

BIO-INSPIRED NEURO-CONTROLLERS FOR ROBOTIC HEADS

ADVANCED SEMINAR

submitted by
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Abstract

This report describes five existing bio-inspired neuro-controllers for robotic heads. The models of the controllers and the implementations are presented and evaluated in terms of performance to reproduce humand behavior, biological plausibility and scientific contribution.

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Chapter 1

Introduction and overview

Eyes are one of the most important organs of humans because they provide vision and orientation. Since a long time the architecture of the eyes fascinates people. The ultimate goal would be to create a working neuro-controller which has the same performance or even a higher performance than human eyes. The applications for such systems would be endless. During the last two decades bio-inspired eye movement controllers based on neural networks attracted the interest of more and more scientists. Different eye movement models have been proposed and some have been implemented into robot heads. The experiments and works often focus on different aspects of eye movements for example different eye movement classes or brain regions.

Within this report an overview of five bio-inspired neuro-controllers for robotic heads are presented and evaluated in terms of performance to reproduce human behavior, biological plausibility and scientific contribution. For a better understanding of the evaluated models an overview of the most important functional classes of human eye movement is given in the first chapter. The most important brain regions are briefly introduced in the last section of the introduction. This report presents the following five neuro-controllers:

- A biologically inspired controller for fast eye movements (2011) by Lesmana and Pai [LP11]
- A robotic head neuro-controller based on biologically-inspired neural models (2005) by Asuni et al. [ATL⁺05]
- Implementation of a neurophysiological model of saccadic eye movements on an anthropomorphic robotic head (2006) by Manfredi et al. [MMD⁺06]
- Biomimetic gaze stabilization based on feedback-error-learning with nonparametric regression networks (2001) by Shibata and Schaal [SS01]
- Cerebellar-inspired adaptive control of a robot eye actuated by pneumatic artificial muscles (2009) by Lenz et al. [LAP⁺09]

1.1 Functional classes of human eye movement

Within this section the functional classes of human eye movement are briefly introduced. Understanding the functions of the classes is essential for understanding the eye movement models.

Fovea

The fovea is responsible for sharp central vision. Animals with a fovea have high resolution of the visual input in a limited visual field. The human fovea is 1.5mm in diameter and has 140.000 cone cells per mm^2 [Gra04]. Every cone feeds onto 1 - 3 ganglion cells and every ganglion cell receives information from one cone.

Saccades

Saccades bring points of interests to the fovea. It is the movement between two fixation points. The eyes move in the same direction. Saccadic eye movements have to be very fast because during a saccade the images are blurred which degrades vision. Lesmana and Pai [LP11] explain that a saccade of 10 degrees takes less than 50 ms. Saccades are controlled by the brainstem and the cerebellum written by Schmitt et al.[SCSM14].

Vestibulo-ocular reflex

The vestibulo-ocular reflex (VOR) induces eye movements in order to compensate head rotations and linear movements (translations). The eyes move with the opposite velocity of the human head. The latency of the reflex initiation is less than 15 ms as stated by Leigh et al. [LZ15]. Vestibular eye movements are much faster than other visually stimulated eye movements because head motions are signalled sooner than image motions captured by the retina. The VOR is calibrated by the cerebellum.

Vergence

Eye movements in disjunctive directions are called vergence. When an object moves frontal towards an observer the eyes move in the opposite direction (convergence). If the object moves backwards the eyes rotate to the other side (divergence). Vergence movements are slower with 20 to 25°/s measured by Yang et al. [YZKH07] than saccades with 500°/s as written by Brouwer et al. [DBYB⁺02].

Smooth pursuit

Smooth pursuit allows an observer to closely follow moving objects. In comparison to the VOR it does follow an object while the head is not moving but the object is. VOR follows stationary object during head movements.

Opto-kinetic reflex

The opto-kinetic reflex (OKR) is a combination of smooth pursuit and saccades. When an object moves it is followed by smooth pursuit. After the object moved out of the sight-area the gaze shifts back to the starting point of the object (saccade). Stabilizing images with VOR is faster (less than 15 ms) than OKR which takes about 80-100 ms as written by Shibata and Schaal [SS01]. VOR is faster because it directly inverts the measured head movements in order to control the gaze. In reality VOR and OKR cooperate to stabilize the fixation point.

1.2 Relevant brain areas

In this section the relevant brain regions will be briefly described. Figure 1.1 helps understanding where the different brain regions are located.

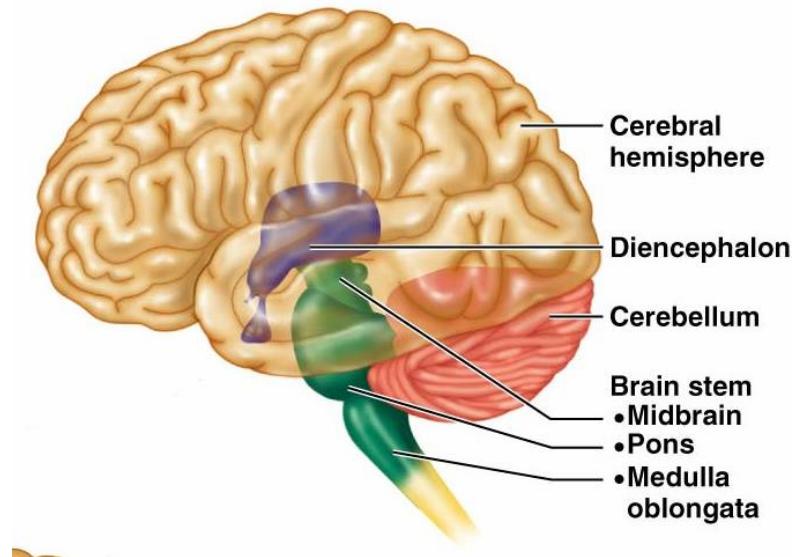


Figure 1.1: Brain anatomy [edo15]

Brainstem

The brainstem is responsible for motor movements and muscle activity. The learning processes of the VOR takes place in the brainstem and also in the vestibulocerebellum. Models combining the two brain regions were proposed by Coenen et al. [CS⁺96] and Arnold et al. [AR⁺90].

Basal ganglia

The basal ganglia is strongly connected to the brainstem. It controls saccadic eye movements by triggering the neurons in the superior colliculus which was described

by Hikosaka et al. [HTK00].

Somatosensory cortex

The somatosensory cortex holds information about planned eye movements. This is described in a work from Andersen [And89]. Paré et al. [PD11] suggest that the somatosensory cortex is late coming in the human eye circuit and that means that somatosensory cortex only enhances the visual system.

Superior colliculus

The superior colliculus (SC) is part of the midbrain which is part of the brainstem. The SC is able to activate saccadic eye movements. It consists of different layers which contain information about the surrounding world in retinotopic coordinates. Retinotopy is the mapping of the retina to the neurons. Neural activity within the layers move the gaze to the corresponding target in the visual field. The input for the activity comes from the basal ganglia.

Cerebellum

The cerebellum adjusts the brainstem control over time. It fine-tunes the system. For this report the vestibulocerebellum which is part of the cerebellum is focussed.

Vestibulocerebellum

The vestibulocerebellum is a part of the cerebellum and consists of the flocculus and the nodule. It is also called flocculonodular lobe. The flocculus is a small lobe of the cerebellum. It helps humans and animals to hold the balance of the body. Highstein [Hig98] writes that removal of the flocculus disables people from making VOR adaptions. Without the flocculus the eye can not maintain a non-central position after saccadic movements. The flocculus plays an important role in learning motor competences. It improves the brainstem doing fine adjustments of the motor movements. This shows that the flocculus is a very essential part of the brain for eye movements. Shibata and Schaal [SS01] mention that it is known that the flocculus participates in the VOR and the OKR.

Chapter 2

Bio-inspired neuro-controllers for robotic Heads

In this chapter five different neuro-controllers will be presented. Each chapter starts with a brief overview of the authors' work and continues with a summary of the model and the implemented controller. In the end of each section the controller will be evaluated. The works include robots with 1 - 7 degrees of freedom.

2.1 A biologically inspired controller for fast eye movements

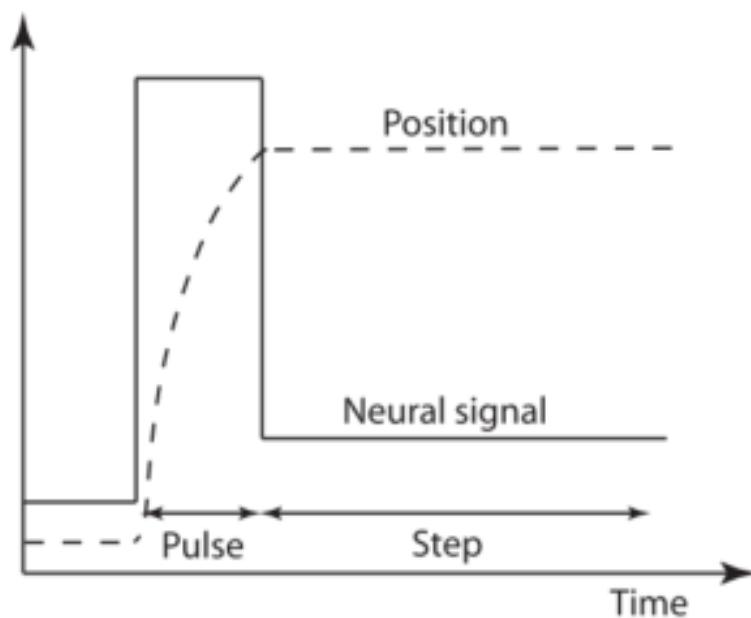


Figure 2.1: Pulse-step behavior during saccades.

Lesmana and Pai [LP11] describe a non-linear control algorithm for eye movements which was inspired by the behavior of humans and animals during saccades. A controller for very fast and accurate eye movement control based on neural networks is proposed. The robot consists of 1 camera with 1 DOF.

Fast eye movements model and implementation

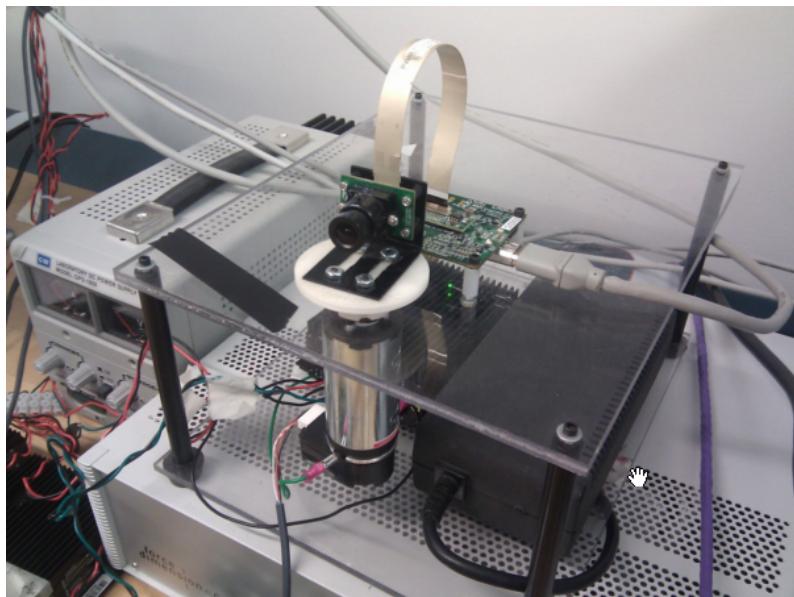


Figure 2.2: Experimental setup of the biologically inspired controller.

Lesmana and Pai [LP11] state that signal processing is faster than neural networks but it can easily become unstable which is a disadvantage. A non-linear pulse step controller seems to be used by animals and humans for eye movement control. The authors are motivated by two main questions:

1. What insights in biological motor control can be gained by building robots based on biological models and are their advantages in comparison to eye simulations?
2. Can biological control models of motor neuron-networks be applied to robots for effective robot control?

The model is based on the pulse-step behaviour of saccades. The characteristics are shown in figure 2.1. During eye movements the neural signal rises directly to a higher position and holds that position as long as the eye moves to the new position target (pulse). After reaching the new position the neural signal decreases to a lower point as long as the position has to be held (step). Lesmana and Pai [LP11] point out that the pulse-step model shown here is a simplification because usually there are not such sharp edges between pulse and step. The control model is a hysteresis controller or switching controller. It switches between pulse and step. Pulse moves the eye as fast as possible to the new target position and after reaching the target holding it during the step-phase.

The controller can be described by an "intelligent" PD controller. The feedback-signal is the control signal instead of the sensor measurement signal (controller output). A forward model estimates the system state out of this control signal which is referred to as an internal feedback and described in [Rob75]. In summary this means that the controller can estimate the output without measuring it, due to knowledge of the output.

Evaluation of the fast eye movements controller

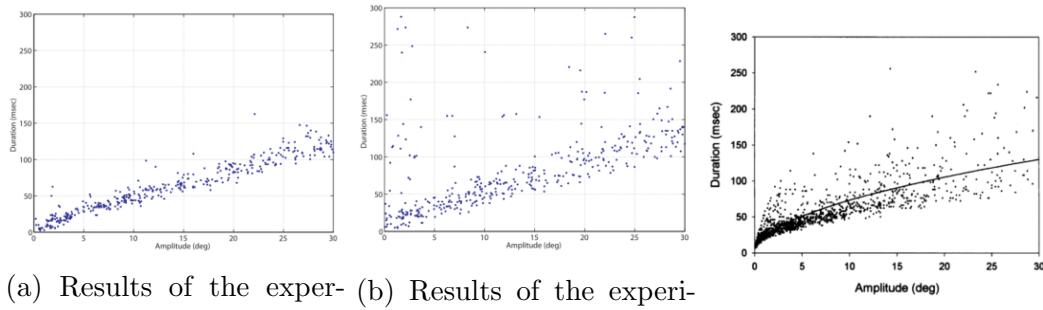


Figure 2.3: Relationship of saccade amplitude and duration

In a first step the model has been implemented in a computer simulation. A linear mass-spring-damper system was used as an input for the movements which should be followed. After learning the digital pulse-step controller gave good results of the wanted parameters with 99.8% fit.

Afterwards the model was implemented into the 1 DOF robot controller as seen in Figure 2.2. Lesmana and Pai [LP11] mention that there are differences between simulations and real-world implementations. Due to changes of physical properties the robot has to permanently make self adaptions. For example motor friction lead to a steady state error (2 degrees) which is higher than expected. The rising temperature of the motor changed the control dynamics. This fact shows implementations in robots can provide additional information on the behavior of models in the real-world. The model from Lesmana and Pai [LP11] can adapt to these changes by applying online learning. The authors used a recursive least squares with exponential forgetting for online adaption which is working properly when only steady input is provided. This may lead to instability.

Figure 2.3 shows a comparison of the relationship of saccade amplitude and duration of the robot and human data. (b) shows that with a camera cable connected the results are not as good as without the cable. The cable adds more dynamics to the system which makes it harder to learn the correct movements. However the results of (a) approximate human saccades properly and even (b) heads the right direction, only the variance is higher. The mean value is almost the same as far as it can be

interpreted from the graphs. This shows that neuron-networks can be applied to robots for effective robot control.

2.2 A robotic head neuro-controller based on biologically-inspired neural models

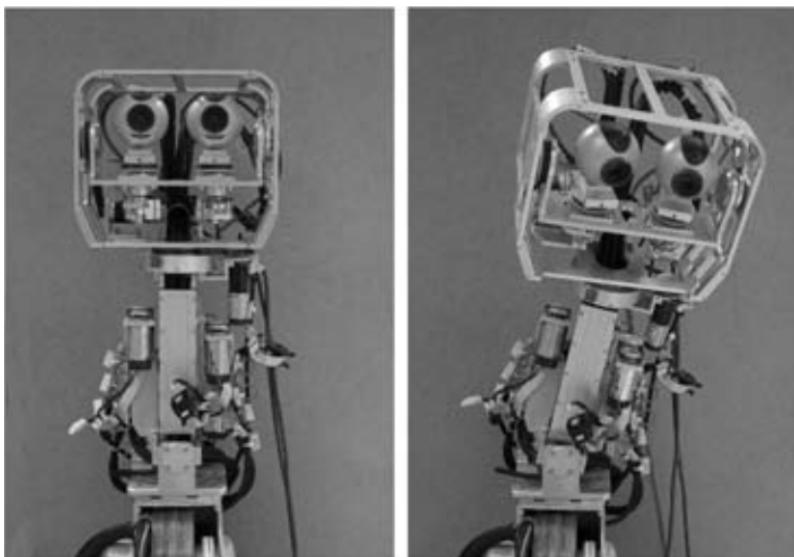


Figure 2.4: ARTS Robotic Head with 7 DOF used for the implementation.

Asuni et al. [ATL⁺05] present a robotic head implementation which addresses the inverse kinematics problem. The aim is to create a neural map structure which helps the robot to reach given fixation points. The implementation is based on organizing neural maps. The system relates sensor data with motor actions. The motor constantly influences sensor data during movements. These relations are stored. The model was implemented into a 7 DOFs robotic head (4 DOFs for the neck and 3 DOFs for the eyes). The robot is shown in figure 2.4.

Inverse kinematics problem solving model and implementation

By solving inverse kinematics equations it is possible to calculate the joint parameters for a desired position of the end-effector of a robot. This was described by Paul [Pau81]. Different solutions for the inverse kinematics problem exist. One solution is to iteratively optimize an approximation which can be very expensive in terms of computationallity. Another example would be to calculate the inverse transform which does not always has a closed-form solutions. For solving the inverse kinematics problem Asuni et al. [ATL⁺05] mention Kohonen's maps which allow to solve visuo-motor coordination problems. But Kohonen's maps suffer from the need of

prior knowledge. A probability distribution is needed before the robot can work on tasks. Kohonen's maps are not suited for dynamic environments in which continuous learning is needed. Due to this fact the presented model consists of self-organizing techniques.

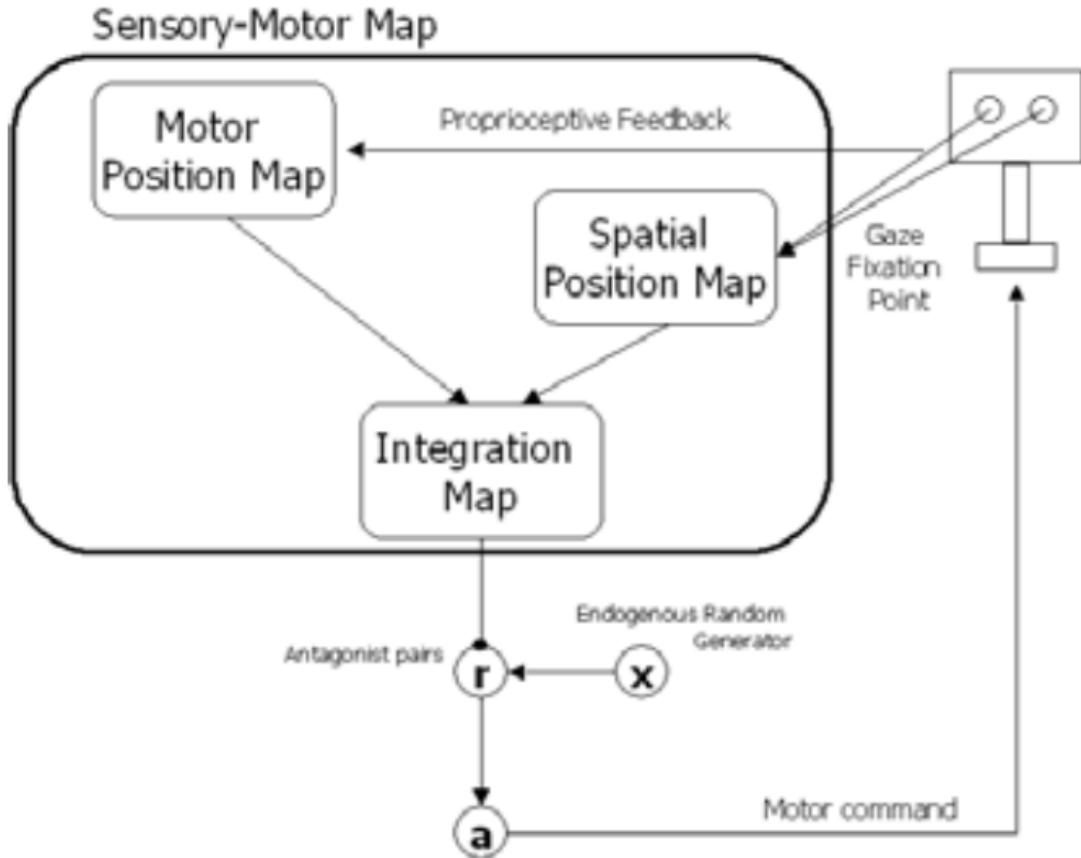


Figure 2.5: Implementation of the neural model.

The transforms of the inverse kinematics relates the possible movements in to joint actuator trajectories. The model used by Asuni et al. maps the gaze direction between an internal and an external reference system. For example for a target fixation point the joint configuration is saved in the external spatial reference system. The internal map encodes joint rotations. Different sub-areas of the input are mapped to single neurons in order to divide the space into subspaces. The coordinate mapping between the internal and external system is inspired by the DIRECT model (Direction-to-Rotation-Effector Control Transform) which was proposed by Bullock et al. [BGG93]. Spatial directions can be transformed to joints rotations. DIRECT correlates self-perception and visual feedback in order to move the joints. The implemented neural model which is illustrated in figure 2.5 contains four different modules:

- The Spatial Position Map (SPM) is the mentioned external spatial reference

system.

- The Motor Position Map (MPM) is the internal motor reference system which holds information about the joint space and self-perceptions.
- The Integration Map relates the SPM and the MPM to each other and activates the r cells to follow given directions.
- The Motor Area contains the x,r and a cells.

The maps were realized with Growing Neural Gas (GNG). GNG can add and remove neurons during the adaption processes. GNG was invented by Fritzke et al. [F⁺95]. The described paper is an improved version. For the SPM, MPM and the Integration Map only one map (Sensors-Motor-Map) has been used in the described paper which is an improved version of the first implementation of Asuni et al. [ALG⁺03]. In their first version the maps have been implemented separately.

Evaluation of the inverse kinematics problem solving robot

The DIRECT model has human-like functionality because it emphasizes moments of success in order to strengthen the synapses and the robot does not only learn during offline task handling but also while being online. The self-organization and topological preservation is inspired by the somatosensory cortex.

Before starting the learning process the system needs information about the number of joints and their motion range. During the experiment the initial learning took about 15 minutes (Intel Pentium 4 processor). Afterwards the eyes were able to follow given targets in the 3D space. Figure 2.6 shows the distance between the current gaze of the robot and the given target fixation point after each learning step.

In comparison to the first implementation of the model by Asuni et al. [ALG⁺03] the required memory space was less and also the computational time has been significantly reduced because the different maps (SPM, MPM and the integrations map) were combined in to one map. The map is called Sensory-Motor Map and correlates the gaze fixation point and the self-perception and the integration of those maps. The robot was able to gaze to target points and follow objects while some joints were locked or with symmetric angles with almost identical performance. During the experiment the eye joints were constrained in a way that the angles were symmetric. The experiments showed that this led to a more anthropomorphic behaviour. Asuni et al. [ATL⁺05] notice that this functionality could be used for implementing a VOR.

Asuni et al. [ATL⁺05] showed a working model for the solution of the inverse kinematics problem. It is very accurate and the computational performance was improved by using GNG. The robot was able to gaze points in the 3D space. The robot maps the vectors of the gaze fixation point onto the joint space in order to learn the inverse kinematics. Robots and humans often have the possibility to reach

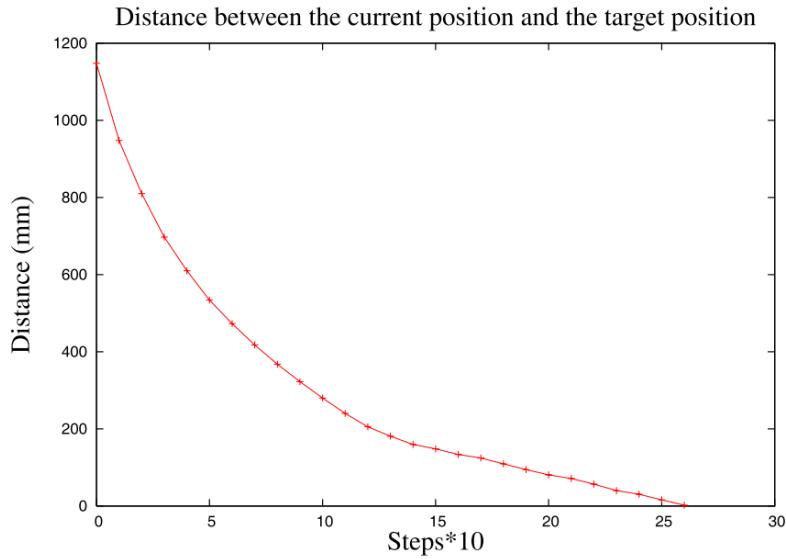


Figure 2.6: Distance between current gaze fixation and the given target.

the same target with different movements due to multiple joints. This is called the joint redundancy problem. The proposed model solves this problem and the inverse kinematics problem which can help robotic-engineers to solve similar problems with a different approach than the mentioned traditional ones like interation or inverse transform.

2.3 Implementation of a neurophysiological model of saccadic eye movements on an anthropomorphic robotic Head

Manfredi et al. [MMD⁺06] implement a biomimetic neurophysiological model based on brainstem saccadic circuitry to generate saccadic eye movements. As a robotic platform an anthropomorphic head was equipped with a 4 DOFs for neck movements and 3 DOFs for eye movements. Figure 2.7 shows the robotic head.

Model and implementation of the saccadic movements circuitry

The saccadic movement circuitry consists of different neuron-groups which control the eye movement. Inside the SC retinotopic maps are saved in different layers. Visual, memory and or motor target related activitiy is saved within the SC. The SC sends projections to the the brainstem saccade burst generator (SBG). The lowest sets of neurons are part of the SBG which is directly connected to the motoneurons for upward, downward, rightward and leftward saccades. The SBG is controlled by the inhibitory omnipause neurons (OPN). The OPN prevents the SBG from firing

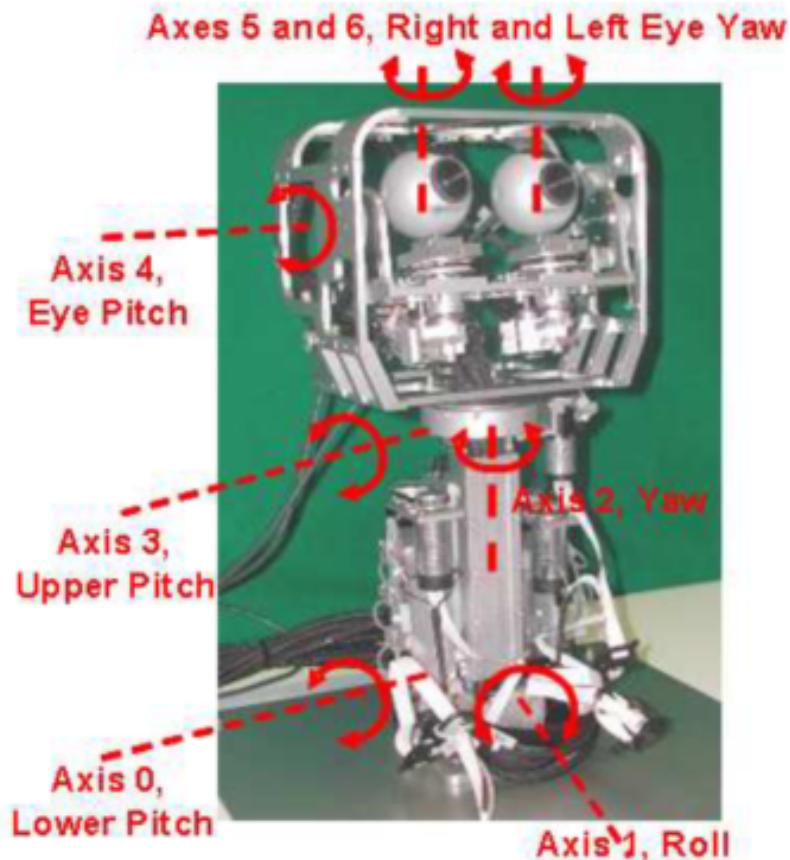


Figure 2.7: Robotic Platform with 7 DOF

during saccades.

The saccade vector is described in retinotopic coordinates (α, β) and transformed into coordinates of the SC surface (X,Y).

Evaluation of the saccadic movements circuitry model

The brainstem saccadic circuitry model is based on the SC and the SBG which shows that the model is implemented with strong inspiration by biology. However the interactions with the cerebellum, the basal ganglia and other cortical areas are missing. Manfredi et al. [MMD⁺06] plan to implement a model of the basal ganglia proposed by Girard et al. [GTSB05] in the future in order to include mechanisms for target selection.

Main goal was to test the execution of saccadic movements during the experiment. Vergence movements are also possible. A stimuli was positioned on different points of the visual field. The retinotopic images were correctly transformed to the colliculus maps. During the experiment the robot head did 210 saccades to 21 different points, 10 saccades for each target. The error compared to the brainstem saccadic circuitry model is 1.56° in average. The eye movement implementation can be considered as

working very accurate compared to the model.

Saccades take 200 ms to initiate after a stimulus. The delay times of the implementation were inspired by biological systems. The humanoid reaction time is realized by adding the difference between the computational time and 200 ms in order to get a constant, human-like initialization time of the saccades.

2.4 Biomimetic gaze stabilization based on feedback-error-learning with nonparametric regression networks

Information processing in humans is influenced strongly by the oculomotor system. The paper of Shibata and Schaal [SS01] shows a way to implement a learning control system which is able to stabilize the reflexes of gaze with focus on the oculomotor control. The system is based on the feedback-error learning (FEL) and non-parametric statistical learning networks. It combines OKR and VOR in one model. Only 1-axis camera movements were implemented due to simplicity of the presentation.

Model and implementation of the oculomotor System

In order to percept visual inputs the retinal image has to stay constant for a certain amount of time. Due to the body movements image stabilization is very important in order to get an acceptable visual input quality. The oculomotor control provides this image stabilization. The work from Shibata and Schaal [SS01] is inspired by the vestibulocerebellum. Research on this brain region suggests a FEL as a control concept. The proposed model combines FEL with nonparametric regression networks to build a fast learning biomimetic oculomotor controller.

The VOR-OKR system can be seen as a negative feedback controller which can not be easily applied because the dynamics of the eye system are not fully known and the feedback pathways have delays. The solution is an adaptive control strategy realized with neural networks which is inspired by the cerebellum and the brainstem. The VOR can be implemented as a feedforward open-loop controller using an inverse model control. The OKR is implemented as a negative feedback controller for the VOR. The FEL was added to the indirect path and provides the learning network. The network is provided with initial knowledge but self-adapts to the environment. The algorithm used for the FEL is a recursive least squares algorithm. The VOR-OKR model is shown in figure 2.8.

Evaluation of the oculomotor system

After 10s of learning the system achieves good VOR performance. Excellent performance is achieved after 40s even with nonlinearities due to off-axis effects. The

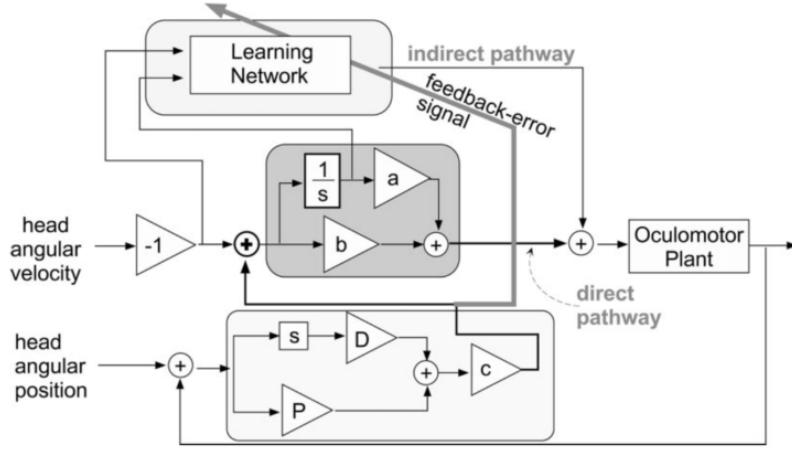


Figure 2.8: The VOR-OKR model with an added indirect pathway which is trained with the FEL strategy

performance of the OKR does not have such a high performance but Shibata and Schaal [SS01] write that in biology the OKR also lacks in performance in comparison to the VOR. The OKR compensates VOR for low frequencies. In the real world humans and animals are equipped with initial performance and then dynamically adapt to the environment with neural networks. The FEL is inspired by this process. Shibata and Schaal [SS01] did a first step on understanding the interplay between the oculomotor system, the visual processes and limb control in humans with focus on the oculomotor system. The model is inspired by the vestibulocerebellum. However the system does not have saccade-movements integrated. Shibata and Schaal [SS01] plan to additionally implement saccades and a zero-error smooth pursuit system in future work. Smooth pursuit is needed to track moving objects and to suppress the VOR so that only one eye movement class is executed at a time.

2.5 Cerebellar-inspired adaptive control of a robot eye actuated by pneumatic artificial muscles

Lenz et al. [LAP⁺09] proposed a model of the cerebellar to control robot eyes. The eye movement is actuated by pneumatic artificial muscles (PAMs). The goal of the implementation is to integrate image stabilization in a robot eye with focus on the VOR and to show that a cerebellar-inspired algorithm is able to solve real-world problems. Figure 2.9 shows the PAMs-robot.

Cerebellar-inspired PAM robot

Motor control of humans is mainly operated by the cerebellum and the brainstem. The focus of the work by Lenz et al. [LAP⁺09] is focussed on the cerebellum and

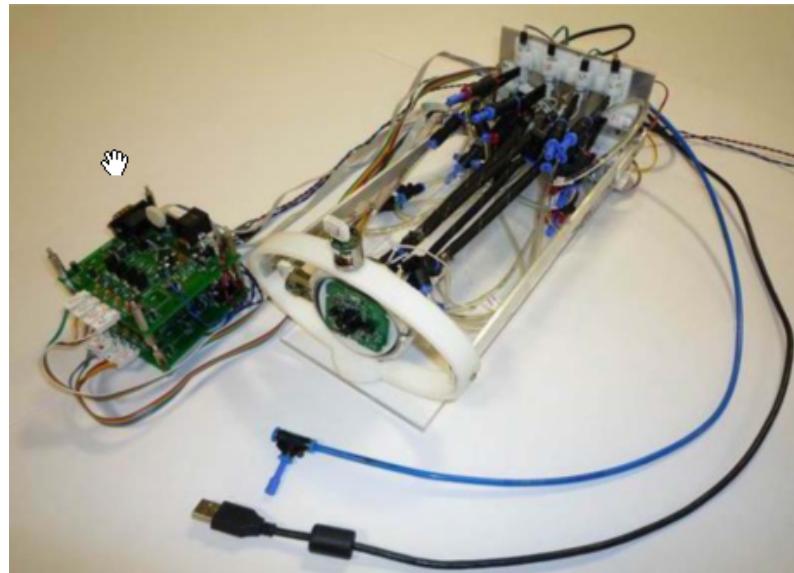


Figure 2.9: (Right) PAMs-robot connected to the (left) embedded controllers

based on the adaptive filter by Fujita [Fuj82]. In comparison to other models the adaptive Filter has advantages in terms of implementation complexity. It does not have theoretical limits on rates of learning and stability and it is possible to easily analyse and interpret the results. The model is not limited to eye movements but can also be used for arm movements which are also controlled by similar brain regions.

Input of the vestibular system is the head velocity signal which is used by the VOR to compensate head movements. The calibration for the VOR is done in the cerebellum. Input of the cerebellem are mossy fibers (MFs). The input signal is processed and distributed by granule cells (GCs). The axons of the GCs form parallel fibers (PFs). The PFs synapse on Purkinje cells (PCs). The synaptic efficacy of PF and PC is altered by correlated firing of climbing fibers (CFs) and PFs. The weighted sum of PF is the output PC. A least mean-mean squares rule is used for modelling PF/PC. An overview can be seen in figure 2.10. $e(t)$ stands for the error signal and is the input of CF. w_i is adapted by correlation learning. The described model has been implemented into the PAM robot.

A fixed low-order linear control is used as a model for the brainstem. The brainstem should be able to make rough eye movements and the cerebellum does the fine-tuning of the brainstem response.

The robot head was equipped with solid-state gyroscopes for measuring movements of the robot head and a 2 DOF robot eye for pitch and yaw. The head was mounted to a moveable platform to be able to create disturbances. The disturbances are compensated by the VOR.

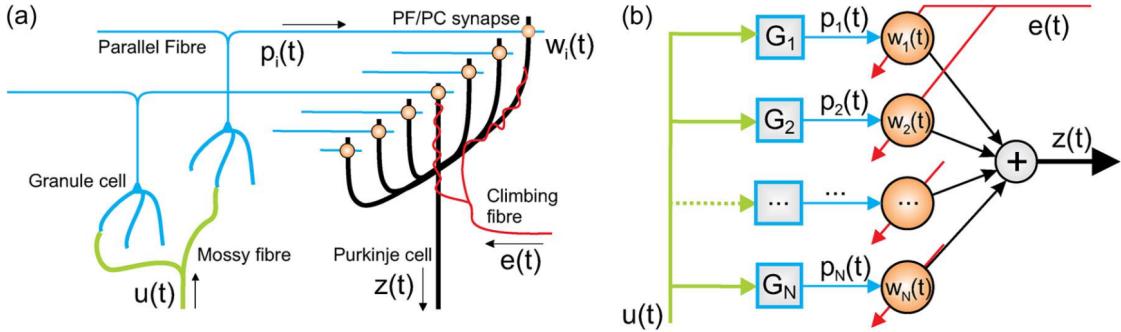


Figure 2.10: (a) schematic part of the cerebellar microcircuit. (b) the interpretation of a as an adaptive filter

Evaluation of the cerebellar-inspired PAM robot

The physical components and also the model are bio-inspired. Electrical motors are more commonly used for robot eye implementations but in terms of human-like realizations pneumatic realizations should be preferred. In terms of application variety, usability and performance the electrical motors often outperform pneumatic muscles.

Simulations and the implementation on the robot had a high similarity in performance which shows that the system was modelled accurately. The functional role of the cerebellum in the VOR was highlighted by Lenz et al. [LAP⁺09]. Electrophysiological recordings show that error signals from sensors are transmitted through the CFs. Model and implementation also directly connect the sensory error signal to drive adaption of the filter weights. An important aspect of the PAM robot algorithm is that the motor command is also an input of the cerebellum. This is inspired by biology and evidence can be found in a work from Büttner-Ennever et al. [BEH96] and in a work from Belton et al. [BM00].

The authors implemented the interplay between the brainstem and the cerebellum which shows that the model is advanced. The brainstem is responsible for gross motor movements and the cerebellum does the fine-tuning, same as in reality. The authors tried to implement as much detail from biology as possible which lead to the detailed and realistic implementation.

Chapter 3

Conclusion

Five bio-inspired robots have been presented in this report. Each work focusses on different aspects. Lesmana and Pai [LP11] described the pulse-step controller and implemented a controller for saccadic eye movements. First in simulation and later in a robot neuro-controller. They asked the question whether the implementation of eye movement into controllers is meaningful or if simulations of the models are enough. An important question because real implementation are more expensive and time consuming in the development. Lesmana and Pai [LP11] found many additional problems in their neuro-controller implementation which shows that only a simulation is not always satisfying. Hardware problems for example camera cables are very difficult to simulate and not every influencing factor can be foreseen. The dynamic changes due to camera cables were also mentioned by Shibata and Schaal [SS01]. One of the main goal of the models is to have robots which solve real world problems. If the algorithms are only run in simulations it cannot be figured out if the self-adapting programms run in a real world with much more dynamics. This shows that real implementations can provide important information and insights for future developments. Simulations can not cover all the complexity of real world problems.

Many different brain regions were covered. The works of Asuni et al. [ATL⁺05] solved the inverse kinematics problem with a very reliable 7 DOF robotic neuro-controller. The work can be helpful to solving existing inverse kinematics problems with the neural-network model based on the DIRECT model. Asuni et al. [ATL⁺05] were inspired by the somatosensory cortex. The work from Manfredi et al. [MMD⁺06] is based on the superior colliculus, but implementation of the basal ganglia and the interplay with the cerebellum and the cortical cortex was still missing. Shibata and Schaal [SS01] tried to implement parts of the brainstem and the cerebellar functions. In their work the eye movement classes for smooth pusuit and saccades were missing, but planned for the future. Lenz et al. [LAP⁺09] implemented the brainstem and the cerebellum in their model. The functions were inspired by biology and the model was very detailed. The interplay between the brainstem and the cerebellum especially the flocculus was explained and imple-

mented. This shows that the model from Lenz et al. [LAP⁺09] is very advanced and close to biology. The main goal is to solve real world problems with it.

Saccadic eye movements and the VOR are the most implemented functional classes of eye movements. Lesmana et al. [LP11] and Manfredi et al. [MMD⁺06] implemented saccades. Manfredi et al. [MMD⁺06] also mention that vergence is possible with their robotic system. Lenz et al. [lenz2009cerebellar] and Shibata and Schaal [SS01] focussed on the VOR. Shibata and Schaal [SS01] also implemented functions of the OKR. A bright variety of eye movements were presented and most of the authors plan to add missing movements in future works. Shibata and Schaal [SS01] for example plan to add smooth pursuit in future works.

As described the different authors show that the models still need some further development. Often not all brain regions are implementend but only specific ones. The same holds for functional classes of eye movements. In the real world the system only works properly if no brain region is missing. Missing brain regions lead to different disabilities. The interconnection of the different brain areas have to be carefully integrated into the existing models. The complexity of the system rises with an increasing number of modules. In future works probably more models and controllers will be combined if they worked in isolation before. Merging the evaluated works can help closing the gap between human and robotic performance. Of course it is still a long way to go to perfectly reconstruct human eye movements and human behavior. The models achieve relatively good performance in their specialized area of application. But no eye movement controller exists which combines the described characteristics in order to perfectly mimic human eye movement behavior. The different works presented in this report have shown that vision is a very complex task with many different input and output parameters and interrelations but a lot of interesting achievements have been reached so far and the development continues.

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