


Figure 22: Functional brain model for grasping with anthropomorphic hands.

4.7.3.7 Functional model of Symbolic perception

This component creates a functional brain model (not data-driven but inspired by machine learning approaches) for symbolic perception. It is based on symbolic vector architecture (SVA) approaches (see Figure 23).

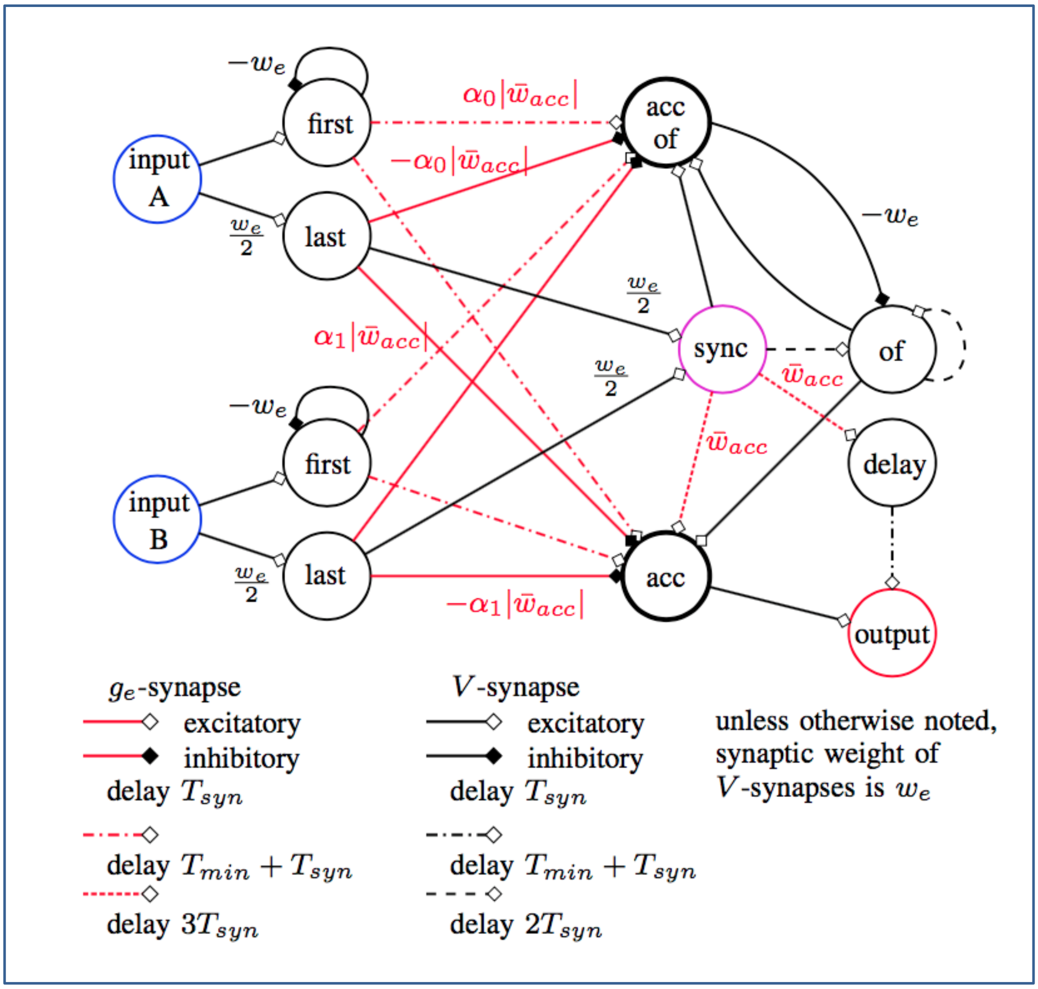


Figure 23: Functional model of symbolic perception

Progress on Component:

In the first few months of SGA1, we developed a spiking neural network that realises an associative memory. Therefore, we rely on exact spike time for signal transmission and value encoding respectively. The method our model is based on are circular holographic reduced representations (CHHR), an instance of vector symbolic architectures, which is a candidate for an associative memory framework described by holonomic brain theory. We have developed a neural network capable of performing addition with modulus (circular addition), required for implementation of CHRR. The structure of the neural network is shown in Figure 23.

Using this architecture, we demonstrate the capacity of spiking neural networks to implement an associative memory with a high degree of recall accuracy. The recordings of spiking dynamics during various computational stages contain elements of the stochastic spike synchrony observed in cortical recordings, as well as clearly separable computational phases suitable for functional analysis, as shown on the plot in Figure 24.

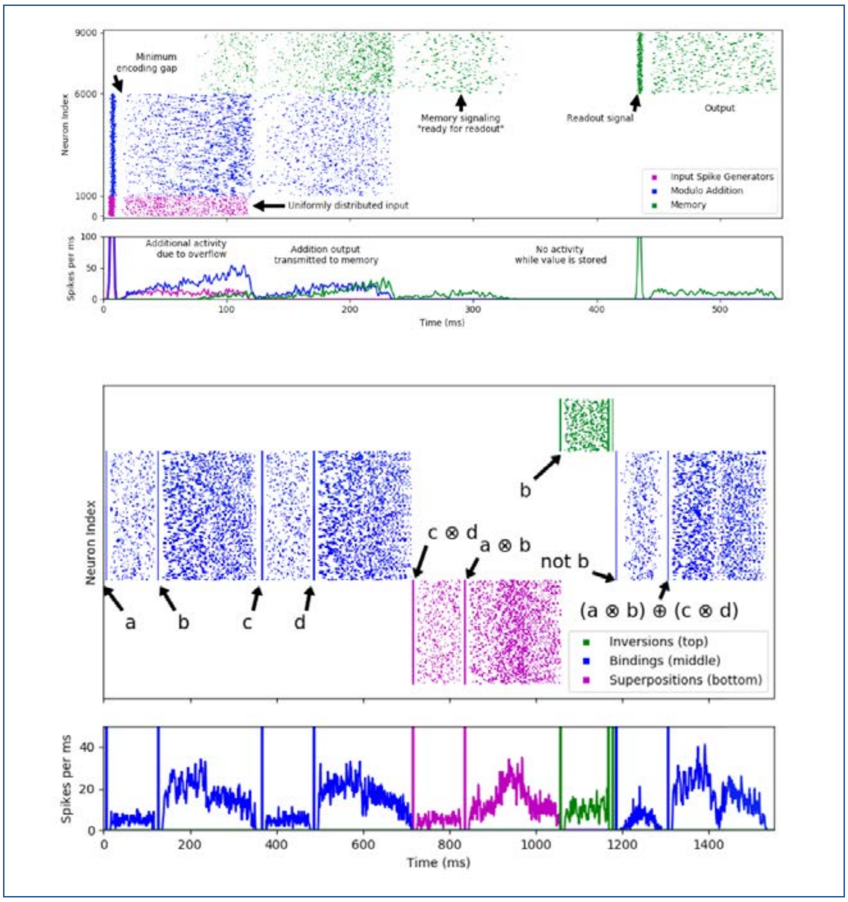


Figure 24: Functional model of Symbolic perception, results

Our network is able to very accurately memorise and recall associated symbolic identifiers under ideal conditions (with no noise), maintaining very accurate and predictable spike timing. Furthermore, we stressed the model with artificial noise in form of spontaneous spiking which is known to exist in cortical tissue and analysed the impact to determine computational requirements (constraints) needed for an exact spike timing framework to work in such noisy conditions. The results of this research are published.

We have also proposed a method of moving from symbolic (lookup table based) encoding approach to sub-symbolic (probabilistic) approach, identifying required structural changes in original convolution-based association operation. We have used our sub-symbolic model for two tasks: scripting a purely symbolic controller for two-wheeled simulated Braitenberg vehicle and visual scene memory (associating locations of seen objects with their label). Results of this work can be seen in Figure 25 and have been submitted for publication.

4.7.3.8 Publications:

Kaiser J. et al., "Towards a framework for end-to-end control of a simulated vehicle with spiking neural networks," *IEEE Int. Conf. Simulation, Modeling, and Programming for Autonomous Robots (SIMPAR)*, 2016, pp. 127-134.

Kaiser J. et al., “Scaling up liquid state machines to predict over address events from dynamic vision sensors”, in *Bioinspiration & Biomimetics*, Special issue on NeuroRobotics: Brain-inspired models for robot control and behaviour (submitted)

Kaiser J. et al. “Spiking Convolutional Deep Belief Networks” in *Proc. Int. Conf. Artificial Neural Networks (ICANN)*, 2017

Peric I. et al. “Semi-Supervised Spiking Neural Network for One-Shot Object Appearance Learning”, in *Proc. Int. Cong. Neurotechnology, Electronics and Informatics (NEUROTECHNIX)*, 2017 (to be submitted)

Ulbrich S. et al. “Kinematic Bézier Maps” *IEEE Trans. Man, System, Cybern.*, 2012

Ulbrich S. et al. “Model-based Polynomial Function Approximation with Spiking Neural Networks”, in *IEEE Int. Conf. Cognitive Informatics & Cognitive Computing*, 2017

Tieck C. et al. “Towards Grasping with Spiking Neural Networks for an Anthropomorphic Robot Hand”, *Int. Conf. Artificial Neural Networks* (ICANN), 2017

Peric I. et al. “Exact Spike Timing Computational Model of Convolutional Associative Memories”, in *IEEE Intl. Conf. Cognitive Informatics & Cognitive Computing*, 2017

Peric I. et al. “Probabilistic Symbol Encoding for Convolutional Associative Memories”, *Proc. Int. Cong. Neurotechnology, Electronics and Informatics* (NEUROTECHNIX), 2017 (to be submitted)

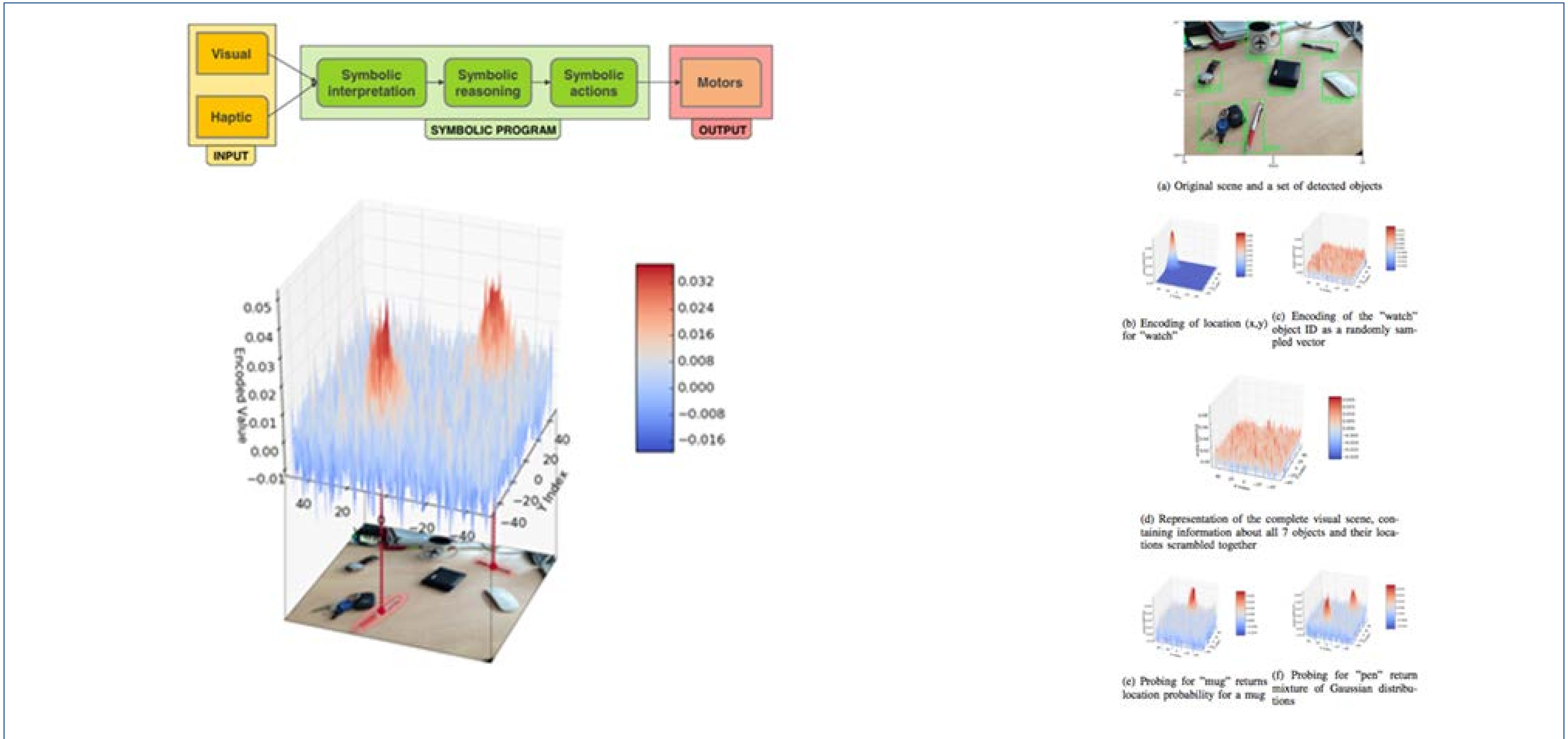


Figure 25: Symbolic controller for visual scene memory and for two-wheeled simulated Braitenberg vehicle

4.8 T10.2.4 WP Lead

4.8.1 Key Personnel

Task Leader: Cecilia LASCHI (SSSA)

This Task involves no personnel costs, only the travel costs of the WP Leader are budgeted. For a report see WP Leader’s Overview at the beginning of this section.

5. WP10.3 Components of Closed-Loop Experiments

5.1 Key Personnel

Work Package Leader: Rüdiger Dillmann (FZI)

5.2 WP Leader's Overview

During the first 12 months of SGA1, WP 10.3 made good progress providing or preparing the components required for the closed-loop experiments of WP 10.1 and 10.2, the CDPs and even beyond research conducted in the HBP. In this period, work focused on the directly required robot models and sensors, the preparation of community-driven model libraries and initial validation, calibration and benchmarks.

Namely, the work on the virtual rodent, which plays a crucial role in WP10.1 and CDP1, made significant progress in Tasks 10.3.1 and 10.3.2 where the focus laid on a realistic appearance and a replication on the rodent musculoskeletal apparatus. Task 10.3.3 refined already existing robots and created novel models of robots and sensors required for research in WP10.2. The fundamental mechanisms for creating large-scale models libraries for experiments that go beyond SGA1 has been implemented. Initial benchmarks and validation of the NRP models against their real counterparts made good process within Task 10.3.4.

While the WP generally made good progress and already contributes greatly to the other Work Packages and CDPs, work was strongly focused on the main pilot experiments. Consequently, a greater variety of strategic and popular models have yet to be created and to be included into a large model-database. This will be one of the main focuses in the remainder of SGA1.

5.3 Priorities for the remainder of SGA1

The priorities for the remainder of SGA1 will include the continued development of the priority models required for the immediate implementation of the pilot experiments of WP 10.1 and 10.2 as well as the respective CDPs. In this context, the mouse model will be continued to include all relevant features such as realistic simulation of fur and the completion of the musculoskeletal apparatus. With respect to traditional robots, the main effort will lie on further populating the library of robot, environment and sensor models. We will therefore continue implement a selection of strategic and/or popular models and provide the means for extending this library by the community. We will take care that the core more of the library is calibrated and validated against its real counterparts.

5.4 Milestones

Table 3: Milestones for WP10.3 - Components of Closed-Loop Experiments

MS No.	MS Name	Leader	Expected Month	Achieved Month	Comments
10.3.1	Implementation plan for WP10.3	FZI	M02	M06	This Milestone has been achieved with the submission of deliverable 10.7.1
10.3.3	First version of the NRP core library of robots, sensors, and environments	FZI	M12	M12	Initial version of library facilities of robots, sensors and environments. These allows users to add their own models and combine them into an experiment with help of a “wizard” user interface. The way how users can add new sensors, for instance, is documented on the example of a strategically relevant neuromorphic sensor (Dynamic Vision Sensor Camera) on the Neurorobotics Blog: http://neurorobotics.net/researchBlogEntry.html?id=5. The same blog entry also displays a new robotic head for saccadic eye movement and demonstrates how additional strategic robots can be added to the Platform. The current state of the environment designer can be seen in this video: https://www.youtube.com/watch?v=1jQQuhvv3mA.

5.5 T10.3.1 Rodent Body Model

5.5.1 *Key Personnel*

Task Leader: Matthias CLOSTERMANN (EAS, subcontracted by TUM)

5.5.2 *SGA1 DoA Goals*

Together with task 10.3.2, this task mostly focuses on developing a realistic dynamic musculoskeletal model of a mouse body, with some resources allocated for photo-realism of the model. The body model will be calibrated using MRI and other quantitative data on the mouse body. It will include whiskers and fur. Different version of the model will be developed, depending on the desired simulation speed and visual realism. Finally, the combined body/musculoskeletal mouse model will be added to the core library of the NRP (T10.3.3).

5.5.3 *Component Progress*

5.5.3.1 Rodent Body Model for the Neurorobotics Platform

Rodent model for simulation in the NRP. The development of the rodent body model is subcontracted. It requires a realistic modelled skeleton, which it encases. The origin of this skeleton is not yet decided and might influence the progress of the Task - several options are being considered at the moment. All in all, the rodent body model should be finished within the next 12 months.

Progress on Component:

In the development of the mouse we had agreed with the project lead at TU Munich to do an additional step. Due to the fact that the availability and usability of a complete bonescan of a real mouse was questionable, we decided to start off by constructing our own mouse skeleton based on anatomical documentation and references. This way we would ensure that the quality would be 100 % consistent all through the project's data output, as well as giving us the freedom to change and modify elements at any point without having to compromise. The skeleton has been finished and even "rigged", meaning we have given it physical attributes such as kinematic chains that will connect and move the single bones in connection with each other like a real skeleton would do. This first stage deliverable has been delivered to TU Munich and is awaiting final approval.

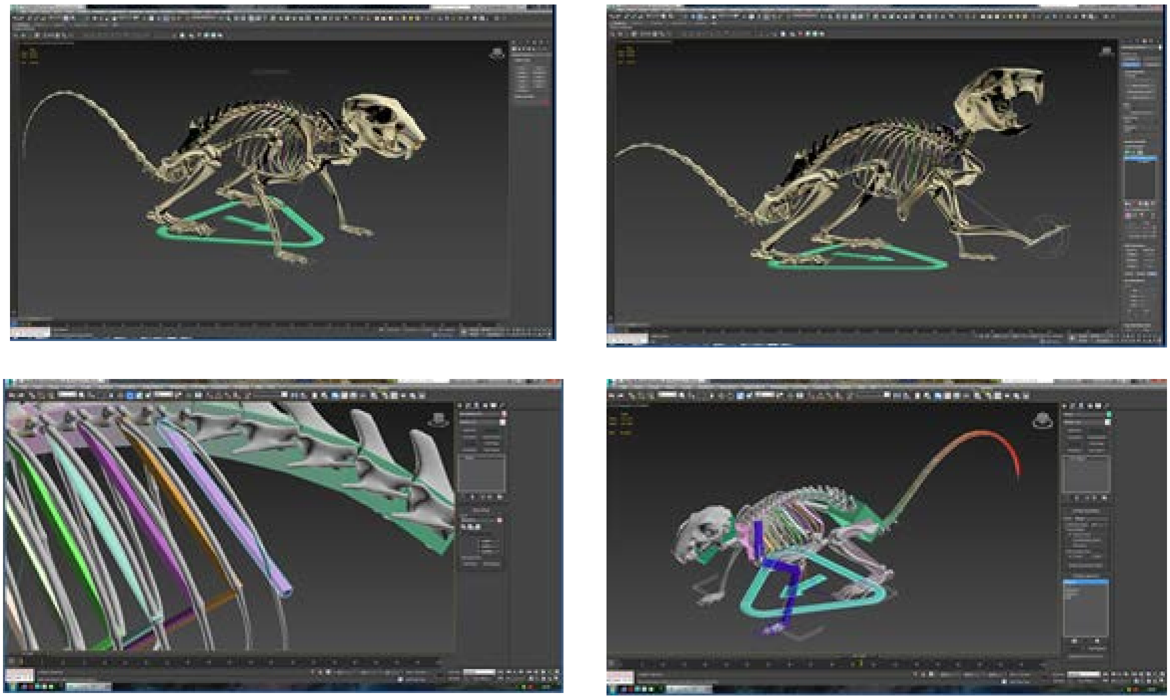


Figure 26: Different views of the new mouse skeleton model, based on anatomical documentation and references

Once this has been given we are ready to move to stage 2, the creation of the mouse's skin & hair, based on and to be animated by the bone skeleton we created.

Deviations

There are no deviations from the original agreement. We are fully on track so far. The technical challenge to be mastered at the next stage is to enable a proper 1:1 export from the working 3D system to the HBP's real-time simulation engine. This however is the normal progression in delivering the final result and there is no doubt that we will achieve the desired results after some iterations together with the colleagues from TU Munich & Truephysics.

Priorities for the remainder of the phase

The task of developing the mouse is a pretty straightforward one. So, as blunt as it may sound, our main priority is simply to get things done in the highest quality achievable with today's tools. The objective for us is to help in creating a versatile communication tool for the scientists that enables them not only to do their work, but also to communicate their work in a way that enhances the public perception of the project.

5.6 T10.3.2 Musculoskeletal models of rodents

5.6.1 Key Personnel

Task Leader: Auke IJSPEERT (EPFL)

5.6.2 SGA1 DoA Goals

Develop an accurate musculoskeletal model of a rodent hind limb. The developed model will be validated to reproduce biologically acceptable results from literature and animal experiments. The model will then be used for locomotion studies by integrating spinal cord circuits for closed loop simulation.

5.6.3 Progress

Description of Component:

- Simulate a single hind model of mouse with three degrees of freedom – Hip, Knee and Ankle.
- Each joint is actuated by a pair of flexor & extensor muscles. Knee and Ankle joints also have bi-articular muscles. Each hind limb consists of 8 muscles, 6 mono-articular and 2 bi-articular.
- Muscles are modelled as Hill-type muscles for which muscle properties are obtained from the literature.
- Extension of single hind limb model to two hind limb models with rigid spine and forelimbs.

Progress on Component:

Experiments:

- Single hind limb forward and inverse dynamic simulation validation: Completed
- Single hind limb Treadmill experiments. - Contact dynamics. Status: Completed
- Real mice locomotion kinematic data driven experiments to measure muscle stretches. First step in validation of the bio-mechanical model with Spinal cord model developed by Courtine's lab - Inverse Simulation. Status: Ongoing
- Validation of simulation experiments with real mice experiments. Status: Ongoing
- Quadruped locomotion with 6 degrees of freedom and 16 muscles. Status: Completed
- Closed loop simulation and single hind limb demonstration with platform integration. Status: Completed
- Integration of closed loop model for hind limb locomotion: Completed
- Model release for locomotion experiments by users: Ongoing

Platform Development:

- Closed-loop testing with NEST allowing biologically realistic simulation of both spinal cord and bio-mechanical model of mouse. This will allow different SP's to test wide variety of brain models and will attract more attention.
- Our models will run on both Webots and Gazebo, hence it can be a benchmarking experiment between different physics engines on the platform.
- Model is integrated with OpenSim plugin of platform for simulation of muscle dynamics.

Platform Use Case:

- Models for studying of rodent locomotion on the Platform, as well as recovery from spinal cord injury.

- To study sensory and cortical signal integration within spinal cord circuits for locomotion (T 10.1.2).
- Will be extended to forelimb reaching tasks.
- Model integration with CPG models from Ilya Rybak's models. This expands the integration of NRP platform with locomotion labs across the world.

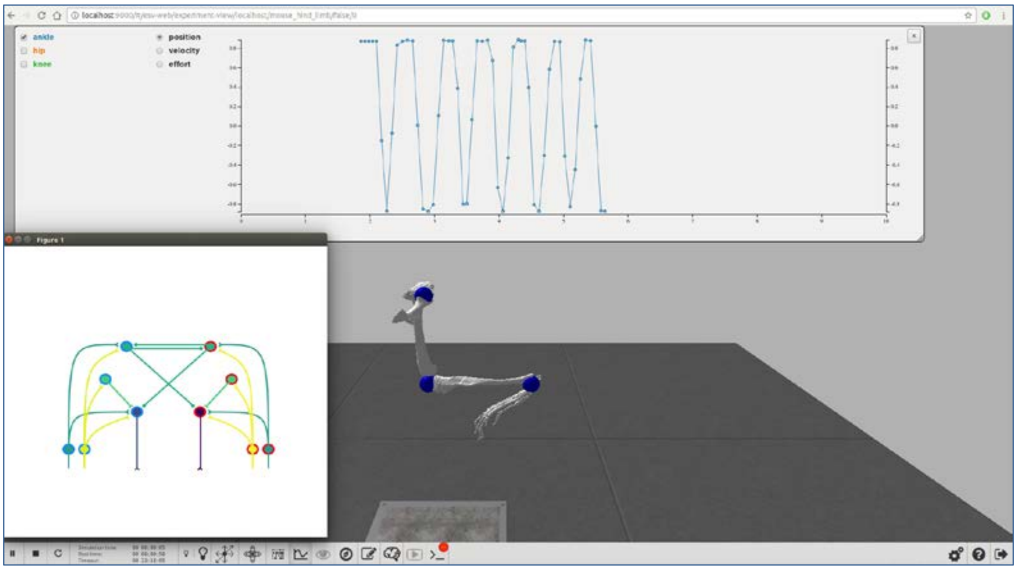


Figure 27: Example of NRP running a closed-loop simulation of the single hind limb musculoskeletal model with spinal cord from T10.1.1.

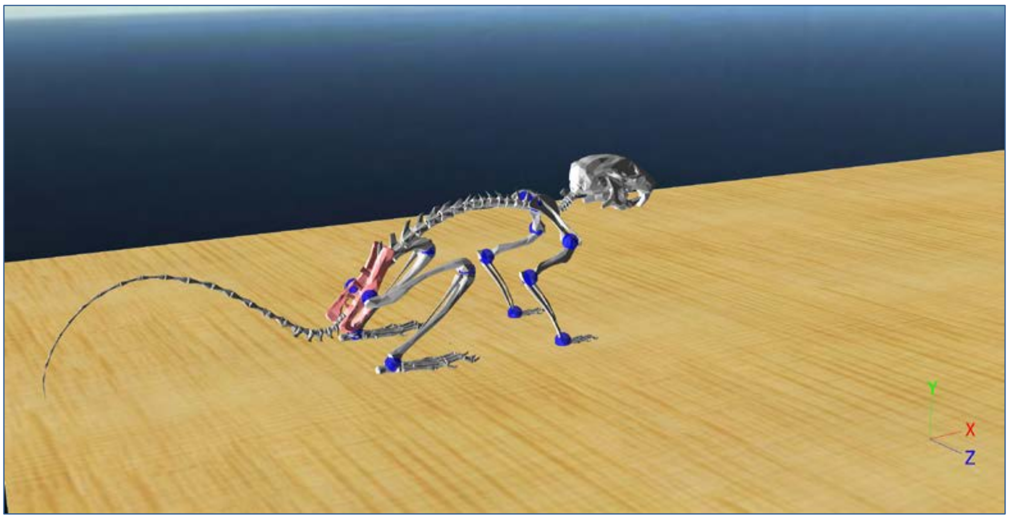


Figure 28: New mouse skeleton model with hind limb actuation used in the locomotion experiments

Charles JP, Cappellari O, Spence AJ, Wells DJ, Hutchinson JR. Muscle moment arms and sensitivity analysis of a mouse hindlimb musculoskeletal model. *Journal of Anatomy*. 2016;**229**(4):514-535. doi:10.1111/joa.12461

Danner, S. M., Wilshin, S. D., Shevtsova, N. A. and Rybak, I. A. (2016), Central control of interlimb coordination and speed-dependent gait expression in quadrupeds. *J Physiol*, **594**: 6947–6967. doi:10.1113/JP272787

Örjan Ekeberg, Keir Pearson, Computer Simulation of Stepping in the Hind Legs of the Cat: An Examination of Mechanisms Regulating the Stance-to-Swing Transition. *Journal of Neurophysiology* Dec 2005:**94**(6):4256-4268; DOI:10.1152/jn.00065.2005

5.7 T10.3.3 Models of robots, sensors and environments

5.7.1 Key Personnel

Task Leader: Rüdiger DILLMANN (FZI)

5.7.2 SGA1 DoA Goals

The aim of this Work Package lies on the creation of a core library of strategic models for robots, sensors, environment and their components required for the simulation in the NRP. On the one hand, this library will contain a selection of Components that are strategically important to implement the pilot experiments as requested by the Work Packages 10.1 and 10.2 but also from other subprojects. They will be curated by the consortium of SP10. On the other hand, the library will additionally be opened to the public so that offering access to simulations of the world's robots becomes a community-driven effort. Implemented as ROS modules, the Components developed in this task can also be used outside of the Neurorobotics Platform by other robotic researchers.

During the first 12 months of SGA1, the focus of this Task lay on providing the fundamental mechanisms and an initial catalogue of strategic models for large-scale model libraries for robots, sensors and environments associated with and integrated into the NRP. A basic set models immediately required for the pilot experiments were created and integrated into the NRP, and existing models were refined (e.g., by adding better sensors or visualisations). Furthermore, the methods required for the expansion towards an open and community-driven effort were investigated.

The building blocks required are each represented by a Component in T10.3.3

- Environment model library
- Sensor library
- Robot avatar library

5.7.3 Component Progress

5.7.3.1 Environment model library

This library contains model of complex environments (mazes, laboratories, outdoor scenes) for the use in the NRP.

Progress on Component:

The main development of the strategic environment model library will start in the second half of SGA1 when the requirements resulting from the pilot experiments will have been identified. In the meanwhile, a replacement of the "virtual room" – the exemplary environment during the RUP has been designed and will be soon used as the standard environment for new experiments. This environment represents an entry point to novel experiments and will feature multiple areas targeting different fields of neuro-/robotics research and the opportunity to embed user-defined areas within. Please see Figure 29 for an impression of the environment.

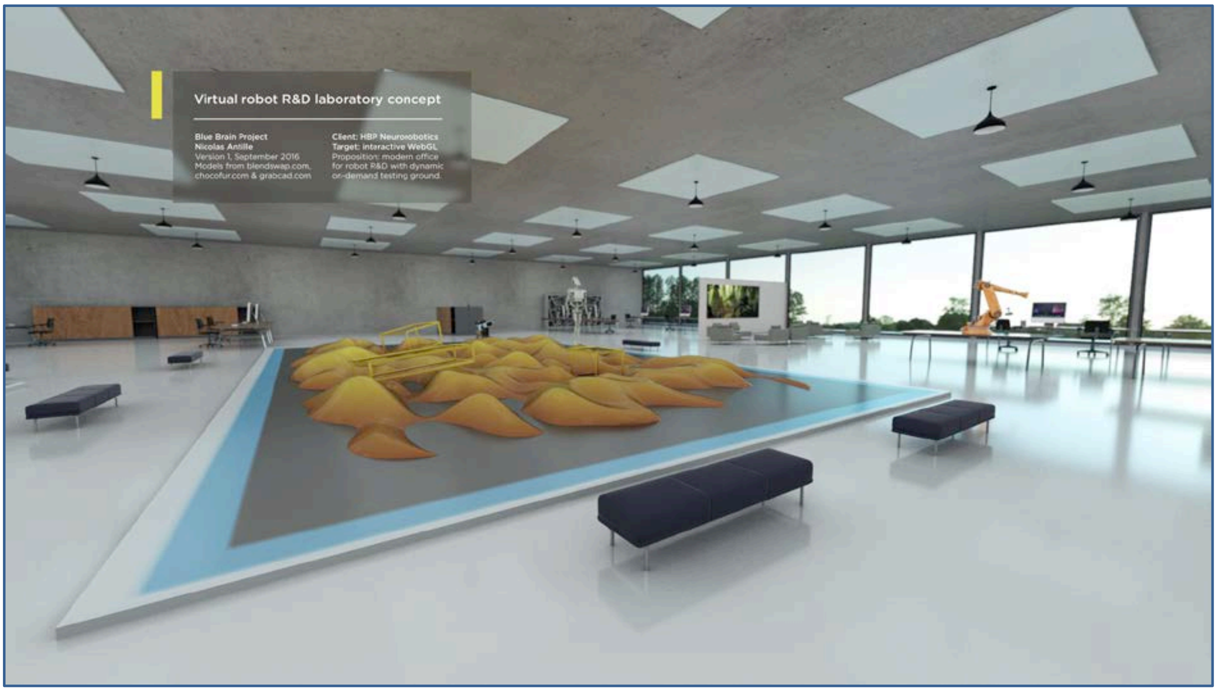


Figure 29: Illustration of the proposed "Holodeck" environment for the Neurorobotics Platform.

5.7.3.2 Sensor model library

This Component represents a library for various sensors to be simulated in the NRP. These sensors are accessible from the RobotDesigner application where they can be assigned and connected to a virtual robot or avatar.

Progress on Component:

In the NRP, we already support a wide range of sensors, namely, any sensor that is directly supported by Gazebo its underlying physical simulator. Mostly, those are classical robotic sensors such as laser scanner and cameras. For many experiments in neurorobotics research, this list has to be extended. For instance, Gazebo does not include or support recent biologically inspired sensors, neither does it include neuroscience's models of organic sensors. However, those types of sensors are important for the HBP and will be a unique selling point for the NRP and its application in neurorobotics research.

For special senses such as vision and balance, we decided to implement them as Gazebo plugins to keep the workflow identical for classical robotic sensors. Essentially, our sensor library will consist of a list of plugins simulating various biologically inspired sensors. We therefore exploit the extensibility of the software the NRP is based on. Technically, each sensor of the library will be distributed as a submodule of a plugin of the Gazebo simulator which is made available on SP10's publicly available source code repository on GitHub. Consequently, to use a sensor from the sensor library, merely a reference to the plugin in the robot description (in the SDF file format) is required. Users of the Platform are not required to manipulate model files directly as this work will be able to be done from with the RobotDesigner application. During the first few months of SGA1, we evaluated and decided on this approach, and exemplarily implemented a simulation of the Dynamic Vision Sensor (DVS) – a biologically inspired vision sensor often referred to as "artificial retina". The sensor is available in a physical form and is used in experiments in WP10.4 which will facilitate future benchmarking and the translation of experiments to physical robots. The software we developed is open-source and available on our SP10's open source code repository on GitHub.

In the coming months, we will also adapt our implementation of COREM, a retina simulation framework [1,2], and wrap it in a Gazebo plugin for distribution as well as any additional sensor required by the currently developed pilot experiments.

So far, we did not develop a gazebo plugin simulating the vestibular system, since an inertial measurement unit (IMU, classical robotic sensor) already provides similar information. We therefore added an IMU to the iCub robot model. Unlike the DVS, there is no "in silico" vestibular sensor, which we could use for modelling our simulation.

For somatosensory senses related to muscles such as muscle spindle or Golgi tendon, we decided to implement them in our fork of Gazebo, with the OpenSim integration. Indeed, advanced muscle simulation needs a lower level access to the physics. The library used to simulate muscles, OpenSim, natively provide feedback emulating muscle spindle and Golgi tendon organs.

Similarly, a first prototype of the tactile sense is also implemented with direct access to the physics. This prototype has two discrete output states, touch and not touch.

5.7.3.3 Robot/Avatar Library

This library provides a strategical set of robots (industrial, humanoid, simplified human and rodents etc.) and biological avatars (rodent, human, etc.).

Progress on Component:

During the first month of SGA1, we focused on the inclusion of models of strategic importance for the research and development of the pilot experiments proposed in WP10.2. The strategy here is that each robot is specific to a given research field. The library includes models partially developed during the RUP which have been further improved in this phase. These models are the humanoid iCub, the Schunk LWA4P six-axes manipulator and the anthropomorphic Schunk SVH hand. Please see Figure 31 and Figure 31 for descriptions of the progress made during the last 12 months. It is also possible for any user to add new avatars to the library, with the help of the Robot Designer.

Figure 30: The model of the humanoid robot “iCub” has been extended by an IMU unit (inertia and acceleration sensors) (left) and the models of anthropomorphic hands have been attached (right).

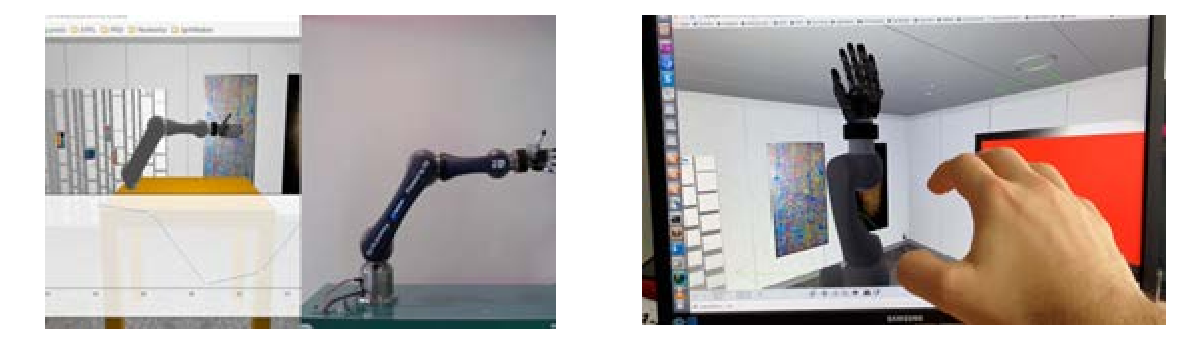


Figure 31: The Schunk LWA4P six-axes arm (left) with the anthropomorphic SVH hand (right) is the robot used for experiments related to grasping and manipulation

The models are integrated into the Neurorobotics platform and available in the experiments. Furthermore, the simulation was synced to a real model and connected to motion capture and finger tracking hardware.

Apart from these models and the virtual mouse developed WP10.1, additional models were created. They include an active stereo head, and two humanoid models suited for replaying motion capture data and acting as an avatar.

The active stereovision head models real physical hardware that is built and available in the SP10 consortium. It features two simulated DVS camera sensors and is of strategic importance for researchers working on oculomotor control and stereo-vision (SP4 and CDP4). Additionally, this robotic head can be mounted on the humanoid robot HoLLiE (https://www.fzi.de/en/research/projekt-details/hollie/) which is of importance for researchers working on visually guided grasping (focus of CDP4 in SGA2).

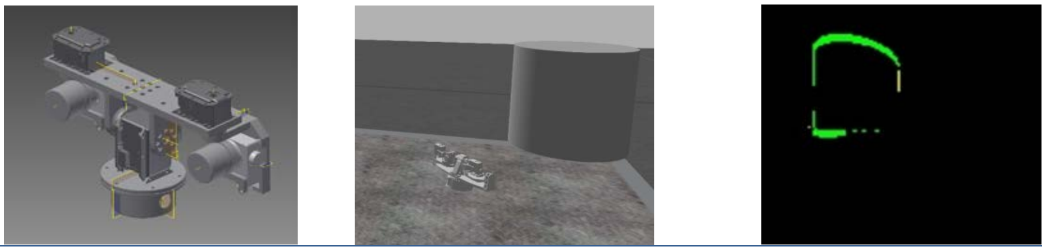


Figure 32: Image of the newly develop robot head (left), its early integration into the NRP (middle) and the display of the simulated DVS camera resulting from eye motion (right)

In order to include human motion capture data from various freely accessible scientific databases, we integrated parts of the "Master Motor Map" project into the Neurorobotic Platform. Replayable motion capture data can be used as target for supervised learning methods. This software, developed at the Karlsruhe Institute of Technology (KIT) includes a standardised humanoid avatar that we integrated into SP10's Platform. In total, it consists of 81 rotational joints that are controlled by 50 generic control plugins and actuators. This model allows the connection to a large-scale motion capture database associated with the MMM project that includes additional motion data from other sources such as the database offered by the CMU. The process of having a full human musculoskeletal model is incremental. We start with simple kinematic models, then moving to well stablished robots, the add functional muscles, then porting to human-like simplified models, and then to complex musculoskeletal models.

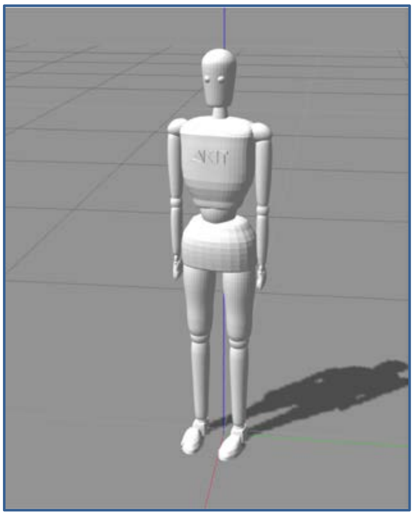


Figure 33: Human Model used by the Master Motor Map project

This data will be used to train neural motion controllers for grasping and manipulation as investigated in WP10.2 but also more complex controllers for whole-body motions and walking.

The model will be finalised and officially integrated into the NRP in the remainder of SGA1.

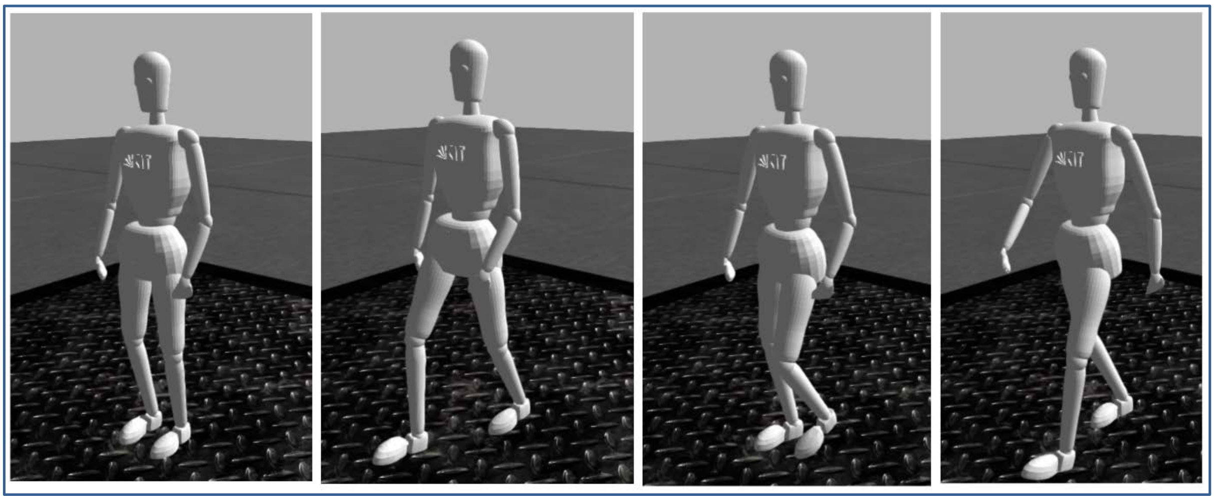


Figure 34: The MMM model allows not only for the transfer and replay of whole-body motions, such as walking or running, but also manipulation that will be a valuable resource and interface for experiments based on programming by demonstration (PBD) where a robot learns from a human teacher

In parallel to the MMM model, we evaluated importing human avatar models designed by the open source “MakeHuman” software project. This software allows for creating detailed human characters by directly specifying fine-granular properties such as age, gender and muscle masses. This approach would allow for simulating development/ontogenesis based the simulations of characters at different age and will also increase the general visual appearance. However, such human character models have to be simulated as soft-bodies which increases the complexity of their simulation. To allow for an easy transition to humanoid robots and its control principles, the RobotDesigner was extended to convert the human character models into virtual robots composed of non-intersecting and disjoint rigid bodies (see Figure 35). In the remainder of SGA1, this work will lead to a representative humanoid avatar that is also compatible with the MasterMotorMap approach reported above.

Figure 35: A prototype of a humanoid avatar created with the MakeHuman software

This is converted into a humanoid robot by converting deformable soft bodies into disjoint rigid bodies connected by rotational joints (left). Proposal for a visual appealing humanoid avatar (middle). This model can also be used to replay motion capture (right) and will be made compatible with the MasterMotorMap integration.

Martínez-Cañada P. “A Computational Framework for Realistic Retina Modeling”, *Int. J. Neural Systems*, 26(07), 2016.

Ambrosano A. et al. (2016). Retina Color-Opponency Based Pursuit Implemented Through Spiking Neural Networks in the Neurorobotics Platform. *Biomimetic and Biohybrid Systems*. Living Machines, 2016.

5.8 T10.3.4 Benchmarking and validation of NR models

5.8.1 Key Personnel

Task Leader: Olivier MICHEL (Cyberbotics, third party to EPFL)

5.8.2 SGA1 DoA Goals

To develop a series of benchmarks allowing the evaluation of the quality of the neurorobotics simulation models, including robots, sensors and actuators. Benchmarks for neuro-muscular robotics models should be developed, as well as benchmarks for standard, off-the-shelf robotics systems.

The purpose of benchmarks is to ensure that robot models, including sensors and actuators, and environment models, including various objects, are realistic. Realistic means that the behaviour of simulated robots running neuro-controllers will be similar, to some extent, to the behaviour of their real counterpart robots running the very same neuro-controllers. Because it already contains models of robots and sensors that were accurately calibrated against real systems, Webots was used to develop benchmarks that allow the calibration of simulation model benchmarks. Once complete, these benchmarks allow to compare the calibration of various robot simulators including NRP (Gazebo) and Webots, between them and with real robotics system. This will contribute to validate the calibration of the simulation models provided in the NRP.

The benchmarks in these Tasks are developed to allow an objective comparison, not only between neurorobotics simulations and the physical reference, but also between different simulators. In particular, we are using Webots to validate the Neurorobotics Platform and to compare its performance. The agreement between Cyberbotics and EPFL for SGA-1, covers explicitly the use of Webots for these and other purposes. While it might be useful in the future to support different simulation backends, there are currently no plans to integrate Webots into the Neurorobotics Platform.

The simulation models of robots, including all sensors and actuators, will be calibrated accurately against their real counterparts, i.e., real robots. This process involves a series of precise measurements on the real devices performing standard robotics operations and the adjustment of the simulation models so that the simulation behaviour matches the behaviour of the real robot. As a result, the simulation parameters will be refined regarding the mass distribution of each component, the motor positional limits, maximum velocity, maximum torque, the sensors properties, including noise, non-linear response function, range, etc. Eventually, the models will be improved to better capture the physical properties of the real devices, for example motor backlash. Note that the level of precision we target is very high. It is based on our experience of transferring simulation results to real robots. In many cases, the difference observed between simulation models and their real counterparts can be explained by a lack of precision at different levels which we identified (mass distribution, motor latch, etc.). By improving our simulation models at these levels, we will minimise the differences between simulation models and real robots. Thus, this will render our simulation tools more relevant and useful. Benchmarks will be defined to validate the calibrated models. These benchmarks will include several metrics based on standard error (SE) measurements involving both analytical models and real hardware. The benchmark will define different compliance classes, depending on the type and application of the model. A minimal compliance class for all models of the NRP core library will be defined. All models in the NRP core library will be required to pass the calibration benchmarks in order to be validated.

The benchmark will be released to the scientific community so that models in the NRP community library and external models can be validated and compared.

- benchmarking of the swimming salamander robot (including simulation of fluid dynamics).
- benchmarking of the artificial muscle based humanoid walker.
- benchmarking of existing commercial robotics systems.

5.8.3 Progress

Experiments:

- We designed a simulation based on the salamander robot swimming into the water to benchmark the fluid dynamics capability in NRP simulations. We collaborated with EPFL teams (Auke-Jan IJSPEERT) on calibrated simulation models and benchmarks for musculoskeletal robotics systems: refining and calibration of a salamander robot model.
- We designed a simulation based on a humanoid walker including artificial muscle modelling. We collaborated with EPFL teams (Auke-Jean IJSPEERT and Grégoire COURTINE) on calibrated simulation models and benchmarks for musculoskeletal robotics systems.
- We created a series of five robot benchmarks in order to calibrate the simulation models accurately based on calibrated models of real robots included in Webots. These robots include the NAO v4, Robotis OP2, e-puck, Thymio II and Pioneer 3DX. They will be automatically integrated in the NRP via the Webots backend. See section 7.11.3.1.

Platform Development:

The series of five robot benchmarks are being integrated in the web site (to be publicly available on 16 June) before being integrated into the platform along with the Webots backend. This is an interesting milestone for assessing the openness and scalability of the NRP. The integration of the benchmarks in https://robotbenchmark.net is a dissemination activity to promote the use of the benchmarks developed for the NRP. https://robotbenchmark.net actually provides a simulation environment (based on Webots) into which the benchmarks are completely defined and can be experimented interactively. From there, they can be ported to real robots or various simulation backends. Note: the web site of https://robotbenchmark.net was developed independently by Cyberbotics (not funded by the HBP). Only the benchmarks development was funded by the HBP.

Platform Use Case:

The different benchmarks developed in this Task will be used directly by the NRP users. NRP users will be able to modify the control of the robots and check impact on the resulting benchmark metrics in the Platform. Also, the very same benchmark experiments could be run on real robots as well, with the same evaluation metrics so that it will be possible to compare the real-world results to the simulation results, and thus assess the calibration of the simulation models.

5.9 T10.3.5 WP Lead

5.9.1 Key Personnel

Task Leader: Rüdiger DILLMANN (FZI)

This Task involves no personnel costs; it is only budgeted with travel costs for the WP Leader. For a report see WP Leader’s Overview at the beginning of this chapter.

6. WP10.4 Translational Neurorobotics

6.1 Key Personnel

Work Package Leader: Jörg Conradt (TUM)

6.2 WP Leader's Overview

Within the first 12 months of WP10.4 multiple real-world robotic platforms have been operated under neuronal designed controllers, and several of those systems have been interfaced to neuronal computing infrastructure (here predominantly the SpiNNaker neuro-computing System, WP9)

Most of the interfaces between robots and neuro computing hardware have been established through an external computer (SpiNNaker <-> Ethernet <-> PC <-> Robot), which severely limits transmission bandwidth and introduces large latency for sensor perception to control. A direct interface between SpiNNaker's native communication bus and external hardware (sensors and robots) is under development in WP10.4.3, but currently only available for select robots and under limited software/infrastructure support.

More coherent and more complete integration of existing sensors and physical robots into the NRP is high priority in WP10.4.

Currently, several prototype example robot systems are available under neuronal control running on neuromorphic hardware, which demonstrate the proof-of-principle as outlined in the WP10.4 task description. The WP focuses on getting more "ready-to-use" systems available (both as physical robot instances and as simulated robots in NRP), so that users from other SP can apply and test neuronal models on their robots of choice in both, simulated and real-world scenarios. More intense interaction with WP10.5 is envisioned to achieve this objective.

WP10.4 was designed as exploratory endeavour in early stages of HBP, such that researchers can evaluate different robot platforms and multiple well-established methods in robotics towards suitability of integration into the NRP. Different types of robots, from distributed design to exploratory hardware (such as MyoRobotics) up to industrial role-model robots have been investigated. The results have produced a concise focus on a few robotics use cases, which we propose to follow up in SGA2.

6.3 Priorities for the remainder of the phase

The existing proof-of-principle systems well demonstrate the applicability and favourable scalability properties of neuronal control architectures for real-world robots. Priority for M12-24 will be (1) extending existing systems to more complex environments and control problems (therefore requiring larger neuromorphic computing hardware), and (2) extending the toolbox of available robotics research systems in the NRP simulation as well as real robots to be used by other members of HBP "out of the box".

For aspect (1), WP10.4.3 is actively enhancing an existing SpiNNaker IO board (allowing more different and more complex robotic systems to directly connect to SpiNNaker), and to integrate the IO board into the neuro-computing software toolchain developed in SP9. Such an interface board overcomes the current bottleneck in communication between SpiNNaker hardware and robots and the NRP which currently relies on a single Ethernet interface. Simultaneously, advanced versions of the MyoRobotics muscles are developed in WP10.4.1, which will directly influence system design in SGA2. WP10.4.2, WP10.4.4 and WP10.4.5 are scaling up the complexity of their respective robotics tasks to demonstrate achievable complexity of neuronal computing systems for robot control.

Regarding aspect (2), all teams are in close interaction with the NRP developers to continuously increase quantity and complexity/functionality of real-world robots in the NRP. This includes integrating a larger number of existing and new robotic systems, each at more granular level. Independently, a formal process of real-time message/data exchange between NRP and the SpiNNaker neuro-computing infrastructure is developed. Both together allow a flexible toolbox with exchangeable neuronal computing hardware vs. traditional PC and simulated vs. real-world robotic systems for any participating scientist.

Overall, WP10.4 expects that after addressing aspects (1) and (2) by the end of SGA1 this Work Package provides infrastructure for other HBP participants to explore neuronal control algorithms (optionally on neuro-computing hardware) to interface sensors and robots in closed-loop scenarios, either in simulation within NRP or on simple real physical robots or both.

Regarding the benefits of adding real robots to HBP we agree that adding a such must provide repeatable and quantifiable results beyond what can be done in simulation; or at the very least validates simulations of complex settings. Hence, we will devote more resources within the remaining time of SGA1 and SGA2 to identify such systems and experiments, and clearly address aspects that provide additional benefits beyond simulation, e.g. in settings where simulations are difficult or unlikely to generate adequate (e.g. noisy) real-world resemblances.

6.4 Milestones

Table 4: Milestones for WP10.4 - Translational Neurorobotics

MS No.	MS Name	Leader	Expected Month	Achieved Month	Comments
10.4.1	Implementation plan for WP10.4	TUM	M02	M06	This Milestone has been achieved with the submission of Deliverable 10.7.1
10.4.2	Instantiation of robotic sensors and actuators and neuro-robotics control algorithms in NRP	TUM	M12	M12	Within this Milestone, we integrated different simulated and real-world robotic sensors, robotic actuators and bio-inspired robots into the NRP. From a sensor perspective, we integrated real-world tracking sensors and a simulated Dynamic Vision Sensor to the NRP. The real-world tracking integration enables the interaction between the simulated NRP world and the real-world. This integration is especially important for the 10.4 work package because this work package focuses on bringing the NRP simulations and algorithms to real-world robotics. Additionally, we implemented a simulation of the Dynamic Vision Sensor (DVS) within the NRP such that users can use the spiking output of the biologically inspired DVS as input for their visual brain models. This simulation computes the change in the simulated frames to approximate the change of brightness and triggers a corresponding spike event once a certain threshold of brightness change is reached. From an actuator perspective, a baseline for musculoskeletal actuators has be added to the NRP. In this first step, the tendon routing models have been created as plugins to Gazebo. Currently, we are working on calibrating the simulation models with the physical robot actuators to guarantee simulation fidelity. From a robot perspective, the Myorobotics anthropomimetic robot Roboy and the 6-DOF NST Robot Head have been setup within the NRP and are usable within experiments.

6.5 T10.4.1 Design and control of muscoloskeletal robots for the NRP

6.5.1 Key Personnel

Task Leader: Alois KNOLL (TUM)

6.5.2 SGA1 DoA Goals

Integrate the musculoskeletal Robotics toolkit Myorobotics and Roboy into the NRP as well as improving the simulation models of the real hardware to enable realistic experiments

6.5.3 Progress

Description of Component:

- Adapt Roboy and the Myorobotics framework to use ROS and Gazebo, so the robots are compatible with the NRP
- Implement a controller that makes the physical muscles behave like hill-muscles, enabling the brain-derived controllers to work with a standardised muscle model;
- Implement different controllers facilitating calibration as well as joint angle deduction for joints without direct sensing based on tendon configuration;
- Validate the controllers' accuracy through an external tracker-based measuring system
- Build bio-inspired legs based on the two platforms;
- Update Roboy to use the Myorobotics electronics to unify the software frameworks and validate their inclusion into the NRP

Progress on Component:

- A ROS-enabled driver for the Myorobotics hardware has been developed, allowing to control all motors with ROS Control based controllers.
- Originally it was planned to replace the electronics inside the original Roboy to make it compatible with the Myorobotics interface. However, in the light of the plans to build a second generation Roboy as well as the constraint space within Roboy, it was more fit to develop a ROS library for CANopen and have it use the same interface as the Myorobotics electronics, effectively leading to the same result at lower cost. This work is nearing completion, a first version was publicly tested at the first HackRoboy in December 2016 (www.hackroboy.com).

Figure 36: Roboy's Legs

- The new legs have been completed and tested during the same event. To have simpler legs to gain experience with walking algorithms, we decided to build an additional set of simplified legs inspired by NaBiRob from the RoMeLa laboratories coined PaBiRoboy (partially anthropomimetic bipedal roboy).
- To implement the simulation model of Myorobotics into the NR platform, a muscle model with via-points as well as a muscle wrapping plugin for Gazebo has been developed.

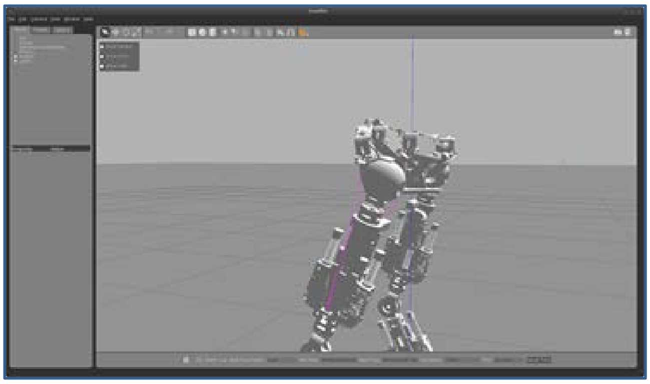


Figure 37: Gazebo Model of Roboy's legs

- A prototype algorithm to estimate joint-angles tendon-configurations has been developed with Prof. Darwin Lau, University of Hong Kong.
- Currently, work towards integrating his library CASPR as a ROS version with Myorobotics is ongoing. The library provides workspace analysis as well as forward and inverse kinematics and dynamics for tendon driven robots. A DAAD grant for this project under the name “myoCDPR” has been acquired to cover travel costs to and from Hong Kong.
- To validate the controllers’ accuracy through an external tracker-based measuring system, a low-cost tracking solution based on the commercial HTC Vive virtual reality headset has been developed. First prototypes are functional and work is currently ongoing towards mass producing the sensors to mount them on the robot.
- An Autodesk Fusion360 to SDF exporter has been developed. It allows for the direct export of robots into the SDF format – including joints and joint limits. Making it easy to design robots in CAD and then directly use them in Gazebo and the NRP. The Roboy project is currently igniting a partnership with Autodesk to formalise this development.

Platform development:

- Roboy has been integrated as a model into the Platform. It served as a good benchmark for model complexity.
- Roboy is also driving the requirement towards the inclusion of custom gazebo plugins for robots to be able to run the tendon simulation in the NR platform.

6.6 T10.4.2 NRP and motor-actuated robots (iCub)

6.6.1 Key Personnel

Task Leader: Cecilia LASCHI (SSSA)

6.6.2 SGA1 DoA Goals

The aim of this Task is to provide tools for the control of motor actuated robots through the NRP framework. Such tools will allow to:

- Communicate with the robot through the use of a robotic middleware compatible with the NRP
- Provide a suitable version of the NRP able to achieve real-time performances in order to exploit the compatibility with the neuromorphic hardware from Task 10.4.3 and use the synchronisation mechanisms implemented in the NRP for brain and robot simulation;
- Provide a robot configuration interface to access and adjust sensors and motor parameters based on the task to be executed.

Possible candidate robotic platforms for such a task are the iCub robot and the biped humanoid robotic platform named SABIAN. Both these Platforms are available at SSSA.

6.6.3 Component Progress

6.6.3.1 Real-time closed-loop neurorobotic systems for real motor-actuated robots

The aim of this component is to provide a suitable version of the NRP able to achieve real-time performances in conjunction with neuromorphic hardware for controlling real motor-actuated robots.

Behavioural models, provided by T10.2.2, will be used to test the effectiveness of the developed technology.

Progress on Component:

Models developed as part of T10.1.2 and T.10.2.2 have been tested on motor-actuated platforms.

In particular, the proprioceptive feedback model, developed as part of T10.1.2, was employed on an iCub robotic platform, in conjunction with a SpiNNaker board, in order to translate sensory information. This was achieved by developing a custom communication layer between the two platforms. For further details on the results of these experiments, please refer to:

Lorenzo Vannucci, Egidio Falotico and Cecilia Laschi (2017), Proprioceptive Feedback through a Neuromorphic Muscle Spindle Model, *Frontiers in Neuroscience, vol 11, pp 341.* http://journal.frontiersin.org/article/10.3389/fnins.2017.00341/full

The gaze stabilisation model developed as part of T10.2.2 was tested on both the iCub robotic platform and on the SABIAN humanoid robot, to stabilise the gaze under disturbances generated by an oscillating platform and by locomotion, respectively.

6.6.3.2 NRP interface for motor actuated robots

This Component will provide suitable interfaces for motor actuated robots. These interfaces will comply with the NRP currently adopted robotic middleware (ROS). Possible candidate robotic platforms for such a component are the iCub robot and the biped humanoid robotic platform named SABIAN.

Progress on Component:

A ROS interface has been integrated in the control architecture of the iCub robot in order to allow to interface this robotic platform with the NRP. Currently, ROS is the only communication interface towards the simulated robots in the NRP. For compatibility with the current architecture of the NRP, we considered to use a ROS interface. In the next steps towards a real-time solution, we will assess the performances and take action accordingly.

6.6.4 Publications

Falotico E, Vannucci L, Ambrosano A, Albanese U, Ulbrich S, Vasquez Tieck JC, Hinkel G, Kaiser J, Peric I, Denninger O, Cauli N, Ronneau A, Klinker G, von Arnim A, Guyot L, Peppicelli D, Ros E, Maier P, Weber S, Huber M, Plecher D, Röhrbein F, Deser S, Roitberg A, van der Smagt P, Dillmann R, Levi P, Laschi C, Knoll A, Gewaltig M-O. (2017) “Connecting artificial brains to robots in a comprehensive simulation framework: the Neurorobotics Platform”, *Frontiers in Neurorobotics*, Volume 11 Issue January 2017.

Vannucci L, Falotico E, Laschi C. “Proprioceptive feedback through a neuromorphic muscle spindle model”, submitted to *Frontiers in Neuroscience* - Neuromorphic Engineering (under review)

Vannucci L, Falotico E, Tolu S, Cacucciolo V, Dario P, Lund HH, Laschi C. “A comprehensive gaze stabilisation controller based on cerebellar internal models”, submitted to *Bioinspiration & Biomimetics* (under review)

6.7 T10.4.3 NRP and Neuromorphic Hardware

6.7.1 Key Personnel

Task Leader: Jörg Conradt (TUM)

6.7.2 SGA1 DoA Goals

This Task addresses the development of infrastructure for neuromorphic sensors, neuromorphic actuators (e.g. SP10.4.1), and neuromorphic computing systems (SP9, e.g. SpiNNaker) to allow real-time closed-loop robot control in simulation (NRP) and real-world robots. It will develop interfaces to connect such neuromorphic hardware (sensors, actuators and computing substrate) to the NRP.

6.7.3 Progress

To achieve the plug&play abilities of traditional computers for neuromorphic sensors and actuators to the neuromorphic hardware SpiNNaker and to enable real-time processing of in- and output spikes, we developed an interface board. This interface board is beneficial as the Ethernet interface of the SpiNNaker boards severely limits real-time processing of in- and output spikes. As our interface board will connect to the SpinLink bus directly, the developed system will ultimately allow a throughput of up to 6 MPackets/s and translates the SpinLink protocol to industry standard protocols that can connect natively to sensors and actuators.

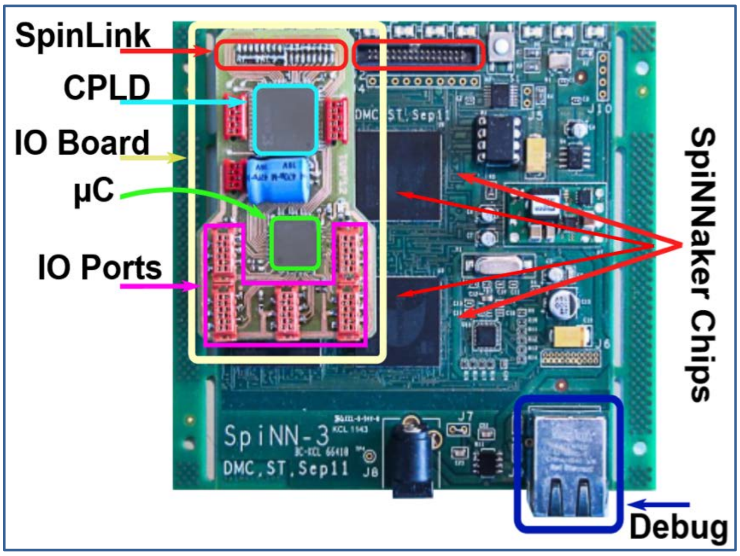


Figure 38: Interface board to connect external devices to the four chip SpiNNaker system. The interface board consists of the CPLD, the Microcontroller and the five UART ports to connect actuators and motors.

Within the initial project phase, we developed, produced and tested an interface board, shown in, that enables the communication to SpiNNaker simultaneous via five UART ports and allow to natively connect to embedded vision sensor, mobile robotics and advanced robotic actuators. The benchmarking of the system yielded a throughput of 500 000 events/s, which is significantly faster compared to the Ethernet interface with about 20 000 events/s. Using the first prototype of the interface board, we developed and integrated robotic and neuromorphic computing system shown in (the Spomnibot), and performed line-tracking only using neural computation based on input from neural sensors. Additionally, we connected a 2-DoF MyoRobotics arm developed in SP10 Task 10.4.1 to SpiNNaker using the interface board. Applying cerebellar models developed by Eduardo ROS (SP10 WP 10.1.4), we performed motor-controller learning using spiking neurons without a host computer. The setup is shown in Figure 40.

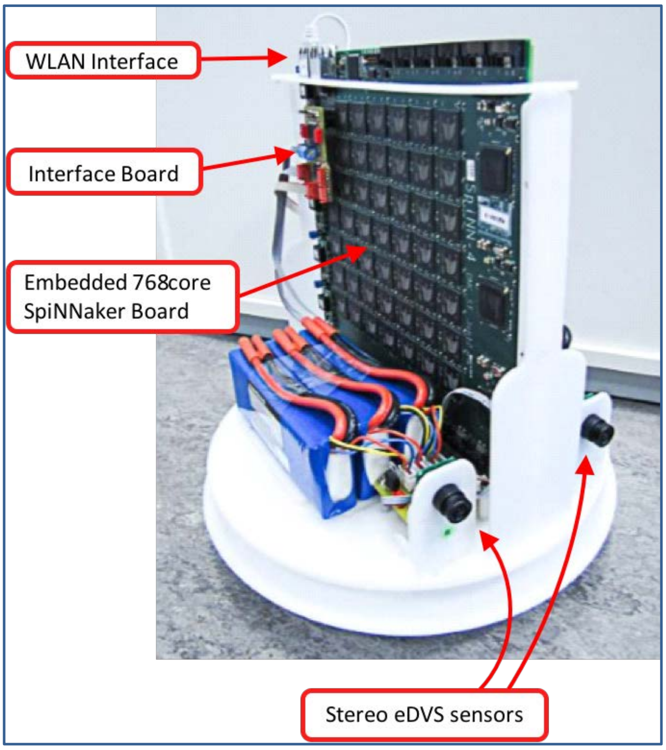


Figure 39: The Spomnibot developed at NST consisting of a 48 Chip SpiNNaker Board connected to the two eDVS sensors for environment perception and the omnidirectional drives via the interface board.

The first iteration focused on demonstrating the technical feasibility of the interface board. We are currently extending this interface board in a second design iteration to increase the number of native protocols, the spike throughput and the usability. The second iteration allows to communicate via UART, SPI, CanBus, and high-speed USB. The throughput will be increased by integrating a more advanced microprocessor and optimised CPLD programming. To increase the usability of the interface board we are actively collaborating with the SpiNNaker Team in Manchester (SP9) to introduce our codebase into the SpiNNaker toolchain and actively communicate with future end-users of the interface boards. Currently, we are discussing the usage of the SpiNNaker interface boards with the research group of Prof. Dillmann from Forschungszentrum Informatik (SP10 WP 10.2), research group of Prof. Dambre from University of Ghent (SP10 WP10.4) and the research groups of Prof. Mayr from the Technical University of Dresden (SP9) and Dr. Schmucker (SP9, University of Hertfordshire).

The preliminary outcomes of connecting MyoRobotic with SpiNNaker are largely published in [1], but work is ongoing. Current and planned research will extend the cerebellar motor control model in terms of number-of-neurons and later in terms of multiple instances of control systems. Both with the goal of overall improved precision for control, initially for the 2 DOF system, but later also for a more complex robot demonstrator with significantly higher number of (coupled) degrees of freedom. We expect that such a system (musculo-skeletal robot with many DOF) will convincingly demonstrate the control power of large-scale models; both, in terms of neuromorphic hardware and neuromorphic control.

Currently, we are assembling, programming and testing the second prototype and will begin benchmarking within the upcoming months. Afterwards, we plan on collaborate with the previously mentioned partners to perform experiments that evaluate the performance, applicability and usability.

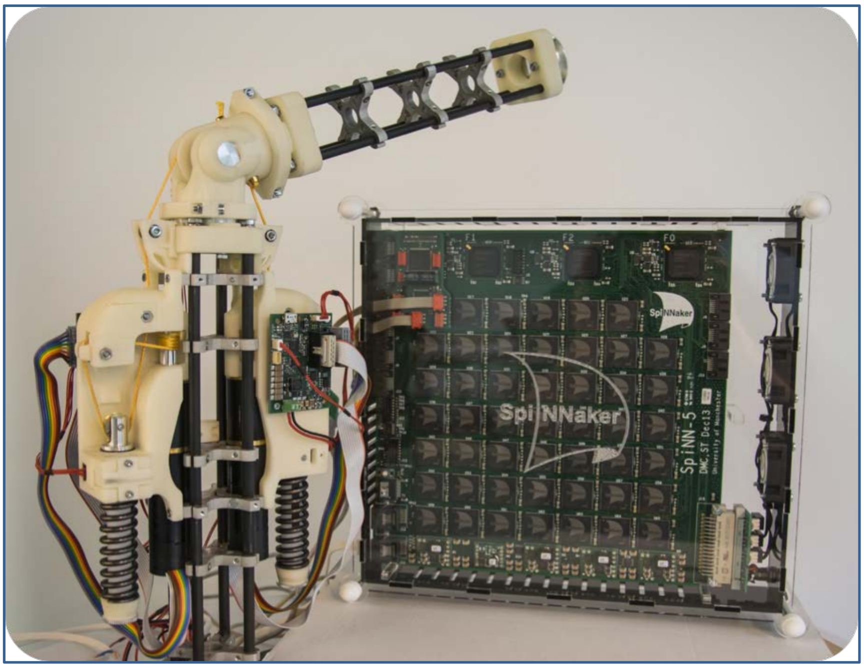


Figure 40: The 2-DoF MyoRobotics arm developed within Task 10.4.1 is connected to the SpiNNaker system via the interface board

This system can learn motor control running a cerebellar motor controller on the SpiNNaker hardware in real-time, utilising only neuromorphic computing components from sensor input to motor actuation.

[1] Richter, C.; Jentzsch, S.; Hostettler, R.; Garrido, J.; Ros, E.; Knoll, A. C.; Röhrbein, F.; van der Smagt, P.; Conradt, J.: *Musculoskeletal Robots: Scalability in Neural Control*. IEEE Robotics & Automation Magazine, 2016

6.8 T10.4.4 Self-adaption in modular robots

6.8.1 Key Personnel

Task leader: Henrik H. Lund (DTU)

6.8.2 SGA1 DoA Goals

To develop a bio-inspired motor control and motor learning system for modular robots. The model will integrate cerebellar-like learning mechanisms, the Locally Weighted Projection Regression (LWPR) machine learning algorithm and an adaptive feedback controller to control a modular robot. The nucleus of the control system will reproduce the modularity of the anatomy of the cerebellum. It will consist of a set of adaptive cerebellar modules, which are capable of learning the input-output relationship of dynamic processes. The cerebellar modules mimic the input-output characteristics of the motor apparatus of the modular robot. They adapt the corrections by means of a teaching inverse reference signal. Their activation is triggered every time a change is experienced. The self-adaptation will allow the modular robot to achieve task-fulfilling behaviours regardless robot complexity. The biomimetic learning architecture will be validated both into the NRP and with available physical robots. The system will be tested in context switching experiments changing the morphology of the robot.

6.8.3 Progress

Development of a bio-inspired modular control architecture. The bio-inspired closed-loop control architecture integrates a machine learning (LWPR) technique and a cerebellar-like microcircuit to provide real-time neural control. The result is a compliant system for motor learning that can scale to several neurally controlled robot modules.

The architecture was tested on the benchmark example of balancing a ball on a table. This standard task could look trivial from the robotic and control fields point of view, but serves as an initial benchmark task. Traditionally, the problem has been solved employing conventional control law together with computer vision techniques. However, this approach assumes a fixed robot morphology defined and described a priori to the experiment, and there is no run-time adaptation to the "biological changes" as we see in human beings. Balancing a ball on a table is a relevant example of how humans learn to calibrate, coordinate and adapt their movements. Hence, we investigate how robots can achieve this benchmark task following the biological approach. Probst et al. 2012 also followed the biological approach; they tackled the problem taking into account the dynamics of the system, four different forces are found by means of a liquid state machine and applied in four different points of the table to achieve the balancing task. A supervised learning rule is used for the training step, which concludes that after 2 500 s no further improvement of performance is obtained.

The vision of the current architecture work in this task is to reduce the amount of (sometimes implausible) a priori information the control system needs, leading to a real-time robotic control system that is capable of learning autonomously how to perform determinate physical tasks and of adapting to changing conditions. This approach introduces a fast and flexible control architecture that can be applied to different robotic platforms without any/excessive customisation. Hence, the task developed a bio-mimetic modular learning control architecture that is based on the modular cerebellar learning concept, machine learning optimisation (by LWPR algorithm), and on the traditional adaptive feedback control.

In order to evaluate and validate its functionality, the architecture was implemented for the experiment "iCub ball balancing experiment (empty world)" in the Neurorobotics Platform (soon available for users), in which the pitch and roll of the right wrist of the iCub robot platform are controlled in order to obtain the most accurate balance of the ball. This is done by means of minimising the error position of the ball with respect to the centre of the table. The learning process time was reduced to less than 60 s and was achieved on the go, without an offline supervised step (compared with 2 500 s supervised learning). This can be directly associated to how a human being would solve a similar task.

In the next step after the validation of the architecture in this benchmark task, the architecture was exploited to control a 2-DoF Fable robot module in order to demonstrate its advantages. The Fable module was combined with the neuro-inspired controller SpiNNaker mimicking the cerebellar modularity, i.e. showing how the neural core can be replicated and dedicated to a specific robot part or module. Both SpiNNaker and the LWPR algorithm allow the internal scalability: the first in terms of neural cores and the latter in terms of incremental locally linear models. The experiment represented the proof of principle of a system that can scale to several neurally controlled compliant modules.

Thereafter, another work (already submitted for publication) exploited a modular adaptive feedback error learning architecture shown in Figure 41 for controlling a modular robotic setup. This modular architecture embeds a set of Unit Learning Machines (ULMs) that mimics the cerebellum's microcircuit. The main aim is to verify the interdependence between the modular cerebellar anatomy and a modular body as a useful starting point for both robotics and neuroscience. Indeed, modularity might be the key organisational principle that the central nervous system (CNS) employs for achieving versatility and adaptability in motor control.

Next steps after M12 will be to test the feasibility of the approach with a modular setup comprised of more robot modules snapped together in a worm- or snake-like structure. This should show how in the future, researchers and developers will be able to assemble distinct modular configurations for carrying out a variety of tasks with minimal modifications, enhancing the usability of the NRP. All robot modules could be linked to identical ULMs and overall the system can be used for different scalable robotics platforms, i.e. Myorobotics, iCub, etc. Further, integrating between the various subtasks, generalisation experiments will show how the modularity of the fast and flexible modular control architecture allows it to be applied to different robotic platforms in NRP without any/excessive customisation.

The modular robotic approach will become important for the NRP to allow easy user definition of body morphology and alteration of body morphology for neuroscientific investigations of plasticity, e.g. such as the influence of body size and morphology changes over both shorter and longer time span on neural restructuring.

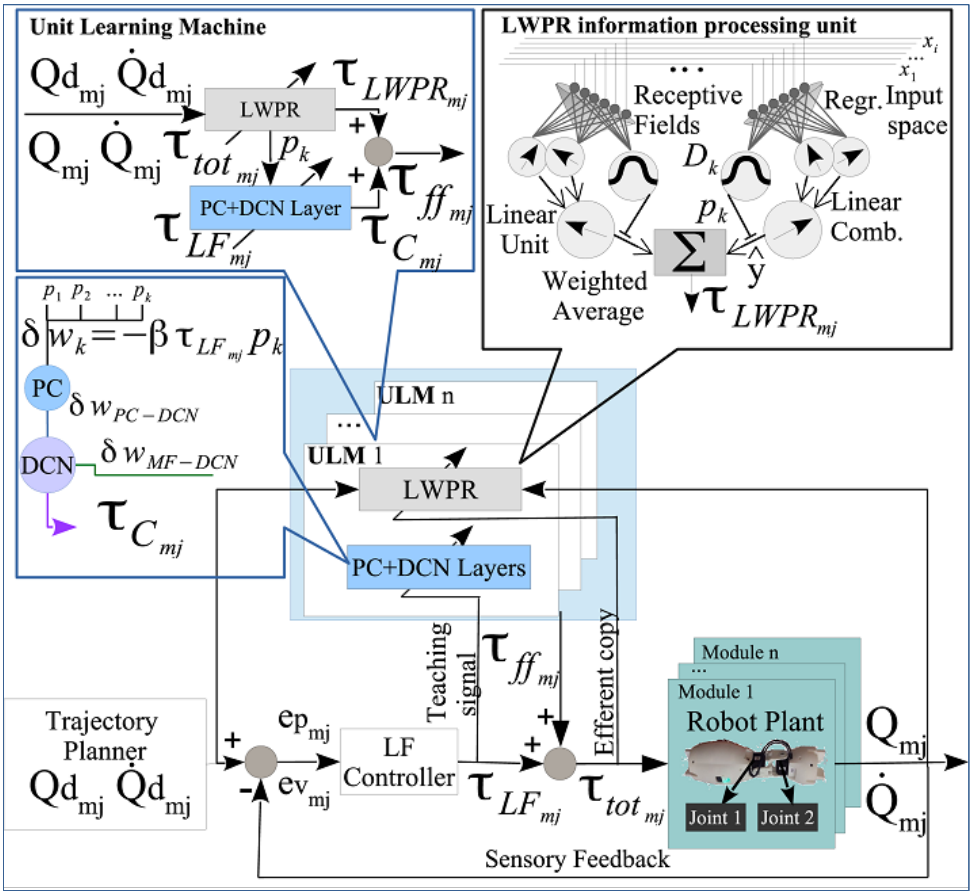


Figure 41. The modular control architecture consists of three main parts that supervise the control during a task

The trajectory planner block computes the desired joint angles and velocities; The LF controller generates the adaptive feedback commands from the sensory errors; the cerebellar ULMs which act as feed-forward controllers. Inside each ULM, the machine learning engine (LWPR) is combined with a cerebellar-like circuit (PC + DCN Layers) to perform the accurate motor control in torque and learning of the IM of a single robot module.

References

Levinson, Stephen E., Aaron F. Silver, and Luke A. Wendt. "Vision based balancing tasks for the iCub platform: A case study for learning external dynamics." Workshop on Open Source Robotics: iCub & Friends. IEEE Int'l. Conf. on Humanoid Robotics. 2010.

Awtar, Shorya, et al. "Mechatronic design of a ball-on-plate balancing system.2 Mechatronics 12.2 (2002): 217-228.

D. Probst, W, Maass, H. Markram and M. Gewaltig. "Liquid computing in a simplified model of cortical layer IV: learning to balance a ball". ICANN 2012, Part I, LNCS 7552, pp. 209-216, 2012

[4] S. Vijayakumar, A. D'souza, and S. Schaal, "Incremental online learning in high dimensions," Neural computation, vol. 17, no. 12, pp. 2602–2634, 2005.

[5] I. Baira Ojeda, S. Tolu, H. H. Lund (2017) "A Scalable Neuro-inspired Robot Controller Integrating a Machine Learning Algorithm and a Spiking Cerebellar-Like Network" In: Mangan M., Cutkosky M., Mura A., Verschure P., Prescott T., Lepora N. (eds) Biomimetic and Biohybrid Systems. Stanford University, California, Living Machines 2017, July 26-28. Lecture Notes in Computer Science, vol. 10384, pp. 375-386. Springer.

[6] A. d'Avella, M. Giese, Y. P. Ivanenko, T. Schack, and T. Flash, "Editorial: Modularity in motor control: from muscle synergies to cognitive action representation," Frontiers in Computational Neuroscience, vol. 9, p. 126, 2015.

6.8.4 Progress on Component:

- Achievement of the motor control and learning by means of Unit Learning Machines (ULM).
- Embedding of the LWPR Machine Learning algorithm and a cerebellar-like model within the ULM.
- Implementation of distinct cerebellar-like circuitries which considered the Purkinje cell layer and the Deep Cerebellar Nuclei cell layer
- The Purkinje and DCN layers were implemented analytically and in the form of spiking neural networks using SpiNNaker.
- We tested and validated the modular control architecture on a worm-like structure comprised of Fable robot modules (see Figure 42).

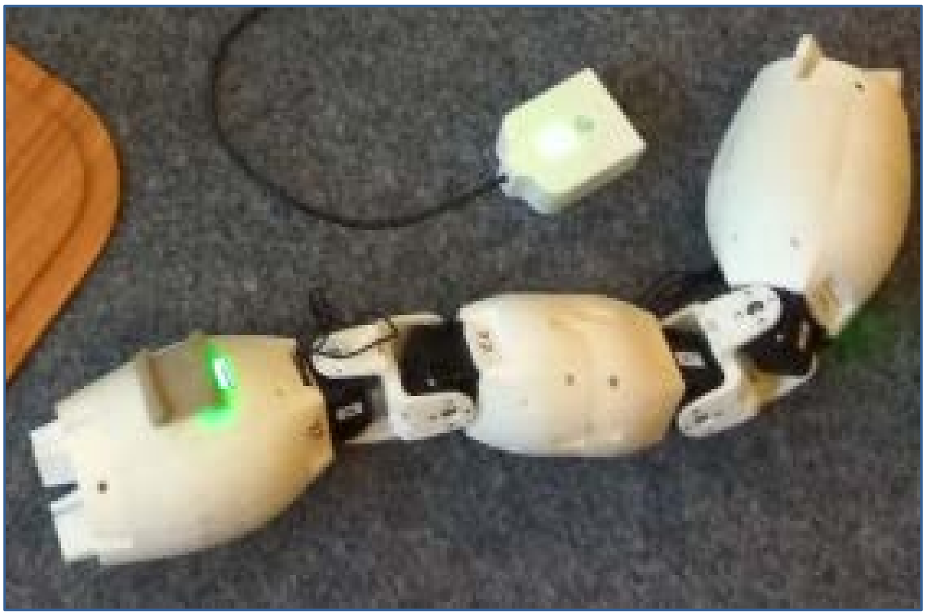


Figure 42: A worm-like structure comprised of Fable robot modules

- Integration of Fable modular robot and SpiNNaker.
- Addition of a spiking cerebellar microcircuit to the Unit Learning Machines.
- Full integration into the NRP in collaboration with the Scuola Superiore Sant'Anna. Towards the generalisation of the algorithm not only with modular robots but also with other robots available in the NRP, we carried out a ball balancing experiment with the iCub humanoid robot in the NRP. The model of the iCub was modified for the achievement of a ball balancing task getting a fast and stable behaviour.

Platform use cases:

- iCub ball balancing experiment combining computer vision and the Unit Learning Machines (see Figure 43).

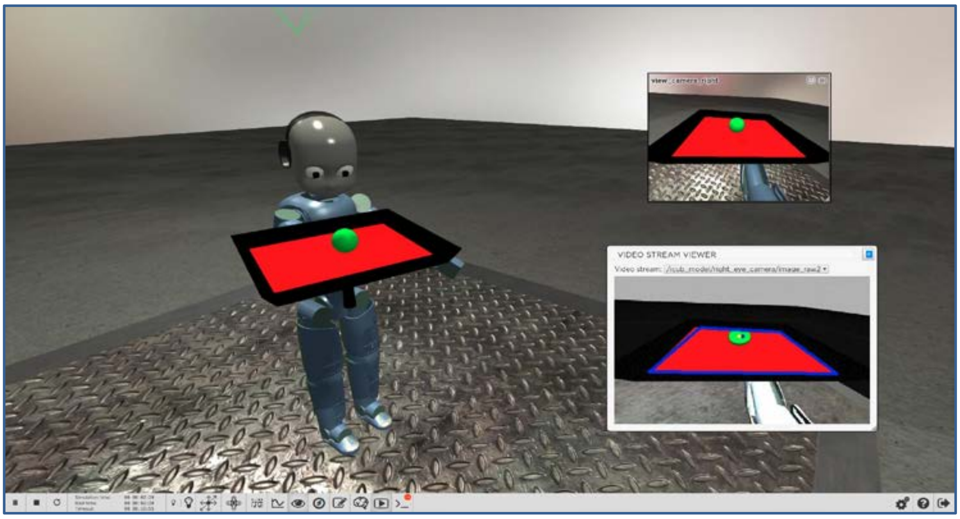


Figure 43: iCub ball balancing experiment combining computer vision and the Unit Learning Machines

Related publications:

Ojeda IB, Tolu S, Pacheco M, Christensen DJ, Lund HH "A Combination of Machine Learning and Cerebellar Models for the Motor Control and Learning of a Modular Robot". *Proceedings of the 2017 International Conference on Artificial Life and Robotics* January 19-22, 2017 Seagia Convention Center, Miyazaki, JAPAN International Meeting Series Editor-in-Chief Masanori Sugisaka Editors: Yingmin Jia, Takao Ito, Ju-Jang Lee ISBN 978-4-9908350-2-6.

Ojeda IB, Tolu S, Lund HH "A Scalable Neuro-inspired Robot Controller Integrating a Machine Learning Algorithm and a Spiking Cerebellar-like Network" Accepted paper for *Living Machines* 2017.

Ojeda IB, Tolu S, Jessen JD, Lund HH "A Bio-inspired Modular Control Approach for Scalable Robotic Configurations" *IROS* 2017.

6.9 T10.4.5 Real-time control with reservoir networks

6.9.1 Key Personnel

Task Leader: Joni DAMBRE (UGENT)

6.9.2 SGA1 DoA Goals

This Task applies reservoir computing as a stepping-stone to establish robust embodied neural models realising spinal cord functionality for real-time gait motor control in quadruped robots with passive compliance. A major difficulty in robots with passive compliance is the fact that their dynamics and kinematics cannot be described exactly by analytical models. Instead, control policies must be robust to morphological variability (e.g., the exact value of joint friction or spring constants) between individual robots as well as through time for each single robot. We therefore aim to develop a generic approach for learning tuneable embodied neural building blocks for real time motor control and validate them on quadruped robot models: the NRP mouse model when it becomes available (this is our long-term objective), and in the shorter term on a simpler physical quadruped robot platform with passive compliance. The models will be made available through the Collaboratory. A secondary aim of this Task is to provide a test case for using the SP10 NRP in compliant robot design and optimisation.

The relevance of the scientific objectives listed above for the platform development can be summarised as follows:

- to develop and demonstrate a spiking closed loop controller for locomotion that is capable of adapting to changes in morphological properties, and to demonstrate this controller in a compliant quadruped, both as a simulated model in the NRP and as a physical robot; and

- to use this to investigate to what extent a simulation platform like the NRP can reduce the training/learning time on the physical robot, i.e., how controllers can be developed in simulation that are as robust as possible to variability in the physical world.

6.9.3 Progress

Roughly 3 months were spent in evaluating the NRP and the mouse model in order to provide user feedback to the developers. This happened in close interaction with the NRP development team (interaction with several Tasks of WP10.5, attendance to regular skype meetings) and has led to concrete recommendations (e.g., the requirements to a muscle model, the possibility to do batch simulations without visualisation).

As the simulated mouse is still under development, the focus of this Task is now on the methodology and the compliant quadruped robot platform, where we are working along three lines: (a), (b) and (c). In what follows, we summarise our progress along these three lines:

(1) **Methodology for obtaining robust and easy-to-train spiking closed loop motor control for physical compliant robots using reservoir-computing:** A population-based reservoir model was developed based on balanced populations (see e.g., Van Vreeswijk and Sompolinsky, Science, 1996 or Brunel, Journal of Computational Neuroscience, 2000). It can be trained either using the full spiking model (implemented in Nest) and on a 4-node SpiNNaker board) or a simplified model in which populations are replaced by their rate-based input-output transfer curve. The latter case is aimed at speeding up the simulations, in particular when exploring and optimising different gait patterns. Here, the reservoir is driven with a periodic signal that acts as a trigger and stabilises the frequency of the gait. A single reservoir is capable of generating the CPG patterns for all actuators of the robot (see Figure 44).

Correspondence between the reservoirs with population nodes and using actual spiking populations was evaluated in the NRP by observing robot response in an open-loop situation. In particular, the population size was tuned to be as small as possible, while generating sufficiently smooth motor control signals.

In M13-M24 this model will be used to generate the spiking closed-loop controller of objective (i) above by adding sensor feedback, which will be evaluated on the simulated and the physical robot. Later (e.g., in SGA2), it can also serve as a baseline for evaluating both spiking and non-spiking biologically plausible models developed elsewhere in the project (e.g., the model of T10.1.1), with respect to control accuracy and hardware performance (e.g., speed, power efficiency).

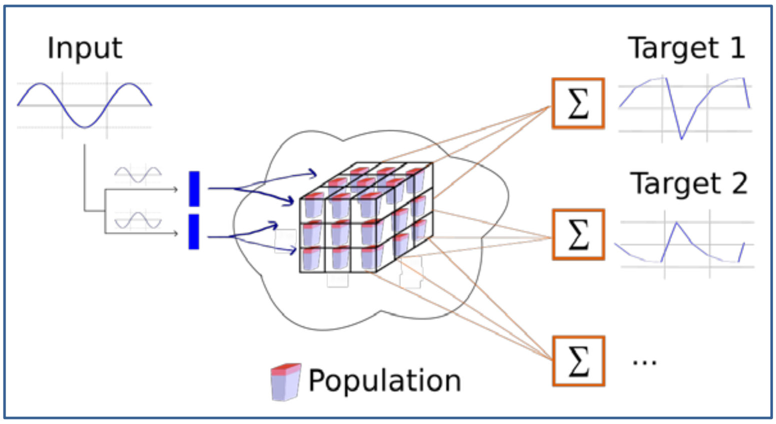


Figure 44: Population-based reservoir model

(2) **Providing an autonomous compliant quadruped robot and its simulation model in the NRP to demonstrate our approach:** because SGA1 runs for only 2 years and the SP10 mouse robot is not available yet, we opted for to start our work on the autonomous Tigrillo Robot platform. This was developed in our lab before and outside SGA1 and therefore readily available. The simple Tigrillo robot and its control serve as a stepping stone for more advanced compliant robots and the simulation of compliance, which will be relevant for a compliant simulated mouse in the NRP, a future physical implementation thereof using advanced compliant actuators (Myorobotics) and other future compliant robots. Locomotion is necessary and immediately relevant for the mouse. The robot is currently being adapted to include a 4-node SpiNNaker board for real-time closed loop spiking motor control and an Arduino Due board for interfacing with the actuators. This was done using support from the SpiNNaker team and input from Task 10.4.3. When the interface board from Task 10.4.3 is released, it will be integrated on the robot to enable sensor feedback. During M6-12, the adapted electronics and body parts were designed and fabricated and assembly was started. After assembly, and successful testing, we aim at first experimental demonstrations of open loop spiking motor control at latest in M18 and closed loop control as planned before the end of SGA1.

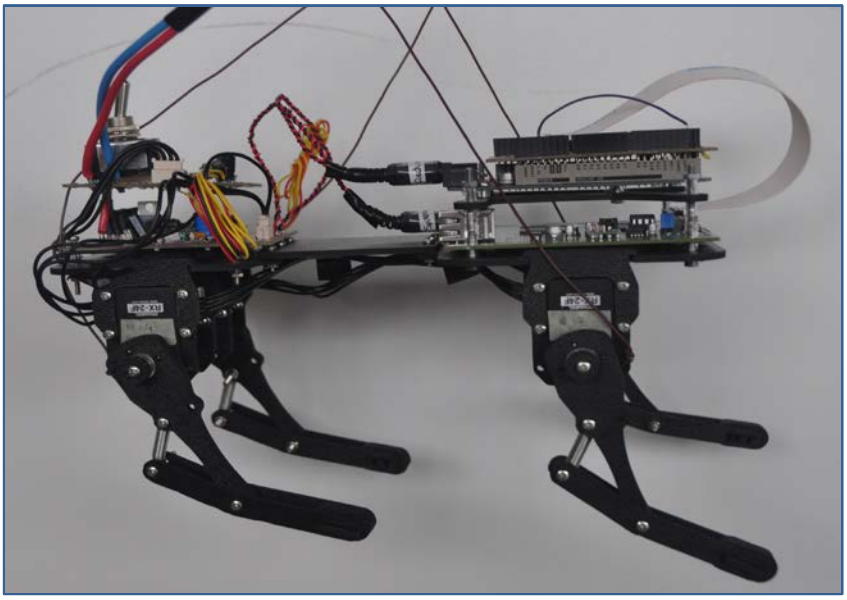


Figure 45: Adapted Tigrillo robot with SpiNNaker and Arduino Due

(3) Methodology for obtaining robust gait patterns in simulation that are transferrable to robots with slightly different morphological parameters: the research question we want to address here is how a closed-loop simulation platform such as the NRP can be used to design a neural controller and learning strategy in simulation, such that it is as robust as possible against morphological and other variations that may occur in the physical world, in order to minimise the necessary learning time on the physical robot. First, a methodology for obtaining energy-efficient embodiment was developed using a simulated model (mass-spring-damper) system (published: Urbain et al. "Frontiers in Neurorobotics", 2017). Conclusions from this study are now used to achieve robust and power-efficient embodiment for our Tigrillo quadruped robot. A first version of a simulation model for Tigrillo was implemented in Gazebo (local NRP installation). Awaiting the release of script-based access to the NRP and the release of the Virtual Coach, a methodology for obtaining transferable embodied gait patterns using simulation was developed using another Bullet-based simulation platform (MuJoCo). We optimise for a population of robots of which the morphological parameters (dimensions, spring constants, mass, location of the centre of mass, …) are sampled from an underlying distribution that models the variations that can occur in the physical world. We use evolutionary optimisation (CMA-ES) to search motor actuator patterns that are both power efficient and stable for random samples of individuals from this population. The patterns are obtained by optimising the parameters of the parameterised CPG used in [Gay et al., IROS, 2013]. Initial open loop experiments using the old Tigrillo robot (not yet equipped with spiking control) indicate transferability of control patterns learned in simulation to the real robot as well as the spontaneous emergence of different gaits for different energy budgets (journal publication in preparation). Given the recent release of the Virtual coach, we will now transfer this methodology to the NRP and use it to train spiking controllers that are robust to morphological variations.

6.9.4 Training followed in HBP:

One PhD student participated to Nest for robotics user workshop (3-4 Nov. 2016), and two PhD students participated to HBP Winter School.

6.9.5 Inputs to other parts of the HBP:

Thus far, the experience gained in T10.4.5 has provided valuable input to the NRP software developers (WP10.5) and frequent interaction also occurred with parts of WP10.1 and SP9 (SpiNNaker team).

The Tigrillo 3D-model has served as the first benchmark for the integration if OpenSim in the NRP (T10.5.2) which was necessary to provide stable simulation of compliant parts. Tigrillo served this purpose because it was simple enough to allow fast implementation and because it can be seen as an intermediate step to providing stable simulation of the mouse using OpenSim. The experience from T10.4.5 with OpenSim is now used by other groups targeting the simulation of compliance in the NRP.

Other notable interaction during the first 12 months of the project consisted of suggestions to the NRP developers to improve user-friendliness and to facilitate new robotics users to efficiently develop neural control algorithms. E.g., the Virtual Coach was implemented in response to experiences and feedback from T10.4.5 and requirements for a standalone installation of the NRP were fine-tuned through input from T10.4. Practical requirements related to the support of sensor inputs to SpiNNaker were passed on to the SpiNNaker team (SP9).

6.9.6 Publications:

Urbain G, Degrave J, Carette B, Dambre J, Wyffels F (2017). Morphological Properties of Mass-Spring Networks for Optimal Locomotion Learning. *Front. Neurorobot*. 11:16. doi: 10.3389/fnbot.2017.00016

6.10 T10.4.6 WP Lead

6.10.1 Key Personnel

Task Leader: Jörg CONRADT (TUM)

This task involves no personnel costs; it is only budgeted with travel costs for the WP leader. For a report see WP Leader’s Overview at the beginning of this chapter.

7. WP 10.5 Simulation and Visualisation Tools for Neurorobotics

7.1 Key Personnel

Work Package Leader: Axel von Arnim (FORTISS)

7.2 WP Leader's Overview

This first year in SGA1 has seen dramatic improvements in the NRP, in terms of stability and availability. The year was actually divided in two periods. During the first period, feature development was somewhat frozen and we went through important refactoring and architecture improvements to address flaws and instability problems.

The second period caught up on features and early user requirements (our pilot experiments Use Cases). Here is a list of the features that we managed to deliver in the 1.2 release (M12), as they appear on our website:

- Support for bigger brain models *(requirement from CDP-1)*
- Graphical transfer functions editor
- Basic brain visualisation *(requirement from CDP-1)*
- Python API for batch simulations (Virtual Coach) *(requirement from DTU)*
- Object scaling
- New template experiments
- Camera Streaming *(requirement from FZI)*
- Object Scaling
- Environment Enhancements

Details on them are given in the relevant Tasks sections hereunder.

The experts in the last review report have asked in the "General comments" section for a plan to increase the number of users. The plan is now clear and twofold. A first set of users is taken directly from within SP10 with the pilot experiments and the integration of other experiments as they are requested by SP10 researchers. This worked out quite well, as, on top of the pilot experiments, we had eight requests to integrate experiments that are detailed on the roadmap below (four of them have been honoured at the time of writing). These users have been of course using other tools in the past to achieve their goals, but they are now using the Platform which will eventually serves them better since **they** are submitting the requirements. For example, the Virtual Coach was an explicit requirement by the team of Prof. DAMBRE at DTU. Camera streaming was a requirement by Prof. DILLMAN's team in FZI. A second set of users is coming from the outside, over the account request page of our website. We have 136 requests at the time of writing, 80% of which are basic user requests (they only want to discover the Platform, not use it yet). For them we have a plan in the early second year (now), to make their Platform experience more interesting (See roadmap). Test accounts (full access limited in time) are on hold until we have a scalable architecture. They are given a basic account instead. Project accounts (permanent full access) have been granted when requested by SP10 partners only for now.

Another point raised in the "General comments" section and in C1 was about our workflow and management personnel which was judged positively. We run the same workflow and implemented this split into a developer team and a research team. The developer team has now 6-month release cycles, which give way more flexibility to deliver ambitious features and still incorporate user requirements on the go. Now we need a brief review of the Scrum roles we have.

- The Scrum Client, Dr. Gewaltig (EPFL), keeps the long-term goals of the Platform and monitors progress.
- The Product Owner, Axel von Arnim (FORTISS), translates these goals into a roadmap and a release plan, sets priorities, incorporates user requirements delivered by users and Science Coordinators (Stefan Ulbrich (FZI), Letizia Allegra (LENS), Alexander Kuhn (TUM).
- The Scrum Master, Dr. Luc Guyot (EPFL), ensures the implementation work is done time- and quality-efficiently and moderates the team's scrum related meetings.

In section A of the same document, the status of two pilot experiments was asked about. This is covered in the scientific sections above. But on top of this, the development team has organised a so-called "Install Party" at FORTISS in April 2017 which has led to the integration of four user (SP10) experiments. Other experiments are on the starting blocks.

In section B, OpenSim is mentioned, which is addressed in the T10.5.1 section.

Section D was about our plans for Docker. This is covered in WP10.6, but here we can already say that Docker is, as of M12, running the Platform on our development servers, making the deployment process way easier. Production (staging) servers will be ported to Docker soon and the move to the Piz Daint cluster of the HPAC Platform (SP7) is a longer term goal (SGA1) depending also on support for Docker on their side.

Concerns in E and G were about the scientific use cases and how we manage the requirements and waiting users. We have a continuous communication with the people of the pilot experiments. They feed us with bug reports and requirements. Our active forum (https://forum.humanbrainproject.eu/c/neurorobotics) gets them quickly unblocked from usage issues or small bugs. More annoying issues are incorporated into our Jira backlog, in dedicated Epics that have high priority. Longer term user requests are posted to our public tracking tool (https://bitbucket.org/hbpneurorobotics/neurorobotics-platform/issues) and taken care of in the roadmap. The Virtual Coach is an excellent example of an implemented user request. The users are set liaison engineers that help them using the Platform and gather their issues.

A concern in the conclusion was that the NRP is less mature than other HBP Platforms. That is true, but we have caught up in the last year and the existence of running experiments from real users and related publications is a proof that maturity is growing. Still an important step to become a realistic public platform will be the move to HPC resources (Piz Daint cluster) with the related scalability and the capacity to support large brains. This is planned for end of SGA1.

7.3 Priorities for the remainder of the phase

In this section, a roadmap with the next releases in SGA1 is probably the most explicit piece of information. Note that version 2.0 has a slightly lighter plan than 1.3 because we expect some of the ambitious 1.3 features to be delayed or generate issues (Piz Daint mainly).

Table 5: Priorities for the remainder of the phase

1.2.1 (June 2017)	1.3 (October 2017)	2.0 (April 2018)
4 new user experiments	4 new user experiments	new user experiments **requirements from existing 8 user experiments**
CDP-1 experiment MVP:	CDP-1 experiment V1 - extended muscle visualisation	CDP-1 V2 - full M platform - both forelimbs equipped

- good enough muscle simulation - basic muscle visualisation in frontend - mouse model with 1 limb equipped, passive muscle support - simplified mouse brain - MVP experiment with basic transfer functions/spinal cord - M sled in empty world	- muscle simulation performance increase - robot designer supports muscle attach points - full dynamics CDP-1 simulation (active muscles) - interactive neuron selection (brain visualisation) - full mouse brain support (not real time though) - brain activity visualisation - modular spinal cord integration	- distributed mouse brain (faster)
Basic user showcase experiments: - dedicated servers for basic users with fully docked Platform - continuously running simulations (virtual coached) - live commented simulations - no limitation on number of users - new didactic welcome page for basic users	"Holo deck" new virtual lab: - full model available - collection of subparts (full room, only part equipped) in env library - env designer more flexible, dynamic objects library	Big brain support - MUSIC new API supports dynamic ports - reset distributed brain - automatic number of processes calculation - continuous ports support - TFs in separate process (?) - loads 10^4 brains
	Migration to Piz Daint - puppetised docker servers on BBP resources - automatic setup script (container launch & update) - manage PIz Daint with slurm script - 20 VMs in CSCS which spawn gazebo and nest on Piz Daint	Scalability on Piz Daint
	Virtual Coach replay - implement all frontend features - collab support - profiling - reinforcement learning example - snapshot / import brain weights - dynamic maze generation (?) - record and replay simulation data - replay biological data	Virtual Coach distribution - distribute simulations over a cluster
	Modern interfaces (Sandro) - all views rearrangeable - drag&drop between views - views on multiple hardware	Nengo integration - clean integration as a second brain simulation - holliearm experiment with nengo
	Create experiments from scratch - all collab features supported in local or client server mode	

	- online robot, env, brains library - upload of custom models	
	Robot Designer - supports collab - supports local "collab" - muscle attach points	

Table 6: Milestones for WP10.5 - Simulation and Visualisation Tools for Neurorobotics

MS No.	MS Name	Leader	Expected Month	Achieved Month	Comments
10.5.1	Implementation plan for WP10.5	FORTISS	M02	M06	This Milestone has been achieved with the submission of Deliverable 10.7.1
10.5.4	First release of the Neurorobotics Platform Software	FORTISS	M12	M12	The first version of the NRP was released on 10 May 2016, version 1.1 was released on 13 October 2016 and the next version (1.2) will be released in a few days.

We are actively monitoring feature demands and ease-of-use. The most important instruments for us are the many user-workshops that SP10 has organized since the start of SGA-1. During these workshops, we help users implement their work and at the same time monitor their needs, suggestions and problems. A table in the WP6 section describes the results of these activities.

7.4 T10.5.1 Simulation of physics (mechanics, light, sound, etc.)

7.4.1 Key Personnel

Task Leader: Fabian AICHELE (TruPhysics, subcontracted by TUM)

7.4.2 SGA1 DoA Goals

This Task will improve the physics simulation of the World Simulation Engine (T10.5.2) to make it suitable for the simulation of soft robots and skeleton-muscle systems. These require the simulation of deformable materials (e.g. muscles or skin) and high geometric detail, a feature that is not provided by state of the art robot simulators such as Gazebo. This Task will therefore improve available collision detection algorithms to deal with highly detailed deformable 3D models and kinematic assemblies, and to provide the high degree of geometric detail and physical plausibility, than is required by the NRP.

7.4.3 Component Progress

7.4.3.1 NRP - Physics simulation

GPU-based collision detection will not be available in SGA1, because the SOFA integration plan was postponed in favour of integrating OpenSim. OpenSim is a state-of-the-art skeleton-muscle simulation framework developed by the National Center for Simulation in Rehabilitation Research at the University of Stanford[3]. It proved to be simpler to integrate, is already used by researchers within SP10 and as such, is a requirement in the Platform.

A survey on user needs has led to the conclusion that users do not so much need realistic, but symbolic muscle visualisation and modelling. With our 1.2 release end of March 2017 (M12), we showcase a first integration of the OpenSim symbolic muscle simulation engine into our Platform.

In order to add OpenSim as additional physics engine to the Gazebo simulator, a new physics engine plugin has been developed that allows the usage of OpenSim as both a conventional rigid-body physics engine and its skeleton-muscle system dynamics simulation features. The source code of OpenSim has been adapted as part of the implementation of the new physics engine plugin to allow incremental modifications to a running simulation (e. g. insertion and removal of new robot or environment objects). The plugin is exposing OpenSim's full range of muscle modelling features, including the specification of indirect muscle attachments that allow to model muscle attachments via tendons wrapping over bones (e. g. elbow or knee, see **Error! Reference source not found.** for a simplified example).

Gazebo's model specification language SDF has been extended to allow the seamless addition of muscle system definitions to existing robot models available in the platform. An extended muscle system specification format that allows the usage of different skeleton-muscle system simulations (such as the simulator used by the Roboy platform[4]) will also be added. A muscle visualisation feature has been added to the Gazebo simulator client GUI; a muscle visualisation feature for the NRP Web cockpit is currently in development. As first robot model based on OpenSim, a simple four-legged kinematic model with a basic muscle system is available in the Platform (see **Error! Reference source not found.**). The second experiment using OpenSim showcased in the Platform is inspired by the experimental setup for stroke rehabilitation research[5] as described in **T10.1.6** ("Simulation of motor rehabilitation experiment in rodents").

Based on the model of the M-Platform described in T10.1.6 and an anatomically accurate model of a mouse's skeleton (see **Error! Reference source not found.**), this experiment will model the muscle apparatus of a mouse's foreleg to enable muscle excitation-based actuation of the mouse's forelimb instead of the standard motor-based actuation provided by Gazebo. The objective of the experimental setup is to actuate the mouse foreleg model by using muscle excitations created by a suitable mouse brain model. The muscle actuation pattern is to be determined by tactile and dynamic feedback as provided by the OpenSim engine, based on the motion behaviour of the M-Platform created in T10.1.6.

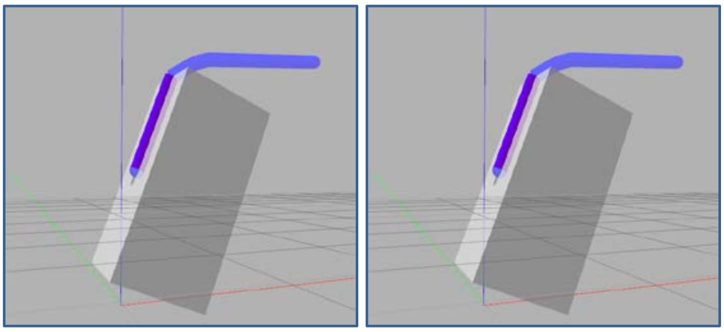


Figure 46: OpenSim muscle wrapping over a rigid body

[3] http://opensim.stanford.edu/
[4] http://roboy.org/
[5] "A robotic system for quantitative assessment and poststroke training of forelimb retraction in mice", Spalletti C, Lai S, Mainardi M, Panarese A, Ghionzoli A, Alia C, Gianfranceschi L, Chisari C, Micera S, Caleo M.; https://doi.org/10.1177/1545968313506520

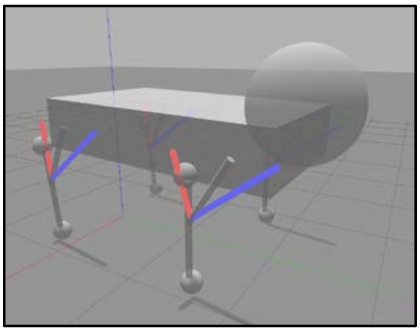
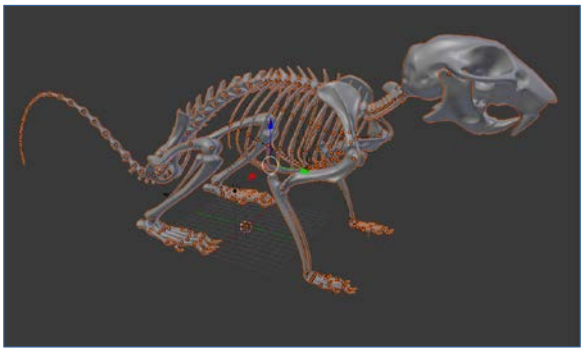


Figure 47 (left): "Tigrillo" robot model with simple muscle model

Figure 48 (right): Model of mouse skeleton used for the CDP1 V1 experiment



7.5 T10.5.2 World Simulation and Closed-loop engine

7.5.1 Key Personnel

Task Leader: Marc-Oliver GEWALTIG (EPFL)

7.5.2 SGA1 DoA Goals

This Task adapts different software modules to the needs of the NRP and integrates them into a coherent system: The World Simulation Engine. The most important modules are the robot simulator (e.g. Gazebo), a physics engine (e.g. Bullet, ODE or SOFA.) and the Closed-loop engine, which synchronises the robot/environment simulation with the brain simulation. This Task also develops and documents the application program interfaces between the different modules of the NRP software and also between the NRP software and the tools running on other HBP Platforms, such as the Brain Simulation Platform and the Neuromorphic Computing Platform.

7.5.3 Component Progress

7.5.3.1 NRP Web cockpit (ExDFrontend)

Description of Component (from PLA)

The NRP Web cockpit, also known as ExDFrontend, is the frontend of the NRP. This is where you can launch and watch a neurorobotics simulation. It is tightly integrated into the Collab portal. Repository: https://bbpcode.epfl.ch/code/#/admin/projects/neurorobotics/ExDFrontend

Progress on Component:

The Web Cockpit has a couple of additions as of M12. It offers now, apart increased stability, a brain visualiser, impressive rendering improvements (support for shadows, PBR rendering, colour profiles, sky boxes, fog, …) and a settings panel to tune them. Some more discrete features such as the auto-save of edited files, the ability to customise an experiment's details or the avatar navigation make the user experience seamlessly better.

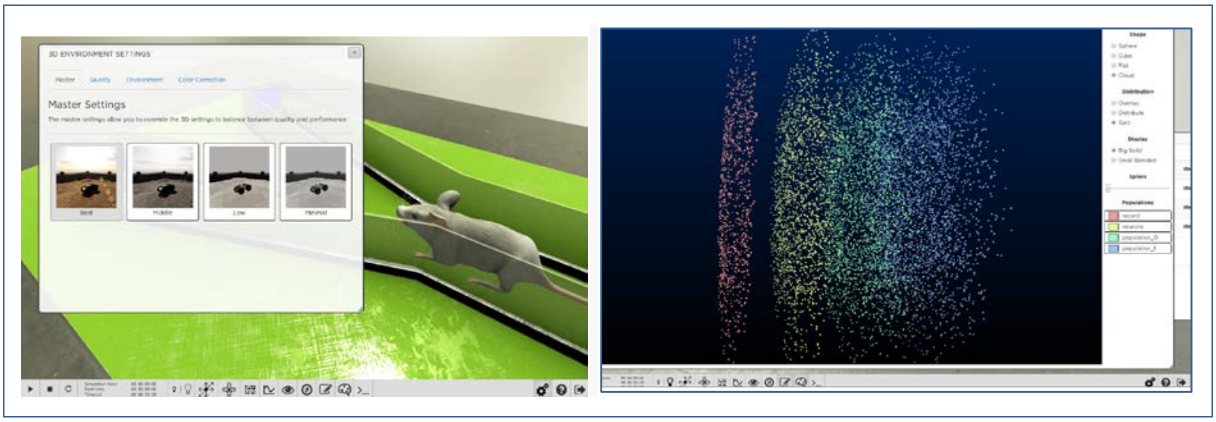


Figure 49: Rendering improvements of the mouse experiment, graphical settings pane (left) and brain visualiser (right).

7.5.3.2 NRP Brain-Body Integrator (BIBI)

Description of Component (from PLA)

The NRP Brain-Body Integrator, also known as BIBI, is the framework which allows neuroscientists to connect brain models to sensors and actuators of robot models within the NRP. The communication between the brain and the body is implemented by means of the so-called "transfer functions" which read and write data via ROS topics.

Progress on Component:

The Brain-Body Integration (on the backend part) has improved support for uploading/downloading transfer functions. Also, the error checking mechanism and the population name edition have been improved a lot.

7.5.3.3 NRP Closed Loop Engine (CLE)

Description of Component (from PLA)

The NRP Closed Loop Engine (CLE) is the Component which allows to simulate a brain wired to a robot evolving in a virtual environment. The CLE runs two simulators, the brain and the robot simulator, and keep them synchronised. Repository: https://bbp-code.epfl.ch/code/#/admin/projects/neurorobotics/CLE

Progress on Component:

The CLE has undergone major refactoring. Key component of the stability issues that we had after the first public release, it has been largely rewritten to handle multithreading, concurrent access (watcher mode), error management, automatic discovery of world simulation crashes, making simulations now run way smoother than one year ago. Also, it now supports distributed NEST, either on a local NRP installation or on a cluster. Performance with distributed NEST is though disappointing, due to flaws in the CLE design, which will be worked out in the following of SGA1 together with the MUSIC developers in SP9.

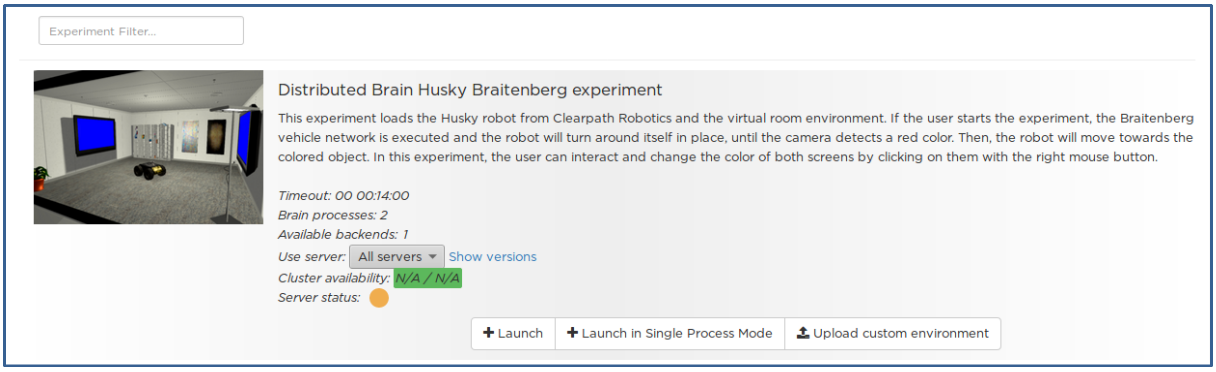


Figure 50: The experiment list now shows a distributed version of the benchmark Husky Braitenberg experiment

7.5.3.4 NRP Services (ExDBackend)

Description of Component (from PLA)

The NRP Services software, also known as ExDBackend (Experiment Designer Backend) is the set of web services offered by the NRP to set up, launch and interact with an in-silico neurorobotics experiment. A neurorobotics experiment is a scenario in which a brain model embodied in a robot model are simulated. Repository: https://bbpcode.epfl.ch/code/#/admin/projects/neurorobotics/ExDBackend

Progress on Component:

As the CLE, the backend (the software component handling client requests and managing the simulation lifecycle), has been largely refactored, for the same reason. It runs also multithreaded now, simulation lifecycle has been redesigned, and failed simulations are handled without messing up the server. We have added also a new layer between the client (Web Cockpit) and the backend, namely a proxy server that polls the backend servers for availability. This was previously done by the Web Cockpit, leading to UI blocks when some server was unavailable. With the proxy, this is hidden from the Web Cockpit which always gets a fresh list of available servers asynchronously.

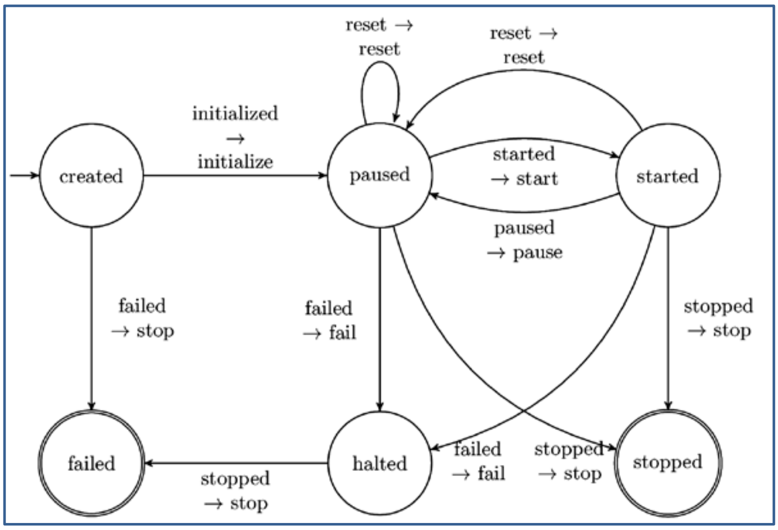


Figure 51: The new simulation state lifecycle

7.6 T10.5.3 NRP User Experience (NRP Cockpit)

7.6.1 Key Personnel

Task Leader: Gudrun KLINKER (TUM)

7.6.2 SGA1 DoA Goals

This Task develops innovative tools for immersive high-fidelity rendering and real-time user interaction, enabling life-like neurorobotics experiments with users in the loop.

The Neurorobotics Cockpit is the central user interface to the NRP. The NR Cockpit will give the user full access to the underlying simulation data, while the experiment is running and the virtual robot is performing assigned tasks. It will allow users to control the experiment and to visualise all simulation data. For this purpose, the cockpit will consist of a freely (ad hoc) configurable combination of display and interaction devices - some stationary and others mobile - to present inter-related visualisations of all relevant aspects of an experiment as 3D (VR)-type renderings in combination with magic lenses to explore details. The cockpit will provide a multi-modal interaction interface extending regular WIMP-based schemes with touch and 3D input based on tracked tangible objects, displays and users' limbs.

7.6.3 Component Progress

7.6.3.1 NRP Cockpit - Online user interaction

Online user interaction / input interpretation within experiments during runtime: Some experiment scenarios might directly involve users or depend on human interaction. In order to make these experiments possible, a system will be developed that integrates user input directly into the platform during runtime of an experiment, with the possibilities for the input to influence all parts of the NRP (environment, robot, brain

Progress on Component:

Human navigation with an avatar representing the user now enables the user to be fully immersed in the scene, as if the user could walk around the robot. When multiple users join, they all have an avatar and see each other, enabling interesting sharing and interaction possibilities.

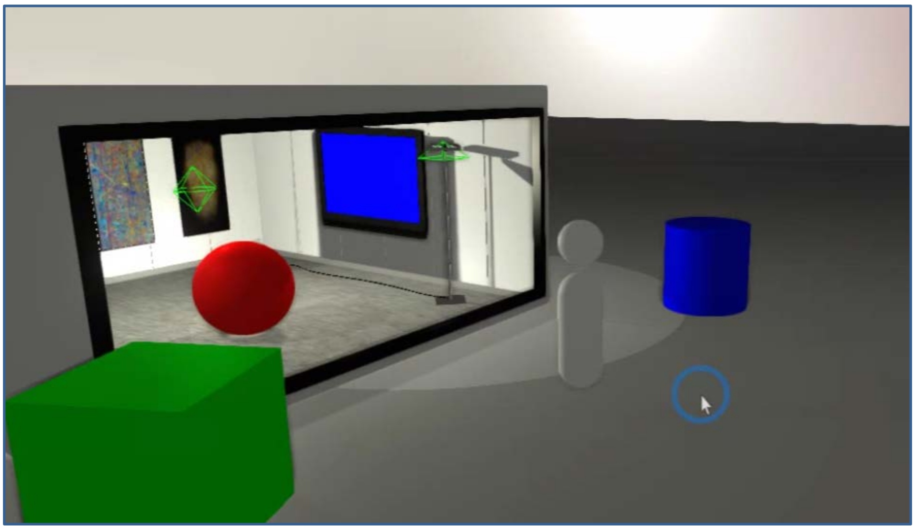


Figure 52: When the NRP is used collaboratively, the user can displayed as an avatar in the 3D scene. Thus one collaborator can anticipate the point of view of another collaborator.

7.6.3.2 NRP Cockpit - Dynamic reconfiguration

Dynamic (re)configuration of in-/output devices and interactivity between devices In order to make full use of different display modalities the devices in use should be easy to integrate into the workflow and the NRP should have capabilities of visualising interdependencies between the devices, e.g. the effect/results of changing parts of the experiment (brain) should be visible throughout other views on experiment data. This will not only ease the process of debugging experiments but also help in identifying causes & effects during simulations.

Progress on Component: This component has not yet been addressed.

7.6.3.3 NRP Cockpit - Input devices

Depending on Use Case scenarios described in Component 1 (desktop, multi-user, VR, …) an NRP user needs to have access to input devices suited for the working environment. Furthermore, specialised user tracking devices like Kinect, Myo, LeapMotion, etc. offer possibilities of more complex/natural input by the user that allows non-standard ways of interacting with simulations.

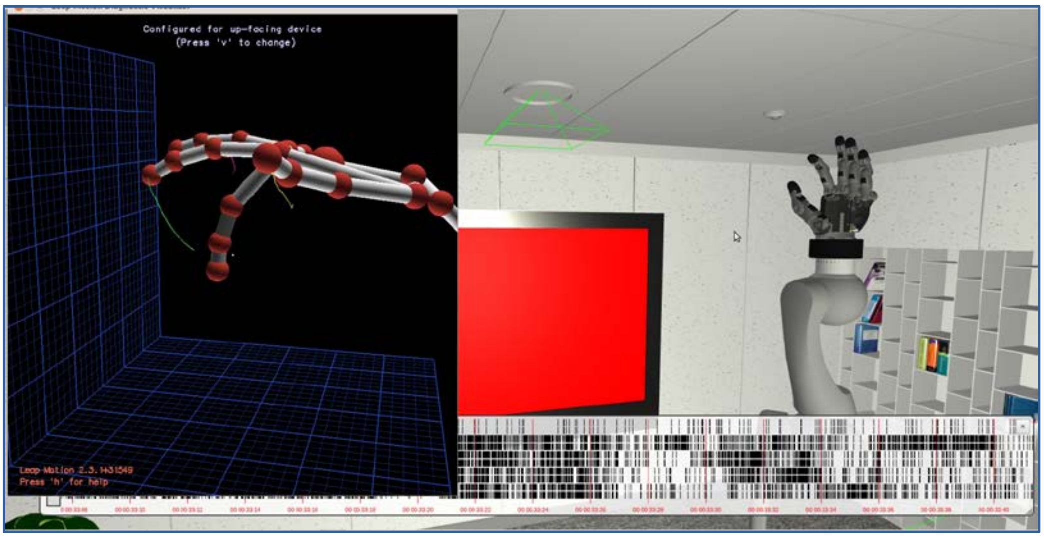


Figure 53: Leap Motion data visualiser (left) and Schunk hand reproducing finger motions (right)

Progress on Component:

The integration of novel hardware controllers has been investigated for Myo armband and Leap Motion. Input delay between client and server has been investigated as a first feasibility study for remote interaction. A Myo has been used to control a robot arm's rotation and grasping motion live in simulation. The user avatar model is expanded to allow arm movement in the same way. A combination of Leap Motion and Myo has been used to research ways to classify Myo's EMG data beyond what the SDK provides. Virtual Reality and augmented reality glasses will be further investigated in SGA1, first setups using the Hololens are already undergoing.

7.6.3.4 NRP Cockpit - Output devices

Users of the NRP Cockpit should have access to different screen configurations depending on the situation. Possible scenarios: desktop cockpit/operator views for managing experiments - displaying relevant aspects of the simulation distributed over multiple screens/devices multiple users working collaboratively in the same physical space VR environments of simulation This includes user interfaces tailored to the situation/devices used.

Progress on Component:

The NRP Web Cockpit has been redesigned to handle views in a generic way. This is work in progress, but it already enables to select whatever view to be displayed as the main view or to display it in a sub window. For example, the spike view could be set as the main view whereas the 3D scene could be displayed in a small sub-window, and vice-versa. Multi-screen layout is still being fostered.

7.7 T10.5.4 Environment and experiment designer

7.7.1 Key Personnel

Task Leader: Rüdiger DILLMANN (FZI)

7.7.2 SGA1 DoA Goals

This Task develops tools to create, change and customise an experiment's environment and execution flow.

Task Description:

This Task develops the tools to construct and to represent different environments on possibly multiple screens. Hereby all reusable Software component (packages) which are helpful will be imported from external resources. The involved environmental models do not describe only static environments but also dynamic scenes. So for example a complex dynamic situation can be constituted by a group of mobile robots. In addition, also outdoor scenes will be considered which are often non-static. The user will be enabled to modify and extend the environmental models graphically in an interactive manner. The experiment designer utilises the environmental models and complements it with an appropriate experiment, which is roughly predefined and finally selected by a user. The detailed execution of an experiment will be done with state machines, where the user can define small experimental changes. The experiment designer will allow planning experiments with one or several robots, including interactions between robots. Another type of experiment is represented by the performance of closed loop experiments where e.g. camera pixel-based pulse-coded output is given to the visual cortex and then via the motor cortex such trains of pulses go out.

7.7.3 Component Progress

7.7.3.1 NRP - Experiment Library

This Component represents a library of experiment where researchers can access and upload experiment templates used in their experiments. It links to the NRP Environment model library.

Progress on Component:

The NRP proposes a new set of template experiments, including experiments with the Hollie arm and the Schunk hand from FZI, featuring force-based control, CPG control or even reinforcement learning. The mouse experiments have been improved, both graphically and from the robustness. We have added also a fully neuronal image recognition based experiment with a Husky robot that runs a 3000-neuron brain.

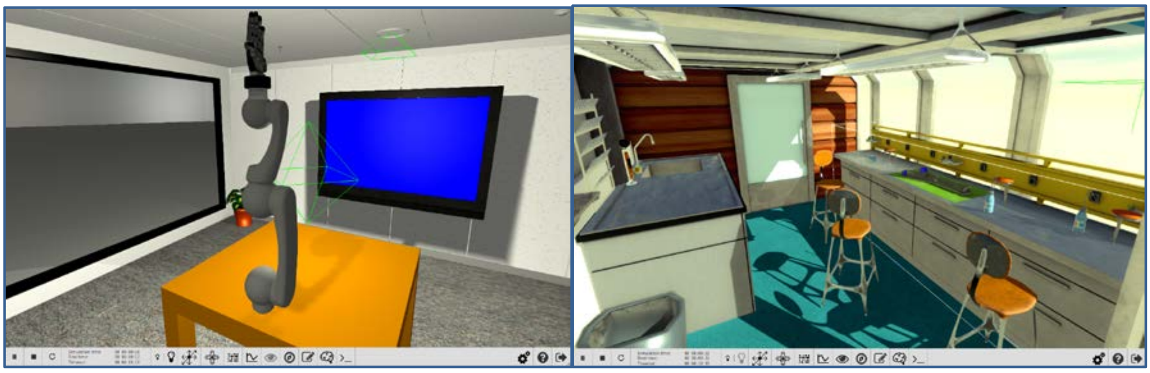


Figure 54: The new Hollie/Schunk hand with CPG control (left) and a new virtual biology lab environment (right)

Navvis was contracted to create measurements similar to Google street view. Their laser scans together with 3D images can be used to create 3D virtual objects and environments for our Platform. Together with our virtual robots of real robots such as Roboy, this would then allow us to have virtual equivalents to physically existing models. In the future, this can enable us to verify virtual experiments on physical robots to bridge the reality gap.

7.7.3.2 NRP - Experiment Designer

The experiment designer is tool embedded into the NRP cockpit. It utilises the environmental models and complements it with an appropriate experiment description, chosen roughly predefined from a library and finally selected by a user. The detailed execution of an experiment will be done with state machines, where the user can define small experimental changes. The experiment designer will allow planning experiments with one or several robots, including interactions between robots. Another type of experiment is represented by the performance of closed loop experiments where e.g. camera pixel-based pulse-coded output is given to the visual cortex and then via the motor cortex such trains of pulses go out.

Progress on Component:

No impressive improvement to report in this Component. It still uses SMACH as a script-based interface to the user. Graphical interface is scheduled for a later time.

7.7.3.3 NRP – Environment Designer

Tools in the Neurorobotics Cockpit to construct and to represent different environments. Reusable software Components (packages) which are helpful will be adapted from external resources. The involved environmental models do not describe only static environments but also dynamic scenes and outdoor scenes. The user will be enabled to modify and extend the environmental models graphically in an interactive manner.

Progress on Component:

On the Environment Designer, there has been little progress. Mainly stability, and the possibility now to resize added objects.

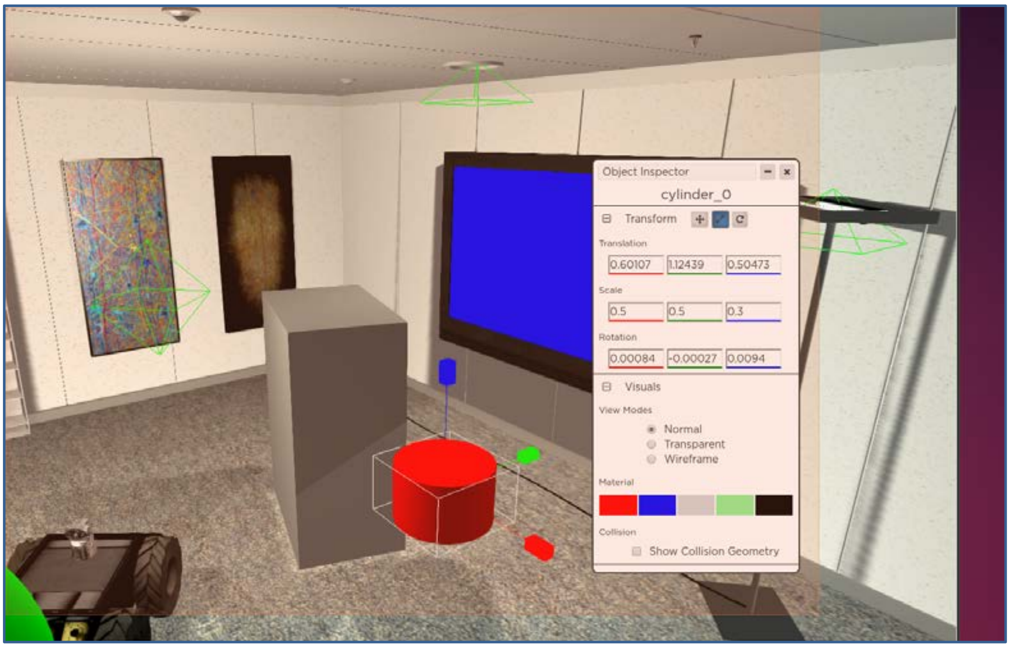


Figure 55: The Environment Designer enables to rescale simple objects

7.8 T10.5.5 Robot Designer

7.8.1 Key Personnel

Task Leader: Alois KNOLL (TUM)

7.8.2 SGA1 DoA Goals

Task develops the tools needed to construct robots from reusable parts and to import models from external resources.

Task Description:

The user will be enabled to modify and extend robot models graphically in an interactive manner. Available software packages will be used and imported from external resources. This designer considers the kinematic and dynamic restrictions of different types of robots (stationary or mobile, individual or multiple) together with basic muscular-skeletal models (e.g. from T10.3.2). The evaluation and validation of the different robot designer will be performed by benchmarks in the virtual world of NRP and partially with real, hard robots. The validation of soft robots (e.g. mouse) can only be done by simulation (see T10.5.1) where we can integrate the interplay of muscles (dynamics) e.g. for gripping and represent the corresponding skin deformations.

A full web robot designer is not realistically doable because of obvious web interfacing limitations. A Blender-based robot designer is moreover very interesting because it provides all the features from Blender that are commonly used by 3D designers. The NRP will still offer basic robot editing capability as part of the web robot library, as these will be useful to designers for quick tests and adjustments. The integration of our Blender-based robot designer in the Neurorobotics Platform is achieved with seamless import and export capability directly to/from the Collaboratory portal. This separation between a full standalone designer and light web versions has been defined in the SP10 roadmap document.

The input and the output of each brain model are analogue pulses. This sounds simple but the interpretation of the pulse code e.g. of a retina even for elementary features or even more for the recognition of human faces is till now not well known. Conversely the output of the motor cortex e.g. to move the hand is not exactly known. Therefore, we will collect all available software, e.g. from SP4 and SP6 to implement bidirectional interfaces which we also call transfer functions.

7.8.3 Component Progress

7.8.3.1 NRP – Robot Designer in the NRP Cockpit

The robot designer will be partially integrated into the web-based cockpit of the NRP. This version will not allow the user to create complex models from scratch. Rather, it allows adding sensors to an existing model of the robot library and minor modifications. Another aspect is the assembly of robots from predefined parts.

Progress on Component:

A web robot library has been added to the Web Cockpit to let the user choose a robot in an empty experiment. For now, no modifications to the robot are possible from the web user interface. This will be investigated later, possibly in SGA2, as it is possible to modify robots from the Standalone Robot Designer.

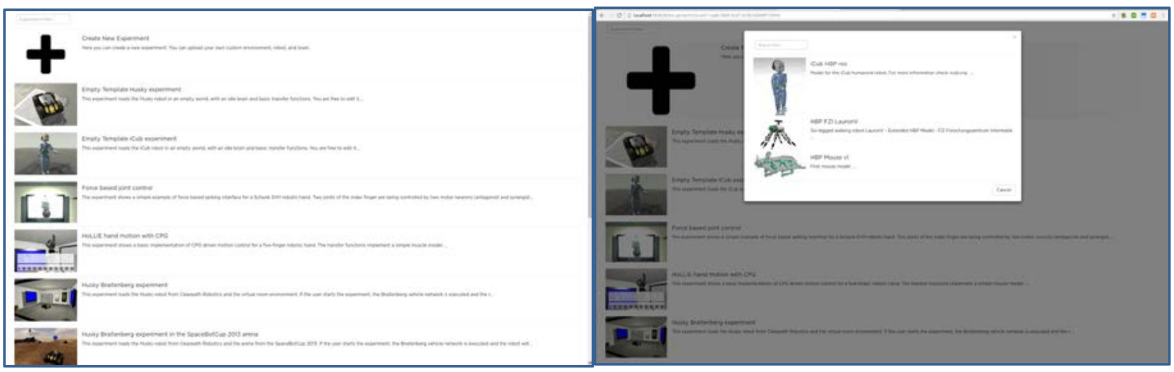


Figure 56: The new experiment (left) and robot library (right).

7.8.3.2 NRP - Standalone Robot Designer

Standalone version of the RobotDesigner realised as a Blender Plugin. This continues the effort of the RUP to design sophisticated complex robot models outside of the NRP.

Progress on Component:

The Standalone Robot Designer (Blender extension) has been added the support for SDF file format, the native Gazebo file format. Moreover, it can now export a whole robot, including meshes and materials to a self-contained zip file. This zip file, thanks to newly implemented Collab access can be uploaded to the private user's Collab storage. Later in SGA1, this robot will be available from the graphical robot library discussed in the section above.

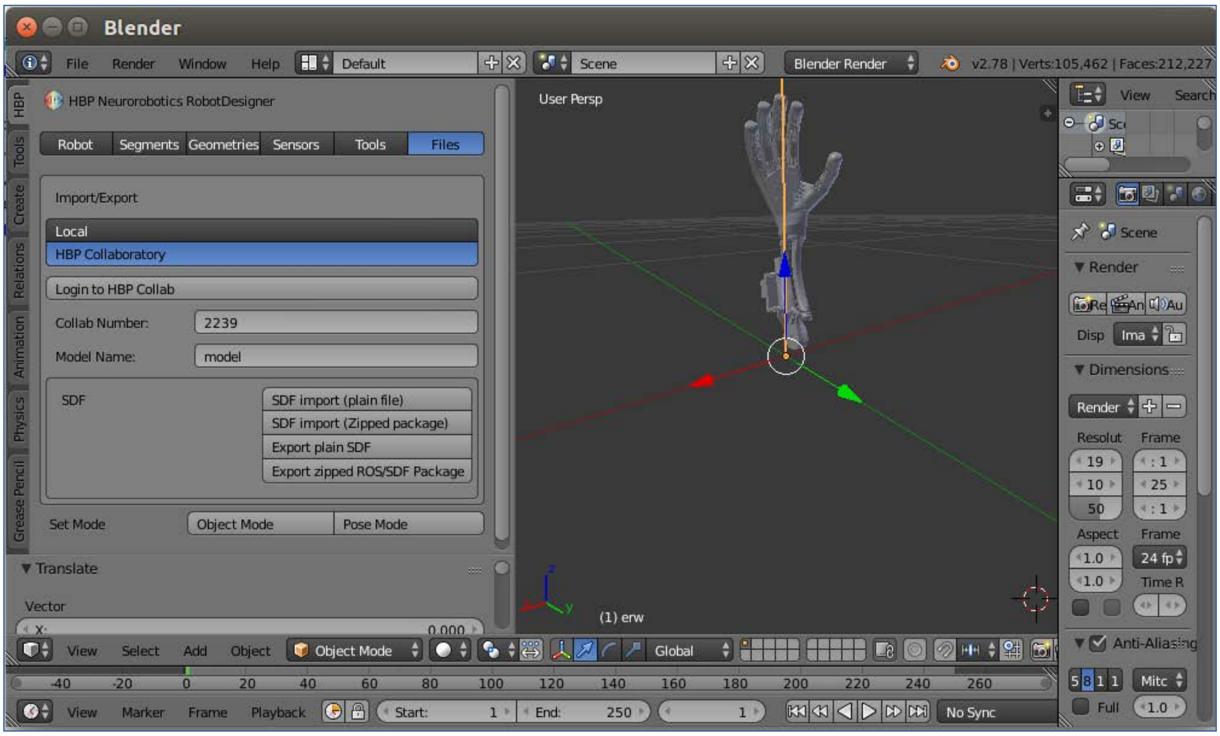


Figure 57: The robot designer plugin for Blender with export-to-Collaboratory. This plugin gives advanced users the full power of Blender to design highly complex robot models. These models can then be uploaded to a collab in the NRP.

7.9 T10.5.6 Brain-Body Integrator

7.9.1 *Key Personnel*

Task Leader: Cecilia LASCHI (SSSA)

7.9.2 *SGA1 DoA Goals*

The Brain Interface & Body Integrator enables the user to connect brain models to the robot sensors and actuators, providing the tools to specify a brain model within the SP6 Brain Simulation Platform and connect it with the robot sensors and actuators.

Task Description:

This feature is partially available inside the NRP. It will be extended and enhanced with a larger library of transfer functions (developed as part of WP10.1 and WP10.2) and a user-friendlier graphical interface.

7.9.3 Component Progress

7.9.3.1 NRP - Transfer Library

A library of Transfer Functions (TFs) mediating between brain models and robot actuators. It will include TFs elaborating on different sensor inputs, and driving a wide spectrum of robotic actuators. Third party libraries such as the COREM retina framework will be added in order to embed state of the art models within the platform. The user will be able to select TFs from the library and, possibly, adapt them to design custom neurorobotics experiments.

Progress on Component:

The Transfer Functions library has been extended with many transfer functions from the new experiments, including the retina, the DVS camera, the experiments with Hollie Arm and Schunk hand, the mouse experiments. The user now has a wide range of template transfer functions to get inspiration from.

7.9.3.2 NRP - Transfer Function UI

Web interface for editing Transfer Functions. In this Component, the interface will be enhanced so to provide the user with a better experience. The user will be able to pick and adapt transfer functions from a library in order to design interactively the behaviour featured in the experiment.

Progress on Component:

Not much progress on this, the main progress having been achieved on the backend side (see T10.5.2). The UI stays globally the same as in the RUP. A prototype graphical transfer functions builder is being added, but not yet finished.

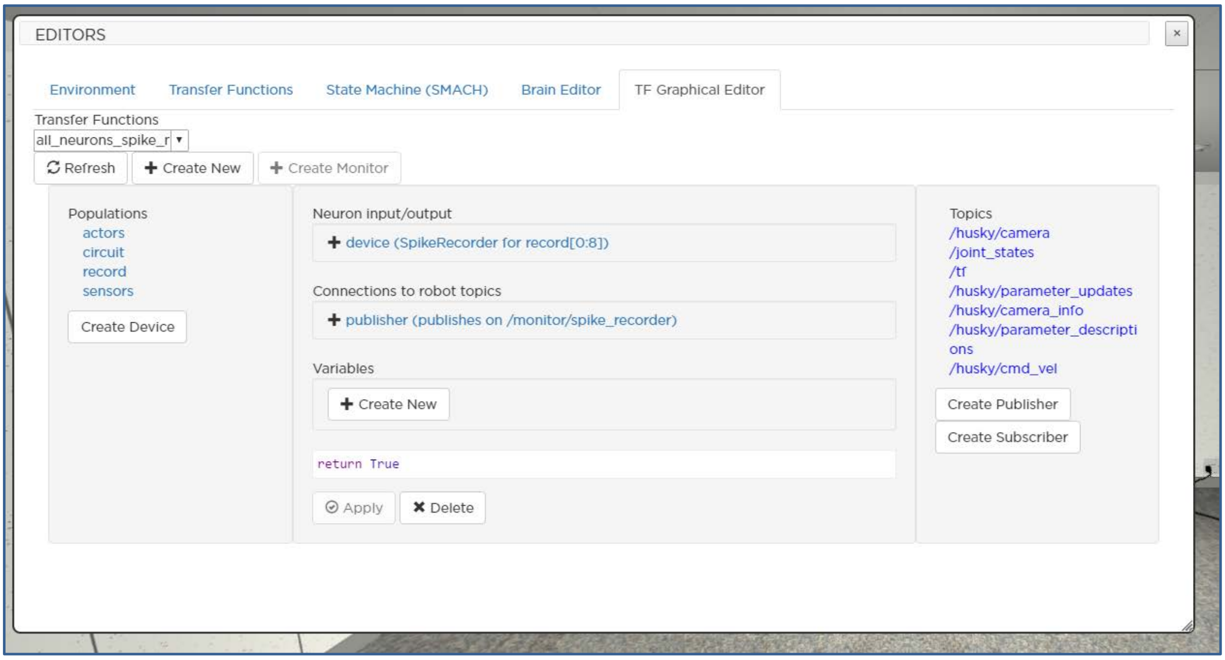


Figure 58: The prototype graphical transfer functions builder.

7.10 T10.5.7 Virtual Coach

7.10.1 Key Personnel

Task Leader: Alois KNOLL (TUM)

7.10.2 SGA1 DoA Goals

The aim of the Virtual Coach is to provide the NRP with the ability to run many sequential instances of evolutionary- or learning-based experiments in a fluid manner without requiring direct graphical user input and events. The events and interactions that impact the simulation can be generated by the user programmatically (reliably and in a repeatable manner). This is critical functionality for designing learning experiments based on repetition - e.g. learning neural connectivity weights that evolve over time from repeated exposure to certain stimulus with minor variations over many hundreds of trials. The Virtual Coach will therefore provide the users with the ability to easily implement such sequential experimental runs with transfer or reuse of parameters and brain models between them, and to compare different experiment results at the end.

Task Description:

Develop a software tool allowing researchers to define and execute multi-stage training protocols for robots (specification of timing, stimuli, correct and incorrect behaviours, and reward signals for each stage). These are necessary in the context of behavioural and reinforcement learning experiments.

7.10.3 Component Progress

7.10.3.1 NRP - Virtual Coach

T10.5.7 will work with SP10 and CDP5 to create a playground for researchers to design reinforcement learning experiments. It is tied to the main product of SP10, the NRP. Connecting to the Platform's backend will allow researchers to run experiments using the preferred brain and world simulators, while connecting to the frontend will allow the users to design and tune an experiment.

Progress on Component:

In M12 we release the first version of the Virtual Coach component. It is a Python-based NRP cockpit. It encapsulates in python the standard REST calls that the Web cockpit itself uses to manage an experiment. So, every feature available in the Web cockpit will be available in the virtual coach. In this release, it is possible to launch, start, pause, stop experiments in parallel, get logging data (spikes, joints), compare them in Jupyter Notebook. A showcase experiment features a reinforcement learning Husky robot in Jupyter Notebook Experiment editing will be implemented in the next release.

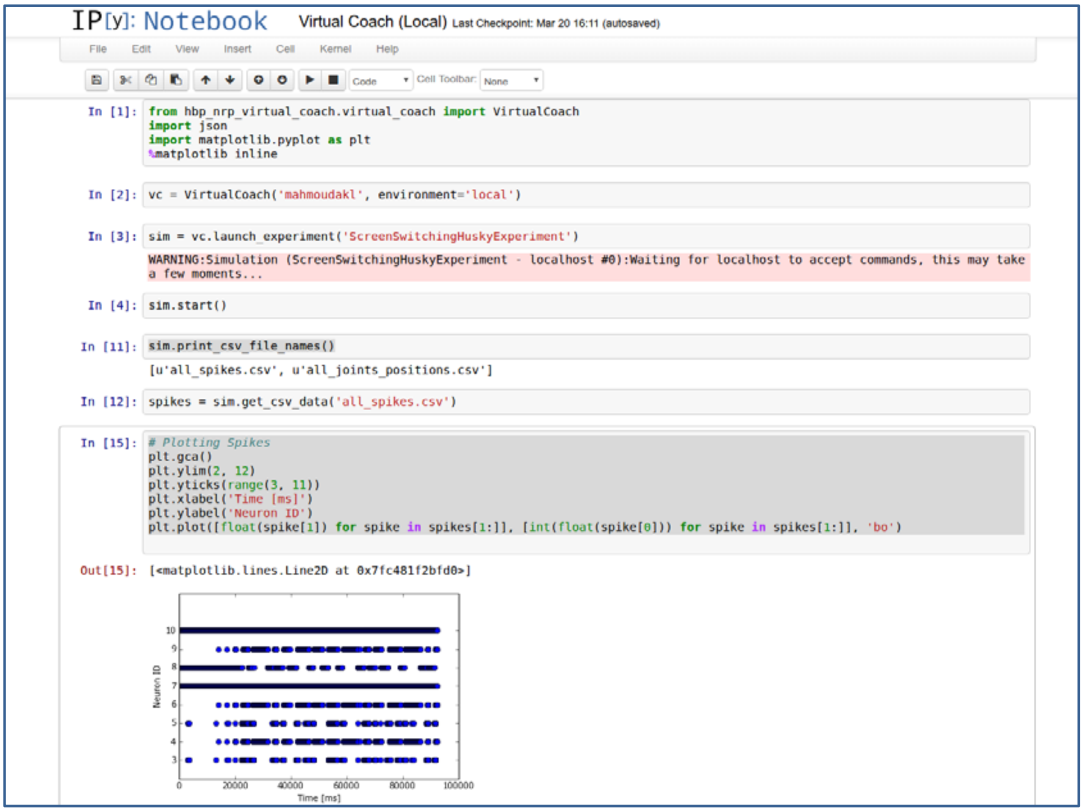


Figure 59: A simulation launched from Jupyter Notebook. Simulations can be started and controlled using the *Virtual Coach* module. This allows users to script many experiments in batch mode.

7.11 T10.5.8 Benchmarking and validation of physics and light simulation

7.11.1 Key Personnel

Task Leader: Olivier MICHEL (Cyberbotics, 3rd party to EPFL)

7.11.2 SGA1 DoA Goals

This Task will develop tools and progressive benchmarks to measure and improve the accuracy of physics simulations and rendering engines. It will also define quality scales to measure the progress of new versions of the physics and rendering engines.

Please refer to the description provided in Task 10.3.4 in this document (section 4.8) for a discussion on the purposes of the benchmarks, the relationship between HBP and Webots and the integration of the benchmarks in https://robotbenchmark.net.

The physics and the light models will be calibrated accurately to match the real physical behaviour. The physics calibration relies on the comparison between analytical models of physics behaviour and the numerical models resulting from the simulation physics engine. Based on this comparison, numerical models are improved to better match the analytical models. Several analytical models from the state-of-art literature will be used, related to rigid body dynamics, fluid dynamics, soft bodies, friction, etc. The light calibration involves the comparison between real world pictures and the images resulting from the 3D rendering of the simulation engine. Thanks to the recent progress in real time 3D rendering with powerful GPUs, OpenGL shaders, GPU computing, etc., significant progresses can be achieved in the accuracy of 3D rendered images for all current light models, e.g., directional lights, point lights and spot lights. They include shadows, light textures, ambient occlusion, focus, motion blur, anti-aliasing, etc. A series of benchmarks will be defined for both physics and light simulation with metrics based on standard error (SE) measurements involving both analytical models and real world pictures. The simulation models will be required to pass the benchmarks in order to be validated.

7.11.3 Component Progress

As a first stepping stone, tools and progressive benchmarks have been developed in Webots to measure and improve the accuracy of physics simulations and rendering engines. It will also define quality scales to measure the progress of new versions of the physics and rendering engines.

Progress on Component:

Webots is an excellent tool to generate benchmarking experiments and measurement tools, which will in a later step be ported to the NRP.

We had the idea of integrating Webots as an alternative World Simulation Engine in the NRP to be able to develop universal benchmarking tools. Furthermore, opening the NRP to various simulation backends could attract more users and provide more features. But this goal goes beyond the scope of SGA1 and was abandoned. It would have involved a high amount of work to modularly re-design in the NRP backend components to make them more generic and scalable.

Still, to come to these conclusions, we investigated different technologies:

- WebGL-based visualisation: the simulation data is streamed to the NRP Web Cockpit using the 3D data formats used in the NRP. The advantage of this solution is the fluid interaction with the scene.
- WebRTC visualisation: we created a web video streaming interface, based on Janus, gstreamer, and Webots, to investigate the possibility to stream the remote simulation 3D rendering computed on the server to the NRP Web Cockpit. The advantage of this solution is that, once implemented, it simplifies the integration of additional backends but the video streaming requires more bandwidth than WebGL-based streaming and it does not make use of the Web Cockpits advanced interactive features.

The decision to not include Webots and other backends in the NRP produced the need for a separate on-line infrastructure to develop a proof-of-concept suite of benchmarking tool. This suite of tools will be ported to the NRP so that users can test their robot models and controllers in a benchmark infrastructure against real experiments.

In addition to the 5 benchmarks developed in Task 10.3.4, we designed and implemented a vision-based benchmark: visual tracking with SONY Aibo ERS7. In this, the robot task is to detect a target object and follow it while it is moving in a cluttered environment based on the images recorded by the pan-tilt camera. During the execution the percentage of the frames in which the target object is correctly detected is measured.

Figure 60: Visual tracking benchmark (SONY Aibo robot ERS7)

The benchmarks are available at the web site (to be publicly available on 16 June). For each of these benchmarks, we provide a precise description of the task and of the measured metrics. The user can modify the robot controller program to test his own program and we provide instructions and system information to let him reproduce the benchmark in a real experiment. Additional users can log in on the benchmark infrastructure to store their benchmark performances and compare them with other users.

Figure 61: Edit robot control program to benchmark

These benchmarks not only evaluate the quality of the robot models but also evaluate the quality of physics and light simulation by checking that the resulting objects and robot appearance and behaviour are realistic. In fact, realistic robot behaviours and robot camera image processing are only achievable if the simulation of physics and light is precise and robust. The physics and light simulation used in these benchmarks has been calibrated and improved in last 20 years thanks to the Webots users' feedback and various calibration tests.

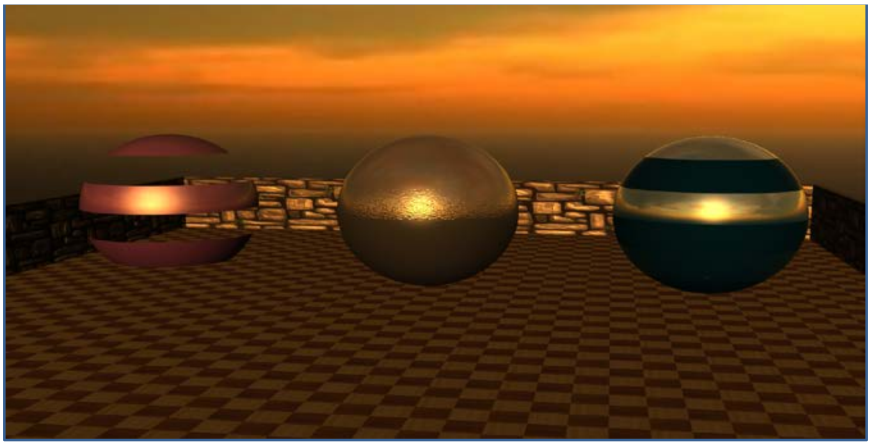


Figure 62: Examples of realistic rendering features to be benchmarked

But to further improve the light and rendering realism, we investigated and developed advanced OpenGL rendering techniques in the scope of the HBP: physically based rendering (PBR), multi-texturing, bump mapping, normal mapping, advanced lighting, additive texture soft shadows. These techniques produce realistic computer generated images to be used as benchmark reference to assess the accuracy of the simulation backends with respect to real images. In order to validate this approach, we developed rendering benchmarks allowing us to compare the images with analytical models and real world pictures. Also in this case, given that Webots is not integrated on the NRP, the new objective for SGA1 is to be able to compare the Webots benchmarks, calibrated against real images, with the results in the NRP Web Cockpit so that users can evaluate the quality and realism of the rendering and light simulation on the NRP.

One of the objectives would also be to benchmark the models developed within the HBP project. For this reason, we start working on the integration of a benchmark based on the musculoskeletal model of a rodent developed in Task 10.3.2 We choose this experiment because measurements on rodents are available and they can be used to compare the benchmark results with the real experiment results. Given that this experiment is also available on the NRP, it will be possible to the evaluate the physics simulation quality by comparing the behaviour resulting from applying the exact same controlling program in the benchmark and on the NRP.

Platform Development:

Provide an infrastructure with a set of initial benchmarks to evaluate the quality of the NRP simulation.

Platform Use Case:

Evaluate the quality of the simulation on the NRP against the real experiments by comparing the results of some pre-defined features in the NRP simulation with the results achieved on the calibrated benchmarks.

7.12 T10.5.9 Software integration, packaging and release

7.12.1 Key Personnel

Task Leader: Axel von Arnim (FORTISS)

7.12.2 SGA1 DoA Goals

This Task will ensure the coherent integration of all software parts, the packaging and release of the Platform to the end-users, using industry-level and widely spread tool chains.

Task Description:

Together with T10.6.1 and T10.6.2, it will provide a robust and standard release process that will guarantee the quality defined by the aforementioned Tasks. The software integration step will make sure that all software parts can communicate securely together, have loose dependencies one with the other and can be tested separately as well as together with integration tests. Packaging will make sure that the software will be available for deployment (T10.6.1) as autonomous packages in well-defined formats with support for versioning and automatic package generation. The release will follow a well-defined plan defining all steps and guaranteeing quality and transparency to the user. This will be achieved by connection with T10.6.3. The release frequency will follow an explicit roadmap and be high enough to ensure continuous user involvement.

7.12.3 Component Progress

7.12.3.1 NRP software packages

The NRP software packages comprise all the packages a user needs in to install and use the Neurorobotics tools on her/his computer or with her/his own infrastructure.

Progress on Component:

The major improvement in this Component has been the introduction of systematic integration testing in release 1.2 (M6-M12). Every git commit is integration tested manually before being merged, against systematic and deterministic test cases which are kept up-to-date with regards to the Platform's new features. The workflow is that all developers can peer review and individual commits, then they validate them for integration tests and finally validated commits are integration tested by a team of three testers who merge them in the end. If a commit does not pass integration tests, it is blocked until a fix is provided and integration tests are passed on the fix again. This process has brought impressive progress on stability of dev and production servers.

The release cycles, compared to the RUP, have been extended to 6 months, based on prior experience that shorter cycles block long-term and effort-demanding epics to be implemented.

Deployment is, as of M12, still following the former process: building of python/Javascript/RPM packages on Jenkins, installation on servers using puppet scripts, shared resources on GPFS mounts. Meanwhile, we have made great progress on Docker deployment. Users may now already download and install a complete Platform locally with Docker.

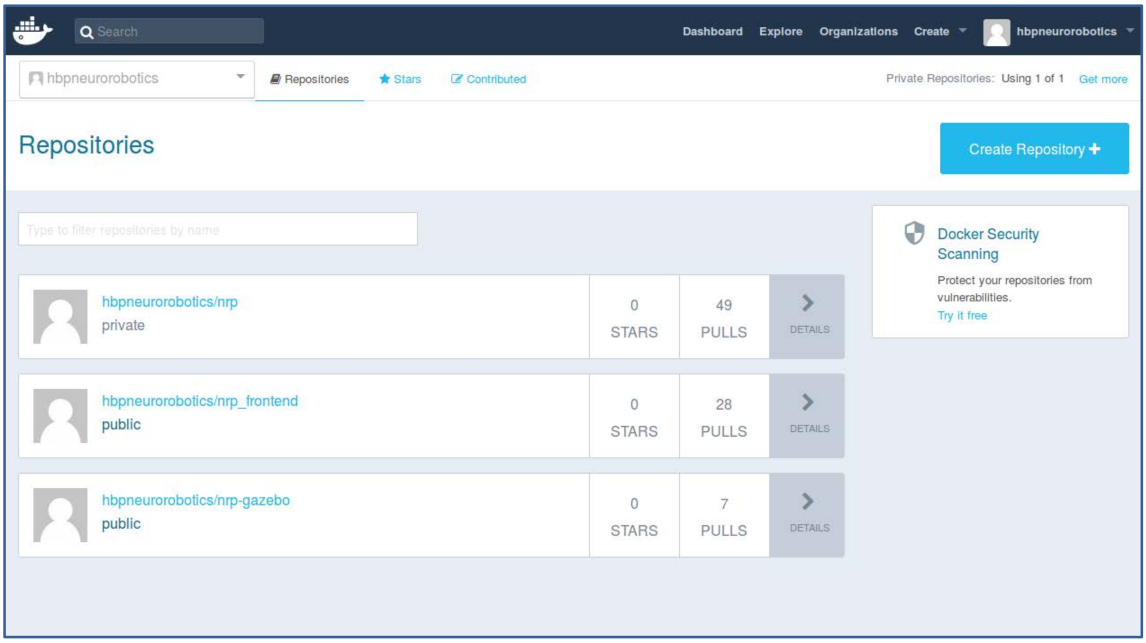


Figure 63: Our docker images on Dockerhub.com.

7.13 T10.5.10 WP Lead

7.13.1 Key Personnel

Task Leader: Axel von Arnim (FORTISS)

This Task involves no personnel costs; it is only budgeted with travel costs for the WP leader. For a report see WP Leader's Overview at the beginning of this chapter.

8. WP10.6 Neurorobotics Platform

8.1 Key Personnel

Work Package Leader: Alois KNOLL (TUM)

8.2 WP Leader's Overview

Stability and code quality have increased thanks to systematic end-to-end tests and bi-weekly deployment in development environment. This makes us very confident in our ability to timely deliver the version 1.2 of the NRP, planned for April 2017 (Month 43).

The installation process of the NRP on personal computers has been significantly simplified and thoroughly documented. It is now possible to efficiently guide users who need to change our code base in order to implement their custom *in silico* experiments. The deployment process in development environment has also been simplified with the help of Docker, a standard virtualisation tool. The deployment of our simulation services via Docker on CSCS Lugano test clusters (Kale and Greina) has been much slower than anticipated. Although we have maintained our effort on this Task, numerous security constraints made it more difficult than expected.

We also observed that server failure notifications are too verbose and too sensitive. They need to be adapted so as to extract more meaningful reports and allow quicker responses. The creation of Docker images for the whole platform and their successful use with different virtual machines and test clusters will allow the final migration to the Piz Daint cluster (CSCS, SP7).

This migration is essential in our strategy to enlarge backend resources so as to offer interactive simulations of large brains without user queue. The first user workshop held in January 2017 in Munich has revealed different ways scientists would need to access the NRP. It has also outlined the importance of specific features. Our roadmap has undergone important changes when integrating their feedback. In particular, we decided to accelerate development supporting larger brain models in simulations and batch simulations.

8.3 Priorities for the remainder of the phase

The priority for the remainder of this phase is the complete migration to Piz Daint cluster. This migration will enable us to handle most of our users' needs: permanent availability of servers and computational power for the simulation of larger models. The next steps are Greina and TDS benchmarks that we will carry on with our partners of SP7.

8.4 Milestones

Table 7: Milestones for WP10.6 - Neurorobotics Platform

MS No.	MS Name	Leader	Expected Month	Achieved Month	Comments
10.6.1	Implementation plan for WP10.6	TUM	M02	M06	This Milestone has been achieved with the submission of Deliverable 10.7.1

8.5 T10.6.1 Platform integration, deployment and operation

8.5.1 Key Personnel

Task Leader: Alois KNOLL (TUM)

8.5.2 SGA1 DoA Goals

The goal of this Task is to reliably deploy and operate the NRP in a stable production environment.

Task Description: This Task is responsible for operating the NR platform servers, installing/deploying the NRP software and operating the Platform. It will plan, provision and maintain the NRP servers, plan storage and compute capacity based on the projected user numbers. It will also provide services such as user registration, sign-in and fine grained access right management.

8.5.3 Component Progress

8.5.3.1 NRP – integration, deployment and operation

Maintenance of the NR platform servers, installation/deployment of the NRP software and operation of the platform.

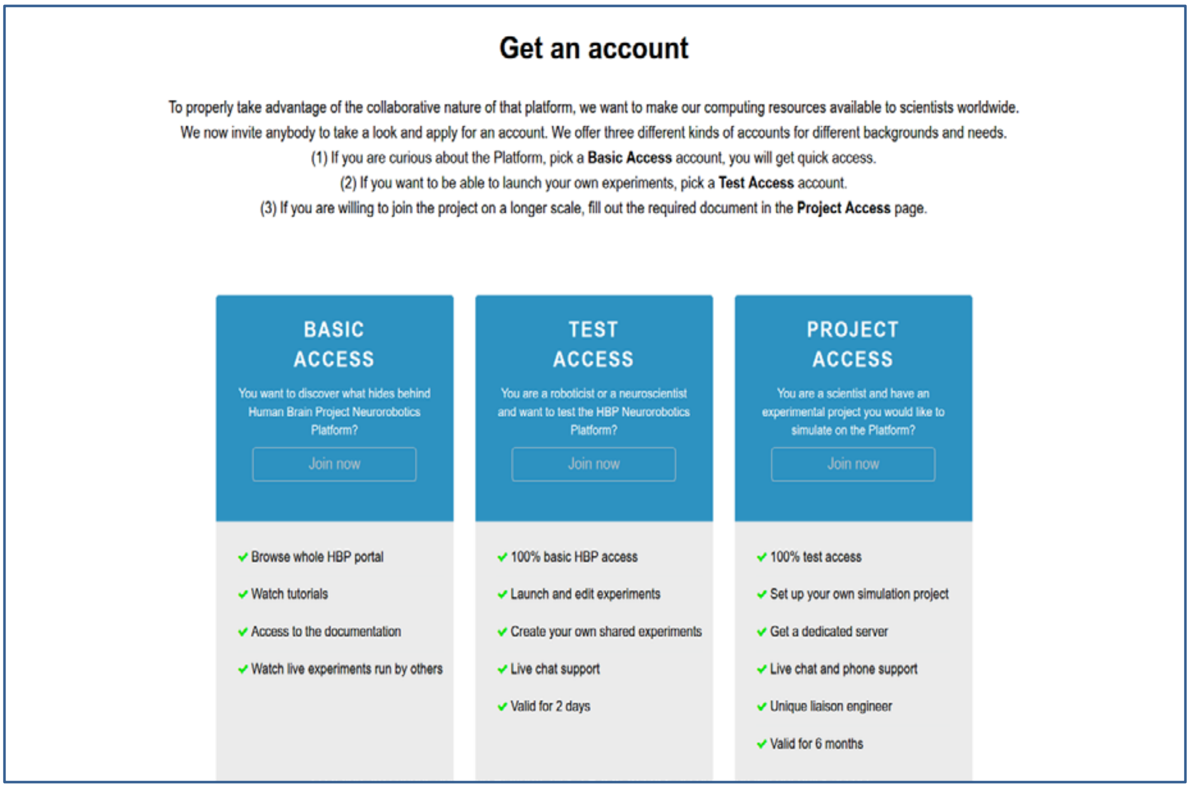


Figure 64: Account policy available in HBP Collaboratory

8.5.4 Progress on Component:

Significant development effort has been made to generate portable installations of the platform that can be deployed to different supercomputing cluster backends using the standard "Docker" virtualisation tool. This will enable Platform deployment on significantly larger supercomputing clusters with security restrictions that currently prevent the Platform from being deployed natively without Docker virtualisation. Several proofs of concept of Docker deployments have been tested successfully and efforts are being coordinated to deploy to different clusters.

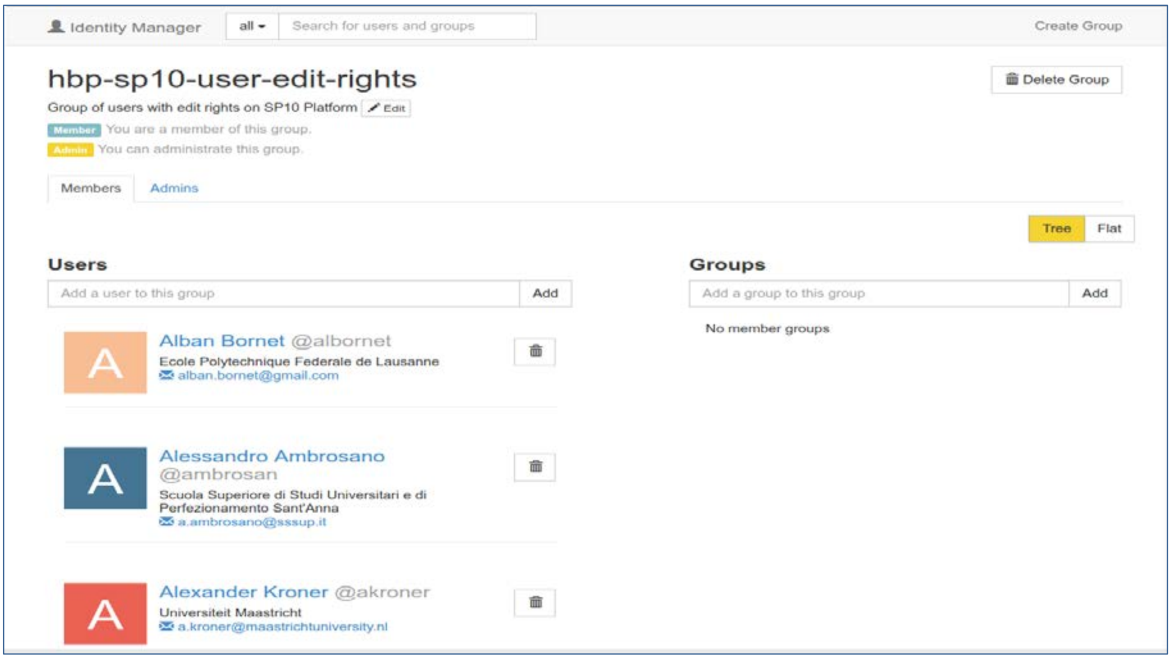


Figure 65: Collaboratory Platform user rights

In addition, progress has been made towards the development of standalone Docker images to explore the capability of a local installation for users working with Linux, Windows, and MacOS. Ready-made Docker images will greatly simplify the installation and configuration process for users running experiments on their own computers.

User access to the platform is maintained through close integration with the HBP developed Collaboratory services and provides granular levels of access to platform resources depending on validated user requirements, see Figure 64 and Figure 65.

8.6 T10.6.2 Platform testing, profiling and quality assurance

8.6.1 Key Personnel

Task Leader: Mark-Oliver GEWALTIG (EPFL)

8.6.2 SGA1 DoA Goals

This Task ensures that the NRP delivers reliable and responsive software while offering an optimal user experience.

Task Description: This Task monitors the NRP infrastructure. It measures key performances statistics such as uptime and utilisation of the NRP servers (CPU and memory) as well as of the network. The performance statistics will be used to improve the NRP Software and to determine the requirements and capacity for the next generation infrastructure. The Task will provide user analytics to improve usability of the NRP Software.

8.6.3 Progress

The CPU usages of both frontend and backend were profiled with a view to increase responsiveness in interactive simulations.

In the frontend, this has driven a refactoring of our rendering routines. As a result, 3D navigation is now smooth on any supported browser.

In the backend, the allocated CPU power was proved to be insufficient to address our needs when using multiple processes to run the brain simulation. This leads to a gradual resize of the virtual machines hosting our services.

staging-cleserver-15	2	20GB	2GB	8 months
staging-cleserver-9	2	20GB	2GB	7 months, 3 weeks
staging-cleserver-16	2	20GB	2GB	7 months, 2 weeks
staging-cleserver-8	4	20GB	4GB	3 months, 1 week

Figure 66: Gradual increase of computational power from 2VCPU to 4VCPU for staging

Inspection of the numerous requests made by our proxy server led us to enable partial multi-threading of our REST services. As a result, no timeouts occur anymore when launching *in silico* experiments from the NRP.

We also profiled our usage of the HBP Collab storage with a view to speed up operations on files. A first enhancement was achieved by refactoring backend code responsible for downloading and uploading. Further speedup is expected with the new Collab storage version, which is currently under test.

In order to debug and to check the efficiency of the code written by users in the frontend code editors (brain model, transfer functions and state machines), we introduced a web console, see Figure 67. This web console is now widely used by developers when testing new features or new experiment templates which will be provided to users.

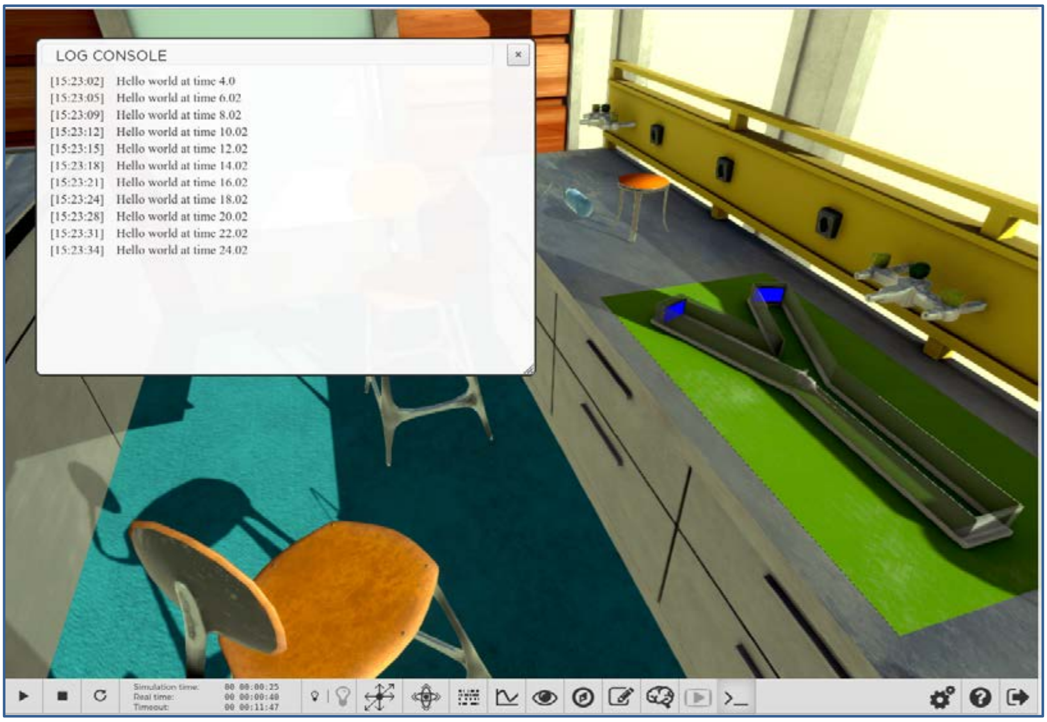


Figure 67: Web-console for live debugging of user code

As usual, Neurorobotics platform logs, errors and request status are reported in online dashboards (Kibana boards on Figures 3, 4, and 5, Icinga board on Figure 6) which help fix problems arising after every new deployment.

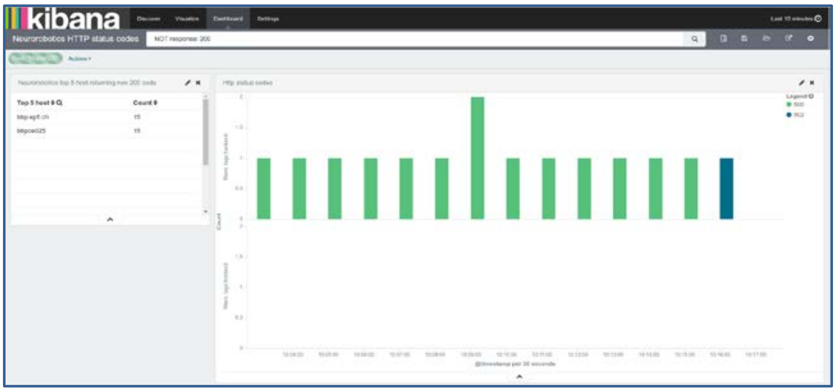


Figure 68: Status board: one machine out of 20 responds with status 500

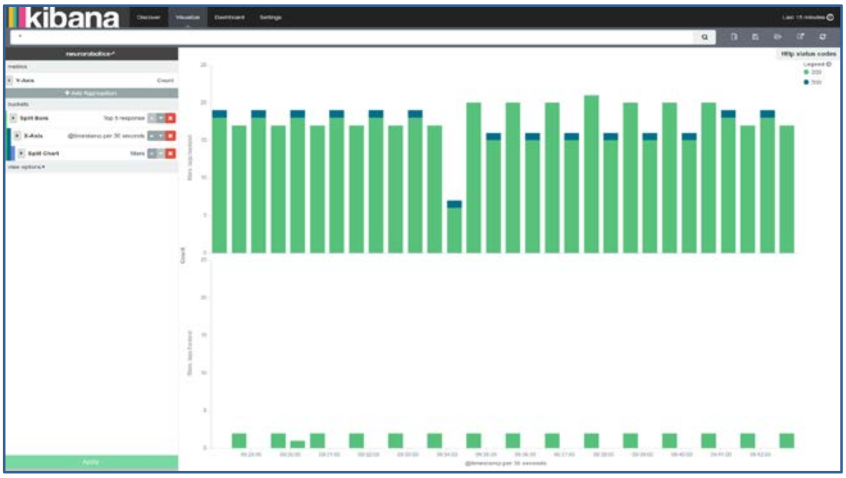


Figure 69: Status board: probes on the faulty machine

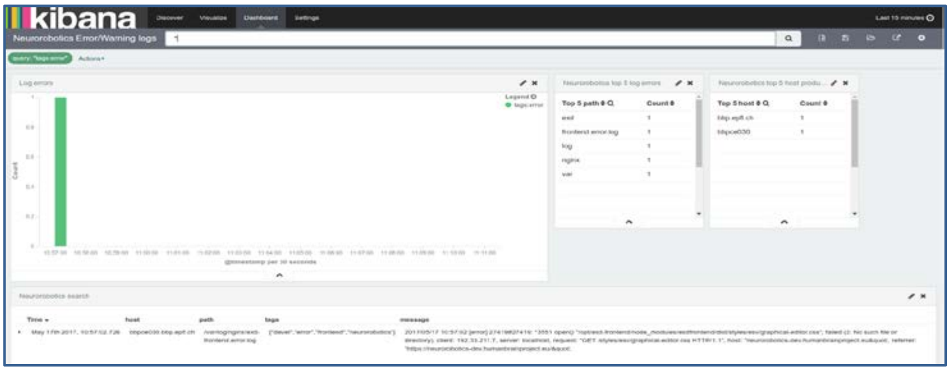


Figure 70: Error logs

Figure 71: Error logs: missing css file detected on the frontend server in development environment

We also carry on monitoring user activity thanks to Google Analytics dashboards.

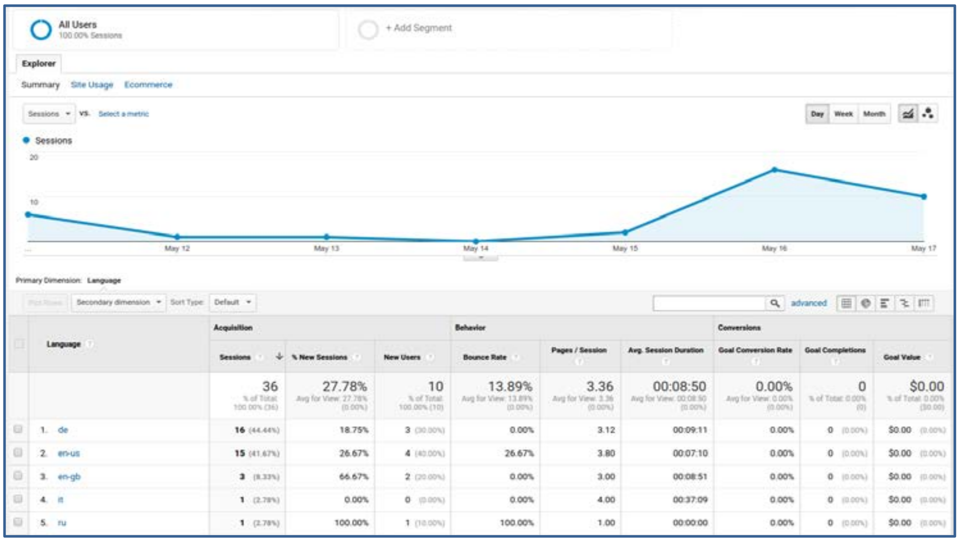


Figure 72: Daily visits and provenances

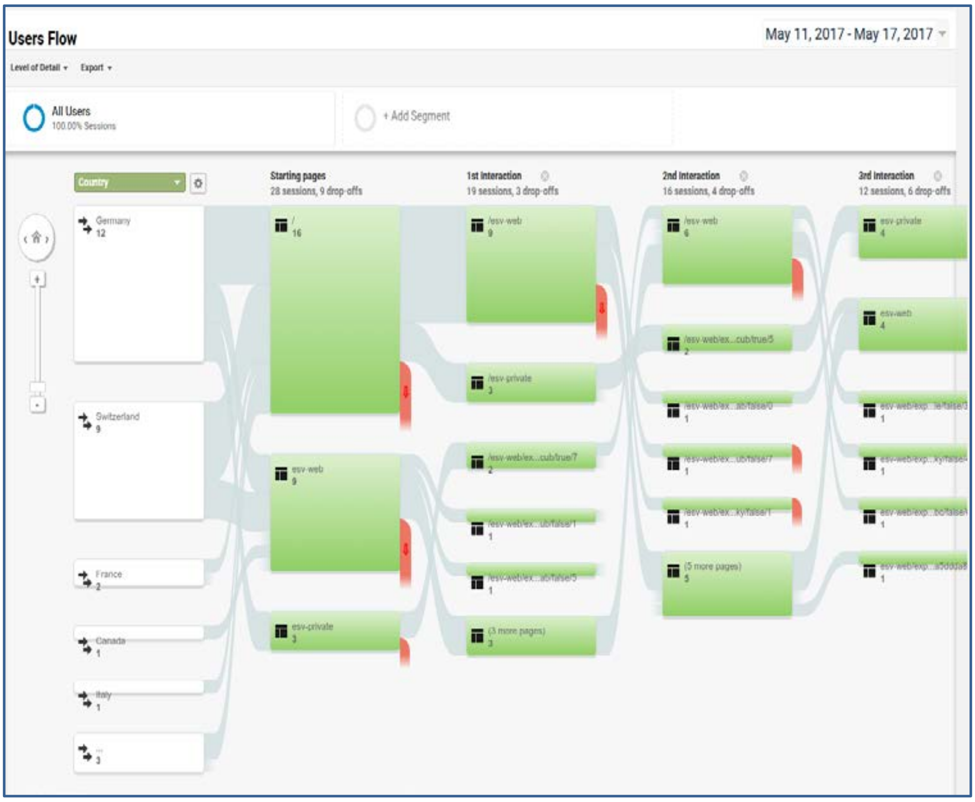


Figure 73: Users flow

Since the beginning of the project, the quality of the NRP code is enforced via different continuous integration tools. The latest Jenkins report shows for instance that 91% of the source code is covered by unit tests (see Figure 74).

Code Coverages(Cobertura)

Job ↓	Packages	Files	Classes	Methods	Lines	Conditionals
neurorobotics.BrainSimulation #71	100%	100%	100%	N/A	86%	100%
neurorobotics.BrainSimulation.gerrit #95	100%	100%	100%	N/A	86%	100%
neurorobotics.brainvisualizer #21	100%	100%	100%	98%	98%	86%
neurorobotics.brainvisualizer.gerrit #29	100%	100%	100%	98%	98%	86%
neurorobotics.CLE #756	100%	100%	100%	N/A	87%	100%
neurorobotics.CLE.gerrit #1616	100%	100%	100%	N/A	86%	100%
neurorobotics.CLE.PyNN.0.8 #25	100%	100%	100%	N/A	87%	100%
neurorobotics.ExDBackend #859	100%	100%	100%	N/A	90%	100%
neurorobotics.ExDBackend.gerrit #2151	100%	100%	100%	N/A	90%	100%
neurorobotics.ExDFrontend #1177	100%	100%	100%	93%	95%	81%
neurorobotics.ExDFrontend.gerrit #3634	100%	100%	100%	93%	95%	81%
neurorobotics.ExperimentControl #97	100%	100%	100%	N/A	92%	100%
neurorobotics.ExperimentControl.gerrit #119	100%	100%	100%	N/A	92%	100%
neurorobotics.nestify #46	100%	100%	100%	N/A	90%	100%
neurorobotics.nrpBackendProxy #42	100%	100%	100%	96%	95%	88%
neurorobotics.nrpBackendProxy.gerrit #115	100%	100%	100%	96%	95%	88%
neurorobotics.SlurmClusterMonitor #43	100%	100%	100%	100%	95%	100%
neurorobotics.SlurmClusterMonitor.gerrit #34	100%	100%	100%	100%	95%	100%
neurorobotics.VirtualCoach #18	100%	100%	100%	N/A	98%	100%
neurorobotics.VirtualCoach.gerrit #27	100%	100%	100%	N/A	98%	100%
neurorobotics.WSLib.gerrit #4	100%	100%	100%	100%	100%	100%
Total:	100%	100%	100%	94%	91%	82%

Figure 74: Code coverage of Neurorobotics projects

8.7 T10.6.3 Documentation, user support and user training

8.7.1 Key Personnel

Task Leader: Alois Knoll (TUM)

8.7.2 SGA1 DoA Goals

The goal of this Task is to provide comprehensive end user documentation, support, and training.

Task Description: This task develops comprehensive the user level documentation for the NRP and its software. It supports users by answering user questions and providing community forums and mailing lists, and it trains users through workshops and educational online material, such as webinars.

8.7.3 Progress

User documentation at various technical levels is continuously developed and released at each major technical milestone (see Figure 75). Additional documentation has been produced: it details the development of the design, structure, and implementation of new experiments for end users. Moving forward, this documentation will enable end users to effectively utilise the platform without developer support.

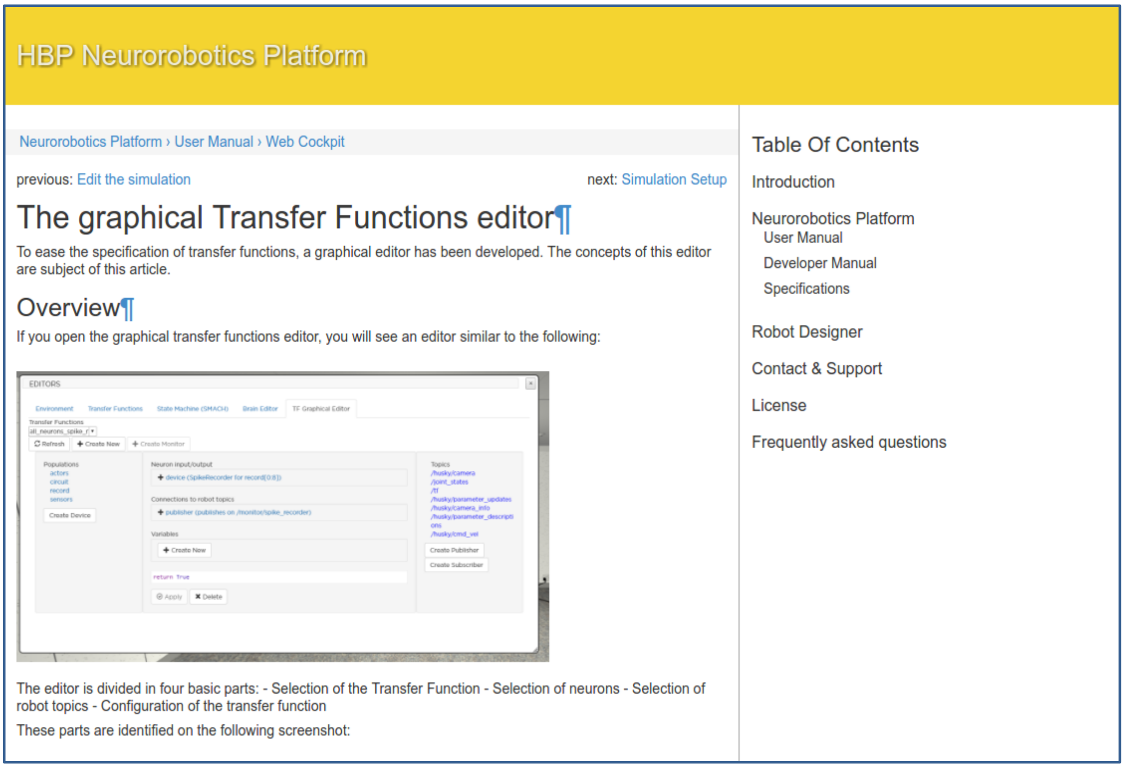


Figure 75: Online documentation of the latest NRP features in the HBP Collab

Ongoing user support has been established and provided through the HBP forum (https://forum.humanbrainproject.eu/) and direct developer contact for a number of users developing their own experiments using the Platform. This has resulted in valuable user interaction and has driven various aspects of the platform requirements/refinement.

The first NRP User Workshop was held in January 2017 and brought together potential users from within the HBP neuroscience and robotics communities with Platform developers for several days of interactive presentations and discussions. Platform developers actively solicited and collected user feedback and requirements that have been integrated into the platform development roadmap.

For user engagement and dissemination, SP10 has organised a number of user workshops in 2017 that have resulted in 6 integrated pilot experiments. We follow the process described in the SGA1 road map document: a selected set of researchers are invited at a given user workshop, each is assigned a Liaison Engineer who will help them during the workshop and after to set up their experiment. They also write together a detailed documentation for others to be able to run it. On Platform release, a video clip will be released demonstrating the new experiment. Hereunder is a list of these user workshops so far.

Table 8: Overview of NRP User workshops between January and July 2017

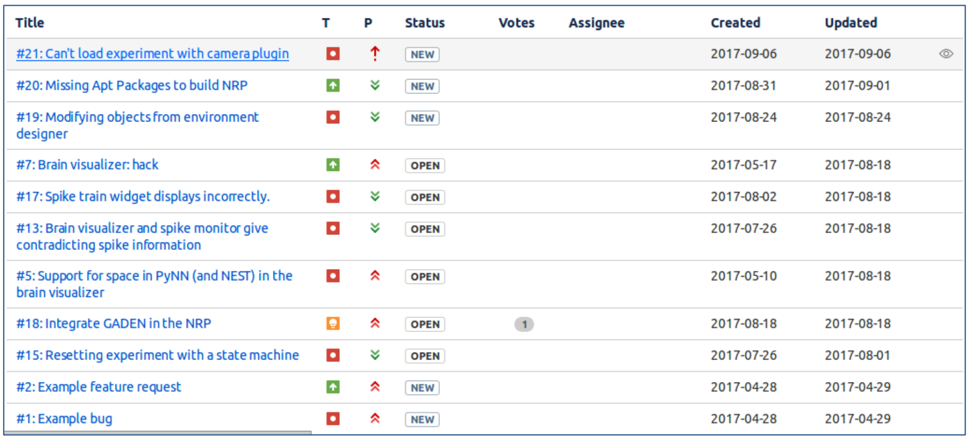
User workshops	Experiments integrated in the NRP	Scientist (experiment Mentor)	Liaison Engineer
User Workshop, January 2017, TUM	Introductory workshop, no hands-on session		
User Workshop, January 2017, FZI	Visual segmentation Visual Saliency detection	Alban Bornet (EPFL) Alexander Kroner (SP4)	Jacques Kaiser (FZI) Jacques Kaiser (FZI)
"Install Party", April 2017, FORTISS	iCub neural ball balancing (https://bbpteam.epfl.ch/project/spaces/display/HSP10 /Ismael%27s+iCub+ball+balancing+experiment) DVS tracking (https://bbpteam.epfl.ch/project/spaces/display/HSP10 /Jacques%27+DVS+tracking+experiment) Visual segmentation (https://bbpteam.epfl.ch/project/spaces/display/HSP10 /Alban%27s+Visual+Segmentation+Experiment) Mouse locomotion (https://bbpteam.epfl.ch/project/spaces/display/HSP10/ Shravan-Emanuele%27s+locomotion+experiment)	Silvia Tolu (DTU) Jacques Kaiser (FZI) Alban Bornet (EPFL) Shravan Tata (EPFL)	Ugo Albanese (SSSA) Luc Guyot (EPFL) Luc Guyot (EPFL) Emmanouil Angelidis (FORTISS)
User Workshop, July 2017, FZI	Tigrillo gait (https://bbpteam.epfl.ch/project/spaces/display/HSP10 /Alexander%27s+-+Gabriel%27s+Tigrillo+gait+experiment) Braitenberg Miro (https://bbpteam.epfl.ch/project/spaces/display/HSP10	Gabriel Urbain (UGENT) Martin Pearson (SP3)	Emmanouil Angelidis (FORTISS) Susie Murphy (EPFL)

	/Braitenberg+MiRo+experiment)		

Contact with users is also established through our website http://neurorobotics.net which points to a registration form. The SP10 group is informed of account requests by emails.

Our community Manager, Susie Murphy, receives on average 20 requests per month for a basic account (documentation and demos) and 3 requests per month for a test account (fully featured for 3 weeks of trial).

Moreover, starting on M12, the Platform has been available for free download from Bitbucket (https://bitbucket.org/hbpneurorobotics/neurorobotics-platform). New users are getting access to the Platform by this means every month. The Bitbucket bug tracker and our active forum (https://forum.humanbrainproject.eu/c/neurorobotics) are proof of this (Figure 76 and Figure 77).



Title	T	P	Status	Votes	Assignee	Created	Updated
#21: Can't load experiment with camera plugin			NEW			2017-09-06	2017-09-06
#20: Missing Apt Packages to build NRP			NEW			2017-08-31	2017-09-01
#19: Modifying objects from environment designer			NEW			2017-08-24	2017-08-24
#7: Brain visualizer: hack			OPEN			2017-05-17	2017-08-18
#17: Spike train widget displays incorrectly.			OPEN			2017-08-02	2017-08-18
#13: Brain visualizer and spike monitor give contradicting spike information			OPEN			2017-07-26	2017-08-18
#5: Support for space in PyNN (and NEST) in the brain visualizer			OPEN			2017-05-10	2017-08-18
#18: Integrate GADEN in the NRP			OPEN	1		2017-08-18	2017-08-18
#15: Resetting experiment with a state machine			OPEN			2017-07-26	2017-08-01
#2: Example feature request			NEW			2017-04-28	2017-04-29
#1: Example bug			NEW			2017-04-28	2017-04-29

Figure 76: Our Bitbucket issue tracker

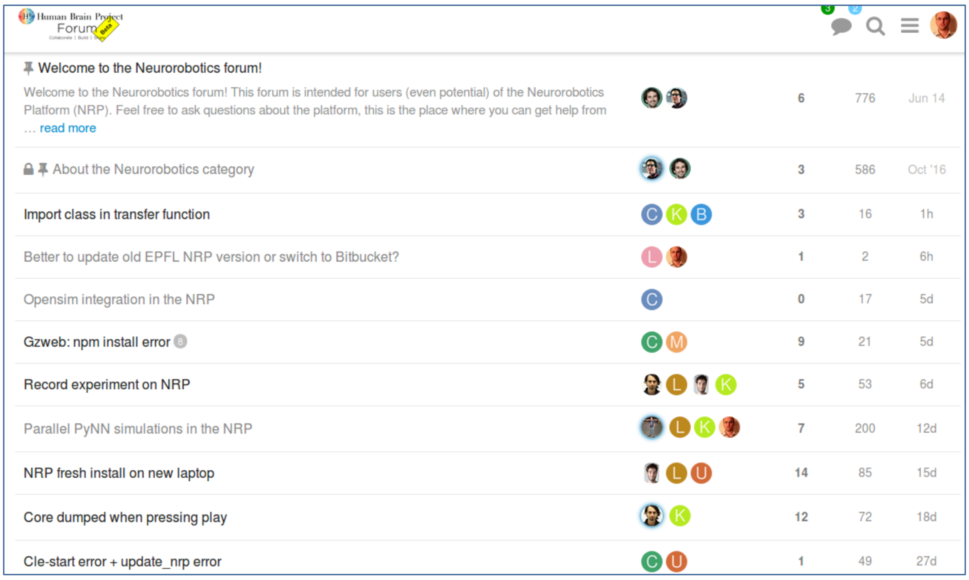


Figure 77: NRP user forum

8.8 T10.6.4 WP Lead

8.8.1 Key Personnel

Task Leader: Alois Knoll (TUM)

This Task involves no personnel costs; it is only budgeted with travel costs for the WP Leader. For a report see WP Leader's Overview at the beginning of this chapter.

9. WP10.7 Scientific Coordination and Community Outreach

9.1 Key Personnel

Work Package Leader: Florian Röhrbein (TUM)

9.2 WP Leader's Overview

The SP10 has become a highly visible part of the HBP in the scientific community. This was achieved by numerous activities in the organisation of events, presentations but also meetings across SPs. The lead to a very high load of business trips for the SP10 leader and the SP10 manager but also countless videoconferences. Noteworthy are also the strong ties to Japanese research groups that have been established during SGA1. Also, community engagement has been intensified. Innovation and Technology Transfer is on a good track. All reports including semester reports and periodic reports have been submitted in time. The SGA2 draft proposal has been submitted.

9.3 Milestones

Table 9: Milestones for WP10.7 - Scientific Coordination and Community Outreach

MS No.	MS Name	Leader	Expected Month	Achieved Month	Comments
10.7.1	SP10 strategy report on ethics, innovation, and community engagement	TUM	M05	M06	This Milestone has been achieved with the submission of Deliverable 10.7.1 "Release Plan for the NRP for SGA1 and Project Implementation Proposal" and the contributions to the SP12 document "Ethical Advisory Board & Rapporteurs: Identified SP Ethical Issues" (see EMDESK document manager). For the innovation aspect, we successfully identified a suitable candidate that will be employed by TUM in February 2017.
10.7.2	First NRP user workshop	TUM	M12	M12	The first NRP user workshop was held 11/12.1.2017 in Munich, for details see www.neurorobotics.net

9.4 T10.7.1 Subproject Leader (a)

9.4.1 Key Personnel

Task Leader: Alois Knoll (TUM)

This Task involves no personnel costs; it is only budgeted with travel costs for the SP Leader. For a report see SP Leader's Overview at the beginning of this document.

9.5 T10.7.2 Subproject Leader (b)

9.5.1 Key Personnel

Task Leader: Marc-Oliver Gewaltig (EPFL)

This Task involves no personnel costs; it is only budgeted with travel costs for the SP Leader. For a report see SP Leader's Overview at the beginning of this document.

9.6 T10.7.3 Scientific coordination and WP lead

9.6.1 Key Personnel

Task Leader: Florian Röhrbein (TUM)

9.6.2 SGA1 DoA Goals

This Task will coordinate subproject reporting and writing of Deliverables; monitor scientific progress within the subproject, organise SP-wide meetings, organise one BoD meeting, co-ordinate with the External Relations Team on issues related to innovation, coordinate with the Ethics Manager and with SP12 on issues related to ethics, provide support to partners on issues related to administration, innovation and ethics, act as a point of contact with the HBP Administration. Additional funds (other goods and services) are reserved to organise meetings such as SP meetings and SIB meetings.

9.6.3 Progress

Many meetings on various levels have been organised, from daily "stand-up meetings", weekly site-specific events, inter-WP and cross-SP meetings, up to SP10's quarterly Neurorobotics Performance Shows. These are 2-day meetings with all members of SP10 as well as guests from other SPs and took place during the reporting period in Geneva (SGA1 kick-off, June 2016), Pisa (October 2016) and Munich (January 2017). Members of SP10 participated also in other SP's meetings, e.g. the SP3 meeting in Amsterdam (October 2016), the SP9 meeting in Dresden (March 2017), various events organised by SP4 at EITN, management meetings with SP11 and meetings of ethic rapporteurs (SP12). We contributed to the goals of the cross-SP Data Governance Working Group with regular meetings, participated in almost all Community Coordinator videoconferences as well as Science Coordinator videoconferences. Further highlights include

- A "Lecture Series in Neurorobotics" was started at TUM with speakers from SP2 and SP4 but also leading scientists from Canada, USA, Japan and Australia.
- Many Neurorobotics Presentations were given across Europe, but also in Chile, USA, China, Japan, South Korea and Singapore.
- Presentations were also given to the general public at the occasion of open days or the world-wide "Pint of Science" event.
- The 2nd European-Japanese Workshop in Neurorobotics was held in Tokyo and the 3rd edition has been prepared to take place in Geneva in June 2017.
- SP10 organised workshops have been accepted for ICRA (Daejon, South Korea), the Bernstein BCCN conference (Berlin), the European Robotics Forum (Edinburgh) and for BioRob Conference (Singapore).
- Physical robots were presented at the STOA event in Brussels, the Open Day in Florence and at local events

9.7 T10.7.4 Dissemination and community engagement

9.7.1 Key Personnel

Task Leader: Marc-Oliver GEWALTIG (EPFL)

9.7.2 SGA1 DoA Goals

The goal is to make our subproject and its progress public, to advertise our platform so we can get new users and possibly new partners.

Description:

Task 10.7.4 will be responsible for supporting community activities elsewhere in the SP. This will include organisation of community workshops, acting as a point of contact between the

SP and community users, and communications towards participating communities. The Task operates and maintains the SP10 web sites and develops brochures and info material.

9.7.3 Progress

A completely new website was developed at http://neurorobotics.net that relies on multiple Wordpress blogs to create and update dynamic content. The first Wordpress account allows for content management that can be distributed among the entire SP, which then eliminates any bottlenecks of having only one developer that has to upload every single change. This leads to a dynamic website that is still easy to maintain.

The second Wordpress account is used as a scientific/research blog. Every scientist from SP10 can post their scientific progress there to show to the world what they achieved and to document the progress in an easily readable manner.

To see just how big the difference to the old version is, it can be reviewed and compared at http://neurorobotics.net/old/.

All the social media accounts (Twitter, Facebook, YouTube) have been assigned to people to assure regular updates so we keep our public presentation up to date and relevant. Furthermore, the Twitter account is linked to our research blog on Wordpress so that every blog post will automatically create a tweet announcing that post. Along with these changes, people are encouraged to create videos to visually illustrate our progress.

9.8 T10.7.5 Innovation and Technology Transfer

9.8.1 Key Personnel

Task Leader: Alexander KUHN (TUM)

Other Researcher: Evgeny KALECHITS

9.8.2 SGA1 DoA Goals

The Task will be devoted to assessing economic potential of innovation opportunities and intellectual property available at / expected to result from SP10, developing commercialisation and technology transfer strategies for select options, identifying and structuring specific business and technology transfer initiatives and projects, assessing institutional environment for technology transfer and establishing industry and partner contacts required for technology transfer.

Description:

This Task will be responsible for technical coordination within the subproject and for coordination with other SPs. It will involve: coordination of platform testing, standardisation of data formats, terminology and development processes; coordination of documentation and dissemination of standards; coordination of software development; coordinate of user engagement; representation of SP10 on the SP Technical Coordinators Committee. The second half of the Task is devoted to identifying innovation opportunities with the SP, establishing industry and partner contacts and to encourage partner projects around SP10 innovation.

9.8.3 Progress

For the first part of this Task several actions were taken:

- Coordination with SP7 and SP9 towards the development and integration of NEST (neural simulator), PyNN (neural simulator interface), MUSIC (neural simulator interface), and other standard tools to be used across the HBP
- Active participation with the NEST user community in the form of user and developer workshops

- Report was developed in which the current state of the NRP is investigated. Missing steps towards a fully functional and standardised brain model integration workflow in the NRP have been identified
- Planned future cross-SP user workshop coordination events to introduce users to standard toolsets and derive user requirements and use cases in more detail

For the second half of this Task a new work stream was launched as part of SP10 on 1 March 2017 to explore options for innovation and technology transfer within the Neurorobotics domain of the HBP. Actions completed within the work stream to date:

- A dedicated team member hired to work on the innovation and technology transfer sides of SP10
- A short-term work plan (immediate first steps) developed with an aim to launch the process of identifying existing and prospective technology transfer options within SP10
- A preliminary screening of immediately observable technology transfer options within SP10 conducted, resulting in the selection of Agricultural robotics and Autonomous driving as the first two options to explore in the near term
- A kick-off meeting / workshop on technology transfer and innovation conducted with the core SP 10 team to ensure involvement of the team in the innovation process
- A framework for a structured analysis of technologies and solutions available / expected from SP 10 and the assessment of commercialisation attractiveness developed

9.9 T10.7.6 Preparation of Grants and Report Documents

9.9.1 Key Personnel

Task Leader: Marc-Oliver Gewaltig (EPFL)

9.9.2 SGA1 DoA Goals

To support the preparation of periodic reports as well as the proposal for SGA2

9.9.3 Progress

In close collaboration with Task 10.7.3 all reports and proposals have been prepared and submitted in time, in particular the D10.7.1 Release Plan for the NRP for SGA1 and Project Implementation Proposal. Also, input was collected from internal users and developers regarding SGA2.

10. Co-Design Projects

SP10 is contributing to CDP1, CDP4 and, to a lesser extent, to CDP5. The main reports are written by the respective CDP leader and can therefore be found in the M12 reports of SP1, SP2 and SP9. In this document, all CDP contributions are reported on a task basis.

11. Dissemination

Dissemination is addressed in its own Task, the reader is therefore referred to the report given in the corresponding section of Task 10.7.4 "Dissemination and community engagement".

12. Education

Student in SP10 participated in the 1st HBP Young Researchers Event, the 3rd HBP School and also in the 1st HBP Student Conference to which a lecturer from SP10 was invited. A lecture was also given at the HBP-sponsored spring school "International College IK" (March, 2017)

13. Ethics

The SP10 ethics rapporteur (Florian Röhrbein) was actively involved in all matters of Ethics and Society, he participated in meetings with SP11, responded to polls, questionnaires and other requests. A 2-day physical meeting was held in March 2017 in Bristol with a focus on robotic systems.

With Alan Winfield (SP11) we paid attention to potential ethical issues associated with the sharing and collective development of experimental data and results. Since our Platform is a collaborative tool with features that enable researchers to share and re-use experiments, ownership of hypotheses, data and results may become difficult to determine in some cases. We remain aware of this issue.

As the research develops, we will also look ahead to longer-term ethical issues associated with developing physical robots controlled by neural networks, operating in physical environments. Potential ethical issues primarily revolve around robot-human interactions. Looking even further ahead, we are aware that very complex simulations raise the possibility of machine consciousness and the moral status of such consciousness. SP10 therefore presented their current state and future perspectives in a workshop held at EITN in Paris.

14. Innovation

A dedicated work stream was launched as part of SP10 in March 2017 to explore specific options for innovation and technology transfer within the Neurorobotics domain of the Human Brain Project. The goals of the Innovation activity specified as follows:

- Find industrial / business applications for the corpus of technologies of collaborative robotics / Artificial intelligence developed and tested based on the Neurorobotics Platform;
- Screen and prioritize industry / business problems that can be efficiently solved with specific technologies or ideas developed within SP10;
- Formulate innovation and technology transfer project concepts and plans based on the results;
- Prioritize and develop opportunities through academic and industry partnerships.

Beyond that, SP10 seeks contacts and cooperation with partners from the industry looking to leverage the Neurorobotics platform for the testing of brain-inspired solutions in industrial robotics. SP10 is also able to give such industrial partners the opportunity to benefit from the knowledge accumulated within the research done by platform users who contribute the results of their experiments to the community.

By the end of March 2017 the following progress has been achieved:

- A team member hired to work on the innovation and technology transfer problems;
- Agrirobotics identified as a platform-level idea for implementing collaborative robotics / AI in industry (Priority 1 opportunity);
- Autonomous driving / automotive simulations identified as a prospective area of application for specific technologies (Priority 2 opportunity);
- A plan was created to develop the concept of Agrirobotics platform up to a level that would allow for the establishment of academic and industry partnerships.

Actions chosen as immediate next steps within the SP10 Innovation agenda are as follows:

- Detailed in-depth analysis of technology transfer potential within two selected areas: Agricultural robotics (first priority) and Autonomous driving (second priority);
- Development of the Agrirobotics platform concept and establishment of academic and industry partnerships required to explore and drive it further;
- Structured assessment of technologies and solutions available / expected from SP 10 using the framework developed.

15. Publications

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