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Should mobile robots have a head ?

A rationale based on behavior, automatic control and signal processing

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Abstract. This paper presents an interdisciplinary study of the role of the head in multisensory integration and motor-control organization for the production of voluntary spatial actions. It combines elements from biology and engineering. First, morphological and behavioral characteristics of animals able to perform voluntary spatial actions through evolution are examined. The complexity of state-space representation and observation of multi-joint mobile robots is then described in the context of automatic control, and perception-related characteristics brought by the presence of a head are presented from the perspective of signal processing. Finally, the role of the head in locomotion and manipulation for animals and robots is discussed, paving the way for future robot design.

Keywords: head, voluntary action, behavior, mobile robot, sensory integration, biomimetics

1 Introduction

A robot is a machine equipped with sensors, which provide it with information about its internal state and about the environment, computers that enable it to process sensory data and elaborate motor orders, and actuators that make it able to execute movements. Robots should then be able to perceive, process information and act in the physical world. In order to endow robots with such capabilities, roboticists are free to use the most advanced methodologies and techniques as well as the best adapted materials. A priori, their work should not be constrained by biomimicry concerns as only performance objectives should guide it. However, in the quest of designing systems that are able to sense and drive their movement consistently, animals appear as living models of efficiency. For this reason, roboticists sometimes try to design bio-inspired robots. However, in most cases, the bio-inspiration focuses on a particular functionality that engineers attempt to reproduce. In this perspective, various bio-inspired systems have been designed. Among the most remarkable are the salamander robot



Fig. 1: Examples of anterior structures in different bilateral animals highlighting their heads, sensory and trophic systems. From left to right: Zygoptera, Sepiida, Felidae (*Panthera* lineage), Callitrichinae, Gekkota, Tetraodontidae, Culicidae, Casuarius.

in [12] that demonstrates locomotion modes based on central pattern generators, the use of insect optical flow for navigation in [25], the gecko robot in [18] whose leg coating texture reproduces adhesion abilities, the eel robot in [5] endowed with an electric sense, and, more generally, humanoids robots designed to reproduce bipedal walking [20]. Despite these encouraging achievements, a lot of work remains to be done to understand the key principles that endow living beings with such autonomous navigation capabilities and transfer them to robots. Developing research in this direction is possible only through interdisciplinary studies involving biology and engineering.

With this objective in mind, the present article aims at gathering a set of arguments from life sciences and robotics to demonstrate that the existence of the head under the process of cephalization ([16]) is linked to animals ability to perform voluntary spatial actions and simplifies the integration process of sensory and motor functions for navigation. First, morphological and behavioral characteristics of animals capable of voluntary spatial action through evolution are examined. Then, the complexity of state-space representation and observation of multi-joints mobile robots is presented in the context of automatic control. After that, some perception related features brought by the presence of a head are presented in the light of signal processing. Finally, the role of the head in locomotion and manipulation in animals and robots is discussed, paving the way for future robot design.

2 The Head in animals

The evolution of organisms is related to a large number of external (environmental) and internal (phylogenetic or historical) pressures [4]. Every organism has to perform a series of motor actions to ensure its fitness at any time of its life. These actions are produced by functional structures in response to environmental stimuli. The process of natural selection has governed the shape of these structures and their functioning under different but complimentary proximate and ultimate causes through the evolutionary time [31]. Therefore, each individual has to optimize various motor strategies to respond to the diverse constraints of its environment (abiotic and biotic) and to its physiological needs (i.e., feed and cover the physiological demands, find mates and cover the reproductive effort, find partners for social interactions, etc.). This ability to perform different motor actions through various integrated systems, such as

limbs or jaws, necessarily relies on appropriate decision mechanisms initiated and controlled by complex releasing factors [14]. Anatomy and functional morphology associated with developmental research make it possible to empirically categorize the structures and the motor patterns involved in these motor actions. Behavioral ecology and other disciplines (i.e., cognitive phenotypes studies) provide an understanding of their sensory-motor bases. Some of them are determined as taxes (animals simply heading towards or away from sources of stimulation), some other as fixed action patterns (FAPs, or activities with a relative fixed pattern of coordination [15, 27]).

The evolutionary and ecological pressures involved into a trophic web can be considered as playing a primary role (though not the only one) to explain the diversity of these actions in organisms. In such a web, individuals are either predators and/or preys at one time of their life and thus have to select actions within contrasting contexts to gain food and energy while avoiding being injured or killed. A rough review of all metazoan organisms into extinct and extant food web shows that they can be divided into three major categories, according to their primary feeding behaviors [6, 9]: fixed organisms with no voluntary exploratory movements, organisms whose movements follow any type of gradient (e.g., chemical), and organisms capable of voluntary movements. This difference remains in the diversification of all taxa, although our understanding of the earliest evolution of metazoans is still a controversial problem.

The earliest traces of voluntary motor actions seem to appear at the Ediacaran-Cambrian boundary (560-555 Mya). Within this context, ecosystem engineering attempts to explain how voluntary activities have affected the biological diversity of organisms through their ecological and evolutionary implications (i.e., nutrients flow modification, sediments transformation). Although faunas of both eras were probably temporally separated by a mass extinction, some forms of moving bilaterian animals that are characteristics of the Cambrian fauna are suggested to be present since the late Ediacara [6, 9]. Although their evolution is not discussed here, paleontological evidences (organisms and traces) suggest that bilateral organisms developed voluntary tasks associated with two main strategies in aquatic environment: movement on and in the substratum, and navigation at benthic and pelagic levels in the water column. From anatomical descriptions, these actions were associated with a structural anterior-posterior organization. Notably, some authors ([22]) suggested that hydraulic burrowing was performed by bilaterian animals with a frontal organ that can be called *head*. Thus, the earliest traces of voluntary motor actions appear to have been produced by bilaterian animals. From these geological times (Cambrian explosion) they have developed elaborate strategies such as active hunting and escaping from predators, suggesting a possible causal relationship between the spatial abilities and the morphotypes of these animals.

Most of the major groups of bilaterian animals show rather similar morphotypes with two successive anterior-posterior regions of the body: an anterior region, called *head*, cumulating a series of sensory systems (visual, olfactory, vomerolfactory, auditory, etc.) with specialized trophic systems, and a posterior

region comprising morphological devices permitting body deformations in order to move in determined directions. The head comprises a series of symmetrical complex structures (e.g., eyes, ears, whiskers, antennae) and the exteroceptive sensory organs (ESOs), that sense exteroceptive stimuli for actively interacting with the environment and generating voluntary spatially related actions (see Fig. 1). The head can be either fixed or mobile, probably to improve the success of actions implying the integration of sensory information or recruiting the trophic structure. This morphotype with accumulated morphological and sensory systems into the anterior region includes a central nervous system (CNS) to integrate the sensory information and produce coordinated motor orders for the body and the head (move towards a prey and catch it). Studying the evolution of such organisms through their centralized nervous system shows two alternative possibilities from the analysis of the brain–body complexity among extant Bilateria. The first one, a diffuse nerve plexus with ganglionated systems, probably existed in Ediacaran organisms that were not able to produce voluntary coordinated actions. The second one, an anterior cephalic nerve system (brain or a series of nervous ganglions) arose in the common Bilateria ancestor. From this point, ecological pressures could have triggered the evolutionary pattern of complex actions, in the context of two body regions with highly different morphological and functional traits. Indeed, within trophic webs, the predatory-prey strategies involved into an escalatory “arms race” can be as complex as needed to produce highly diversified morphological systems and FAPs under the control of the nervous system. Along the evolutionary process of the various phyla, these FAPs have been modulated by a series of traits such as learning or cognitive abilities. As soon as animals are able to voluntarily control their actions at any stage from initiation, they can exploit diverse ecological niches.

In conclusion, one of the main characteristics of all organisms that developed the ability to produce complex voluntary spatial actions along their evolution is the morphological, developmental and functional dichotomy of the body regions into a head, mobile or not, integrating the majority of sensory systems and the rest of the body.

3 A Head for state observation in mobile robotics

Although robots are not subjects to physiological needs, we show in the following that the morphological solutions that arose in animals capable of voluntary spatial actions are relevant for state estimation in mobile robotics. Consider the problem of endowing a multi-joint mobile robot with the capacity to autonomously drive its motion in space. The theoretical frameworks that allows engineers to formalize this problem is the one of automatic control, the science of modeling, analysis and control of dynamic systems.

Basics in automatic control. Three fundamental notions are used to describe the system to be controlled: the state, the control input, and the output. The state $\mathbf{x} \in \mathbb{R}^n$ is a minimum-dimension vector which fully describes the system configuration at each time. The state-space representation is not unique but



Fig. 2: Three different multi-joint mobile robots at LAAS: the flying manipulator Aeroarm (left), the mobile manipulator Jido (center), and the humanoid robot Talos (right). The usual choices for their root frame placement are displayed.

its dimension is imposed by the nature of the system. The control input $\mathbf{u} \in \mathbb{R}^m$ describes the rudders thanks to which the system can be driven and the output $\mathbf{y} \in \mathbb{R}^p$ is the vector of data provided by sensors. Using this formalism, the state-space representation of the system is given by :

$$\dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{u}), \quad (1a)$$

$$\mathbf{y} = g(\mathbf{x}, \mathbf{u}), \quad (1b)$$

where Eq. (1a) is a differential equation that describes the system dynamics and Eq. (1b) expresses the output as a function of the state and the control. Making the robot able to control its movement consistently as a function of its current state amounts to synthesizing a feedback control law $\mathbf{u}(\mathbf{x})$ that, injected in Eq. (1a), yields a closed-loop equation of the type $\dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{u}(\mathbf{x})) = \tilde{f}(\mathbf{x})$, uniquely determining the behavior of the robot as a function of its state. However, usually the value of the state is unknown as it cannot be directly measured. In order to implement such a closed-loop controller, one needs to estimate the state of the robot from the sensory data that are measured at the output, a fundamental problem in automatic control, known as the observation problem.

State space representation and control of a multi-joint mobile robot.

Contrary to manipulator robots, which are rigidly fixed to the ground by their basis, mobile robots can move freely in their environment. Depending on their locomotion mode they can strongly differ as shown in Fig. 2.

Let us first focus on the kinematics of multi-joint mobile robots by neglecting the dynamic effects induced by the acceleration of masses. The kinematic state of these systems must include a parameterization \mathbf{q} of their polyarticulated structure, hereinafter called *internal state*, and a parameterization of their pose \mathbf{p} , i.e. position and orientation with respect to the external world, that will be referred to as *external state*. In order to simply illustrate these definitions, let us consider the case of mobile robot made of three bodies linked by two rotational joints, as depicted in Fig. 3a. Each joint is actuated by a motor and thanks to the combination of both rotations this worm-like system is supposed to be able

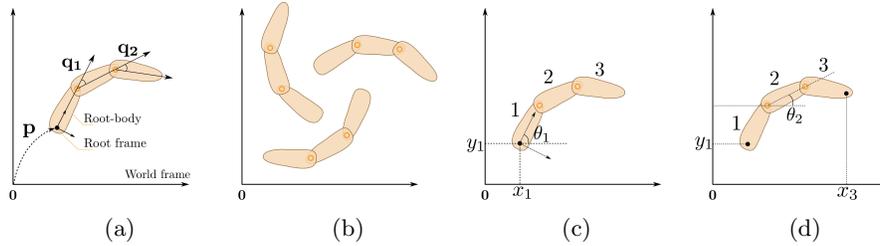


Fig. 3: Illustrations of the internal and external states of a simple polyarticulated mobile robot. (a): Absolute parameterization of the system in the plane. (b): Between the three cases depicted, only the external state of the system is changed. (c): The external state is parametrized by fully positioning the first body. (d): The parameterization of the external state is distributed on the three bodies of the robot.

move in the plane. The internal state of the robot is defined by two angles q_1 and q_2 . Once both angles are fixed, the pose of the robot in the plane depends on two degrees of freedom in translation and one in rotation as shown in Fig.3b. Hence, five scalar parameters are necessary to fully describe the kinematic configuration of the robot in the plane. Though the parameterization of the internal state by means of q_1 and q_2 appears to be quite natural, many parameterizations can be used to describe the external state. Figures 3c and 3d depict two of them, encoded with respect to a world frame. In the first one, the pose of the first body is fully determined by its orientation θ_1 and the coordinates (x_1, y_1) of a point attached to it. Whereas in the second case, the parameterization is distributed over the three bodies, including the abscissa x_1 of a point on the first body, the orientation θ_2 of the second body, and the ordinate y_3 of a point on the third body. From a mathematical point of view, if all variables can be determined with the same accuracy, both parameterizations are equivalent. In practice, we will demonstrate in the sequel that, as the measurement relies on sensors, these two parameterizations cannot be implemented with the same level of accuracy.

Extending this reasoning to the kinematic modeling of a tri-dimensional multi-joint robot with n rotational joints, it comes out that the state representation must include $n + 6$ parameters: n to describe the internal state plus 6 to describe the external state. Then, joint velocities are considered as control inputs. As soon as the dynamic effects induced by the acceleration of the robot bodies are no more negligible, kinematics modeling becomes insufficient. One needs then to consider a model of the robot dynamics in consistency with Euler-Newton's laws of mechanics (see [26] for details). In that case, the dimension of the robot state is doubled. Then, the internal state includes $2n$ parameters which encode the joint position and velocities, whereas the external state includes 12 parameters: 6 to parameterize the pose of the robot plus 6 to express its velocity. Then, the control input is the vector of joint torques.

The observation problem. As previously explained the state variables cannot be directly measured and must be reconstructed from data provided by sensors

at the output. Ideally, the sensors should be installed in such a way as to limit geometrical transformations and data processing. Usually the internal state of robots can be easily reconstructed from encoders located at the joints. It is then possible, modulo proprioceptive biases and flexibilities, to have a good knowledge of the internal structure of the robot and its variation. However, as previously explained, several parametrizations can be used to represent the external state. These parametrizations fall into two main categories as illustrated by the worm-like mobile robot example (see Fig. 3 (c) and (d)). In the first one, the exteroceptive sensors are used to fully measure the pose and the velocity of one of its bodies, called *root-body*, whereas in the second, the exteroceptive sensors are distributed on different bodies of the robot providing partial measurements of their pose and velocity. In view of the inherent proprioceptive biases and the flexibility of the structure these two strategies are not equivalent. Indeed, with the first strategy, the quality of the estimation of the pose and velocity of the root-body only depends on the accuracy of exteroceptive sensors mounted on it. Whereas using the second strategy, the estimation of the complete pose and velocity of any one of these bodies is degraded by proprioception inaccuracy. In sum, for the sake of accuracy, it is preferable to attach all exteroceptive sensors to one root-body in order to fully reconstruct its pose and velocity, and then deduce the relative configuration of other bodies from proprioception, rather than distributing the exteroceptive measurement on different bodies and then integrating them through proprioception. Furthermore, this strategy offers a natural way to decouple the exteroceptive anchoring of the robot in its environment and the estimation of its internal state. In practice, the 12 state variables describing the pose and the velocity of the root-body can be reconstructed from the measurement provided by an inertial central unit, combined with exteroceptive sensors such as cameras, laser, microphones, sonars, etc.

Head morphology and exteroceptive sensors. Considering the analogy with the notion of root-body in robotics, it is interesting to remark that, in animals, the anatomic symmetries of the head and the positioning of the ESOs on it offer natural spatial references. Whether they are eyes, ears, whiskers, antennae, or of any other sort, exteroceptive sensors are symmetrically placed on the head and turned outward, making the “center of the head” as a common virtual origin for multi-sensory perception. This organization provides a natural and simple way of defining right, left, up and down direction for the animal, playing exactly the same role as a reference frame in geometry. Following this idea, interesting works have been carried out in humans based on the perception of visual and auditory target alignment [3, 21, 30]. They reported the existence of a similar origin for vision and hearing in humans strongly linked to the position of the ESOs. The sagittal plane of the head and the direction of gravity provided by the vestibular system constitute two fundamental geometrical references which, combined with visual and auditory data, provide all the necessary kinematic information to fully localize the head pose and estimate its velocity with respect to its environment.

In summary, the accuracy of state estimation and the ability to discriminate space is improved and simplified by symmetrically gathering exteroceptive sensors on a single body. It is worth stressing that this is also one of the features provided by the head in bilaterian animals, which might be strongly linked to their ability to generate voluntary movements requiring state observation.

4 A Head for signal processing and cognition

Centralizing exteroceptive perception and its processing. The purpose of exteroceptive multisensory fusion is to combine a variety of sensory signals to mutually enrich them in order to make the perception as complete as possible. The fusion of these different signals can only be accomplished by collecting and matching information, a solution provided by the brain. For instance, the McGurk effect [17] and other experiences of sensory enrichment [8, 11, 7] are evidences that the addition or the removal of a sensory modality makes it possible to change the overall interpretation of a phenomenon. Alongside, the spatial proximity of the ESOs resulting from their attachment to a head, enables a spatially and temporally coherent acquisition of the different exteroceptive sensory modalities involved in multisensory perception. This seems essential since most of the physical processes living beings have to measure vary in space and time. Thus, if the ESOs were dispersed over the body, it would be necessary to estimate the measurement that they would have provided from a same spot and at the same time, in order to coherently enrich each other. For example, picture an imaginary creature with its ears placed on its hands and its eyes placed on its head. The spatial matching of the two resulting signals would require to estimate what the ears would have acquired if they had been located near the eyes, or vice versa. It goes without saying that this problem is of such mathematical complexity (equations of propagation, diffusion, diffraction, dynamics, etc.) that the centralization of ESOs on the head considerably simplifies the problem of coherent multisensory fusion. Cephalization, the evolutionary trend in which the concentration of the nervous system along with the migration of the ESOs result in a head, thus provides an efficient solution with regard to both acquisition and processing of multisensory signals.

Shortening of the brain-ESO transmission channel. A second feature provided by cephalization is the proximity of the ESOs with regard to the CNS. This observation relates to the fields of information theory and data transmission, which attest that shortening a transmission channel limits a large number of undesirable effects, such that attenuation, phase distortion, delays and different noises that depend on the type of transmission and on the environment. According to Shannon [28], who connected the bandwidth of a communication channel to its signal-to-noise ratio introducing the notion of channel capacity, the less distorted the signal, the higher the admissible bitrate. In the context of visual, auditive and inertial data transmission, shortening the connections between the brain and the ESOs is one way of increasing the capacity of this transmission

channel in order to increase the admissible flow rates which contribute to the richness of animal perception.

Stiffening the exteroceptive kinematics. Another interesting characteristic of the head is the kinematic limits that it imposes between the ESOs, especially in the clade of craniates. These animals are chordates with a cartilaginous or bony skull protecting the anterior part of the CNS. This rigid support strongly constrains the mobility between the ESOs which are fixed on it, limiting it to voluntary and very well calibrated displacements (eye saccades, ear and nose inflections, etc.). These kinematic constraints simplify the mathematical relationship between the signals acquired by different sensory modalities, enabling simple implementation of intermodal processes. For instance, the vestibulo-ocular reflex relies on simplified and very well calibrated transformations between the inner ear and the eyes. Moreover, these kinematic constraints make it easier to estimate the relative placement of the various ESOs, by reducing the number of parameters to be estimated. For instance, the distances between the two eyes, the two ears, the inner ears and the eyes, etc., are constant in most craniates. Thus, the estimation of the extrinsic calibration of the ESOs, which is necessary for multi-sensory fusion (see [33]), is simplified.

Head mobility for enhanced perception As the ESOs are gathered on it, endowing the head with sufficient mobility and proprioception is a way of mechanically filtering and stabilizing perception. Indeed, as the head is attached to the body, dynamic effects of the body moving during locomotion may induce disturbance on exteroceptive measurements. Notably, in legged organisms, foot contacts with the ground generate strong undesirable accelerations that are transmitted throughout the body via its musculo-skeletal structure. Decoupling the movement of the head from the one of the body is an efficient mean of compensating for these disturbances. Such a decoupling has been observed in humans during walking, based on vestibular data [24] and thanks to the vestibulo-collic reflex that stabilizes visual and auditory perception [32]. In [13], it was explored how this stabilization of the head could mechanically contribute to the balance of bipedal walking. In addition, the mobility of the head allows for an efficient implementation of active exploration strategies that are essential to perception [2]. Indeed, moving the head alone is more precise and requires less energy than performing whole-body exploration. This mobility however must be supported by a rich proprioception at the neck level, as observed in many animals and in humans [23].

5 The role of the head in locomotion and manipulation

The head at the front-end of the movement for locomotion. Addressing the question of the head position with regard to the body is highly relevant in the context of locomotion. Animals whose morphology is bilateral are structured along a mouth-anus axis and, except for bipeds in which this axis is verticalized, their locomotion is directed along this axis. Whatever the mode of bilateral locomotion (flight, swimming, legged locomotion,...), the head of these animals

precedes the rest of their body. The ESOs placed on the head sense the part of the environment ahead and the motor system is specialized to produce this forward movement. A very wide range of species including fishes, worms, insects, birds and mammals follow this model for locomotion. Interestingly, in engineering, such a model of locomotion directed along a main axis with specialized thrust and control has guided the conception of many vehicles. Wheeled vehicles are certainly the most representative ones among them. Thanks to the rolling-without-slipping constraint, which prevents instantaneous lateral movement, the control is greatly simplified. It boils down to two control gears, one for steering the wheels and the other one for controlling the acceleration. One can imagine how complex would be the control to stay the course and avoid drift if the wheels were spherical instead of circular. The same phenomenon applies to boats equipped with a centerboard, to planes, etc. In general, all of these systems are differentially flat, and the cascade structure of their dynamics can be controlled from a small number of variables [29]. It is thus possible to easily control the movement of a truck pulling several trailers by controlling only the leading vehicle. As for the head, the steering center of such vehicle is placed ahead to enable the pilot to perceive the part of space towards which the motion is directed.

One Head for supervising manipulation Though many animals possess their mouth as only gripper (worms, fishes, snakes, etc.), and others are equipped with several end-effectors (paws, claws, hands, tentacles) as in mammals, birds or cephalopods, in either case they only have one head. In the second group, the existence of additional effectors enables manipulation behaviors. Each end-effector could be equipped with exteroceptive sensors, although this would lead to a redundant state observation, but having a unique head makes it possible to decouple exteroceptive perception from other motor tasks. Indeed, in these animals, the head is an easily steerable multi-sensory perception platform that can use exteroceptive feedback to coordinate manipulation while providing an independent anchoring with the environment.

6 Conclusion

Though the head is a key structure in animals able to perform voluntary spatial actions (see Fig. 1) and despite the numerous computational arguments presented in this paper, today few robots are supplied with a head that actually plays a functional role in their navigation. The main reason is that robotics is still a very young science and few works really attempt to integrate multisensory perception and motor control in a robust way that would emphasize the need for such a centralizing structure. In humanoid robots for instance, the presence of the head is mostly motivated by the sake of anthropomorphism. But the root-body that is usually taken into account for modeling their external state is the waist. The reason for this choice is that most walking pattern generators are based on the dynamical link between the center of mass located near the waist in standing position and the center of pressure on the ground. As a consequence,

the pose and the velocity of the root-frame are usually not reconstructed from exteroceptive data but rely on proprioceptive measurements along the leg, plus inertial data provided by an IMU located in the trunk. Clearly, in such a scheme, the control and the observation problems appear not to be optimally connected, contrary to what could be obtained by using a head as a pivot body between exteroceptive measurement and internal motor control. In many other robots, as illustrated in Fig. 2, the root-frame used for modeling the external state is usually located along the main axis of the robot basis, in order to simplify the expression of the robot dynamics, but without real concerns of exteroceptive perception. So far, no theory exists to specify where exteroceptive sensors should be placed on a robot in order to optimize the execution of navigation tasks. If today's robots do not appear to suffer from the lack of a head, it is reasonable to assume that this structure will appear necessary as soon as tasks will require deeper multisensory and sensorimotor integration. Finally, the structural role played by the head in sensory data acquisition and processing could be involved in the emergence of higher cognitive capacities related to the representation of space, the construction of motor plans and the ability to learn and generalize.

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