A vestibular interface for natural control of steering in the locomotion of robotic artifacts: preliminary experiments

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Abstract. This work addresses the problem of developing novel interfaces for robotic systems that can allow the most natural transmission of control commands and sensory information, in the two directions. A novel approach to the development of natural interfaces is based on the detection of the human's motion intention, instead of the movement itself, as in traditional interfaces. Based on recent findings in neuroscience, the intention can be detected from anticipatory movements that naturally accompany more complex motor behaviors.

This work is aimed at validating the hypothesis that head movements can be used to detect, slightly in advance, a person's intention to execute a steering during locomotion, and that a natural interface can be developed for controlling the navigation of a robotic artifact, based on this principle. A prototype 'vestibular' interface has been developed to this purpose, based on a 3-axial artificial vestibular system, developed by part of the authors for humanoid robotics applications. Three different experimental sessions have been carried out by using: (1) a driving video-game; (2) a robotic endoscope, with a 2-DOF steering tip; and (3) a mobile robot with a camera on-board.

The experiments showed that anticipatory head movements occur even when the person is driving a device, like those used in the experiments, and that such head movements always anticipate commands to the input device. The results indicate that the proposed hypothesis is valid and that a further research effort is worthwhile in the direction of using this novel principle to develop natural interfaces, which in fact can be very useful in many tasks, with different devices.

1. Introduction

Robotics Technology is becoming more and more pervasive in human environments [1]. Robots are getting closer to human life in a variety of ways and shapes: not only as humanoids [2], but also as task-specific robotic tools, as smart robot appliances [3], and even as bionic robotic parts to be connected to the human brain and body [4]. This is in fact one of the front-edge challenges of robotics, which poses novel and critical problems not only in the design and development of human-like components, but also in the study and development of natural ways of interaction and interfacing between the natural body, especially the brain, and the robotic parts [5].

The main scientific problem in interfacing natural and robotic systems is to understand how the human brain can perceive the artificial parts as own parts and to what extent they can be controlled in a natural way by the brain. It is therefore crucial that the interfaces for bionic systems allows the most natural transmission of control commands and sensory information, in the two directions. This requires a novel approach and design method, which integrates multidisciplinary expertise and starts from models of human sensory-motor coordination for modeling and developing interfacing mechanisms that exploit them at the best, to obtain natural perception and control.

Traditional interfaces are based on user's motor actions, typically mapped onto a different geometry and kinematics, i.e. those of the input devices. Such cortical re-mapping between the motor areas involved in the use of the interface and those involved in the motor task at hand introduce an additional cognitive burden onto the users. Many authors suggest the adoption of multimodal devices to reduce the users' concerns on how to communicate the intended commands, thus making them more free to focus on the tasks and goals [6]. Furthermore, detecting the uses' motor action on the input device and transmitting it to the robot introduce a delay from when the movement is planned in the human brain to when it is accomplished by the robot.

A more suitable approach to the development of natural interfaces is based on the detection of the human's motion intention. This can be detected as it originates in the brain, by means of brain-machine interfaces [7], or when the control signal is transmitted in the nervous system to peripheral districts [8]. Nevertheless, it is argued in neuroscience that, in humans, simple movements anticipate to some extents other complex sensory-motor behaviors [9,10,11]. Such anticipatory movements may be used in a context-dependent manner for building natural and intuitive interfaces. The two main advantages of this approach are: (1) the detected movements are naturally associated with motor behaviors and as such they would not put any additional cognitive burden on the person; (2) the detected movements occur well in advance of motor behaviors and therefore they would help obtain a timely reaction in the controlled robotic system.

This work is based on the hypothesis that head movements can be used to detect, slightly in advance, a person's intention to execute a more complex sensory-motor task, i.e. steering during locomotion. In our experiments, head movements are proposed to be used as a natural interface to control and to trigger steering in the locomotion tasks performed by 3 different robotic artifacts. In the experimental scenarios of this first investigation, the subject wears a "vestibular interface" detecting his/her head position and motion and a wearable display that provides the visual feed-back coming from the on-board cameras. The person is asked to use a traditional input device to steer the robotic artifacts, while head movements are detected and recorded. The objective of this work is to experimentally show that anticipatory head movements occur even when driving different devices, that such natural head movements performed by the subject before steering are adequately detected by the vestibular interface and that they could be conveniently used to control the locomotion of a robotic device.

2. Methods and tools

2.1. Neuroscience background

In many everyday activities, humans carry out more than one motor task simultaneously, even when the motor behavior appears relatively simple. Movement sequences, defined by both the component movements and the serial order in which they are produced, are the fundamental building blocks of the motor behavior. It is known that the serial order of sequence production is strongly encoded in medial motor areas even if understanding to what extent sequences are further elaborated or encoded in primary motor cortex still remains controversial [12].

Over the last decades several efforts were dedicated to understand how the central nervous system manages the serialization of movements and a consolidate finding is the existence of *anticipatory movements* that are likely to be acquired during developmental age [13].

Broadly speaking, anticipatory movements are motor responses that support the production of the main motor activity and that occur before likely sensory events. These movements are in contrast to reflexive actions and are necessary to compensate for delays present in sensory and motor systems. Smooth pursuit eye movements are often used as a paradigmatic example for the study of anticipation [14,15].

Many authors have investigated various types of anticipation. For example, Land et al. [9] reported that during everyday activities, gaze fixations always are close to the object being manipulated, and very few fixations are irrelevant to the task occurred. Moreover, gaze arrives at the object to be manipulated some 0.5 seconds before any indication of manipulation. Johansson et al. [10] demonstrated that gaze in manipulation tasks consistently fixates future object contact points well before the hand reaches these locations and anticipates reaching trajectory via-points. In a similar way, head movements are believed to anticipate body motions, such as turning while walking [11,16]. Some neuroscientific bases that may explain the anticipatory triggering of orienting reactions may lie in the neural networks governing head direction in space during navigation. In this case, it is suggested that anticipatory orienting synergies belong to the behavioral repertoire of human navigation and may reflect the need to prepare a stable reference frame for the intended action.

In our work, we make use of some acquired findings of neuroscience research in order to provide a motivated novel approach to the design of innovative natural interfaces. These interfaces will exploit the information carried by the anticipatory movements for a better understanding and detection of upcoming complex motor actions.

2.2. The vestibular interface

This work has been carried out by using a 3-axial artificial vestibular system, developed by the authors for humanoid robotics applications, to be mounted on anthropomorphic robotic heads [17]. The artificial vestibular system is inspired by the main functional characteristics of the human vestibular system, detecting head linear accelerations and angular velocities along 3 axes. It integrates 1 tri-axial accelerometer and 3 uni-axial gyroscopes in order to similarly detect linear accelerations and angular velocities along 3 axes. All the electronic components are mounted on a single surface, thus limiting the total system dimension and weight and allowing a suitable mounting both on robotic and human heads. The sensors used for the design of the vestibular interface are: 2 mono-axial Piezoeletric Vibrating Gyroscopes (GYROSTAR®, by muRata), 1 mono-axial ultra small Vibration Gyro sensor (XV-3500CB, by Epson) and 1 ultrasmall tri-axial accelerometer module (H48C, by Hitachi), as shown in Fig.1.

The gyroscopes working principle is based on the detection of the Coriolis force, which is generated when a rotational angular velocity is applied to the vibrator inside the sensor. All the sensors used are extremely small and lightweight and provide movement information that are adequate to the requested application. The Piezoeletric Vibrating

Gyroscopes by muRata is used for the angular velocity detection around the Pitch and the Roll axis, while the mono-axial gyroscope XV-3500CB is employed for detecting the angular velocity around the Yaw axis. This device is a complete angular rate sensor with all of the required electronics on one chip. The mono-axial gyroscope XV-3500CB offers the particular feature of measuring the angular velocity around an axis orthogonal to its mounting surface. In this way, all the 3 gyroscopes can be integrated on a single plane, as shown in the CAD drawing (Fig.2).

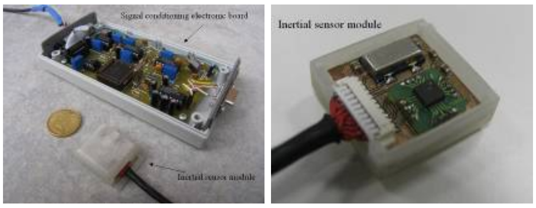

Fig. 1. Prototype of Artificial Vestibular System and signal conditioning electronic board.

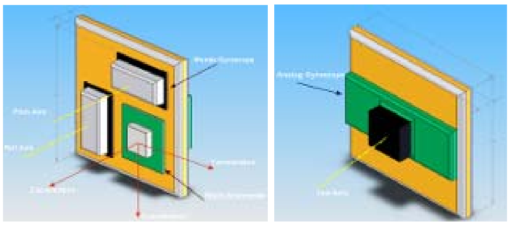

Fig. 2. CAD drawing of prototype artificial vestibular system: (left) top and (right) view.

The tri-axial accelerometer module H48C is composed of a MEMS technology sensor's chip and of a CMOS-IC chip with the op-amplifiers. As for the 3 mono-axial gyroscopes even the tri-axial accelerometer can be placed on the same plane therefore allowing a strong miniaturization of the total system. The A/D conversion, amplification and filtering of the several signals are processed by a specifically designed and developed electronic board. This is composed of 14 operational amplifiers for the filtering and the amplification of the signals and by a 20 MHz PIC 16F877 for the conversion of the signals from analog to digital. The board is connected to the PC by means of a standard RS-232 port using serial codification information (Fig.1). All the channels are filtered with a high-pass filter with a cut-off frequency of approximately 0.3 Hz in order to reduce the effect of temperature drift, while a low-pass filter with a cut-off frequency of approximately 6 Hz has been connected to suppress output noise component. The filtered signals are then amplified with a two stages operation amplifier allowing to modulate the total gain of amplification according to the operating range of the specific application. Table 1 shows the range of total amplification gain for all the suitable sensor outputs and their corresponding values of full scale and resolution.

TABLE I. ELECTRONIC BOARD TOTAL AMPLIFICATION GAINS

	Electronic board total amplification gain						
	Total gain		***Full Scale (+/-)***		***Sensitivity***		
	Min	***Max***	***Min***	***Max***	***Min***	***Max***	
MuRata Gyros	10	77	1 [rad/s]	5.2 [rad/s]	9.76E-4 [rad/s]	5.11E-3 [rad/s]	
Epson Gyros	10	77	1 [rad/s]	4.5 [rad/s]	9.76E-4 [rad/s]	5.11E-3 [rad/s]	
Hitachi Accelerometer	1	4.24	1.5 [g]	3[g]	1.46E-3 [g]	2.93E-3 [g]	

Moreover, a dedicated software, with a GUI (Fig.3), has been developed for the further steps of signal processing and integration.

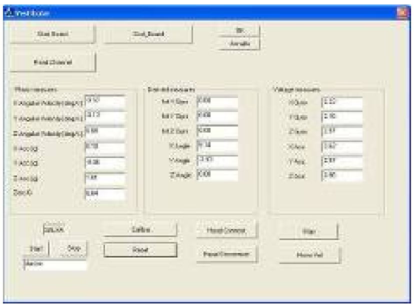

Fig. 3. GUI of the artificial vestibular system.

The whole module for signal processing consists of two subsequent steps of elaboration: filtering and amplification. In the first step, in order to suppress high-frequency noise, a real-time fourth order single-pass Butterworth low-pass filter with a cut-off frequency of 6 Hz is applied to all the sensor outputs (voltage measures). In the second phase, the voltage measures are amplified according to the sensor scale factor, converted into the respective physical values (angular velocities for the gyroscopes; accelerations for the accelerometers) and filtered again:. In this application the system calibration was performed according to existing well-known procedures [18]. Finally, the static angle of the artificial vestibular system on the pitch and roll axes was calculated from the accelerometer outputs, while dynamic angles were obtained from the gyroscopes outputs by means of numerical trapezoidal integration.

3. Experimental Validation

3.1. Experimental methodology

In order to investigate the principle of a vestibular interface based on head anticipatory movements, experimental trials were set-up in which head motion were compared with the actions on a traditional input interface, during driving tasks. This kind of experiments was aimed at identifying: (1) if head motion actually anticipates steering, even when driving different devices, instead of walking; (2) if the timely detection of head motion can be used to enhance the interface in driving.

The experimental validation was organized in three sessions. The common set-up for the three experimental sessions consists of a number of subjects wearing the prototype vestibular interface, on top of their heads, and a binocular wearable display (I-Glasses by Video Pro 3D), for visual feedback. In all the three sessions the subjects were asked to perform a driving task, but different devices were driven in the three sessions, with different input interfaces:

1. *driving video game*: a commercial video game was used in this session, where a car is driven by a using a gamepad by Logitech, along a rally circuit. This experiment was conceived in order to investigate the working hypothesis when the subjects are asked to drive a virtual artifact, and receive images of a simulated environment;
2. *robotic endoscope*: the navigation trials were performed by using a robotic endoscope with a 2-DOF steering tip and a simulated bent tube. A joystick was used as input interface, and the image from the endoscope tip was sent to the subject as visual feedback. In this case, the device to be controlled is a real system, though the environment is not ‘natural’ for the subject, and so the feedback images;
3. *mobile robot*: a small robotic platform with wheels and a camera on-board was set-up for this session. The subjects were asked to drive the mobile robot by using a mouse, in a doorway passage task. The images from the on-board camera were fed back to the subject. In this case, the robotic platform performed a real navigation in a real environment that is natural for human locomotion.

3.2. Experimental trials with the driving game

Eight subjects were involved in the experimental trials with the driving video game, and each of them was asked to perform three full laps in a circuit with 7 turns. The subjects were given a view of the circuit from inside the car and they could give the following commands: (1) steer right; (2) steer left; (3) speed up; (4) slow down.

The input interface, i.e. the gamepad, was modified so as to record the actions selected by the subject. Specifically, the left and right steering commands were recorded. At the same time, the 6 signals generated by the vestibular interface worn by the subject were recorded and synchronized with those coming from the gamepad. See Fig.4 for a view of the experimental scenario.

Fig. 4. A view of the experimental trials with the driving game

The signals from the vestibular interface were compared with those from the input interface and the synchronization was achieved by using an audio trigger. The signal corresponding to the angular velocity of the head during rotation (yaw axis) resulted to have a good correlation with the signals corresponding to right and left steering. Typical results are depicted in Fig.5 that shows the two signals recorded in one of the trials. If looking at the zero-crossing of the head velocity (i.e. the local minima of the head position) it is clear how they always anticipate a steering command. The time of anticipation is in average close to 0.5 sec. Also, the versus of the head rotation is coherent with the corresponding steering command even if the amplitude of the two signals is not always proportional. Additional actions on the input interface can be observed, which are not anticipated by a head rotation. These usually correspond to adjustments of the car heading, especially after side-slips.

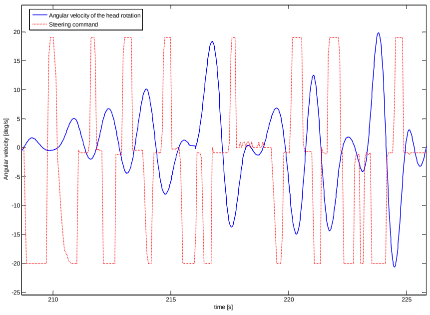

Fig. 5. Compared angular velocity of head rotation and movement of the input device in right-left steering, in the case of the driving game

3.3. Experimental trials with the robotic endoscope

The robotic endoscope used in the second experimental session was designed and developed for spinal neuroendoscopy, a minimally invasive technique aimed at exploring the subarachnoid space inside the spine. Due to the narrow dimensions of the lumen (its thickness ranges from 2 up to 8mm in humans) and to the presence of fragile nerve roots and blood vessels [19], unassisted manual neuroendoscopy is impossible to be done in practice. To this aim, a robotic endoscope for neuroendoscopy has been already proposed by part of the authors [19]. It consists of three main units: the *end effector* is a flexible multi-material multi-lumen catheter, whose external diameter is 2.7mm, housing 10 longitudinal channels: the endoscope (0.5mm of diameter, 6000 pixels of resolution) is hosted in the central one, while the steering capabilities are ensured by 3 pulling cables (hosted in three lateral channels), actuated by the *Intelligent Drive Unit:* it interprets the driving commands from the surgeon, tests their safety by means of a vision-based software module (the *Cognitive Unit*), and transfers them to a set of two stepper motors, pulling the steering cables. The *Cognitive Unit* processes all the information coming from the endoscopic camera and from the sensory system attached to the patient. It co-operates with the surgeon, implementing a shared control strategy during the intervention, for example by preventing him from performing too dangerous maneuvers: a *segmentation module* recognizes dangerous structures (e.g. blood vessels and nerve roots) in the image from the camera; a *navigation module* keeps trace of their position and structure even when they exit the field of view of the endoscope. A more detailed description of these two vision-related sub-systems was presented in [20]. The combined action of the *Cognitive Unit* and the *Drive Unit* is intended to overcome erroneous maneuvers of the surgeon, so as to ensure safe navigation. In Fig.6, a comprehensive view of the robotic endoscopic platform is shown, with a detail of the motor unit and the steering tip.

Fig. 6. On the left the robot-assisted endoscopic platform is set in the operating room; on the right, from top to bottom, the motor unit and the steerable catheter tip are shown.

The experimental task was done in a mock-up simulating the navigation inside a curved white plastic tube; where the lumen appeared as a black circular spot in the endoscope image, which was fed back to the subjects through the wearable display. The subjects were asked to navigate towards the end of the tube, by keeping the black spot in the center of the image field. They used a joystick as input device. The signals coming from the vestibular interface and from the input joystick interface were synchronized and compared. Fig.7 shows the signal corresponding to the angular velocity of the head during rotation (along the yaw axis) and the signal corresponding to right-left steering, for one of the trials.

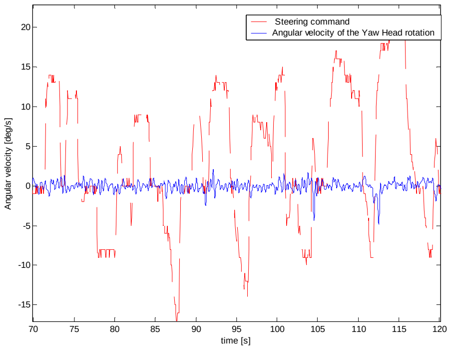

Fig. 7. Compared angular velocity of head rotation and movement of the input device in right-left steering, in the case of the robotic endoscope

In this session the movements of the head during the experimental task were negligible. We envisage two main possible reasons explaining the lack of anticipatory movements of the head in this experimental scenario: first of all, the smaller dimensions of the image, as well as the narrow field of view of the endoscope are such that the subject could not have a real 'immersive' perception; secondarily, this task could have been perceived as a precision task, i.e. heading towards the black spot of the lumen, rather than as a navigation task.

3.4. Experimental trials with the mobile robot

A Pioneer I mobile robot by RWI was equipped with a digital video camera, as an experimental platform for the third sessions of experiments. A mouse was set-up as the input interface for driving the robot. The image was fed back to the subject through the wearable display.

The task asked to the subjects was to pass through a door, located at a distance of approximately 30 cm from the robot starting position, and to turn left in a corridor just after the doorway passage. A typical example of the task, with the real path and the superimposed velocity vectors during the path, is reported in Fig.8.

During the task, the robot was remotely operated by moving a mouse on a flat desk. The forward-backward movement of the mouse controlled the direction of motion whereas the amplitude of the movement controlled the velocity of the robot that was set between -400 mm/s (backward direction) and +400 mm/s (forward direction). A polynomial relation between mouse movements and robot velocity was implemented in order to avoid abrupt velocity variations possibly related to small movements of the input device.

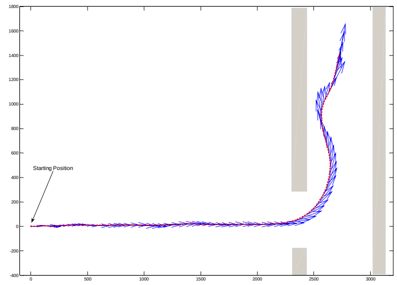

Fig.8. Example of the robot path with superimposed velocity vectors along the path

The steering of the robot was controlled using the left-right movements of the input device. In this case, in order to achieve a more reactive behavior of the robot, the central plateau of the previous control curve was avoided in favor of a sinus-like relation between the steering command and the steering velocity. With this tuning, even for movements of small amplitude, the steering velocities of the robotic platform was comparable to the velocities of rotation of the head and the users reported good sensations during the navigation. Both curves are reported in Fig.9. During each experiment, the odometric data of the robot (i.e. position, orientation and velocities) were recorded together with the data coming from the vestibular interface an from the input device. All the data were synchronized using an audio signal trigger.

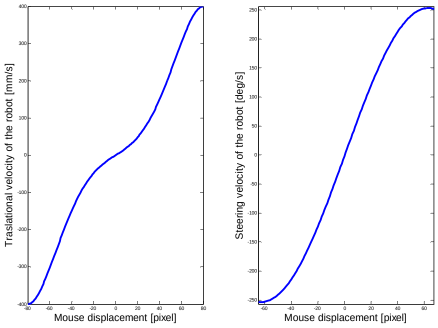

Fig. 9. Relation between mouse displacement and corresponding (left) translational velocity and (right) steering velocity

The synchronized signals from the vestibular interface and from the input interface are compared in Fig.10, for one of the experimental trials. In this case, too, the signal corresponding to the angular velocity of the head in rotation (yaw axis) resulted to have the best correlations with the signals corresponding to right-left steering. In this experiment the only remarkable event is the one occurring immediately after the passage of the door when a rapid steering command is issued to the robot in order to turn the corner. This happens approximately 7 to 8 seconds after the task starting. Then the steering command is kept constant for about 1 second and then another corrective steering is issued in order to adjust the alignment of the robot with the corridor. It is worth noticing that in both cases the steering command is anticipated by a coherent rapid movement of the head in the same direction that starts about 0.6 s before the steering command. Moreover, by looking at the zero-crossing of the head velocity it may be noticed that the head movement is almost completed in the very beginning of the steering command.

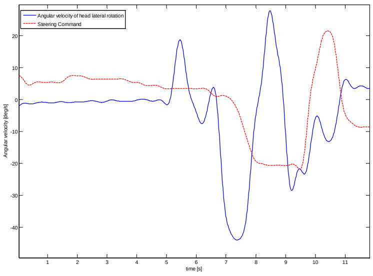

Fig.10. Compared angular velocity of head rotation and movement of the input device in right-left steering, in the case of the mobile robot

4. Conclusions

This work has investigated for the first time the hypothesis that natural interfaces can be developed, based on anticipatory movements that are demonstrated to be involuntarily associated with more complex motor behaviors, in humans. This is in fact a novel principle for natural interfaces, deriving from a joint investigation by roboticists and neuroscientists, which integrates multidisciplinary expertise. The proposed approach starts from models of human sensory-motor coordination for modeling and developing interfacing mechanisms that exploit them at the best to obtain natural perception and control.

Preliminary experiments have been conducted for the case of the head anticipatory movements associated with steering, during locomotion. The results obtained with three different experimental set-ups showed that anticipatory head movements occur even when the person is driving a device, like those used in sessions 1 and 3 of the experiments, instead of being walking. Actually, for one of the experimental scenario this result was not obtained. A comparative analysis of the three cases induces to think that a critical role is played by the perception that the person can have of navigation/locomotion. This was in fact reduced in the second scenario, due to the smaller dimensions of the image and the narrow field of view. This interpretation may be further confirmed by some preliminary results that we obtained when the feedback was given to the user by mean of a traditional monitor rather than using a wearable display. In these cases, we were not able to detect any significant movement of the head in none of the above reported scenarios. This circumstance was in fact perceived by the user not as a fully-immersive navigation but rather as a driving task of an external artifact.

Experimental results also showed that head movements always anticipate commands to the input device: though steering commands may be issued even without an anticipatory head movement, when a head movement is detected a related action on the input device can always be detected as well.

Also, the head movements occurred visibly in advance with respect to the steering command, e.g. up to 0.5 sec, which is a significantly anticipation in case it is used for controlling a robotic device.

In conclusion, the results obtained with this first experimental work indicate that the proposed hypothesis is valid and that a further research effort is worthwhile in the direction of using this novel principle to develop natural interfaces, which in fact can be very useful in many tasks, with different devices.

Further developments will concern the use of the signals from the vestibular interface for controlling a robotic device, thus realizing a real interfacing mechanism. An evaluation of the improvement of the control of the device, as well as of the perceived friendliness and easiness of use of the interface will be then possible and needed.

Acknowledgments

Part of the work described in this paper has been supported by the EU within the NEUROBOTICS Project (The fusion of NEUROscience and roBOTICS, IST-FET Project #2003-001917), and the MiNOSC Project (MicroNeuroendoscopy of Spinal Cord, IST-R&D Project #QLG5-CT-2001-02150).

The authors wish to especially acknowledge the fruitful discussions and collaboration with Prof. Alain Berthoz, Prof. Joe Mc Intyre, Prof. Roland Johansson and Prof. Ben Edin.

The first development of the artificial vestibular system was conducted with the support of the Humanoid Robotics Institute (HRI) of the Waseda University, at RoboCasa, a joint laboratory supported by the Italian Ministry of Foreign Affairs, General Directorate for Cultural Promotion and Cooperation.

References

[1] Y. Hirata, “Robot Technologies for Human-Robot Cooperation Systems in Ubiquitous Age”, in *2003 International Symposium on Microelectronics*, Boston, MA, USA, November 16-20, 2003, pp.560-565

[2] A. Knoll, G. Bekey, T. C. Henderson, “Cui bono robo sapiens?” *Robotics and autonomous systems, Special Issue on Humanoid Robots*, 37(2-3):73–80, Elsevier Science, 2001.

[3] M.J. Johnson, E. Guglielmelli, C. Suppo, A. Pisetta, F. Leoni, G.A. Di Lauro, M.C. Carrozza, C. Laschi, P. Dario, “A fetch-and-carry robot appliance for elderly and disabled persons”, in *Assistive Technology – Shaping the Future*, G.M. Craddock,

L.P. McCormack, R.B. Reilly, H.T.P. Knops (Ed.s), Assistive Technology Research Series, IOS Press, 2003, pp.534-538.

[4] P. Dario, Sandini G., Aebischer P. (Eds), *Robots and Biological Systems: Towards a New Bionics?*, NATO ASI Series, Springer-Verlag, 1993.

[5] M. Gasson, B. Hutt, I. Goodhew, P. Kyberd, K. Warwick, "Bi-directional human machine interface via direct neural connection", *2002 IEEE International Workshop on Robot and Human Interactive Communication*, Berlin, Germany, September 2002.

[6] D. Perzanowski, A.C. Schultz, W. Adams, E. Marsh, M. Bugajska, "Building a Multimodal Human-Robot Interface"; *IEEE Intelligent Systems*, Vol.16, Issue 1, Jan-Feb 2001 pp.16-21.

[7] J.M. Carmena, M.A. Lebedev, R.E. Crist, J.E. O'Doherty, D.M. Santucci, D.F. Dimitrov, P.G. Patil, C.S. Henriquez, M.A.L. Nicolelis, "Learning to Control a Brain–Machine Interface for Reaching and Grasping by Primates", *PLoS Biology*, Volume 1, Issue 2, 2003, pp. 193-208.

[8] X. Navarro, T.B. Krueger, N. Lago, S. Micera, P. Dario, T. Stieglitz, "A critical review of interfaces with the peripheral nervous system for the control of neuroprostheses and hybrid bionic systems", *J Pher Nerv Sys*, 2005 (accepted).

[9] Land M., Mennie N., Rusted J. "The roles of vision and eye movements in the control of activities of daily living". *Perception* 28(11):1311-1328, 1999.

[10] R.S. Johansson, G.B. Westling, A. Backstrom, J.R. Flanagan, "Eye-hand coordination in object manipulation", *Journal of Neuroscience*, 21:6917-6932, 2001.

[11] A. Berthoz, *The Brain's Sense of Movement: Perspectives in Cognitive Neuroscience*, Harvard University Press, June 2000.

[12] X. Lu, J. Ashe, "Anticipatory activity in primary motor cortex codes memorized movement sequences", *Neuron*. 2005 Mar 24;45(6):967-73.

[13] J.C. Van der Heide, B. Otten, L.A. van Eykern, M. Hadders-Algra, "Development of postural adjustments during reaching in sitting children", *Exp Brain Res.* 2003 Jul;151(1):32-45.

[14] E. Kowler, A.J. Martins, M. Pavel, "The effect of expectations on slow oculomotor control-IV. Anticipatory smooth eye movements depend on prior target motions", *Vision Res* (1984) 24:197-210;

[15] S.G. Wells, G.R. Barnes (1998) Fast, anticipatory smooth-pursuit eye movements appear to depend on a short-term store. *Exp Brain Res* 120:129-33.

[16] R. Grasso, P. Prévost, Y.P. Ivanenko, A. Berthoz, "Eye-head coordination for the steering of locomotion in humans: an anticipatory synergy", Neuroscience Letters 253 (1998) 115-118

[17] F. Patanè, C. Laschi, H. Miwa, E. Guglielmelli, P. Dario, A. Takanishi, "Design and development of a biologically-inspired artificial vestibular system for robot heads", *IROS 2004, IEEE/RSJ International Conference on Intelligent Robots and Systems*, Sendai, Japan, September 28 – October 3, 2004.

[18] F. Ferraris, U. Grimaldi, M. Parvis, "Procedure for Effortless In-Field Calibration of Three –Axis Rate Gyros and Accelerometers", Sensors and Materials 1995, vol. 7(5), p. 311-330

[19] L. Ascari, C. Stefanini, A. Menciassi, S. Sahoo, P. Rabischong, P. Dario, "A New Active Microendoscope for Exploring the Sub-arachnoid Space in the Spinal Cord", *IEEE International Conference on Robotics and Automation (ICRA)*, Taipei, September 19-22, 2003.

[20] L. Ascari, U. Bertocchi, C. Laschi, C. Stefanini, A. Starita, P. Dario, "A segmentation algorithm for a robotic microendoscope for exploration of the subarachnoid space", *IEEE International Conference on Robotics and Automation (ICRA)*, New Orleans, USA, April 28-30, 2004.