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# Robotics Insights for the Modeling of Visually Guided Hand Movements in Primates

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## Abstract

In this chapter we focus on the modeling of cortical activity related to planning and control of visually guided reaching hand movements in primates. We bring a new light to this problem by considering the visual-servoing framework in robotics. A review of representative theories and models describing the neuronal processes related to 3D representation of space, motor control and visuomotor integration in Neuroscience is first presented. The kinematics and dynamics of manipulators and the basics of visual-servoing techniques in robotics are then recalled. In particular, for the control of a robotic arm with a deported camera, we underline the fact that the task-Jacobian is dependent on all the joints of the kinematic chain linking the camera to the end-effector. This point suggests that the motor activity during a visually guided movement of the hand cannot be completely encoded within a body-centered reference frame as claimed by numerous models in Neuroscience. Finally, we present an experimental result showing the existence of gaze-related signals in the monkey premotor cortex during visually guided reaching. This result corroborates the idea that the eye position with respect to the head and the head position with respect to the body, which belong to the kinematic chain linking the eye to the hand, must also be coded by neurons in premotor and motor cortex.

## 1 Introduction

Several complementary approaches such as Neurophysiology, Psychophysics or Clinical studies are used in Neurosciences to characterize the activity of different cortical areas involved in the representation of space and the control of movements. Based on the analysis of experimental results, neuroscientists try to elaborate models to describe the functioning of the *Central Nervous System* (CNS), and characterize the nature of data processing performed in each area of the brain. For this modeling task, the point of view of roboticians may be of great interest. Indeed, the problem of perception and motor control is central in robotics. To conceive robotic systems able to navigate autonomously, engineers need to develop repeatable and robust algorithms to deal with geometry, mechanics and that allow to cope with many constraints such as real-time data processing, noisy measurements, etc. As they are used to take into account these physical constraints for the design of artificial systems, roboticians can be of some help for interpreting experimental results in Neuroscience in view of constructing models.

In this chapter we focus on the modeling of cortical activity related to planning and control of visually guided reaching hand movements in primates. To control such movements the CNS needs to deal with the sensory information that gives the spatial position of the target and the hand and coordinate the activation of different muscles involved in arm control. This task requires different kinds of data processing and coordinates transformations that allow to integrate multisensory data for space representation and define sensorimotor links.

In a first trend of opinion, numerous authors proposed that the planning and control of voluntary movements was based on the coding of the hand movement direction with respect to a body-centered reference frame [25], [26], [15]. This way of thinking was corroborated by the interpretation of reaching experiments in monkeys and inspired by the geometric models of manipulator that link the extrinsic representation of hand position in shoulder-centered reference frame and the intrinsic articular joint parameters of the arm. More recent models propose that the reference input for control is the difference vector between the hand and the target expressed in eye-centered reference frame [13], [18], [46]. This latter idea seems to be consistent with current models that suggest a multisensory spatial representation in eye-centered coordinates for reaching [42]. However, though many authors agree that the difference vector between the hand and the target is encoded with respect to the eye, most part of them still claim that the motor control of visually guided arm movements is independent from eye-position [46].

Our objective is to bring a new light to this question by considering the recent visual-servoing framework in robotics. We propose to identify the hand-eye difference vector, expressed in eye-centered reference frame, with a vision-based task function. On this basis, the reaching movement can be described as a visual servoing task with deported camera. Underlining the fact that the

task-Jacobian is a function of each joint of the eye-to-hand kinematic chain, mathematical arguments can be derived to show that the motor control not only depends on the angular joint parameters of the arm but also on the position of the head and the gaze direction.

The chapter is organized as follows: A review of representative theories and models describing the neuronal processes related to 3D representation of space, motor control and visuomotor integration in Neuroscience is first presented in sections 2. In section 3 we recall the models of manipulator kinematics and dynamics and give an introduction to the visual-servoing framework. On this basis, a discussion is proposed to consider possible analogies with the control of visually guided arm movements in primates. In particular we propose geometric arguments to justify the existence of cortical neurons sensitive to eye-position in cortical premotor and motor areas. Finally, an experimental result showing the existence of gaze-related signals in the monkey premotor cortex during visually guided reaching is presented in section 4.

## 2 The primate visually guided hand movement

Neuroscientists interested in the human ability to reach visual targets need to understand the brain visual processes related to 3-dimensional (3D) reconstruction of the environment and, more specifically, target localization in this 3D reconstruction. They also need to understand the neuronal processes underlying planning and execution of hand movements as well as the biomechanical constraints that the brain has to overcome. Our aim is not to thoroughly describe the outcome of all these fields of research. We present here selected results across these different fields that are necessary to understand how neuroscientists think this very frequent action is achieved.

### 2.1 Multisensory integration for 3D representation of the scene

In human and non human primates, the cortical representation of the surrounding world is essentially visual, as revealed by the large amount of cortex dedicated to vision. Therefore, our internal representation of space, necessary to execute the majority of actions in our everyday life, mainly relies on the visual system. But to be really efficient in every situation, our brain has to take into account other available information like our position in space and its changes in time, oculomotor information etc., to allow a unified and stable perception of the environment. How this unified and stable percept is processed by the brain remains a major question in Neurosciences.

The image of an object located in the visual field falls on both retinæ and stimulates the photoreceptors. Visual information about that object is then transmitted from the retinal ganglion cells through the optic nerve to different sub-cortical relays, the main of them being the lateral geniculate nucleus that in turn projects its afferents to the primary visual cortex (area

V1). Different attributes of the object, like its shape, depth, color or motion,... will be analyzed by different cortical areas located in one of the two main visual pathways. 1) The ventral pathway, classically called the “what pathway”, is mainly dedicated to the analysis of the shape and color of objects to allow their recognition. It starts in the first visual cortical area, area V1, and finishes in the temporal cortex after several analysis stages. 2) The dorsal pathway, called the “where pathway”, is dedicated to the analysis of motion and localization of objects in space. It starts in area V1 and ends in the parietal cortex after several steps of visual processing in the different visual areas specialized for the “where coding”. The receptive fields of visual neurons (i.e the portion of visual space viewed by a single neuron) are really small in area V1, less than 1 degree, and can cover the entire visual field in temporal or parietal cortex. Thus, the neuronal processing performed in the successive areas in both pathways allows the integration of the visual information over an increasingly larger portion of the visual space, leading to a more global representation of the visual scene. It also allows the analysis of more and more complex properties of the visual scene from simple attributes like bars in V1 to faces in the temporal cortex and complex motion in parietal cortex.

To produce any simple motor act such as grasping an object viewed in the immediate environment, we need to localize objects in the visual space, whatever the position of the eyes in the orbit and of the head on the trunk. Consequently, depending on the reference frame that is used, our brain needs to combine information about the position of the images of the objects on the retinae with information about the position of the eyes and of the head. The location and the nature of this neural processing is still weakly understood. Furthermore, retinae are not homogeneous, only the center of the retina called the fovea, is able to detect fine details. As a result, when we are visually exploring our environment, our eyes have to move continuously in their orbit so that the foveae can be oriented towards the different regions of interest of the scene. The eyes are usually moving together with the head and the primate ocular system has to stabilize the gaze via two mechanisms, the vestibulo-ocular (VOR) and optokinetic (OKR) reflexes. The VOR relies on vestibular inputs to compensate for head movement relative to the visual environment. The OKR relies on motion detectors in the retina to compensate for image movement. The consequence of both mechanisms is the image immobility (stability) on the retinas, for a duration long enough to allow signal transduction. The saccades quickly move the eyes between image stabilizations when these reflexes reach their limits.

This dynamic aspect of the localization problem implies that successive “snapshots” must be memorized and combined in order to build a complete representation of the visual scene. This also means that any mechanism involved in this localization processing has to be reactive enough to update new spatial position several times per second.

Clinical studies in humans have described some difficulties in locating visual targets in space following lesions of the posterior parietal cortex [3].

Electrophysiological studies performed in behaving monkeys showed that this cortical area integrates visual and oculomotor signals; light sensitive cells respond with a certain neural gain depending on where the monkey is looking at.

For many years the parietal cortex was believed as being the only cortical site for processing space localization, following the pioneering work of Andersen and col. [1], [2]. Since then, eye position signals have been observed in many cortical areas. In the ventral pathway, effects of eye position have been demonstrated in area V4 [11] and in the inferotemporal cortex [40]. But most studies have focused on the dorsal pathway more involved in localizing objects in space. These works have shown that neurons modulate their visual activity as a function of eye position in several areas in parietal cortex [19], [24], [27], in medio-temporal areas [39] and in V3A [23]. Recent evidences showed that even primary visual cortex, area V1, classically thought as purely visual, participates as well to the neural localization processing by integrating retinal information with extraretinal information about direction of gaze [52].

Though our surrounding space is not flat, almost all the above studies have investigated a localization processing limited to a 2D space, because of the visual stimuli and the protocols used. Since the eyes are horizontally separated, the image of an object viewed in depth is projected on the retinae on slightly different locations, and the brain is able to measure this angular difference, called horizontal disparity, to reconstruct the position in depth relative to (behind, in or in front of) the fixation point. Many visual cortical cells, present in several cortical visual areas, are specialized in detecting and coding horizontal disparity and are classically considered as the neural substrate of depth perception. Studies performed in the primary visual cortex have extended the previous findings on neural spatial localization mechanisms to the third dimension by testing specifically disparity coding and varying the location of visual fixation in depth [50], [51]. For a large majority of V1 cells, horizontal disparity coding was shown to be dependent on the vergence angle in area V1 of awake behaving monkeys in such a way that this 3D property could be coded at a given distance of fixation but absent at others. Changing the distance of fixation, and thus the vergence angle, in absence of visual stimulation also affected the level of spontaneous activity of about half of cells, especially at short distances of fixation. Thus the effect of eye position on visual activity must result from the integration of visual and non visual cues. Among these non visual cues, the proprioceptive and motor signals coming from the oculomotor system are undoubtedly involved in this cortical processing.

The main conclusion of these studies performed in V1 [50], [51], [52], is that V1 neurons encode the position of objects in depth around the fixation point only for certain position of that fixation point in the 3D space. Bringing together the results on the effects of the viewing distance and those of the gaze direction in area V1, the authors come up with the proposal that cortical properties such as orientation and retinal disparity selectivities, that define shapes and volumes of objects, are optimally expressed in a limited range of

3D gaze directions so that information about stimuli in the V1 area is conveyed by cell populations only when the object is present within restricted volumes of space. These modules should be regarded as 3D fields and as being a part of the neural substrate that is involved in sensory-motor transformations for 3D space localization.

The neural modulation observed in the different visual areas could be the basis for encoding, at the population level, the position of objects in multiple coordinates, such as in an eye-, head- (see above) and even body-centered representation [12]. However, clear explicit evidence of such encoding at the single cell level, leading to the expression of a pure head- or body-reference frames, has not been demonstrated yet.

Although visual information seems to play a major role, spatial localization mechanisms must integrate not only visual cues, but also auditory, somesthetic, and vestibular cues. For example, it is necessary to be able to localize a sound in our visual surrounding space. An efficient way to achieve this ability is to have all sensory modalities coded in a common reference frame in order to allow them to participate coherently to the neural representation of space. A study, performed in calcarine V1 of an awake behaving monkey confirms this hypothesis by showing a decrease of latency of neuronal response when auditory and visual stimuli are coherently combined in the visual space [53]. Furthermore, another result obtained in parietal cortex reported that auditory information can be represented in eye centered coordinates [48].

Taken together, these studies suggest that visual information and, perhaps, information from other sensory modalities, are available and coded together with eye positions at all stages of the visual processing. These results imply that all visual areas are to some extent involved in the neural 3-D space localization processing. Information about eye position and head position (in parietal cortex) are implicitly represented at the population level but this does not rule out the possibility that a common reference frame centered on the eyes might be used to facilitate communication between visual and non visual cortical areas.

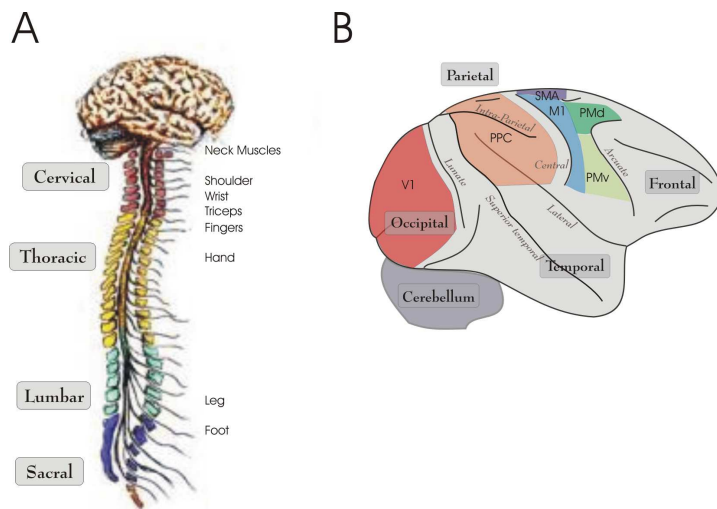
The distributed representation in the different areas composing the hierarchical visual pathways has the advantage to allow information about stimuli of different spatial scales and coding of a large range of visual attributes to be integrated in a similar way with non visual signals. However, some evidences suggest that the parietal cortex should play a more central role in 3D representation of space by computing a more global and integrated representation of the visual scenes [4].

## 2.2 Motor command

A complete description of the motor system is beyond the scope of this section. We will make a simplified depiction of the system anatomy, i.e. the muscles and the parts of the nervous system involved in a voluntary arm movement (main cortical areas, subcortical nuclei, and spinal cord) with the connections

between them. We will then put an emphasis on the main models that describe the coding of arm movements at the spinal and cortical levels. To move the arm, the CNS must generate force slowly with springlike actuators (muscles) that act against a skeleton. It must also analyze inputs from sensory transducers that provide feedback. In addition, the force produced by the muscle not only depends on the command but also on the configuration (muscle length) and the recent history of the limb (muscle fatigue).

There are many parts of the nervous system that are involved in the motor command (spinal cord, cerebellum and other brainstem nuclei, thalamus, basal ganglia, and many areas of the cerebral cortex. See Figure 1). Spinal cord has four divisions - cervical, thoracic, lumbar, and sacral - that contain, on the one side, motor neurons connected to the muscles, and, on the other side, sensory neurons receiving signals from the receptors in the skin, joints and muscles. Motor neurons connected to the muscular apparatus of the hindlimb are in the cervical division of the spinal cord. Spinal cord is linked to the brain (brainstem and forebrain) through sensory and motor pathways. There are many motor pathways descending down from the brain to the spinal cord. The main descending pathway is the pyramidal system projecting directly from the motor cortical areas (M1, PM, SMA and CMA; see Figure 1) onto the spinal neurons. This pathway allows the control of voluntary arm movement. The other descending pathways link different subcortical structures (cerebellum, and basal ganglia for instance) to the spinal cord neurons and are more important in the automatic control of posture, coordination, etc. These cortical and subcortical areas are linked to each other through multiple connections. To describe the physiology of the motor system for reaching, it is important to understand the lowest level of the control that results from activation of neurons in the spinal cord. The stretch reflex is a remarkable example of such a basic control loop which has an essential role in the control of posture. Beyond this reflex, numerous modulus that constitute the basic elements for the control of limbs - such as central pattern generators (GPCs) that allow a scheduled activation of muscles for walking - are located in the spinal cord. Experiments done by Bizzi et al [7] on spinalized animals have shown that microactivations of the spinal cord induce time varying force fields with a unique equilibrium point that allow to position the end-effector of limbs. To control the paw motion, they showed that the muscle activation produces a gradual shift of this equilibrium point from the initial to the final end-effector position, providing an efficient way to reject external perturbations. As proposed in [37], these force fields could constitute computational primitives used by the central nervous system (CNS) for generating a grammar of motor behavior. How do the cortical motor areas that project onto spinal motor neurons select and combine such primitives to execute a voluntary motion of the hand? To solve this problem, the CNS needs to relate the extrinsic configuration of the target and the end-effector, with the intrinsic parameters of the arm, i.e. its angular and inertia parameters. For roboticists these problems are referred to as kinematics and dynamics (see section 2). As



**Fig. 1.** A- Lateral view of the human brain and spinal cord. The four sections of the spinal cord are indicated on the left. The nerves that connect the spinal cord to the upper limb are in the cervical section. B- Lateral view of a macaque monkey brain showing four lobes of the cerebral cortex and the cerebellum. The main areas involved in visually guided reaching movements are mentioned (Visual, Parietal, and Motor areas). Many areas that are mentioned in the text are not shown because they are hidden: V2 and V3 lie in the Lunate Sulcus; MT and PO in the Superior Temporal Sulcus; the basal ganglia and the thalamus are under the cerebral cortex. Abbreviations: V1, Primary Visual cortex; PPC, Posterior Parietal Cortex; PMv and PMd, Premotor ventral and dorsal; SMA, Supplementary Motor Area; M1, Primary Motor. Main sulci are indicated in italics.

stated in section 1.2, a multisensory representation of space, which allows to code the target position in eye-centered coordinates, is available in PPC. On the other hand, numerous authors propose that the intrinsic parameters of the arm are coded in the motor cortex.

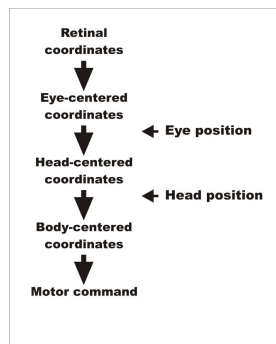
Most neurophysiologists agree that PPC and the frontal motor areas play an important role in visually guided arm movements (including processes such as localization of visual target, visuomotor integration and arm movement planning) (see [30], [54], for reviews). Currently, there is still a debate on the nature of variables controlled in the frontal motor areas, called the “muscles” versus “movement” debate. In the “muscles” side of the debate, there are arguments to show that individual neurons of the primary motor area control single muscles, whereas, in the “movement” side people claim that the control mainly concerns groups of muscles. This discussion is closely related to the control architecture and the location of potential modulus devoted to the computation of kinematics and dynamics. Related to this issue is the determination of the reference frame used to encode locations. Coordinate frames

may be intrinsic with encoded variables such as joint angles, joint angular velocity, or torques generated by the muscles. On the other side, they may be extrinsic, in a Cartesian frame of reference, based on a particular origin in space (fixation point, fovea, head, shoulder, hand, target, etc.). The models of robotics manipulators and the associated control theory have strongly influenced the elaboration of computational models in Neuroscience. As the control of the end-effector is usually defined with respect to the manipulator basis, the shoulder is often considered as the natural reference frame for motor control [14], [26]. Though these authors propose an extrinsic coding of end-effector position, these results can be interpreted in terms of intrinsic coordinates [33], [44]. On this basis, many authors agree that intrinsic parameters describing the configuration of joints between the hand and the shoulder are somehow encoded in the motor cortex. Contrary to robotics arms, these intrinsic parameters are not given by the direct measure of articular joints but deduced from the length of muscles. Besides this intrinsic representation of the arm configuration, the position of the hand and target are known to be encoded in extrinsic coordinates. Different reference frames have been proposed to this end. Numerous authors have brought evidences showing that, during the construction of a motor plan and the execution of a visually guided reaching movement, the CNS encodes a difference vector between the hand and the target in eye-centered coordinates [13], [18], [42]. Considering the role of vision for 3D representation of space in primates (see section 1.2), the coding of this difference vector in eye-centered reference frame seems rather natural. At this stage, an important question arises. How does the CNS control the intrinsic coordinates of the arm, which encode the configuration of the successive links with respect to the shoulder, by considering the difference vector expressed in eye-centered coordinates. This question, which is referred to as visuomotor transformation, will be considered in the next section.

### 2.3 Visuomotor integration

Many studies in the last 20 years tried to link the eye-centered visual representation of the target with the body-centered reference frame used to execute arm movements. The first prominent results were obtained by Andersen and Mountcastle [1]. They recorded single neurons in the posterior parietal area 7a that were coding simultaneously the position of the target on the retina and the eye position in the orbit. Andersen and colleagues then proposed a computational model showing that these two signals were sufficient to code for the head-related position of the target [2], [55]. By analogy, they made the hypothesis that such a mechanism would provide the body-centered position of the target by addition of the signal corresponding to head position on the trunk (Figure 2). However, very few neurons encode target location in a true head-centered reference frame. In such a reference frame, the receptive field of a single neuron should encode the same location in space independently of movements and/or position of the eyes. In fact, the neuronal processes un-

derlying the putative transformations from retina to head and body centered reference frames appear to be distributed over large populations of neurons. The visual and eye position signals interact to form “planar gain fields” in which the amplitude of the visual response varies linearly with eye position [2]. Brotchie and colleagues [12] showed that the head position signals necessary to compute body-centered coordinates of the target also exist in the parietal cortex at the level of population of cells. They conclude that this distributed representation could be the final stage for coding locations in space, or could be used as an intermediate step in the construction of body-centered receptive fields. Altogether, these results tended to prove that the model of

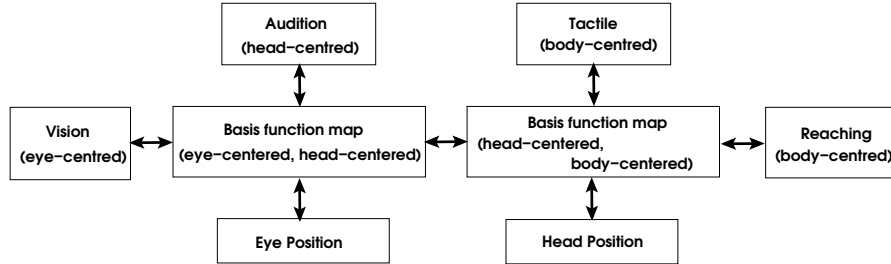


**Fig. 2.** Schema showing how body-centered coordinates of a visual target can be computed from its retinal coordinates and extra-retinal signals. The body-centered localization would be an ideal representation for planning an arm movement towards the target.

sequential coordinates transformation is computationally plausible, based on the existence of required signals related to retinal localization of the target, eye position in the orbit and head position on the trunk. Furthermore, the anatomic pathway from the visual cortex to the motor cortex goes through parietal areas; and lesions of the parietal cortex of humans and monkeys induce visuomotor disorders like optic ataxia (inability to reach an object perceived in space [34]).

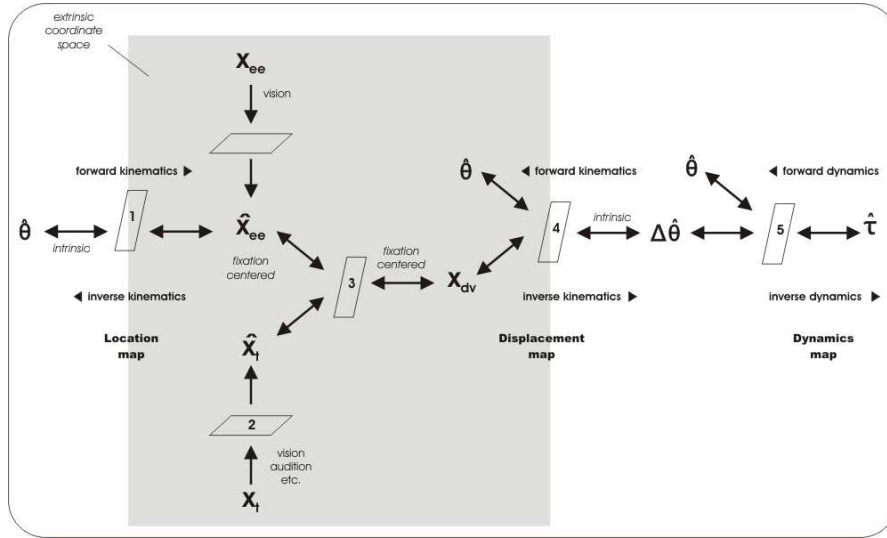
More recently, Pouget et al showed that reaching movements could be coded in eye-centered reference frame [42]. Their data indicates that the position of reaching targets is represented in eye-centered coordinates regardless of the sensory modality used to guide the movement (audition or vision). In addition, they conclude that, these representations are updated after each eye or head movement. As this recoding of auditory target localization in an eye-centered reference frame is counter intuitive in the scheme of the model shown in Figure 2, they proposed a computational model that reconciles multisensory integration and sensory guided arm movements [41]. This model relies on the combination of basis functions and attractor dynamics. Figure 3 illustrates

their basis function network that is designed to reach targets regardless of the input sensory modality. Interestingly, the network can predict the position of a target based on its position in another sensory modality, and also predict the consequences of a reaching movement in all sensory modalities. However, for Pouget et al. [42], the body-centered frame of reference is essential because it is used in the reaching module (right side of the network). R. Shadmehr and S.



**Fig. 3.** Schematic representation of a basis function network for reaching towards visual, auditory and tactile targets. The first basis function map encodes auditory and tactile targets in eye- and head-centered coordinates. This map communicates with a second map which encodes targets in head- and body-centered coordinates.

Wise [46] proposed an overall model inspired from robotics showing the different computations required for planning a reaching movement (Figure 4). The first step consists in computing a difference vector between estimated target location from visual sensors, and estimated end-effector (the hand) location from proprioceptive sensors. Once this difference vector has been computed, the system can work out the joint-coordinate representation that correspond to the actual movement of the arm. The final step consists in alignment between the joint rotations and force commands. As in the Pouget et al. model presented earlier, the authors added a network (network 2 in figure 4) allowing a multimodal representation of the target (for example, a bee may be a visual and auditory target for a reaching movement). The conclusion of these recent works is that movement planning is made in a fixation-centered (Shadmehr and Wise) or an eye-centered (Andersen and colleagues) reference frame. In an attempt to anatomically localize the networks involved in visuomotor integration, it is now accepted that all these computations are made in the dense parieto-frontal network [54]. There is also an agreement to say that the kinematics parameters are most encoded in the parietal areas whereas dynamics is most encoded in the frontal areas close to the central sulcus. In addition, it is very interesting to note that all these authors are strongly influenced by the robotics of simple two-joints effectors, considering that the motor command ( $\delta\theta$ ) of the primate arm only addresses the elbow and shoulder joints.



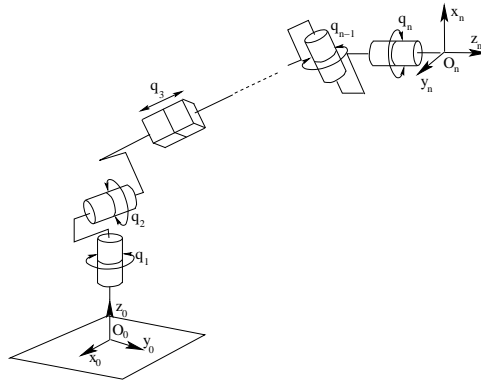
**Fig. 4.** Schematic of a series of computations for planning a reaching movement. Joint sensors provide a measure of arm configuration  $\theta$  and a camera provides an estimate of hand and target locations,  $x_{ee}$  and  $x_t$ , in camera-centered coordinates. A network with bidirectional connections (1) aligns joint- and camera-based estimates of end effector location. From the estimates of target and end-effector locations, another network (3) computes a difference vector  $x_{dv}$  between target and end effector. An additional network (4) aligns this difference vector with a joint-rotation vector  $\Delta\theta$ . This final transformation depends on the arm's configuration  $\theta$ . In some cases, you might want to move to a target that you cannot see, but that relates to a visual target. The network (2) serves this purpose. (From Shadmehr and Wise [46], MIT Press, with permission).

### 3 Robot manipulators modeling and control

In this section we first recall some theoretical results about modeling and control of robotic arms. In a first subsection we introduce the notions of operational and joint coordinates and the statement of kinematic and dynamic equations of manipulators which were developed by roboticists during the 80's and had important impact in the neuroscientific community interested in the coding of voluntary arm movements. These models have contributed to give rise to the concept of intrinsic and extrinsic spaces in Neuroscience. In a second subsection we present the more recent visual servoing techniques which allow to design closed-loop controllers with visual data as input. In view of these results, we discuss in a third subsection the possible analogies with visually guided reaching movement in primates. In particular, we propose a model to explain the existence of neurons in motor and premotor areas whose activity is modulated by eye position during visually guided hand movements.

### 3.1 Classical models of manipulators

Depending on the nature of the task to be performed, different mechanical structures have been proposed by roboticists for the design of manipulators. We focus here on the important class of open-loop kinematic chains, which include a sequence of rigid links connected by articulated joints, between the basis and the end-effector, and roughly follow the structure of primates arms. A general framework has been developed during the 80's to model the geometry, the kinematics and the dynamics of such serial linkages which have proved to be highly coupled and nonlinear [20], [47], [5]. Figure 5 represents a manipulator arm modeled as a serial linkage of rigid bodies including prismatic and revolute joints. Two sets of variables are usually introduced to



**Fig. 5.** Example of robotic manipulator with  $n$  links

model the kinematics of such a manipulator : the *operational coordinates*  $X = (x_n, y_n, z_n, \phi, \theta, \psi)$  describe both the position of the end-effector  $O_n$  and its orientation with respect to a frame attached to basis of the arm ( $\phi$ ,  $\theta$  and  $\psi$  stand for a parametrization of orientation such as the Euler angles), whereas the *joint coordinates*  $Q = (q_1, q_2, \dots, q_n)$  represent the measure of the successive joints. By considering the serial transformation between the basis and the end-effector, one can write the kinematic equation of the arm under the form  $X = f(Q)$ . This relation expresses the configuration of the end-effector as a function of the links involved in the kinematic chain. Now, to find the joint displacement that is necessary to move the end-effector to a specified configuration, one needs to solve the converse problem, called *inverse kinematics problem*. However, as for dexterity reasons the number of joints,  $n$ , is usually greater than six, the problem is not directly invertible and optimization techniques are required to characterize a solution among the possible joint configurations [38]. The geometric relationship between the situation of the end-effector and the joint coordinates is not sufficient to model instantaneous variations of the structure. To this end it is necessary to compute

the derivative of the kinematic equation to obtain a differential relationship between the joint displacement  $\dot{Q}(t) = dQ/dt$ , and the end-effector velocity  $\nu(t) = dX/dt$ . This relation is expressed through the definition of the robot Jacobian  $J(Q)$  as follows:

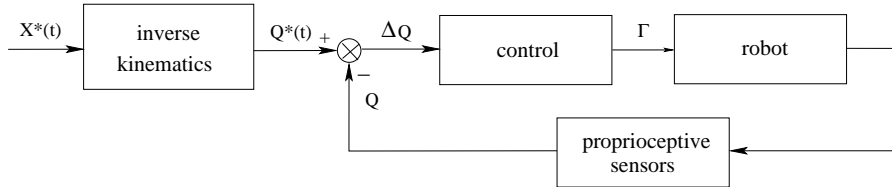
$$\nu = J(Q)\dot{Q} \quad (1)$$

As for the geometric problem, the converse problem called *inverse instantaneous kinematics* needs to be solved to determine the variation of joint coordinates, which allows to drive the end-effector along a prescribed trajectory. It is important at this stage to remark that the Jacobian  $J(Q)$  is function of the  $n$  joint coordinates, which need to be reevaluated at each point. This computation, which is time-consuming, states a difficult problem for real-time control.

Once we know from the kinematic study how to move the manipulator joints in order to drive the end-effector towards a target with a prescribed velocity, we must consider the manipulator *dynamics* to design an adequate control. The dynamics expresses the relationship between the arm configuration, the mass and inertia of different links, and the joint torques exerted by the actuators. This relation usually described by a differential equation is called *equation of motion*, and usually deduced from the Newton-Euler equations of mechanics or from the Lagrangian formulation. It expresses the actuator torques  $\Gamma$  as a function of the joint coordinates and their first and second order derivatives as follows :

$$\Gamma = M(Q)\ddot{Q} + B(Q, \dot{Q}), \quad (2)$$

In this equation,  $M(Q)$  is the so-called inertia matrix and  $B(Q, \dot{Q})$  gathers the effects of gravity, Coriolis and centrifugal forces and frictions at the joint level. On this basis, the closed loop control can be designed according to the diagram represented in Figure 6. In this scheme, the desired configuration of the end-effector comes as the input and the inverse kinematics is used to express the corresponding reference value of joint coordinates. The control torque  $\gamma$  is then defined as a function of the gap  $\Delta Q$  between the current value of joint coordinates, provided by the measure of sensors, and the desired one. This



**Fig. 6.** Classical diagram for the control of manipulators

closed-loop control model has been considered with great interest by neuroscientists. Indeed, the dynamic link between articular parameters and spatial

position of the end-effector offers a mathematical model for human arm control. The notions of operational and generalized coordinates have contributed to the definition of two complementary spaces in Neuroscience: an extrinsic space given by the endpoint of movement and an intrinsic space given by the joint angle and muscle activations needed to achieve the movement endpoint [36]. Several models of control inspired by this scheme have been proposed to describe the motor activity during a reaching task [29]; the authors identifying the basis of the arm with the human shoulder and the end-effector with the hand.

As long as the position of the target with respect of the robot basis  $X^*$  is perfectly known, proprioceptive sensors are sufficient to determine the current value of articular coordinates  $Q(t)$  to implement the control scheme of Figure 5. In practice, the configuration of the target is not *a priori* known and the use of exteroceptive measurement is required. Artificial vision offers an efficient way to cope with this question. The basics of visual servoing techniques, which allow to combine vision and control in robotics are recalled in the next paragraph.

### 3.2 The visual servoing scheme

Thanks to the high frequency of the CCD cameras which equip the robots today, it is possible to design closed-loop controls in which the error to regulate is directly expressed as a function of visual data. This approach, called *visual servoing*, is based on the definition of the so-called *interaction matrix* which defines a differential link between a vector of visual data and the relative position of the target with respect to the visual camera [21]. The *task function* formalism, which was introduced in [43], allows to define such vector functions of sensory data within a rigorous mathematical framework. Task functions can be viewed as a generalization of operational coordinates. On this basis, a new control diagram can be defined, in which the reference input is no more the position of the end-effector but a vector function  $e^*$  of visual data, which corresponds to image features at the expected position of the camera. In this control diagram, which is represented in Figure 7, the current value of the task function  $e$  is deduced from an extraction algorithm in the camera image plane. According to this diagram, as the control is directly defined as a

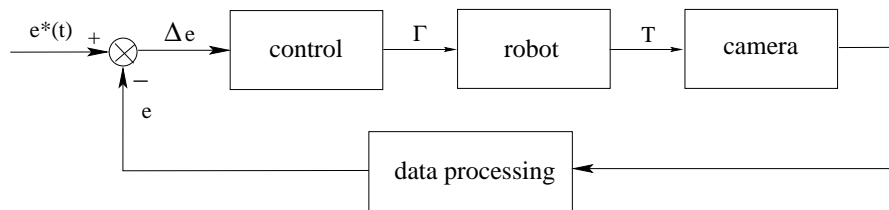


Fig. 7. The visual servoing scheme

closed-loop function of visual data, the robustness with respect to measure uncertainty and modeling errors is naturally increased. Different visual-servoing techniques have been proposed which consider either bidimensional features in the camera image plane (image-based visual servoing) [16], or an evaluation of the target configuration with respect to the camera (position-based visual servoing) [35]. Depending on applications, the camera may be deported or attached to the end-effector of the robot. In both cases, it is possible to express the differential link between the vector of visual data  $e$  and the vector of angular coordinates  $Q$  by a relation of the form:

$$\dot{e} = \varphi(Q)\dot{Q} \quad (3)$$

This equation can be viewed as a generalization of equation (1). In this relation,  $\varphi(Q)$  is defined by the product of three matrices as follows:

$$\varphi(Q) = CLJ(Q) \quad (4)$$

where  $C$  is a combination matrix, which allows to consider more than  $n$  visual signals,  $L$  is the interaction matrix which depends on the nature of visual features, and  $J(Q)$  is the robot Jacobian  $J(Q)$  introduced by equation (1). As a result  $\varphi(Q)$  is clearly dependent on the successive joints  $q_1, \dots, q_n$  of the kinematic chain.

### 3.3 Discussion

Considering this last development, it is now interesting to go back to problem of modeling visually guided arm movements in primates. To illustrate our purpose, let us look at the drawing in Figure 8, which represents a human being executing a reaching hand movement towards a visual target. According to the development presented in §2.1, the 3D position of the target is initially encoded with respect to the eye-centered reference frame  $F_E$ . If we compare this task with the one of driving the end-effector of a robotic arm towards a visual target, there are basically two ways of modeling the problem.

- In the first one, we may suppose that a localization process allows to reconstruct the position of the target with respect to a body-centered frame  $F_S$ , attached to the shoulder. Such a body-centered representation can be obtained by combining the visual position of the target in eye-centered coordinates with the proprioceptive measurement of eye position in the orbit (i.e. with respect to the head) and of head position on the trunk (i.e. related to the body). On this basis, it is possible to implement a control scheme for the arm, similar to the one represented in Figure 6. In this case, the reference input  $X$  is defined by the difference vector between the position of the hand and the position of the target, expressed in the reference frame  $F_S$ . This first control approach seems to correspond rather well with a part of models in Neuroscience which suggest that motor cortical neurons encode hand movements in a body-centered reference frame [15], [25], [26]. However, from an automatic

control point of view, the transformation of visual data into a “blind” body-centered reference frame, which is at the basis of this control scheme, does not appear very robust. Indeed, the need to use proprioceptive signals to express the target position with respect to the basis of the arm introduces inaccuracy in the control loop. It is a well-known result in robotics that sensor-based control schemes, for which the error to regulate is directly expressed in terms of sensory data, are more robust with respect to modeling and measurement errors than methods involving a step of state reconstruction. Furthermore, though early ideas about the common reference frame for target and hand representation in the CNS focused on body-centered reference frame, more recent research however suggest that both data are encoded in eye-centered frame [13], [18] [41]. All these elements suggest a second control scheme.

- The second way of modeling the reaching task, is to consider that the reference input is still the difference vector between the position of the hand and the target, but now, expressed in eye-centered coordinates. This idea, which is today shared by numerous authors is illustrated by the control diagram proposed by Shadmehr and Wise [46], which is reported in figure 4 (left part). To compute the location of the hand with respect to the eye-centered frame  $F_E$ , the CNS could use visual and proprioceptive information about the arm, as illustrated by the network 1 in Figure 4. If the image of the hand falls on the retina, its location can be directly determined with respect to this frame. However, if the hand is not in the field of view, the proprioceptive information of the arm but also the neck and eye are necessary to determine its position with respect to  $F_E$ . Note that proprioceptive measurements were also necessary, in the first control scheme, to compute the position of the hand with respect to the shoulder frame  $F_S$ .

On this basis, the reaching movement can be viewed as a visual servoing task with departed camera and represented by the diagram of figure 7. By analogy, the task function  $e$  can be defined as the hand-target difference vector expressed in frame  $F_E$ . In that case, the vision-based control of the hand is related to the variation of the complete kinematic chain from the eye to the hand. This kinematic chain is represented in Figure 8 as a sequence of dotted-lines ellipsoids linking the eye frame  $F_E$  to the hand frame  $F_H$ . According to the formalism introduced in subsection 3.2, a vision-based controller for this system would be expressed as a function of all the joints of this chain. Indeed, the matrix  $\varphi(Q)$  that appear in equation (3), is dependent on the whole set of joint coordinates  $Q$ , at each time.

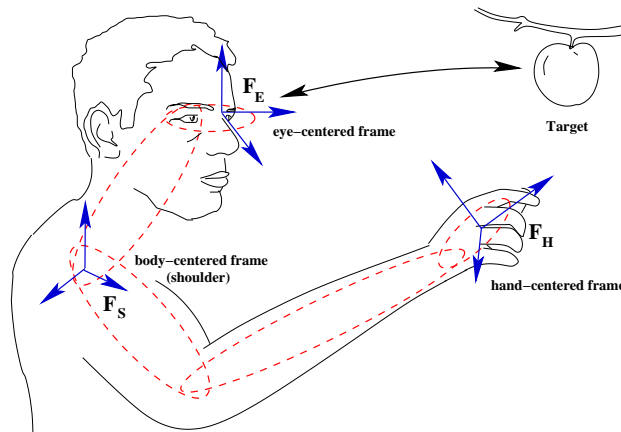
By analogy with this model, if we agree with the idea that the difference vector is encoded in eye-centered coordinate, we could expect that the motor neurons involved in the control of the visually guided hand movement be sensitive to the variation of any joints of the kinematic chain that links the eye to the hand. In particular their activity must be dependent on the direction of gaze and the orientation of the head with respect to the trunk. However, although the existence of neurones encoding the joint parameters of the arm

has been showed in the primary motor cortex M1 and in the premotor areas PMv and PMd [44], [33],[49], [45], the influence of eye position or head position on the activity of motor neurons has only been marginally reported [8], [31], [17]. More surprisingly, considering the fact that the difference vector is encoded in eye-centered coordinates, some authors claim that the activity of motor neurons is invariant with respect to variation of eye position. This reasoning, which still reflects the idea that premotor and motor cortical neurons encode the reaching motion in a shoulder-centered reference frame, is illustrated by the control diagram reported in Figure 4. Indeed, in this figure, the computation of the displacement map represented by the network 4 - that correspond to equation (2) - only involves the joint parameters  $\hat{\theta}$  of the arm. In other terms, according to this figure, the knowledge of the estimation of the arm configuration  $\hat{\theta}$  and the expression of the difference vector in eye-centered coordinates are sufficient for the CNS to compute the variation of joint parameters of the arm,  $\Delta\hat{\theta}$ , that allow to move the hand towards the target. Our model points out the insufficiency of this representation. According to our reasoning, this computation would actually be possible if the head and the eye remained fixed with respect to the trunk and the head respectively. Otherwise, as the difference vector  $x_{dv}$  is expressed in eye centered coordinates, any variations of the eye or head position would modify the expression of the Jacobian matrix  $J(Q)$  and therefore the control of all the joint parameters of the chain.

We believe that this analogy with vision-based control schemes provides a different light to explain the existence of neurons, in premotor and motor areas, whose activity is modulated by gaze direction, as reported by several authors. One of these results is presented in the next section. It concerns experimental results in monkeys showing the activity modulation of movement related neurons, in the dorsal premotor cortex, depending on eye position.

#### 4 Gaze-related signals in the primate premotor cortex

In the last 15 years, much attention has been devoted to the role of sensorimotor areas in coordinate transformations. The aim of most of these studies was to show that, in agreement with a sequential transformation from eye- to body-centered coordinates, premotor and motor cortical neurons encode hand movement in a shoulder-centered reference frame [25], [26], [15]. Noteworthy, eye movements were not monitored in these studies. Graziano and colleagues specifically searched for eye independent responses in the premotor cortex [28]. They concluded that premotor neurons “are in arm-centered, not retinocentric, coordinates”. However, in the legend of figure 3 (p.1056), they noted that “the magnitude of the response varied with eye position”. Similarly, Fogassi and colleagues, whose aim was to find somato-centered neurons in the premotor cortex, reported eye-dependent modulation of the single cells responses

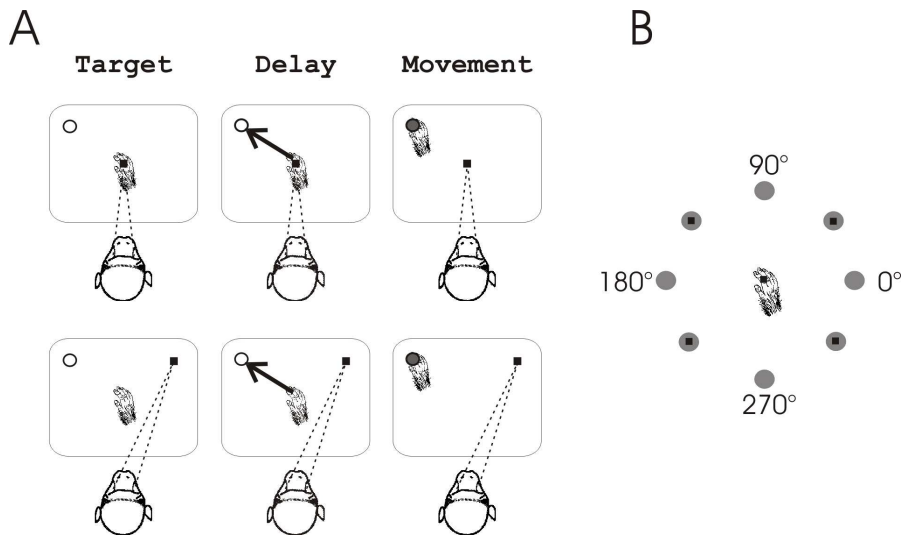


**Fig. 8.** Complete eye-hand kinematic chain involved in a visually guided reaching movement and different reference frames.

(see [22], figure 8 p. 149). At the same period, Boussaoud and colleagues [8] [9], [10] showed that the vast majority of both PMv and PMd neurons combine at least two directional parameters: arm movement direction and gaze direction in space. In their subsequent study [32], they trained monkeys to make center-out arm movements towards eight peripherals targets while fixating a point on the video monitor (Figure 9). As they systematically varied the position of the fixation point, they observed the gaze-related modulation of single neurons activity during the preparation and the execution of identical arm movements. Two examples of PMd neurons are presented in Figure 10. The graph in A shows that the preparation-related activity is maximum when gaze angle is  $45^\circ$  and when the upcoming movement direction is  $291^\circ$ . If gaze is shifted towards  $225^\circ$ , the directional preference of the cell is slightly shifted ( $337^\circ$ ) and less significant. The graph in B shows another example of PMd cell whose preferred direction is drastically changing with gaze direction. For this neuron, the preferred direction jumps from  $194^\circ$  to  $316^\circ$  with opposite gaze angles. At the population level, all these studies agree that more than 90% of the PMd neurons exhibit a preferred direction for arm movement. They also agree that movement-related (including selection, preparation and execution) discharge of more than 70% of the cells is modulated by gaze signals. In continuity with this work, Baker and colleagues [6] showed that gaze-related modulation of cortical motor activity also occurs in humans. Altogether these results show that eye-position is encoded by premotor dorsal neurons.

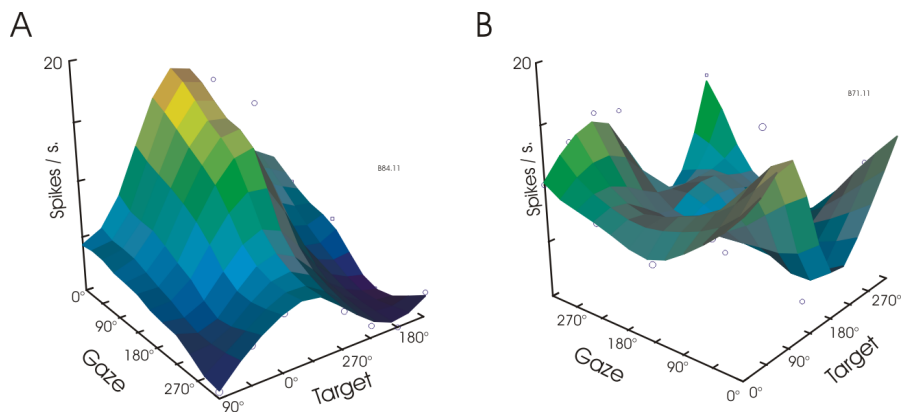
## 5 Conclusion

This chapter illustrates the interest of exchanges between neuroscientists and roboticists in the search for modeling the neuronal activity related to the per-



**Fig. 9.** Schematic representation of the behavioral task. The monkey is facing a video monitor with a touch sensitive screen. While the monkey is looking at the fixation point, with its hand resting at the center of the screen, a target appears. The monkey has to wait for the target dimming to make a pointing movement. The two lines illustrate two different trials in which gaze direction differs. The three columns correspond to the target presentation, the delay preceding arm movement (the monkey is preparing the movement but it is waiting for a go signal) and arm movement execution (the monkey makes a pointing movement towards the target without moving the eyes). In these two different trials, the monkey prepares the same arm movement but with two different gaze directions. B. Positions of the eight targets and the five fixation points that were used in the protocol. For each trial, the selection of one target and one fixation spot was pseudo-randomized. This design allowed Jouffrais et al. [32] to record PMd cells involved in arm movement planning and execution with systematic movement directions and gaze positions.

ception of space and the control of motion. Using the visual-servoing formalism used in robotics, we brought interesting elements for modeling visually guided hand movements in primates. Considering that the Jacobian of a vision-based task devoted to the control of a robotic arm depends on each articular joint, we proposed a model that accounts for the existence of neurons selective to gaze direction in the premotor area PMd. The same reasoning suggests that cortical motor neurons involved in arm movement control encode not only eye position signals but also head position signals (head with respect to the trunk). To our knowledge, such experimental results have not been so far reported. An interesting consequence of this result is that the eye-centered frame appears to be a common referential for observation and control. Indeed, this frame is used for coding the difference vector between the hand and the target and constitutes the basis of the kinematic chain involved in the control of



**Fig. 10.** Effect of gaze angle on the preparation-related activity of two PMd cells. Mean discharge rate of the cells during the delay period is represented as a function of target and gaze angles. Eight target positions and five fixation points were recorded. A. Example of a PMd cell whose discharge is maximal for a target located at  $291^{\circ}$ . This marked preference for  $291^{\circ}$  target is dramatically reduced and partially shifted ( $337^{\circ}$ ) when gaze is oriented towards  $270^{\circ}$ . B. Example of a PMd cell whose preferred arm movement direction is inverted (from  $316^{\circ}$  to  $194^{\circ}$ ) when gaze angle shifts from  $45^{\circ}$  to  $225^{\circ}$ . Preferred directions were computed for each gaze direction with two methods giving highly similar results: 1- maximum value of a sinusoid fitted on the discharge rates as a function of target position; 2- center of mass of the 8 discharge rates. Statistical significance was assessed with a bootstrapping test. See Jouffrais et al. [32] for details.

the arm. Does the eye-centered frame also constitutes the origin of the kinematic chains that make up the body and hindlimbs? This still open question is of great interest for the control of humanoid robots. Indeed, to control the complex structure of this kind of robot, it is necessary to stabilize particular reference frames which are not easy to determine a priori.

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