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SENSOPAC

SENSOrimotor structuring of Perception and Action for emerging Cognition

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I. Project Execution

The neuroscience part of SENSOPAC targeted a goal that has previously been regarded as unattainable, viz. an executable, biomimetic model of a full functional system of the brain. Because of the overall goal of the SENSOPAC project to generate systems for haptic discrimination, the focus of the neuroscience modelling was the cerebellar C3 zone-anterior interposed system, which is involved in arm-hand control and has an extremely rich representation of skin sensory input from the fingers.

A complete biomimetic model requires knowledge at a wide range of levels, ranging from ion channels, synaptic learning mechanisms to local network connectivity and overall structural organization of input-output connections. All these levels of experimental analysis have been targeted within this project, in many cases with new state-of-the-art techniques developed within the project. The specific issues addressed by the experimentalists have been critical remaining gaps in our understanding of conductance level function and learning mechanisms of the cerebellar neuronal circuitry in general as well as specific aspects of *in vivo* local network connectivity and overall system function of the targeted subsystem. The result of the neuroscience work within the SENSOPAC project was successful in that a biomimetic model of the C3 zone-anterior interposed system, taking into account all aspects of neuronal and neuronal network function down to the contribution of specific types of ion channels, was accomplished.

The Large-Scale Analog Model LSAM features the full model system, which within the SENSOPAC project was used to directly control the DLR robotic system in real-time, and was implemented at the neuronal/neuron bundle level of abstraction. The Event-Driven LookUp Table EDLUT model, featuring simulation of spiking neuronal networks, could be used to simulate parts of the system at a higher level of resolution, for corroborating the function of LSAM down to the conductance level. LSAM connected to the DLR robot provided as output haptics related, integrated sensorimotor signals, which could be extended also to signals related to 'imagination' of objects/properties. In this way, the neuroscience part of SENSOPAC showed that signal processing of the type that naturally occurs within the brain can be highly useful for the design of haptically competent cognitive systems.

We examined active sensing, that is how information can be derived using haptic sensors (touch) in both human and robotic interfaces. The work in humans involved collecting and analysing microneurography (recording of nerve cells) data from humans to understand the fundamental principles involved in haptic sensing. Some notable successes were in the study of a new class of sensory receptors in humans that are based in the fingertip nail wall. We found that they responded reliably to forces applied to the fingertips representative for those that occur in object manipulation and exploration tasks. Furthermore, signals in populations of the neurons contain directional information about fingertip forces. That is, force direction reliably influenced the responses in nearly all the afferents and the preferred direction to tangential force components was distributed in all angular directions across afferents. We conclude that signals in the population of receptors contain vectorial information about fingertip forces and signal tactile features of contacted surfaces while being less influenced by textural information. Linked to these human studies were a range of computational studies that elucidated how the brain could decode spatiotemporal (spiking) data from the receptors for discrimination. We concluded that stimulus history affects both spike counts and first spike latencies. Some afferents even transmit high information about stimulation in their first spike latencies. An analysis of latency tuning curves confirms that those afferents respond to past stimulation only, independently of current ongoing stimulation. In addition a new type of artificial haptic sensor has been developed.

An important result of SENSOPAC was the transfer of the neuroscience and haptic results to robotic systems. To this end, a novel, variable-impedance robotic hand-arm-hand system was developed for integration within the project. This DLR Hand-Arm System is a robotic system mimicking the kinematic, dynamic and force properties of the human arm using modern mechatronic technologies. It is based on a variable stiffness drive concept with joint structures as close to the biological counterpart as possible.

The system is designed as a fully integrated hand- arm system that no longer allows the isolated use of the hand or arm. Nevertheless it still can be logically divided into a forearm and hand, including the wrist, on one side, and the arm consisting of a 3-DoF shoulder and a 2-DoF elbow, on the other. The requirements of the hand and arm are quite different. For example, vibration damping is of no relevance for the fingers (finger dynamics are negligible in relation to the applied forces), whereas a good vibration damping performance of the arm, especially in the shoulder, is crucial for the whole hand-arm system. Therefore the design aspects must be separately analysed for both systems.

Compliance to cerebellar control was a key aspect in this system, for instance with respect to the hand kinematics. Within SENSOPAC, a detailed model of the human hand has been realised and results thereof integrated in the robotic system.

I.1 Summary Description of project objectives

I.1.1 Project Summary

The SENSOPAC project combines machine learning techniques and modelling of biological systems to develop a machine capable of abstracting cognitive notions from sensorimotor relationships during interactions with its environment, and of generalising this knowledge to novel situations. The machine, through data-driven methods, aims to discover the sensorimotor relationships and consequently learn the intrinsic structure of predictive and causal relationships that govern movement systems. Detailed neural models of key brain areas will be embedded into functional models of perception, decision making, planning and control, effectively bridging and contributing to Neuroscience and Engineering.

A systematic and integrated approach to studying active sensing and motor control in animals in a hierarchy of defined tasks offered insights into skilled behaviour lead to fruitful applications of bio-inspired mechanisms for perception and intelligent control. Throughout the project, continuous interactions between experimentalists, theoreticians, engineers and roboticists have taken place in order to coordinate the most rigorous development and testing of a complete artificial cognitive system.

I.1.2 Project objectives

The overall aims of the SENSOPAC project are to:

- Understand the sensorimotor foundation of perception and cognition
- Improve our understanding of the neurobiological substrate for action-perception systems
- Build a physical system for haptic cognition
- Develop methodologies to investigate cognition in the brain.

Within these five overall aims, SENSOPAC has two classes of intermediate specific aims. One class is organised around the key problems identified as central to the goal of building a machine to extract and apply cognitive notions from sensorimotor interactions. Each problem-specific aim is tackled through a balanced mix of biological and non-biological approaches to produce biologically inspired deliverables.

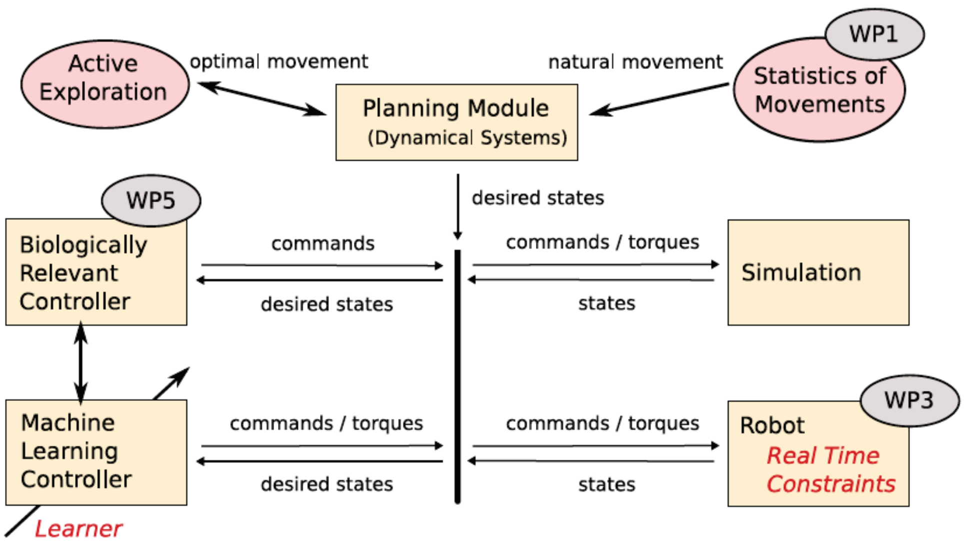
A class of solution-specific aims, which investigate existing biological solutions and build an artificial haptic solution, complements these problem-specific aims. These solution-specific aims provide common resources to tackle the five key problems, providing neural models and a biologically relevant system in which to test results.

The identification of problem-specific aims is the cornerstone of our approach to building a focused collaboration. The identification of a problem provides the common context or common language necessary to integrate the efforts of a diverse group of experts, from the fields of biology, biophysical and systems modelling, machine learning, robots and hardware and software engineering. This level of integration is essential if the engineering of neural systems is to make significant contributions to either the engineering or to the biology.

I.2 Project Organisation

The SENSOPAC project was organized in workpackages with specific tasks related to the management (WP0), knowledge distribution (WP7) or scientific and technical developments (WP1-WP6). Most of the WPs were guided by single WP-leaders, and the overall scientific supervision was led by the Scientific Board, which was comprised of the participants from DLR (scientific coordinator), PAVIA, and UEDIN. The daily management supervision and financial reporting were done by Erasmus and ALMA, respectively. Communication was warranted by many mutual lab visits, numerous emails, common website programs, and scientific symposia.

I.1.1 Project organisation



I.2 Contractors involved

Particip ant. Role*	Partici pant. Numb er	Participant name	Participant short name	Country	Date enter project	Date exit project
CO	1	Erasmus Universitair	ERASMUS	Netherlands	M1	M54

		Medisch Centrum				
CR	2	Sony France SA	SONY	France	M1	M24
SC	3	Deutsches Zentrum für Luft- und Raumfahrt	DLR	Germany	M1	M54
CR	4	Altjira SA	ALTJIRA	Switzerland	M1	M54
CR	5	Diparimento di Scienze Fisiologiche-Farmacologiche Cellulari-Molecolari - Universita degli Studi di Pavia	PAVIA	Italy	M1	M54
CR	6	Umeå Universitet	UMEA	Sweden	M1	M54
CR	7	Lund Universitet	LUND	Sweden	M1	M54
CR	8	Universidadde Granada	UGR	Spain	M1	M54
CR	9	University of Edinburgh	UEDIN	UK	M1	M54
CR	10	University of Cambridge	UCAM-DENG	UK	M1	M54
CR	11	Bar-Ilan University	BIU	Israel	M1	M54
CR	12	Alma Consulting Group SAS	ALMA	France	M1	M54
CR	13	Université Pierre et Marie Curie	UPMC	France	M21	M54

*CO = Coordinator
SC = Scientific coordinator
CR = Contractor

I.3 Work performed and end results

I.3.1 WP1

Leader: UCAM - DENG

Participants: UCAM, UPMC, DLR, UMEA, UEDIN

WP1 Objectives

This WP examines active sensing, that is how information can be derived using haptic sensors (touch) in both human and robotic interfaces. The work in humans involved collecting and analysing microneurography (recording of nerve cells) data from humans to understand the fundamental principles involved in haptic sensing. Its aim is also examining behavioural data to understand what haptic cues we are sensitive to when manipulating novel objects. In addition a new type of artificial haptic sensor has been developed. Understanding the basis of haptic sensing is fundamental for being able to reproduce this behaviour in artificial systems.

WP1 Results

Microneurography of human touch

We examined the function of the clusters of slowly adapting (SA-IInail) mechanoreceptors in nail walls. We found that they responded reliably to forces applied to the fingertips representative for those that occur in object manipulation and exploration tasks. Furthermore, signals in populations of the neurons contain directional information about fingertip forces. That is, force direction reliably influenced the responses in nearly all the afferents and the preferred direction to tangential force components was distributed in all angular directions across afferents. We conclude that signals in the population of SA-IInail afferents terminating in the nail walls contain vectorial information about fingertip forces. The particular tactile features of contacted surfaces would less influence force-related signals in SA-IInail afferents than force-related signals present in afferents terminating in the volar skin areas that directly contact objects. It is well known that the nails are important for performing fine manipulation and haptic tasks. For example, a finger without a nail will compromise a musician's career if the finger involved is necessary to play a note (strings, keyboards) or hold a position (winds). Our findings provide, for the first time, a rationale for the sensory impairment after nail-related injury and generate several novel and testable hypotheses for experimental studies striving to unravel the roles of the SA-IInail afferents for the functions of the hands.

Inter- vs. intradigit integration of haptic information

We have performed haptic discrimination experiments that address the capacity of humans to integrate spatiotemporal information across multiple fingertips and how this might depend on the types of tactile afferents primarily engaged. To explore computational characteristics of tactile processing, we quantified humans' capacity to discriminate temporal tactile features contained in two stimuli delivered to either the tip of a single digit or to different digits belonging to the same and different hands. In addition to supporting the notion of hierarchical schemes for information processing in the somatosensory system, our results bring forth new views on how the functional organization of the system is tailored to natural use of hands. The capacity to detect correlated tactile events shows a considerably higher temporal resolution for stimuli received by a single fingertip than when received by different digits. The lower temporal bandwidth for detecting correlated tactile events across digits of the same hand matches the fact that such events are naturally coordinated by the rather slow motor system. This also agrees with neurophysiological evidence that compilation of the information across digit occurs in separate maps downstream the digit-specific maps. The capacity to detect correlated tactile events across digits of the different hands shows an even lower temporal bandwidth than observed across digits of the same hand and seems to be supported primarily by inputs provided by slowly adapting tactile afferents.

Decoding of spatiotemporal (spiking) haptic data for discrimination

In this computational investigation, we examined how information about tactile stimuli is represented in the firing statistics of tactile afferents. We concluded that stimulus history affects spike counts and first spike latencies. Some afferents transmit high information about past stimulation in their first spike latencies. An analysis of latency tuning curves confirms that those afferents respond to past stimulation only, independently of current ongoing stimulation. This might be explained by afferents responding to the state of the skin at the start of stimulation. Through this mechanism, tactile afferents could signal an 'offset signal' that could be used in order to mitigate otherwise confounding hysteresis effects.

Performing active haptic sensing with spiking neural network models

This study examined temporal coding mechanisms mediating the transmission of spiking tactile signals along the somatosensory pathway. We investigated the working hypothesis that Cuneate Nucleus (CN) neurones may mediate efficient encoding —in terms of both fast and reliable information transfer— of the afferent signals propagating from the fingertip through the peripheral nerve fibres. The main rationale of this research was that the CN network would not constitute a mere synaptic relay, but it would rather convey optimal contextual accounts of tactile inputs to the central nervous system. The outcomes of this research corroborated this hypothesis, and predicted a relevant role for 2nd CN neurons in facilitating fast discrimination of haptic contexts, minimising destructive interference over lifelong learning, and maximising associative capacity for somatosensory memories.

Development of touch sensors

At DLR different generations of tactile sensors, have been investigated during the SENSOPAC project.

The sensing principle of the first generation is based on the formation of conductive pathways in piezo-resisitve flexible materials. If pressure is applied to such materials the volume resistivity decreases. To enable the utilisation as tactile sensors sensitive areas, so called taxels have to be created. The first generation uses metal readout wires to connect the taxels. One of the major goals was the reduction of the number of readout wires to enable the integration of the tactile sensor into robotic hands.

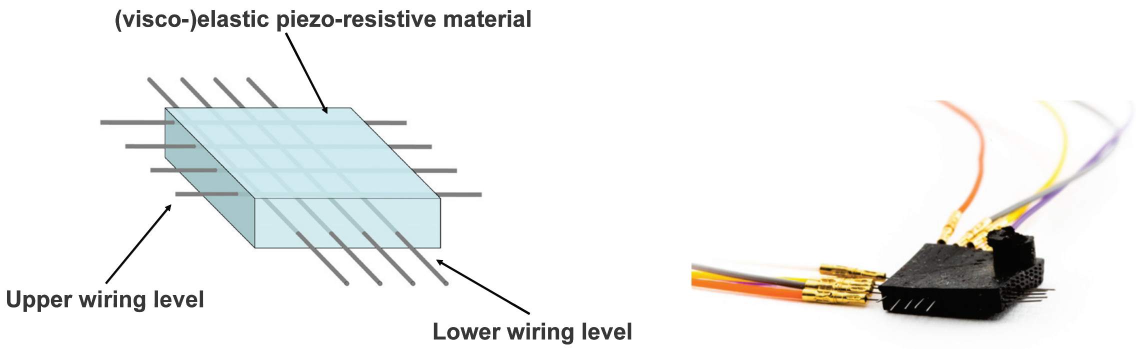


Figure 1: First Generation DLR touch sensor

Therefore an array setup was chosen to connect the taxels. The crossing wires, shown in the above figure, form sensitive taxels at every crossing point. The first generation of piezoresisitive sensor patches provide:

- 25 taxels
- a sensitive surface of 6mm x 6mm
- a resolution of about 1mm²
- reduced number of readout wires (10)

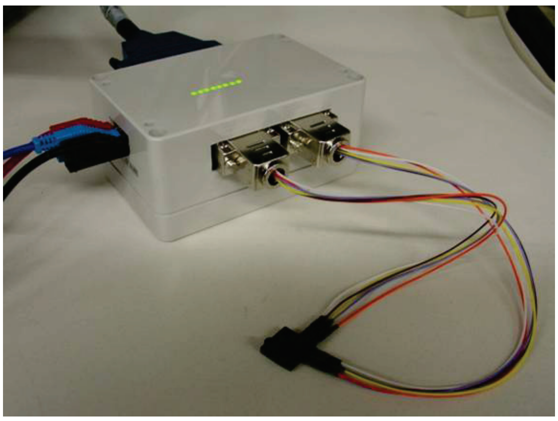


Figure 2: Touch sensor readout

Along with the sensor patches DLR provided the partners with complete readout systems. These readout systems consist of sensor patches, specially designed and manufactured pre-amplification boards, DAQ-cards and software. Using identical readout systems ensures the future comparability of the results obtained by the different partners. Tests of the sensor patches showed, that the sensor allows for the discrimination of different objects which were applied to the sensor patch surface. The below figure demonstrates the results of these indentation tests.

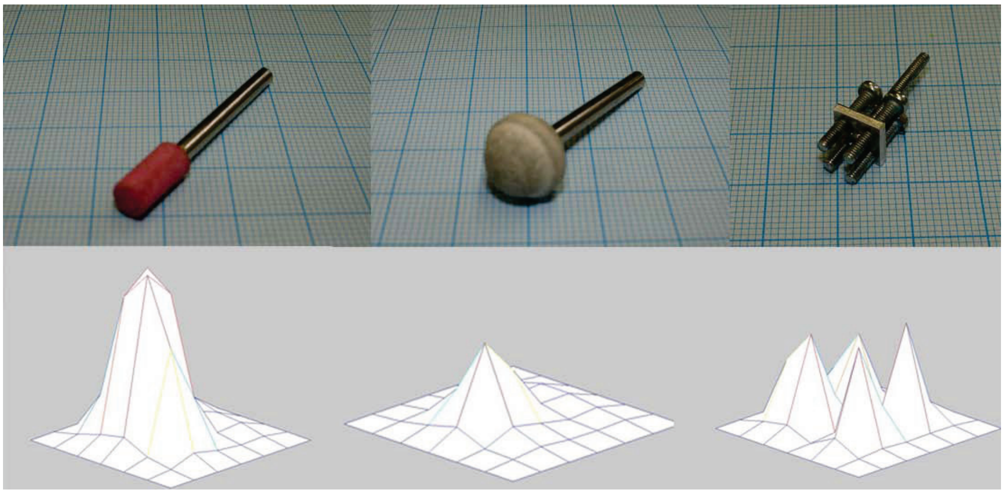


Figure 3: Indenting the DLR tactile sensor. The below graphs shows the measured voltages when indented with the above probes.

Although the first generation sensor patches worked well, alternative approaches towards the sensor hardware have been pursued. Of special interest was the reduction of complexity regarding the setup of the sensor patches themselves and the applied manufacturing process.

As an alternative sensor setup a sensor based on polymer wires has been investigated. The sensitive area consists of conductive wires which are coated with a flexible conductive material. To increase the sensitivity of the sensor patches an alternative transduction principle has been investigated. In contrast to the first generation sensor principle, the coated wire sensor uses the varying transition resistivity between two crossed wires. The transition resistivity depends on the contact surface between the coated wires. As the coating consists of flexible conductive material the contact surface increases if two crossing wires are pressed against each other.

To enable the evaluation of different sensing principles as well as the manufactured tactile sensors a specialised test bed has been set up at DLR. This testbed allows for repeatable indentation of sensor patches and thus enables objective evaluation of different materials and sensor setups. The testbed consists of a non-backdriveable linear motor for the indentation in z-direction and positioning boards for the deviation in x- and y-direction. To measure the applied forces a 6-DoF force-torque sensor is applied.

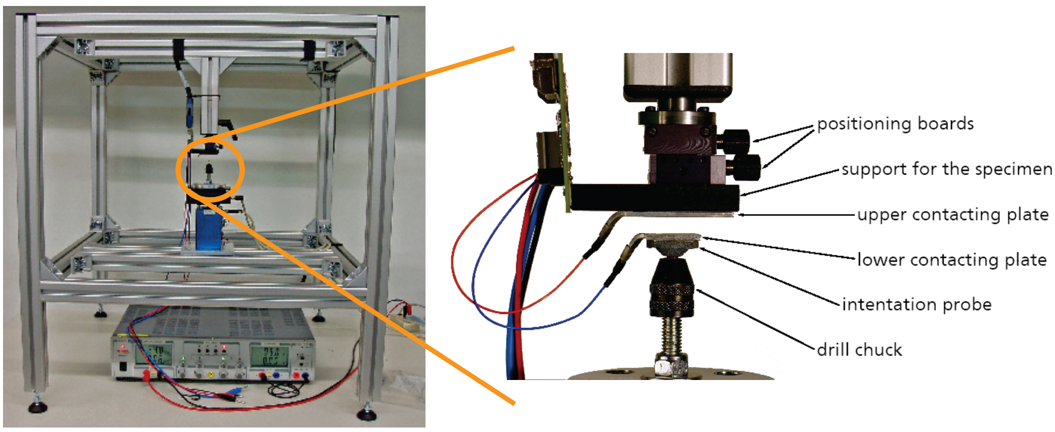


Figure 4: DLR Testbed

During the conducted research three basic challenges for the development of tactile sensors have been identified:

- the piezoresistive properties of the applied polymers.
- the encapsulation of the conductive / piezoresisitive polymer with an insulating polymer material.
- the mechanical and electrical connection of the conductive polymer to standard electronics elements and PCBs.

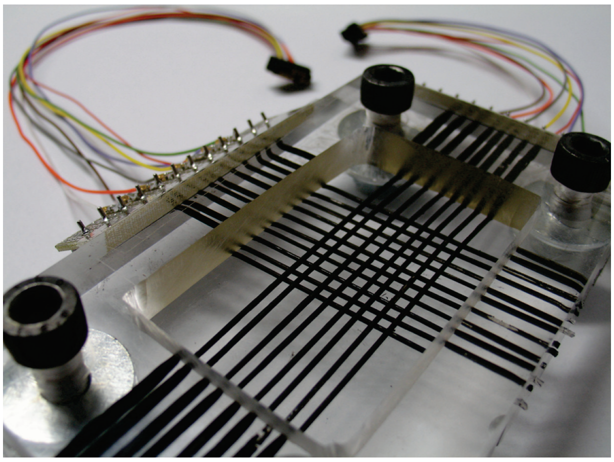


Figure 5: Prototype of the coated wire sensor

The investigated Coated Polymer Wire Setup approach based on polymeric core materials showed that the application of a piezoresistive polymer coating over a conductive polymer core did not generate an advantage over an approach based on an uncoated conductive polymer core. Based on the results of the examination of the coated-wire setups the decision was made to focus on this approach and optimize the mechanical setup and here especially the fixation of the polymer wires in the required geometric placement. The challenge of the electrical and mechanical connection of the elastic polymers and the standard readout electronics circuitry could be met applying floating contacting islands on an elastic polymer film. The basic idea of this approach is the geometric separation of the mechanical contact point form the electrical contact point. The ultimate goal was to free the electrical contacting area from any mechanical stress.

The overall setup results from the evaluation of the different sensor setups that have been evaluated during the SENSOPAC project: Measurement of the change of the transition resistance rather than to try to measure the changes within a solid volume of piezoresistive polymer is a more promising approach towards stretchable tactile sensors.

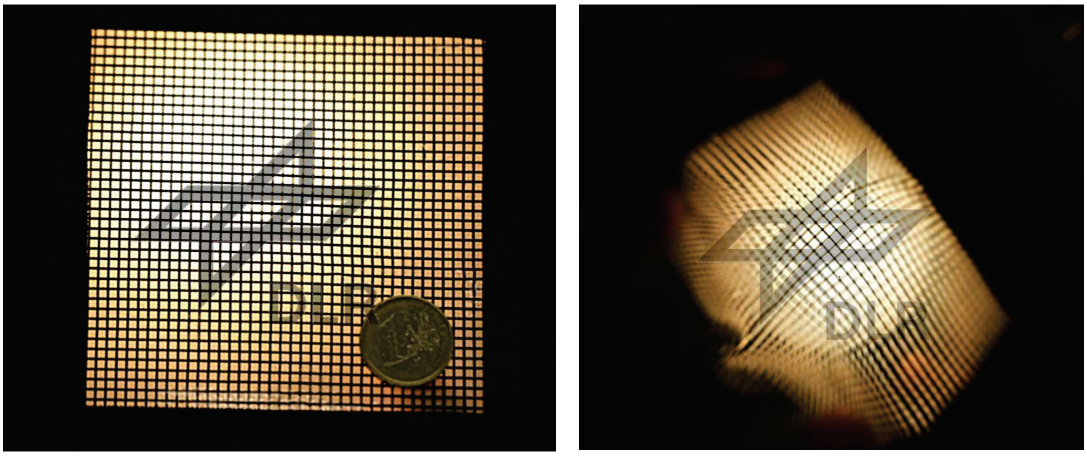


Figure 6: left: DLR tactile sensor; right: wrapped around a light bulb

The sensor setup is applied on an elastic support structure resembling the human skin. As the sensitive area is completely free of rigid parts and is based on an all-polymer approach it can be stretched and is able to cover 3D-freeform surfaces.

As the result of the research towards new tactile sensors which has been conducted during SENSOPAC we were able to realize a tactile sensor that exhibits a sensitive area of 100x100mm with 40 rows x 40 columns resulting in 1600 taxels with a spacing between the taxels of 2.5mm in x- and y-direction. The minimal required offset force required to generate an output signal is currently 0.15 N.

Decoding of spatiotemporal readouts from artificial skin
We characterised the response properties of an artificial skin prototype suitable for *dynamical* fine touch discrimination, i.e. capable of sensing Braille-like indentation patterns applied at relatively large speeds (~50mm/s). These speeds are compatible to those adopted by expert Braille readers. We studied a bio-mimetic framework for the encoding/decoding of artificial tactile signals. Analogue data from the artificial fingertip were encoded through a network of leaky integrate-and-fire neurons, whose spike train outputs were then decoded on the basis of the metrical information. This research aimed at favouring fast and optimal discrimination of Braille-like stimulation patterns. We corroborated the approach based on temporal neural coding, i.e. based on the relative latencies of spikes, to study tactile sensing in robotics.

I.3.2 WP2/4

Leader: UEDIN

Participants: UEDIN, UGR, UCAM – DENG, DLR, UPMC, LUND

WP2/4 objectives

WP2/4 forms the backbone of the statistical machine learning and cerebellar modelling work, where basic tools to both exploit natural dynamics and physics are developed. Furthermore, algorithms and methods are set up for use in the real time adaptive control (and through it) active haptic discrimination of complex object properties such as inertial parameters, mass density and texture. This workpackage has four distinct domains of contribution: Task 2A dealt with exploiting analytical relationship between the action-sensing loop, i.e., use the knowledge of physics (linearity between dynamic models under certain conditions etc.) and methods of exploiting this in incremental manner. Task 2B dealt with algorithms and models for incremental learning of sensorimotor relationships, both from a nonparametric, statistical formulation and from a cerebellar modelling standpoint. Task 2C mainly dealt with identifying, learning and representing multiple context dynamics and furthermore, learning to switch between them seamlessly. This is important not only for control but for haptic discrimination during manipulation. Task 2D was about analyzing efficient representations of continuous/discrete context variables and latent spaces such that concepts can be generalised. This has dealt with both dynamic properties of movement as well as the associated haptic sensory feedback. In addition, these representations were used to

WP2/4 Results

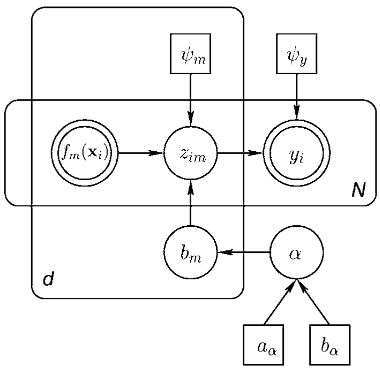
Learning the sensorimotor structure in high dimensions
The ability to learn sensorimotor structures is a key to compliant control of robots in a wide range of environments or tasks. Using learning, inaccurate and un-modelled components of analytical model based dynamics can be compensated for, and furthermore the learnt mappings can include sensory inputs such as haptic data, possibly yielding complex but useful sensorimotor contingencies automatically. The application

of learning in control however poses special requirements to the algorithms, in particular with respect to computational efficiency, the ability to handle high dimensional data, and the facility to train models in an online, incremental fashion. Furthermore, adopting an engineering attitude we can explore biologically plausible approaches to study strategies that biological systems might have developed to address these issues.

Within WP2, learning is studied mainly from the following three viewpoints:

1) We developed statistical machine learning approaches that meet the aforementioned requirements (mainly at UEDIN).
2) We worked on biologically plausible approaches like cerebellar spiking neural networks (mainly at UGR).
3) We studied where and how to integrate learnt models in a control loop, e.g., in feedforward or recurrent architectures.

UEDIN has produced a new implementation of the online learning algorithm Locally Weighted Projection Regression (LWPR). While the algorithm itself had already been proven to be suitable for learning high-dimensional function mappings, previous implementations were either slow (written in pure MATLAB) or rather inconvenient to use. The new implementation uses an efficient low-level core library written in C, but it provides bindings and wrappers for usage from C++, MATLAB/Octave, and Python on multiple platforms, thus making its integration into existing software environments (e.g., the simulator developed at **DLR**) much easier. The software package, together with documentation and tutorials, has been has been made publicly available, and an accompanying paper has been published in the *JMLR* track on machine learning open source software. **UEDIN** has also set up a website for the LWPR implementation, where the documentation and tutorials can be browsed online (http://www.ipab.inf.ed.ac.uk/slmc/software/lwpr).



(a) VBLS with shrinkage prior

Figure 7: Graphical model of VBLS with shrinkage prior

Further, in response to the open question of automatic selection of local complexity parameter in non-linear regression, UEDIN has explored automatic selection of kernel width and dimensionality of local models (Ting, J., D'Souza, A., Vijayakumar, S., and Schaal, S. (2010). Efficient Learning and Feature Selection in High-Dimensional Regression, Neural Computation, vol. 22, no. 4, pp. 831-886) with a potential to scale to high dimensional problems.

Managing sensorimotor structures in multiple contexts

UCAM has worked on evaluating human performance in learning object dynamics and have examined both the representation of object dynamics and how adaptive control can be integrated with optimal feedback control. Results show that subjects could immediately anticipate the force direction for each orientation of the tool based on its visual geometry, and with experience, they learned to parameterize the force magnitude. Surprisingly, this parameterization of force magnitude showed limited generalization when the orientation of the tool changed. Had subjects parameterized a single general representation, full generalization would be expected. Thus, our results suggest that object dynamics are captured by multiple representations, each of which encodes the mapping associated with a specific grasp context. We suggest that the concept of grasp-specific representations may provide a unifying framework for interpreting previous results related to dynamics learning. This work is now published as two papers. The first describes the novel robotic interface: Howard IS, Ingram JN & Wolpert DM (2009) A modular planar robotic manipulandum with end-point torque control. Journal of Neuroscience Methods 181: 199–211 And the second the full experiment and results: Ingram JN, Howard IS, Flanagan JR & Wolpert DM (2010) Multiple grasp-specific representations of tool dynamics mediate skilful manipulation. Current Biology 20:618-623

UCAM also showed that in the presence of an unpredictable task (one in which there is a visuomotor rotation that changes for each movement) that the motor system initially generates highly variable behaviour but eventually converges to stereo-typed patterns of adaptive responses predicted by a simple optimality principle. These results suggest that adaptation can become specifically tuned to identify task-specific parameters in an optimal manner. We developed a novel model that incorporates both adaptive control and estimation of task parameters to simulate behaviour. (Braun DA, Aertsen A, Wolpert DM & Mehring C (2009) Learning optimal adaptation strategies in unpredictable motor tasks Journal of Neuroscience 29(20):6472-6478).

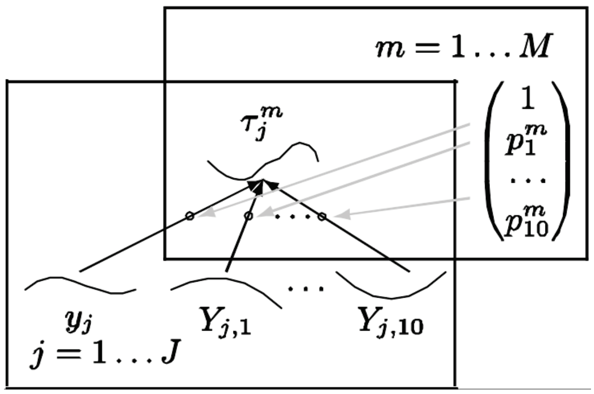


Figure 8: Multi-task GP model

At UEDIN, we have extended our methods to incorporate analytical properties of dynamics contexts into learning algorithms. In particular, we investigated how to learn the inverse dynamics mapping of a robot arm for multiple loads using a single multi-task Gaussian Process regression model. The new multi-task GP approach now explicitly exploits the fact that the underlying nonlinearities **Z**(…) are the same for all contexts, and models the torques with a single covariance function that factorises in the same way as the **Z*r** decomposition above. Therefore, all training data from all contexts can be collected in a single model, and uncertainty can be shared amongst the contexts. Indeed, since the multi-task GP model learns the decomposition, it can successfully predict the torques for combinations of contexts and input space locations that have not been present in the training data, outperforming interpolation between separately learned single-task models (K.M. Chai, C.K.I. Williams, S. Klanke, and S. Vijayakumar, NIPS 2008).

In the framework of multiple contexts management, UGR have studied how different models can be abstracted by a simple spiking cerebellar model. It has become clear that the separability capability at the granular layer is of great importance to reduce interferences between different learned models. This has also been informed by the equivalent LWPR-based simulations: The machine learning approach (UEDIN) uses different LWPR modules to avoid interferences between different learned contexts models. We have studied different ways to encode both sensorimotor signals and context signals at the input of the model extraction engine and we have obtained a trade-off between the accuracy and the capability to abstract different models with low interference. The accuracy of the abstracted models becomes maximal if the sensorimotor signals are prioritised dedicating more encoding and computing resources along the processing data path (Mossy-Granular-Purkinje-DCN cells). Therefore, dedicating specific encoding/processing pathways for the sensorimotor signals of each different model (context) leads to a high accuracy model abstraction capability. Alternatively to a complete separate representation of the sensorimotor signals of different contexts, UGR is also studied how specific context-related signals can efficiently drive the learning process and allow different models (contexts) to be abstracted in a non-destructive manner.

Representation for exploration and active perception

The last major subtopic within WP2 is about finding effective ways of generating exploratory movements, that is, we wish to create movement plans which not just represent a path between two points A and B, but rather yield informative sensor input during the motion. Working towards this goal involves studying

1) dimensionality reduction of movement data, for representing sequences of postures of systems with possibly large degrees of freedom in a *compact* manner,
2) dynamical systems representations of movement plans, for being able to *flexibly* scale movements in space and time,
3) the optimality of movements with respect to the amount of information they yield, for example in a haptic discrimination task, and
4) dimensionality reduction of sensory data, for acquiring a compact description of what is being sensed, ideally yielding “cognitive” notions about the environment.

We have generated novel results in each of these domains. UEDIN has investigated representations of movements which are beneficial for the learning and execution of explorative movements. We have suggested classes of movements for the identification of the mass and of the general inertia properties of a held object. (S. Bitzer and S.Vijayakumar (2009), Latent Spaces for Dynamic Movement Primitives, Proc. 9th IEEE RAS International Conference on humanoid Robots (Humanoids ’09), Paris, France.)

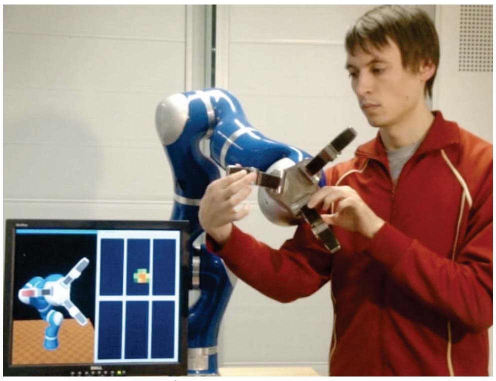


Figure 9: Demonstration of the tactile sensors mounted on Schunk dexterous hand SDH-2.

In addition, we investigated ways to actively extract information from sensory data by using appropriate exploratory movements. For active learning, we are interested in determining the optimal action $\boldsymbol{x}^*$ to take during test time such that the Mutual Information between sensors $\boldsymbol{y}$ and hidden latent state $\boldsymbol{\theta}$, $\mathbf{I}(\boldsymbol{\theta}; \boldsymbol{y} \mid \boldsymbol{x})$, is maximized.

This framework was successfully implemented in the framework of Gaussian Process sensor action modelling and Quadratic Mutual Information (QMI) based action selection (Saal HP, Ting J, Vijayakumar S (2010a). Active sequential learning with tactile feedback. Proc. Int. Conf. on Artificial Intelligence and Statistics (AISTATS) 2010; Saal HP, Ting J, Vijayakumar S (2010b). Active Estimation of Object Dynamics with Tactile Sensors. Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS 2010)). This theoretically well founded formulation was implemented with excellent results on the tactile discrimination of liquid viscosities in real time on a Schunk tactile hand.

I.3.3 WP3

Leader: DLR

Participants: DLR, UEDIN, UCAM – DENG

WP3 objectives

DLR investigated an artificial arm-hand system to provide a rich motor domain for haptic cognition. The arm-hand system follows strong anthropomorphic principles to match the complexity of real-world haptic cognition. Using an antagonistic drive concept for all joints of the arm, we focus on copying the human kinematic and dynamic structure, both for the hand as for the arm. Copying human dynamics properties is important with respect to its controllability by cerebellum-based methodologies; especially the mechanically realised flexibility, which will allow for storing energy and thus for an increased stability. It will therefore require less accurate and lower-frequency feedback loops. The limited applicability of cerebellum-based controllers to classical robotic structures has been reported from various sources in the literature, since the evolutionary development of the cerebellar structure is directly related to the dynamic properties of the skeletomuscular structure. The development within SENSOPAC involves study of the corresponding human kinematic structures and investigating their applicability for artificial arm-hand structures, taking different drive concepts into account.

WP3 Results

Implementation of redundant actuators

After more than a decade of service robotics research, the results of the community regarding major challenges such as grasping, manipulation, and mobility still are not really satisfying and seem to stagnate. In our observation, this is related to major shortfalls in the tool chain and especially the hardware. Since robotic systems get increasingly complex, the danger of damage increases. A single collision during operation may cost huge amounts of money and time. Therefore application developers have to be very conservative when testing new methods and strategies. This slows down progress dramatically und hardly gives a chance to develop radically different control/motion planning strategies.

The dynamical properties of actuators are not sufficient for several human tasks. Particularly in cyclic tasks (e.g., running) or highly dynamic tasks (throwing), the actuators cannot provide the required energy during peak loads without getting to bulky and heavy. Therefore we are convinced that major steps in space and service robotics are only possible if future robotic systems have two major characteristics:

(1) They have to be robust against “every-day” impacts, and
(2) they have to be able to store energy short-term.

This can be achieved by introducing variable passive compliance into future robotic systems. For this reason, we realised a highly anthropomorphic hand-arm system using these promising approaches.

DLR’s Anthropomorphic Hand Arm System

Shoulder and Elbow
The arm of the Hand Arm System, (consisting of a 3-DoF shoulder and a 2-DoF elbow) is as close to the human archetype as possible in terms of kinematics, dynamics, and force. Nevertheless the target must be not to copy nature, but rather to understand the basic functionalities and transfer them to the technical system. Since the arm requirements are rather different from the hand requirements, different actuation principles were investigated. The arm has to carry much higher loads than the fingers. The actuators have to apply the necessary force to counter gravity for the whole arm, which is negligible for the fingers. Furthermore, angular accuracy is much more important, and the dynamics within the system are not negligible, so vibration damping performance is essential for proper functioning of the whole hand-arm system.

To ensure the capability of the arm to perform human tasks in every position within the workspace, ergonomics data for every joint of the human arm were analysed. From this, the final dimensioning of the drives has been derived. Of course the actuation of the arm has to be capable of storing short-term energy. Furthermore, the energy consumption of the system has to be minimised, thus leading to an approach which does not favour antagonism.

Forearm
Since the hand itself has no drives or electronics, these have to be integrated into the forearm. To realise antagonistic drives for the total of 19 active DoF (4 DoF thumb, index, middle finger, 3 DoF ring finger, and 4 DoF little finger) within the hand and the 3 DoF of the wrist and the forearm rotation, 44 actuators, 44 elastic elements and 88 position sensors are located in the forearm.

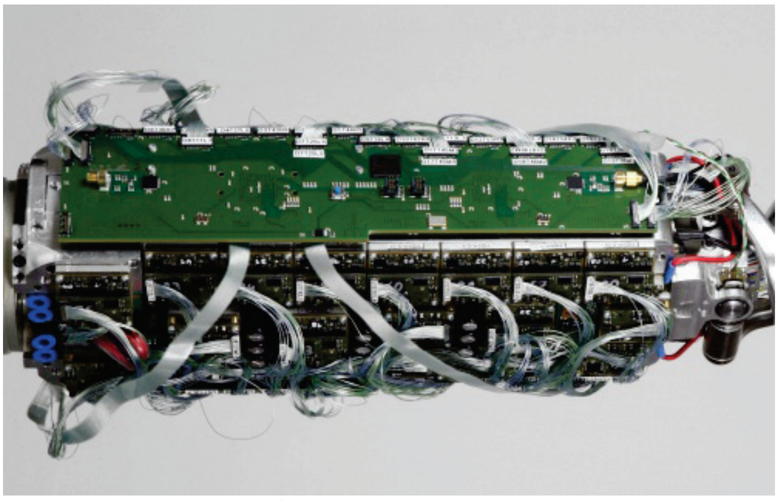


Figure 10 : Forearm

Wrist
To reduce friction by keeping the angle of tendon deflection minimal, as well as to downsize coupling between wrist and finger motion, a 4-bar mechanism wrist, forming a 3-D anti-parallelogram, has been developed.

Anthropomorphic Hand
In the design of an anthropomorphic hand, our goal is to closely copy the properties of the human hand rather than its intrinsic structure. The solutions found in biology must be transferred to technical components and evaluated before they can actually be used.

Anatomy of the Human Hand
The human hand consists of a palm with metacarpal bones and finger bones. The index, middle and ring finger are similar in their structure and configuration, whereas the thumb and little finger differ considerably; the latter has a bone structure similar to the

middle fingers, but its tendons, ligaments and muscles resemble those of the thumb. Furthermore, a thorough understanding of the hand joints is imperative for realising an anthropomorphic hand, since joints found in biology are radically different from technical joints. The human hand mainly uses three kinds of joints, which can be divided into 1-DoF and 2-DoF joints. The 1-DoF joints in the hand all are hinge joints; 2-DoF joints can be divided into two types. The metacarpal (second down) joint of the thumb is a saddle joint but with non-orthonormal axes and has been described geometrically by Kuczynski by the saddle of a scoliotic horse. In contrast, the metacarpal (3rd down) joints of the fingers are condyloid. The main difference between saddle and condyloid joints is that condyloid joints have (roughly) intersecting axes, which saddle joints do not have. For the thumb, the axes of the metacarpal are non-orthogonal screws (**Error! Reference source not found.**11).

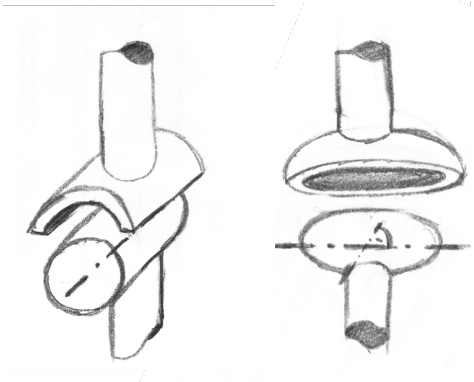


Figure 11: Joint types of the human hand: hinge, condyloid, and saddle joint

Following Kapandji, we consider the metacarpal of the thumb is a 2-DoF saddle joint. The interphalangeal joints of the thumb are similar to those of the fingers.

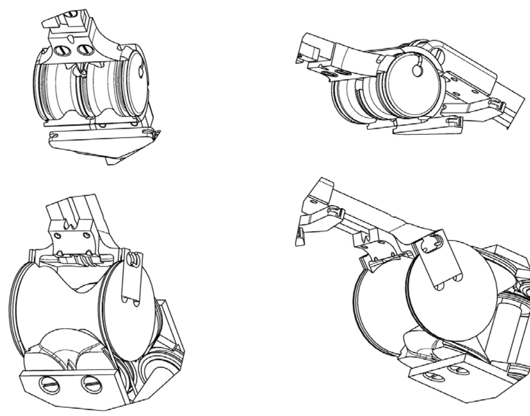


Figure 11: Biologically inspired overload-proof joints

The structure of the finger is designed as an endoskeleton with bionic joints (**Error! Reference source not found.**). The metacarpal joint is designed as a hyperboloidally shaped saddle joint, whereas the interphalangeal finger joints are designed as hinge joints. The proximal interphalangeal joint of the thumb is, in contrast to biology, also designed as a hinge joint. This circumvents the negative side effects of technical condyloid joints, while leaving out the thumbs fifth degree of freedom is not problematic. The kinematics of the new hand is closely adapted to the human hand. So every finger differs in bone-length, size and kinematics. For example, the fifth finger PIP joint has to have an inclination of about 15 deg to enable opposition to the thumb, while the index and middle finger only have minimal inclination. All joints enable dislocation of the bones without damage in case of overload, using the elasticity in the drive train. A fully functional version of the finger, using alloy structure and steel cables, has been attached to an antagonistic drive unit (8 motors; see **Error! Reference source not found.**).

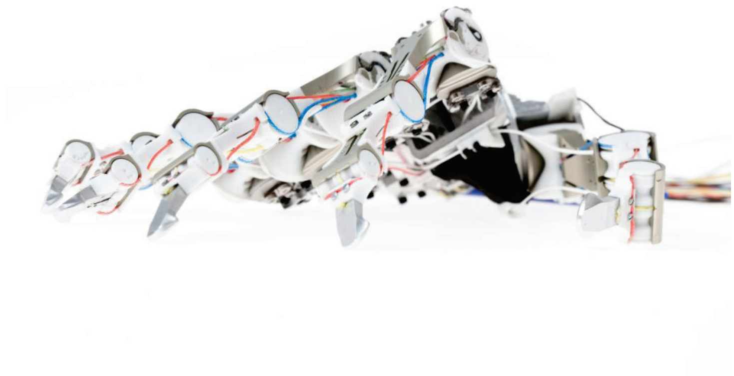


Figure 12: Final finger design

Based on this design, the middle, ring and 5th finger has been designed differing in size, angle of axes (inclination), strength, and even number of DoF. The design of the index finger also has been partly used for the thumb to keep machining and cost effort as low as possible.

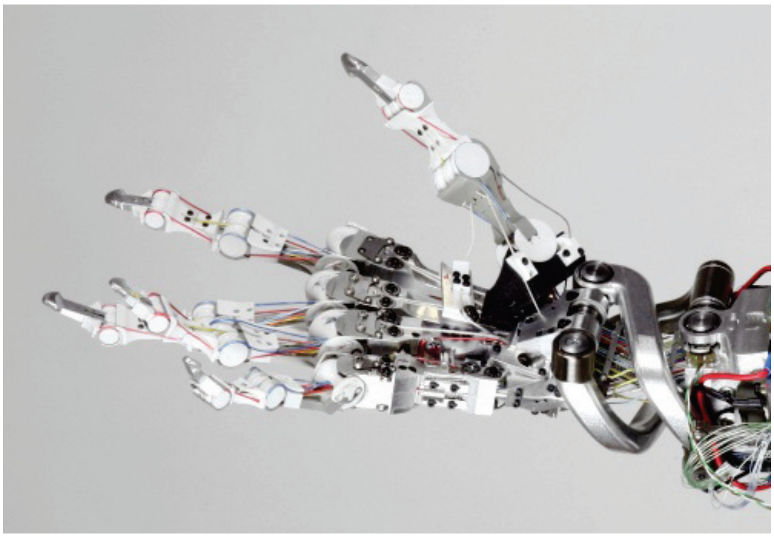


Figure 14: Final hand and wrist

A palm routing the 38 tendons to the fingers has been designed. The focus within the design has been on minimum friction since the latter reduces force measurement precision directly because there is no force measurement within the fingers. Second the palm and the tendons routing have been optimized regarding maintenance to reduce "downtime" of the system due to tendon wear/ brakage. The whole hand has been assembled and attached to the wrist and forearm within the project (**Error! Reference source not found.**15).

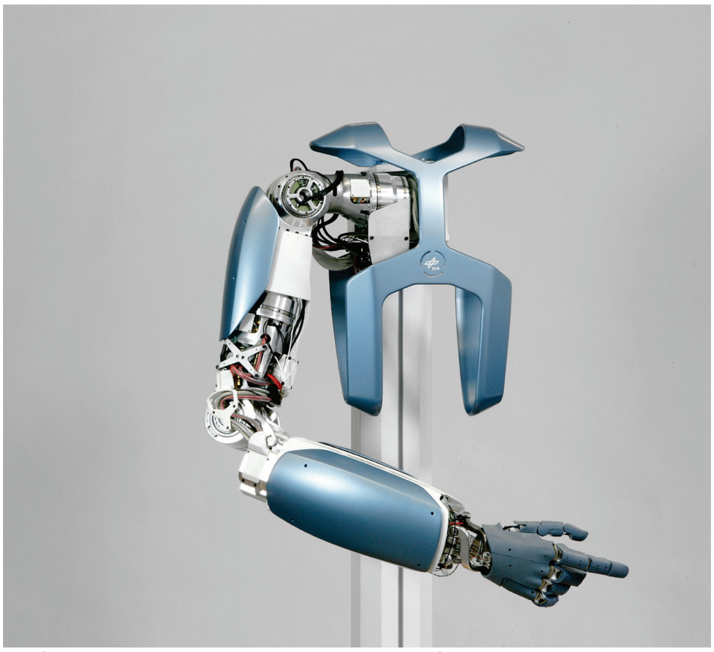


Figure 15: DLR's Anthropomorphic Hand-Arm System

I.3.4 WP5

Leader: LUND

Participants: LUND, PAVIA, UGR, BIU, ERASMUS, UPMC

WP5 objectives

The brain is a highly versatile and adaptive cognitive system, which at present is very far from being matched by any artificial system available. Therefore, in the creation of cognitive systems, it is natural to seek to replicate aspects of brain function. However, a large obstacle for the utilization of brain functions in artificial systems has been that the knowledge of how the brain works is still very limited. The goal of WP5 within SENSOPAC has been to explore and model brain circuitry function in use during haptic discrimination. A key in the work towards this goal has been a description of a neuronal system at a unique level of detail, achieved with state-of-the-art recording techniques for analyzing brain circuitry function and a systematic analysis of the connectivity structure of the neuronal network.

In order to target the goals of SENSOPAC to reproduce brain circuitry operation during sensorimotor interactions in haptic discrimination, the overarching aim of WP5 was to reconstruct the function of one full functional subsystem of the cerebellum, and to implement it in the LSAM (Large-scale analog model) for application to the robotic system. The reason why this effort was focussed on the cerebellum is that an understanding of brain circuitry mechanisms requires a comprehensive knowledge of the neuronal connectivity and the integrative, physiological and plasticity mechanisms for all neuron types that make up the network - this depth of knowledge was only feasible to achieve for the cerebellum because of the quite extensive previous knowledge of the general structure of the neuronal network. For the cerebellum, we had 1) knowledge of all the constituent neuronal elements and their overall connectivity and 2) the establishment of the microcomplex circuitry structure which describes the external input-output connectivity of the cerebellar cortical neurons and constitutes an important frame of reference against which the functions of cerebellar neurons recorded from can be interpreted. In addition, of particular relevance for the SENSOPAC project, the microcircuitry characterization of the intermediate cerebellar system for arm-hand motor control is highly detailed and specific. This system is involved in the control of distal muscles of the arm and hand, has a very rich and detailed representation of input from distal finger skin sensors, and is the system which LSAM seeks to replicate.

However, several pieces of crucial information was lacking, and many of the pertaining questions required the development of new recording techniques to probe the functions of specific, crucial neuron types located deep in tissue in the intact, living brain. In addition, any understanding of neuronal function rests on the properties of the different ion channels that compose the intrinsic responsiveness of the neuron. An additional important goal for SENSOPAC was therefore to be able to describe the function of at least some neuron types at a very high degree of completeness in terms of the activated conductances during processing of synaptic activation. The description of a functional subsystem of the brain will rest on a much more solid neuroscientific ground when the roles of all the different types of conductances can be accounted for.

WP5 Results

The neuroscience work within SENSOPAC has resulted in new recording techniques for obtaining highly detailed information from different types of deep-lying neurons. It has also resulted in some crucial investigations of neuronal function and the functional consequences of synaptic plasticity using gene manipulations. Finally it has seen the birth of a complete, conductance-based model of the cerebellar granule layer. These bits and pieces of information have been important to fill up critical remaining holes in our understanding of cerebellar function and have allowed for the generation of computational models, at different levels of abstraction, for exploring and describing the function of neuronal microcircuitry and brain networks.

The end-result of WP5 is an executable model of cerebellar function, "LSAM" (Large-Scale Analogue Model), incorporating simplifications made possible by our discovery of an accurate, low-parametric Purkinje cell model. In combination with results from the other neuroscience partners within SENSOPAC, we could conclude that the conventional model of cerebellar function is inadequate and need to be revised. The multivariate formulation of LSAM, i.e. a formulation in matrix form accommodating an arbitrary number of microcomplexes, was developed and implemented as a C program.

We integrated the executable implementation of LSAM with EDLUT, a spiking-level simulator developed for exploring neuronal circuitry function at a higher level of detail than in LSAM. This integration allows spiking models to first be developed in a stand-alone EDLUT system, and then be carried directly over to LSAM and used as-is. As an example of application, we plugged in an EDLUT simulation of a granule cell layer into LSAM, using the standard model of granule cells provided with the EDLUT package. LSAM proved to be highly stable, despite high levels of noise.

I.3.5 WP6

Leader: UEDIN, DLR, PAVIA

Participants: UEDIN, DLR, PAVIA, UPMC, ALTJIRA, LUND, UGR, UCAM - DENG

WP6 objectives

SENSOPAC has also integrated the output from the different work packages to develop haptically competent cognitive systems working on the highly advanced robotic arm-hand system used within the SENSOPAC project. In WP6, a first crucial step was to prepare and adapt the different control schemes to operate on the robotic system. With these solutions at hand, the major goal has been to compare and integrate machine-learning based approaches with neuronal circuitry-inspired and biomimetic neuroscience models for implementations of haptically competent cognitive systems in order to seek improvement to the haptic discrimination processes in the cross-talk, or exchange of ideas, between the systems.

WP6 Results

In cooperation between LUND/SICS and DLR, we implemented an interface between LSAM and the DLR robot arm using a shared memory approach. The main difficulty was that LSAM runs non-real-time, while the robot runs in hard real-time, at ten times higher sampling frequency. We were able to solve these problems using a handshake protocol based on semaphores and ring buffers, combined with decimation filters. The implicit low-pass filtering introduces delays having a negative impact on the stability of LSAM's control loop, but these problems could be solved by using a Smith predictor, to which the biomimetic cerebellar controller structure proved to be well suited.

UPMC developed a neuronal circuitry-inspired, artificial haptic discrimination system. The system uses neuronal spiking patterns, generated by the patterns of sensor activation, to discriminate between objects. In cooperation between LUND/SICS and UPMC, we analyzed the requirements of using LSAM for haptic perception. We concluded that LSAM, representing the arm-hand control area of the intermediate cerebellum, can be used as-is and can provide advantages in the haptic discrimination process. In addition, LSAM can be used to simulate internal exploratory processes of the brain, represented in lateral cerebellar systems, which is a natural part of brain object identification could be described.

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